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Äspö Hard Rock Laboratory

Annual Report 2001

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 and the associated research, development, and demonstration tasks, which are managed by the Repository Technology Department within SKB, has 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 a deep repository.

Experiments are performed at Äspö HRL at conditions that are expected to prevail at repository depth, with the aim to increase the knowledge of the long term function of the repository barriers. Another aim with the Äspö HRL is testing of models for groundwater flow, radionuclide migration, chemical and biological processes. The programme for the testing of models includes evaluation of the usefulness and reliability of different models and the development and testing of 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 Experiment, Microbial Project, Colloid Project, and Matrix Water Chemistry Experiments.

The overall objectives of the Tracer Retention Understanding Experiments (TRUE) are to increase the understanding of the processes, which govern the retention of radionuclides in crystalline rock, and to increase the credibility in models used for radionuclide transport calculations, which will be used in licensing of a deep repository. The basic idea of the experiments is to perform a series of in-situ tracer tests with progressively increasing complexity. In principle, each tracer experiment consist of a series of activities beginning with geological characterisation of the selected site, followed by hydraulic and tracer tests, after which epoxy resin is injected in the rock volume. Subsequently, the tested rock volume are excavated and analysed with respect to flow path geometry and tracer concentration. During 2001 five modelling teams have evaluated the TRUE Block Scale tracer tests. In the modelling work it was demonstrated that the used approaches all share the same conceptual basis. It was further shown that the actual differences lie mainly in how many of the immobile retention zones that were included and the way in which heterogeneity in retention parameters is accounted for. Tracer retention understanding experiments are continued within three projects TRUE Block Scale Continuation, TRUE-1 Continuation, and the Long Term Diffusion Experiment.

The Long Term Diffusion Experiment (LTDE), with a duration of 3–4 years, is intended as a compliment to the in-situ experiments and the laboratory experiments performed within the TRUE programme. LTDE is performed to investigate diffusion of solutes into matrix rock under conditions similar to those expected to prevail in a deep repository. The preparations for the experiment included a comprehensive update of the structural model of the investigated site. The ongoing installation of the experimental set-up and the installation of the surface equipment will be followed by series of pre-tests and equipment tests. Thereafter the actual experiment will be started.

Radionuclide Retention Experiments are carried out with the aim to confirm results of laboratory studies performed at conditions similar to those in the field concerning e.g. contents of colloids, organic matter, and bacteria in the groundwater. The experiments are carried out both in the laboratory and in special borehole probes, CHEMLAB 1 and CHEMLAB 2. During 2001 experiments to study migration of actinides (americium, neptunium and plutonium) have been carried out in a drill core in CHEMLAB 2. This core showed a very different behaviour compared to a core used in laboratory experiments. Cutting of the cores indicated that the core studied in the laboratory had an open fracture, whereas, the core studied in CHEMLAB 2 showed only partly open fractures and wide parts of that core had healed fractures which could not be related to flow paths.

The Colloid Project comprises studies of the colloid stability and mobility as well as the role of bentonite clay as a source for colloid generation. In addition, the colloid concentration in groundwater at Äspö HRL will be verified and the potential for colloid formation and transport in natural groundwater will be investigated. The Colloid Project comprises laboratory experiments as well as field tests. A conclusion from the laboratory tests, which have been evaluated during 2001, is that the bentonite colloid formation is strongly correlated to the ionic strength. Colloid formation is favourable at an ionic strength of 0.01 M, whereas, very low concentration of formed colloids is found in suspensions with higher ionic strengths, 0.1 and 1 M.

The Microbe Project has been initiated for studies of microbial activity in groundwater. In-situ generated data will be obtained for microbial activities in the far- and near-field environment at realistic repository conditions, which can only be achieved at underground sites, developed for microbiological research. Three experimental sites have been opened at Äspö HRL. The deepest Microbe site is on the 450-m level and consists of three core-drilled boreholes intersecting water-conducting fractures. This site will be used for e.g. investigations of bio-mobilisation of radionuclides. The second site has a constructed shallow pond with unique populations of sulphur oxidising bacteria that will be used for investigations of biogeochemical cycling of sulphur. The third site, at 296 m depth, is equipped with open flow channels feed with groundwater from a packed off borehole. At this site trace element retention by biological iron oxide systems will be studied. During 2001 most activities have been focussed on planning, equipping and preparing for experiments. The experiments will start during 2002 and run for several years.

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 Matrix Fluid Chemistry experiments 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 most important activities during 2001 have been sampling and analysis of matrix groundwater, completion of pore water diffusion experiments, a pilot study on geological evidence for influence of diffusion processes on pore water chemistry, and a final Matrix Fluid Workshop.

The activities at Äspö HRL include the evaluation of the usefulness and reliability of different calculation models and the development and testing of methods for determination of parameters required as input to the models. An important part of this work is performed in the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes, an international co-operation project. The work within the Tasks 4 and 5 were reported during 2001 and the work within Task 6, Performance Assessment Modelling Using Site Characterisation Data, has started.

Repository technology

The Äspö HRL makes it possible to demonstrate and perform full-scale tests of the function of different components of the repository system that are important for the performance and the long term safety of a repository. It is also important to show that high quality can be achieved in design, construction, and operation of the repository. To fulfil these 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, and Pillar Stability Experiment.

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. During 2001 the canisters and bentonite in an inner section with four deposition holes have been installed and the tunnel in this section has been backfilled and plugged. The experiment is planned to continue during at least 10 and possibly up to 20 years. Instruments are installed to monitor processes and properties in the canister, buffer material, backfill, and the near-field rock. In the outer section the two additional canisters will be installed.

The Backfill and Plug Test has the aim to test different backfill materials, emplacement methods, and full-scale plugging. It is also a test of the hydraulic and mechanical function of the backfill materials and their interaction with the near-field rock. The entire test set-up with backfill, instrumentation and building of the plug was finished in autumn 1999. The inner part of the tunnel is filled with a mixture of bentonite and crushed rock (30/70) and the outer part is filled with crushed rock. Wetting of the backfill through permeable mats started in late 1999 and has continued during the years 2000 and 2001. Water saturation, water pressure and swelling pressure in the backfill and water pressure in the surrounding rock have been continuously measured and recorded. During 2001 it was decided to increase the water pressure in the mats to 400 kPa in four steps, to shorten the time to fully saturate the backfill mixture (30/70), from 5 to less than 2 years.

In the Canister Retrieval Test two full-scale deposition holes have been drilled for the purpose of testing technology for retrieval of canisters after the buffer has become saturated. One full size canister with electrical heaters surrounded by bentonite was installed during year 2000. The heaters were turned on in October 2000 at a constant effect of 1700 W. In February 2001, when the temperature on the canister surface reached approximately 65°C, the effect was increased to 2600 W to obtain a surface temperature of 90°C. Problems with short-circuit in the electrical system of the heaters occurred in the end of 2001. However, it has been possible to provide the needed experimental conditions and the heating has continued. The plan is to continue the artificial water supply and the heating until the bentonite buffer has been fully saturated. Thereafter the technology for retrievel of canisters will be tested.

The Long Term Tests of Buffer Material aim to validate models and hypotheses concerning physical properties in a bentonite buffer and of related processes such as bentonite degradation, microbiology, copper corrosion and gas transport in buffer material under conditions similar to expected repository conditions and at adverse conditions. Adverse conditions in this context refer to high temperatures, high temperature gradients over the buffer, and additional accessory minerals leading to i.a. high pH and high potassium concentration in clay pore water. The testing principle is to emplace "parcels" containing a central tube with an electrical heater, 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. Totally, 7 parcels have been installed. The power in one of the 1-year test parcels was turned off in October 2001. The parcel was brought up with overlapping core drilling and was thereafter split for delivery to the involved laboratories for analysis. The remaining long term test parcels have been functioning without any major problems during the year and temperature, total pressure, water pressure, and water content have been continuously measured and registered every hour.

A Pillar Stability Experiment has been initiated to complement an earlier study performed at URL in Canada. The major aims are to demonstrate the capability to predict spalling in fractured rock mass and the effect of the buffer on the propagation of micro cracks. A feasibility study and preliminary design of an experiment at Äspö HRL were completed during 2001.

The focus of the Task Force on Engineered Barrier Systems during 2001 has been on modelling of THM processes taking place in the bentonite buffer during saturation. This is also the prime modelling objective in the Prototype Repository and the work has therefore been conducted under the umbrella of the Prototype Repository.

Äspö facility

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 2001. To meet the need for additional office space to host the staff of the site investigation in Oskarshamn a temporary barrack was built and an application for planning permission for additional extension of the Äspö surface facility has been submitted.

An extensive rock reinforcement programme was finalised in February 2001. The programme comprises complementary shotcreting, injections, bolting and mounting of mesh. Replacement of corroded light equipment in the deeper half of the tunnel, 220–450 m level, and replacement of sealing on the water pipes in the shaft, 350–450 m level, have been completed.

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 Äspö HRL and the SKB siting programme. During 2001, Äspö HRL had 12 348 visitors representing the general public, communities where SKB has performed feasibility studies, teachers, students, politicians, journalists and visitors from foreign countries.

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.

In the GeoMod Project the existing geological, geomechanical, geohydrological and hydrogeochemical models of Äspö are being updated by integrating new data collected since 1995. The updated models focus on a volume including the tunnel spiral volume from about 340 m to about 500 m.

International co-operation

Nine organisations from eight countries have participated in the Äspö HRL research in addition to SKB during 2001. Most of the organisations are interested in groundwater flow, radionuclide transport and rock characterisation. Several organisations are participating in the experimental work as well as in the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes.

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

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. 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, egenskaper och pågående fysikaliska, kemiska samt biologiska processer benämns djupförvarets naturliga barriärer. Dessa kommer att påverkar integriteten hos djupförvarets barriärer liksom transporten av radionuklider.

Vid Äspölaboratoriet genomförs experiment, vid förhållanden som motsvarar de som förväntas råda på förvarsdjup. Målet med experimenten är att öka kunskapen om långtidsegenskaperna hos djupförvarets barriärer. Ett annat mål med verksamheten vid Äspölaboratoriet är att testa beräkningsmodeller för grundvattenströmning, radionuklidtransport, kemiska och 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 Experiment”, ”Microbial Project”, ”Colloid Project” och ”Matrix Water Chemistry Experiments”.

Bergets förmåga att fördröja transporten studeras med hjälp av spårämnesförsök i ”Tracer Retention Understanding Experiments (TRUE)”. Syftet är att öka förståelsen för de processer som styr fördröjningen av radionuklider samt att öka tillförlitligheten hos de modeller som kommer att användas för beräkning av radionuklidtransport vid licensieringen av djupförvaret. Avsikten med experimenten är att genomföra en serie spårämnesförsök med successivt ökande komplexitet. I princip består varje försök av en serie aktiviteter. Till att börja med genomförs geologisk karakterisering av experimentplatsen, denna följs av hydrauliska tester och spårämnesförsök varefter epoxy injiceras i bergvolymen. Avslutningsvis tas den undersökta bergvolymen ut och flödesvägarnas geometri och koncentrationen av spårämnen analysers. Under år 2001 har fem modelleringsgrupper utvärderat spårämnesförsöken i experimentet ”TRUE Block Scale”. Modelleringsarbetet visade att använda angreppssätt vilar på samma konceptuella bas. Modelleringen visade också att skillnader mellan modellerna huvudsakligen berodde på hur många immobila fördröjningszoner som inkluderats och hur hänsyn tagits till heterogeniteter i de parametrar som beskriver fördröjningen av radionuklider. Spårämnesförsöken fortsätter i tre projekt ”TRUE Block Scale Continuation”, ”TRUE-1 Continuation” och ”Long Term Diffusion Experiment”.

Ett komplement till de spårämnesförsök som genomförs inom TRUE-programmet är ”Long Term Diffusion Experiment (LTDE)”. LTDE kommer att genomföras under 3 till 4 år med syftet att undersöka diffusion av lösta ämnen i bergmatrisen vid förhållanden som liknar de som förväntas i ett djupförvar. I förberedelserna av experimentet ingick en omfattande uppdatering av den strukturella modellen för experimentplatsen. Den pågående installationen av experimentuppställning och utrustningen vid markytan kommer att följas av en serie inledande experiment samt tester av utrustningen. När detta är avslutat kommer själva experimentet påbörjas.

Fördröjning av radionuklider studeras i ”Radionuclide Retention Experiments”. Syftet med experimenten är att bekräfta resultat som erhållits i laboratorieexperiment vid förhållanden som liknar de som råder på förvarsdjup med avseende på till exempel förekomst av kolloider, organiskt material och bakterier i grundvattnet. Experiment genomförs på borrhålskärnor både i laboratorium och i specialutvecklad borrhålsutrusning, CHEMLAB 1 och CHEMLAB 2. Under 2001 genomfördes experiment för att studera migrationen av aktinider (americium, neptunium och plutonium) i en borrhålskärna i CHEMLAB 2. Den studerade kärnan uppvisade ett helt annat beteende jämfört med en kärna som använts i laboratorieexperiment. När borrkärnorna snittades såg man att den borrhålskärna som studerats i laboratoriet hade en öppen spricka, och den kärna som studerats i CHEMLAB 2 hade en spricka som bara delvis var öppen och stora delar av den kärnan hade läkta sprickor vilka inte kunde relateras till några flödesvägar.

Syftet med ”Colloid Project” är att studera stabilitet och rörlighet hos kolloider samt bentonitlerans betydelse som källa för kolloidbildning. Dessutom ingår att verifiera kolloidkoncentrationen i grundvattnen från Äspölaboratoriet samt att undersöka potentialen för bildning och transport av kolloider i naturliga vatten. Projektet omfattar både laboratorieförsök och fältstudier. En slutsats från laboratorieförsöken, som utvärderats under 2001, är att bildningen av bentonitkolloider är starkt beroende av jonstyrkan. En jonstyrka på 0,01 M främjar bildningen av kolloider medan mycket låga koncentrationer av bildade kolloider uppmättes vid högre jonstyrkor, 0,1 och 1 M.

För att studera den mikrobiella aktiviteten i grundvatten har ”Microbe Project” initierats. Fältdata för mikrobiell aktivitet i miljöer representativa för fjärr- och närzon i ett djupförvar kommer att kunna erhållas på platser under jord som anpassas till mikrobiell forskning. Tre experimentplatser har upprättats i Äspölaboratoriet. Den djupast belägna platsen ligger på 450 m nivån och består av tre kärnborrhål som skär vattenförande sprickor. Här kommer till exempel undersökning av radionukliders biomobilisering att undersökas. På den andra platsen har en grund damm anlagts. Dammen innehåller en unik population av svaveloxiderande bakterier vilka kommer att användas för att undersöka svavels biogeokemiska cykel. Den tredje platsen, på 296 m nivån, är utrustad med en öppen kanal som förses med grundvatten från ett borrhål. På denna plats kan fördröjningen av spårämnen i biologiska järnoxidsystem studeras. Under 2001 har aktiviteter inom projektet fokuserat på planering, framtagning av utrustning och förberedelser av experimenten. Experimenten kommer att starta under 2002 och pågå under flera år.

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. I projektet ingår en förstudie som omfattar lakning och permeabilitetsexperiment på material från en borrkärna. I förstudien ingår även lakförsök på krossat material. Fullskaleprogrammet omfattar provtagning och analys av matrisvatten från en isolerad borrhålssektion. De viktigaste aktiviteterna under 2001 har varit provtagning och analys av matrisvatten, slutförande av diffusionsexperiment i porvatten, en pilotstudie avseende geologiska bevis för inverkan av diffusionsprocessen på porvattenkemin samt ett avslutande arbetsmöte.

Aktiviteterna vid Äspölaboratoriet omfattar även att utvärdera användbarheten och tillförlitligheten hos olika beräkningsmodeller samt att utveckla 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 inom Task 4 och Task 5 har rapporterats under 2001 och arbetet inom Task 6 ”Performance Assessment Modelling Using Site Characterisation Data” har startat.

Förvarsteknik

I Äspölaboratoriet kan, för långsiktig säkerhet, 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. För att uppnå detta pågår ett flertal projekt, till exempel ”Demonstration of Repository Technology”, ”Prototype Repository”, ”Backfill and Plug Test”, ”Canister Retrieval Test”, ”Long Term Tests of Buffer Material” och ”Pillar Stability Experiment”.

Demonstration av deponering av kapslar under strålskärmade förhållanden i fullstor skala genomförs inom ramen för projektet ”Demonstration of Repository Technology” som också 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. Under 2001 har kapslar och bentonit installerats i de fyra hålen i den inre sektionen, vilken har återfyllts och pluggats igen. Experimentet kommer att pågå under minst 10 eller möjligen upp till 20 år. Mätinstrument har installerats för att registrera processer i och egenskaper hos kapsel, buffertmaterial, återfyllnad och omgivande berg. I den yttre sektionen kommer ytterligare två kapslar att installeras.

Testning av olika återfyllnadsmaterial, metoder för inplacering och pluggning av tunnlar genomförs i ”Backfill and Plug Test”. Experimentet utgör en test av hydraulisk och mekanisk funktion hos återfyllnadsmaterial samt dess inverkan på omgivande berg. Hösten 1999 var återfyllnadsmaterialet, instrumentering och pluggen installerade. Den inre delen av tunneln är fylld med en blandning av 30% bentonit och 70% krossat berg och den yttre delen är fylld med krossat berg. I slutet av 1999 påbörjades bevätning av återfyllnaden via permeabla mattor och denna har sedan fortsatt under 2000 och 2001. Vattenmättnad, vattentryck och svälltryck i återfyllnaden samt vattentryck i det omgivande berget mäts kontinuerligt och registreras. Under 2001 beslöt man att öka vattentrycket i mattorna till 400 kPa, i fyra steg, för att förkorta tiden för att uppnå full vattenmättnad i återfyllnaden (30/70) från 5 till mindre än 2 år.

I ”Canister Retrieval Test” har två fullstora deponeringshål borrats med syftet att testa teknik för återtag av kapslar efter det att den omgivande bentonitbufferten har vattenmättats. En fullstor kapsel med elektriska värmare omgiven av bentonit installerades under år 2000 i ett av deponeringshålen. Värmarna, med en effekt på 1700 W, sattes på i oktober 2000. I februari 2001, när temperaturen på kapselns yta uppnått 65°C, ökades effekten till 2600 W för att kapselns yttemperatur ska uppnå 90°C. I slutet av 2001 upptäcktes kortslutningar i värmarnas elektriska system. Trots detta, har det varit möjligt att fortsätta uppvärmningen och de nödvändiga experimentella förhållandena har kunnat upprätthållas. Planen är att fortsätta uppvärmningen av kapseln och den artificiella bevätningen av bufferten tills bufferten är fullständigt vattenmättad. Därefter kommer teknik för återtag av kapslar att testas.

Långtidstester av buffertmaterial som syftar till att validera modeller och hypoteser relaterade till buffertens fysikaliska egenskaperna samt processer som berör mikrobiologi, radionuklidtransport, kopparkorrosion och gastransport genomförs i ”Long Term Tests of Buffer Material (LOT)”. Experimentet genomförs både under förhållanden som liknar de som förväntas i ett djupförvar och under ogynnsamma förhållanden. Ogynnsamma förhållanden innebär i detta sammanhang hög salthalt i grundvattnet, hög temperatur, hög temperaturgradient över bufferten, högt pH och hög kaliumkoncentration i bentonitlerans porer. Testmetodiken innebär att paket som innehåller ett rör med elektriskvärmare, kompakterad bentonit, instrumentering och kontrollutrustning placeras i 4 m djupa borrhåll med en diameter på 300 mm. Totalt har sju paket deponerats. Strömmen till värmaren i ett av ettårspaketen stängdes av i oktober 2001. Paketet togs upp med hjälp av överborrning och delades upp i bitar som skickades för analys till de olika laboratorier som deltar i projektet. De övriga deponerade paketen som ingår långtidstestet har fungerat utan några större problem under året. Temperatur, totalt tryck, vattentryck och vatteninnehåll mäts kontinuerligt och registreras varje timme.

Projektet ”Pillar Stability Experiment” har initierats vid Äspölaboratoriet för att demonstrera möjligheterna att förutsäga ny sprickbildning (spalling) runt deponeringshål i sprickigt berg. I projektet kommer även buffertens påverkan på utbredningen av mikrosprickor runt deponeringshål att studeras. Projektet är en komplettering till en tidigare studie som genomförts i URL Canada. Under 2001 har en förstudie slutförts och en preliminär utformning av ett experiment i Äspölaboratoriet tagits fram.

Under 2001 har arbetet inom ”Task Force on Engineered Barrier Systems” fokuserats på modellering av de THM-processer som äger rum i bentonitbufferten under vattenuppmättnaden. Eftersom dessa processer också har utgjort fokus för det modelleringsarbete som pågått inom ”Prototype Repository” har allt modelleringsarbete bedrivits inom ramen för projektet ”Prototype Repository”.

Äspöanläggningen

Driften av Äspöanläggningen har gått programenligt. Ett antal nya projekt rörande skydd, säkerhet och tillgänglighet i anläggningen har initierats, startats eller slutförts under 2001. För att möta behovet av ytterligare kontorsutrymmen för personalen som deltar i platsundersökningen i Oskarhamn har en tillfällig barack byggts. Dessutom har en bygglovsansökan för en ytterligare utbyggnad av ovanjordsanläggningen lämnats in.

Ett omfattande bergförstärkningsprogram slutfördes i februari 2001. Programmet omfattade komplettering av sprutbetong, cementinjektering, bergbultar och förstärkningsnät. Rostig belysningsarmatur i den djupare delen av tunneln (220–450 m nivå) har ersatts liksom tätningar på vattenledningarna i schaktet (350–450 m nivå).

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, Äspölaboratoriet och SKB:s program för platsvalet. Under år 2001 besökte 12 348 personer Äspölaboratoriet. De representerade allmänheten, kommuner där SKB bedrivit förstudier, lärare, politiker, journalister och besökare från andra länder.

En viktig del av verksamheten vid Äspöanläggningen 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. Registrering av förändringar i grundvattnet (hydrauliska och kemiska) hanteras via en direktanslutning till HMS (Hydro Monitoring System).

Inom projektet GeoMod genomförs en uppdatering av de geologiska, geomekaniska, geohydrologiska och hydrogeokemiska modellerna över Äspö, genom att data som samlats in efter 1995 inkluderas. De uppdaterade modellerna fokuserar på en bergvolym som inkluderar den spiralformade tunneln från cirka 340 m till 500 m nivån.

Internationellt samarbete

Under 2001 har nio organisationer deltagit i forskningen 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”.

Avdelningen Djupförvarsteknik, inom SKB, koordinerar två EU-kontrakt ”Prototype Repository” och ”Cluster Repository Project” (CROP). SKB deltar även i flera andra EU-projekt varav deltagandet i fem sker via avdelningen Djupförvarsteknik: FEBEX II, BENCHPAR, ECOCLAY II, SAFETI och PADAMOT.

Contents

1 General

1.1 Background

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

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

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

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

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

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

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

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

- Develop, test, evaluate and demonstrate methods for repository design and construction, and deposition of spent nuclear fuel and other long-lived waste.
- Develop and test alternative technology with the potential to reduce costs and simplify the deep repository concept without sacrificing quality and safety.

- Increase the scientific understanding of the deep repository's safety margins and provide data for safety assessments of the long term safety of the repository.
- Provide experience and train personnel for various tasks in the deep repository.
- Provide information to outsiders on technology and methods that are being developed for the deep repository.

1.3 Organisation

SKB's internal organisation was changed during 2001 to meet the main near term goal, which is to execute site investigations. The new organisation, see Figure 1-2, is set up to provide a focus of activities and use of resources to the site investigations, including drilling, which commence in 2002. The strategy to reach this goal is described in a supplementary report to the RD&D Report 1998 focusing of the issues of repository method, site selection process and site investigation activities, dated December 2000 /SKB, 2000/. The former organisation of SKB is shown in /SKB, 2001b/.

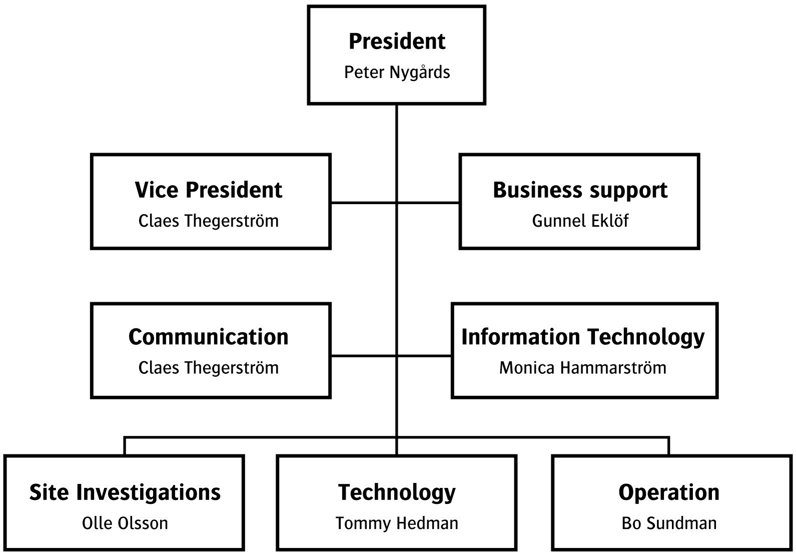


Figure 1-2. *SKB's new internal organisation.*

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

- *Safety and Science (TS)* is responsible for research, safety assessments, and systems analysis.
- *Repository Technology (TD)* is responsible for development and testing of deep repository technology and in-situ research on repository barriers at natural conditions. The unit is also responsible for the operation of the Äspö facility and the co-ordination of the research performed in international co-operation.
- *Encapsulation Technology (TI)* is responsible for development and testing of the copper canister and the design of the Encapsulation Plant. This unit is also responsible for the operation of the Encapsulation Laboratory located in Oskarshamn.
- *Large Projects (TP)* is responsible for large construction projects. Presently the main task of this unit is the construction of CLAB 2 – the expansion of CLAB to a total storage capacity of 8000 tons of spent nuclear fuel.
- *Repository Design (TU)* is responsible for the design and layout of the deep repository. Presently site specific layouts are being developed for the two sites where site investigations are being performed. This department is also responsible for development of the technology needed to build, operate and seal the repository.

1.3.1 Repository Technology and Äspö Hard Rock Laboratory

The new organisation of SKB also involves the organisation of the Repository Technology unit. The Repository Technology unit will be organised in three operative groups (Figure 1-3):

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

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

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.

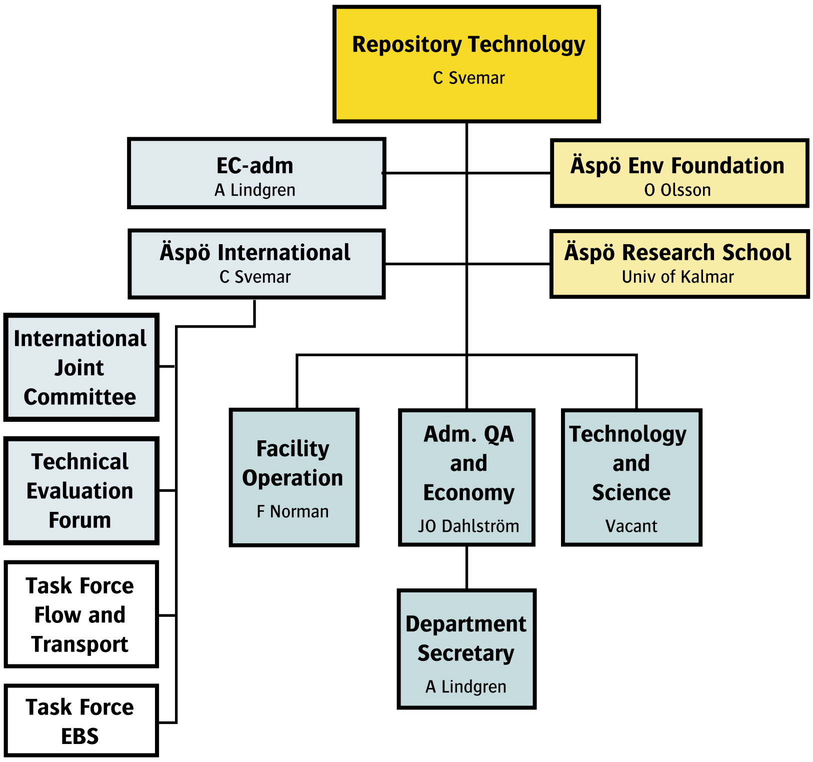


Figure 1-3. New organisation of Repository Technology and Äspö HRL.

1.3.2 International participation in Äspö HRL

The Äspö HRL has so far attracted considerable international interest. Nine organisations from eight countries have been participating in the Äspö HRL in addition to SKB during 2001. The participating organisations are:

- Agence Nationale pour la Gestion des Déchets Radioactifs (ANDRA), France.
- Bundesministerium für Wirtschaft und Technologie (BMWi), Germany.
- Central Research Institute of Electric Power Industry (CRIEPI), Japan.
- Empresa Nacional de Residuos Radiactivos (ENRESA), Spain.
- Japan Nuclear Cycle Development Institute (JNC), Japan.
- Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (NAGRA), Switzerland.
- Nirex Limited (Nirex), United Kingdom (left the co-operation work during 2001).
- Posiva Oy, Finland.
- United States Department of Energy, Carlsbad Field Office (USDOE CBFO).

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

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

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

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

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

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.

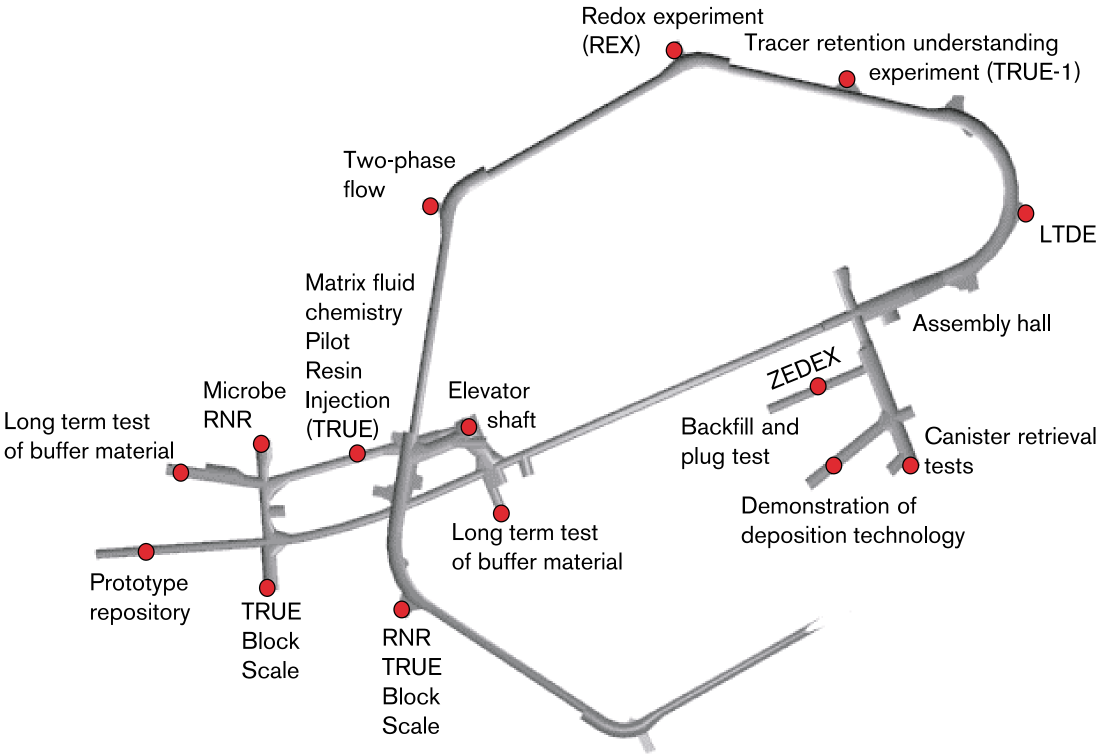


Figure 1-4. Underground excavations at the 300–450 m levels and allocation of experimental sites.

1.5 Reporting

Äspö HRL is an important part of SKB's RD&D-Programme. The 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. The highest report series is the TR (Technical Report) series with grey cover followed by IPR (International Progress Report) having a "yellow" cover. Reports in both those series may be referred to in other works and may be distributed to third party. ITD (International Technical Reports) and TD (Technical Reports) represent the lowest ranked series and are intended for facilitating quick distribution of results and constitute working material which may not be publicly referred to or spread to third party.

Basically 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 (TR)	Director Repository Technology	SKB
Planning Reports – Detailed plans covering each calendar year (IPR)	Contributors	Director Repository Technology
Annual Reports – Summary of work covering each calendar year (TR)	Repository Technology unit	Director Repository Technology
Status Reports – Short summary of work covering each 3 month period (IPR)	Principal Investigators Project Managers	Director Repository Technology
Technical Reports (TR)	Project Manager	Director Repository Technology
International Progress Reports (IPR)	Project Manager	Director Repository Technology
International 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.

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

2 Methodology for detailed characterisation of rock underground

2.1 General

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

The objectives are:

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

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

2.2 Underground measurement methods and methodology

2.2.1 Background

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

2.2.2 Objectives

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

2.2.3 Results

A report on underground investigation methods used during the Construction Phase of the Äspö HRL that is planned to be published during 2002 is being worked on. The report will describe the different methods used with regard to instrument or other working tools and measurement methodology. Resolution and accuracy of the measured values as well as general aspects of errors will be discussed. The evaluation part will address the usefulness and feasibility of the methods. Recommendations on possible modifications will also be given.

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

3 Natural barriers

3.1 General

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

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

The overall purposes are to:

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

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

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

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

A summary of the results obtained, from experiments at Äspö HRL and related analysis performed, within the programme Natural Barriers during the period 1995–2000 is given in /SKB, 2001c/. The ongoing or planned experiments at Äspö HRL are:

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

In addition, to the experiments conceptual and numerical models for groundwater flow and solute transport have been developed through the entire Äspö Project.

3.2 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 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, which will be used in licensing of a repository.

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

Objectives

The TRUE experiments should achieve the following general objectives:

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

Experimental concept

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

Together with supporting laboratory studies of diffusion and sorption characteristics made on core samples, the results of the in-situ tests will provide a basis for integrating data on different scales, and testing of modelling capabilities for radionuclide transport up to a 100 m scale, see Figure 3-1.

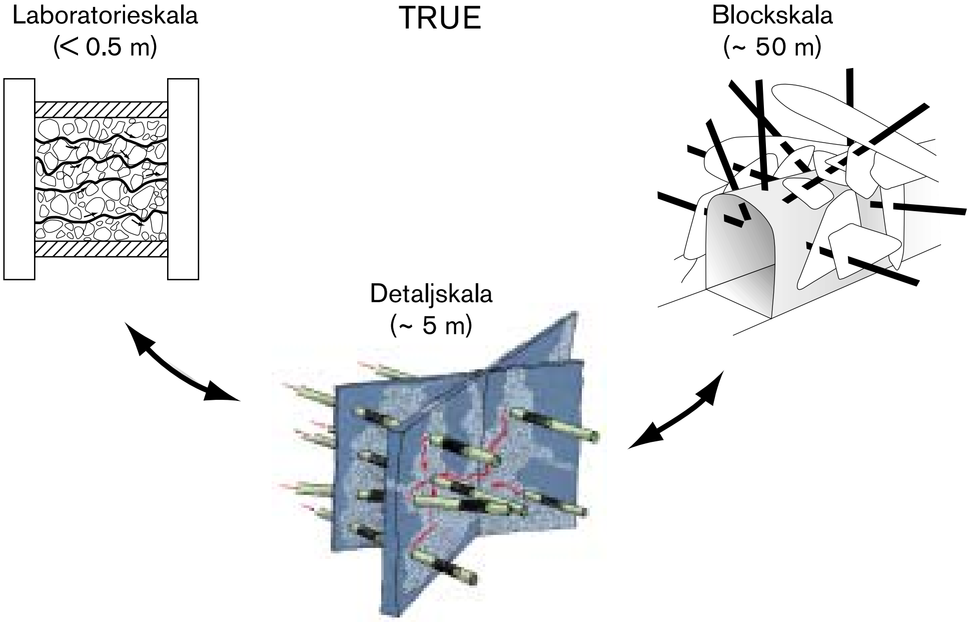


Figure 3-1. *Schematic representation of transport scales addressed in the TRUE programme.*

3.2.1 TRUE Block Scale

Background

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

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

- Increase 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.

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

1. Scoping Stage.
2. Preliminary Characterisation Stage.
3. Detailed Characterisation Stage.
4. Tracer Test Stage.
5. Evaluation and Reporting Stage.

The total duration of the project is planned to be approximately 5 years with a scheduled finish mid 2002.

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

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

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

Tentative modelling work started up during 1997 using a discrete feature network model (DFN). During 1998, the modelling work has diversified with the inclusion of stochastic continuum and channel network modelling approaches. In addition a site scale DFN model has been constructed to allow analysis of density effects and also to generate boundary conditions for the models constructed on a smaller scale. The groundwater chemical data collected from the packed off sections were used in the integrated inter pretation of groundwater flow in the studied block. During the year one structural model update was produced (Sep '98 model) /Winberg, 1999/ which was presented in conjunction with the 2nd Review meeting in November 1998.

During 1999 focus was shifted towards planning and preparations for the upcoming Tracer Test Stage. Work in the field was concentrated on verifying interpreted structures and a structural model was developed based on the new field data including data from the most recent borehole KI0025F02 to form the March '99 structural model. Another important component was the performance of a Pre-test tracer test campaign which clearly demonstrated the feasibility of block scale tracer tests in the selected rock block. Scoping model calculations were also performed to analyse effects of fracture intersections. In a document which provided an outline of the planned Tracer Test Stage /Winberg, 2000/ it was recommended to drill one additional borehole to facilitate verification of the structural model and shorter transport distances. Furthermore, basic questions to be addressed by the tracer tests were formulated and a corresponding set of hypotheses was defined. The plans for the Tracer Test Stage were discussed at the 3rd TRUE Block Scale Review Meeting in October 1999.

The plan to drill a new borehole KI0025F03 was accepted and it was drilled and characterised during the fall of 1999.

The most recent model update, the March 2000 Hydrostructural Model, Figure 3-2, is based on the characterisation data from the new borehole KI0025F03. In building the model the new and existing hydraulic data has been used to reconcile the model /Hermanson and Doe, 2000/. As part of the preparations for the numerical model predictions of the planned tracer tests, simplified conceptualisations of individual intercepts of interpreted deterministic structures, as well as composite structural models of interpreted structures along their extents were constructed.

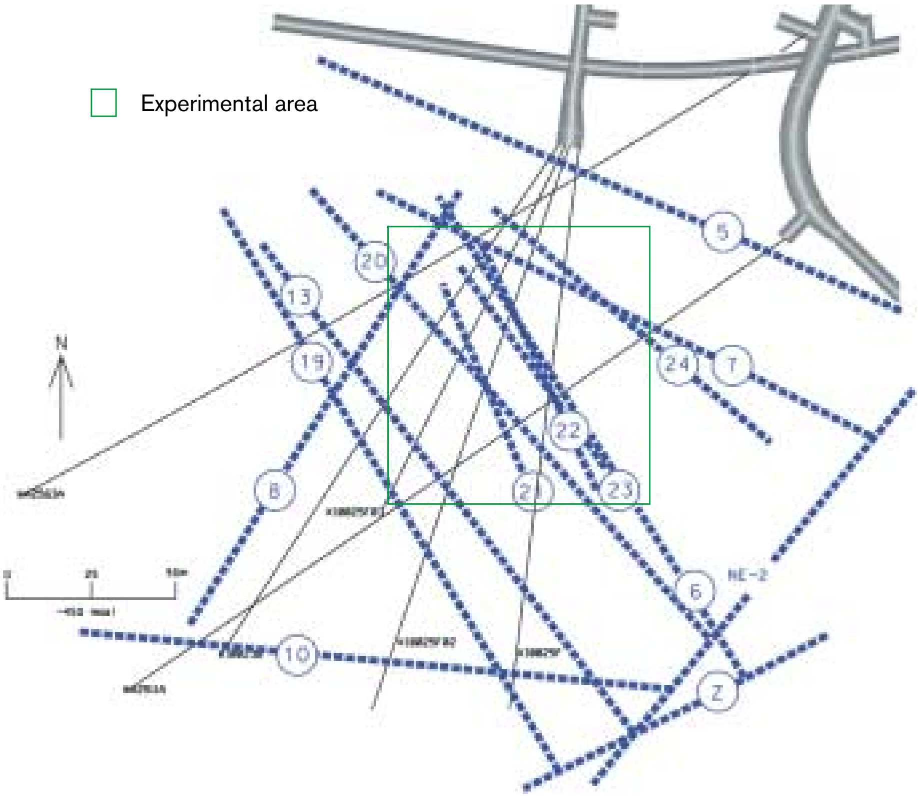


Figure 3-2. March 2000 Hydrostructural Model /Hermanson and Doe, 2000/.

No site-specific through-diffusion or batch sorption experiments were performed on materials from the TRUE Block Scale site. However, a comprehensive mineralogical and geochemical analyses programme was performed. This included analyses made on altered wall rock, fault breccia pieces > 2 mm and the smallest fractions < 2 mm and < 0.125 mm, respectively. Of the latter some 15–45 weight-% comprise the fraction < 0.002 mm, featured by a variable degree of enrichment in clay minerals, calcite, pyrite and FeOOH. Using the measured water chemistry, selectivity coefficients, and mineral-specific cation exchange capacities reported in the literature, integrated cation exchange capacities were calculated for the fine-grained fault gouge material (< 0.125 mm). Subsequently, by applying the cation exchange sorption model, the sorption distribution coefficient (K_d) for the mono- and divalent cations to be used as tracers in the planned Phase C were calculated.

Collected geological samples from structures of interest in the TRUE Block Scale rock block have also been subject to porosity determinations. Two techniques were employed; the water saturation technique and the ^{14}C PMMA method /e.g. Hellmuth et al, 1999/.

Porosity determinations with the two methods were applied to three types of materials; altered wall rock, centimetre sized pieces and millimetre sized fragments of fault breccia. For the first time the ^{14}C PMMA technique was applied to the latter small fractions of crystalline rock. The global picture of porosity, which emanates from the water saturation measurements, is one with a porosity of the intact Äspö diorite bedrock of around 0.40%, and where the higher porosity is found for the fault breccia fragments with porosity in the range of 1.5 to 3%. A conceptual cross-section through a typical conductive structure at the TRUE Block Scale site is shown in Figure 3-3.

The Tracer Test Stage included a sequence of three test phases, denoted A through C /Winberg, 2000/. Phase A /Andersson et al, 2000a/ was focused on identification of suitable injection sections using tracer dilution tests (Tests A1 through A3) and on identification of the best suitable sink sections (Tests A4 and A5). The latter tests were deliberately not continued to complete mass recovery because of time constraints.

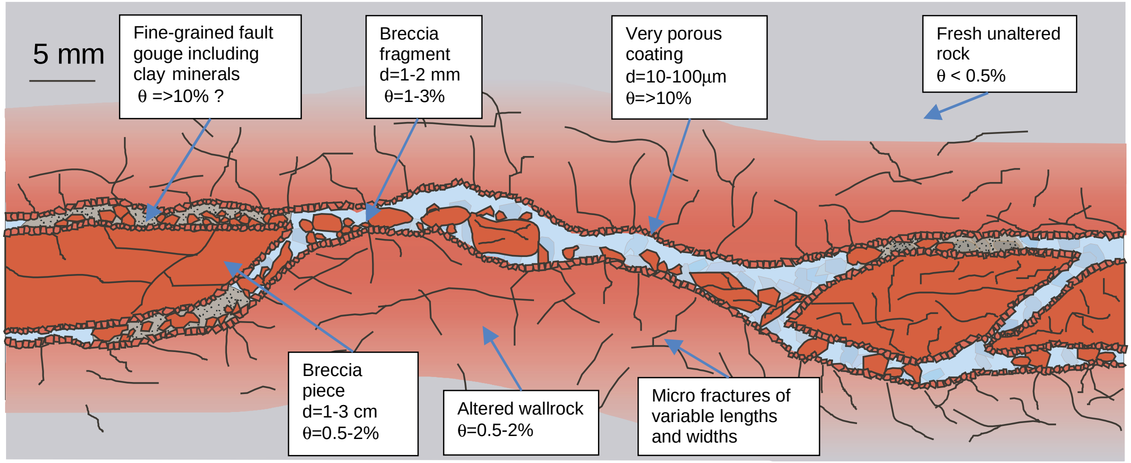


***Figure 3-3**. Conceptual cross-section through a typical conductive structure in the TRUE Block Scale rock volume.*

The principle objective of Phase B /Andersson et al, 2000b/ was to demonstrate sufficiently high mass recovery (> 80%) of flow paths selected for radioactive sorbing tracers, and also to demonstrate matrix diffusion through the use of dissolved ^{3}He gas and variable piping flow rate. The final Phase C comprised a series of four injections with radioactive tracers in three different source-sink pairs involving one or more of the interpreted deterministic structures. In total, 13 flow paths with measurable breakthrough over distances ranging between 12–120 m and mean travel times of 1.5 to 2200 hours have been characterised. Of these, at least 4 flow paths show recoveries > 80% (of which three have been used for Phase C tests). Three flow paths with projected distances 35–50 m show no breakthrough (time is a possible constraint).

The Phase C tests /Andersson et al, 2001/ were carried out using the results of the Phase B tests as a base. The injection of the radioactive tracers was made without interrupting the continuous pumping in KI0023B:P6 at a flow rate of 1.95 l/min. The injections were made in radially converging flow geometry using basically the same equipment and methodology for injection/sampling and analyses used for TRUE-1. In sections with low flow rates, the tracer was forced into the flow path by applying a slight excess pressure using an external injection pump. The projected excess pressure, created by the injection flow rates (10 ml/min or 45 ml/min), was assumed to produce strongly unequal strength dipole flow fields. The location of the injection sections in relation to the pump section is shown in plan view in Figure 3-4. The injections were performed in three Flow paths I, II, and III. Flow path I is interpreted as essentially being made up of one single Structure (#20) although the pumping is made in Structure #21. Flow path II is made up of > 2 structures involving Structures #23, #22 and #20, and Flow path III is assumed to be entirely located in Structure #21.

An interesting observation with regards to the Phase C tests is the observed non-breakthrough of Rb (injection C3) and Cs (injection C2) observed over distances of 30 and 100 m respectively, over a time scale of half a year. The injection C4, made in the same source-sink pair as injection C1, constitutes an in-situ test of radionuclides with a sorption mechanism governed by partial radiolysis and surface complexation. The injection C4, which featured injection of ^{54}Mn, ^{57}Co, ^{65}Zn shows breakthrough of ^{54}Mn, only slight recovery of ^{57}Co and no breakthrough of ^{65}Zn, which is in parity with the hypothesis set up beforehand.

The tests with sorbing tracers in the block scale have been highly successful and constitute a valuable database on transport and retention in the block scale. In conclusion, the possibility to run high quality informative sorbing tracer tests in a block scale network of structures has been successfully demonstrated.

During 2000, two more modelling concepts were included in the palette of modelling approaches; the LaSAR approach /Cvetkovic et al, 1999, 2000/ extended to the block scale and the Posiva stream-tube approach /Hautojärvi and Taivassalo, 1994/. The modelling was devoted to evaluation and calibration of data from the Phase A and Phase B tests, respectively. Following the necessary calibration using information from the Phase A and Phase B tests, the Phase C tracer tests were predicted using all five modelling approaches, including the Stochastic Continuum (ENRESA), Discrete Feature Network (Nirex) and Pipe Channel Network concepts (JNC/Golder).

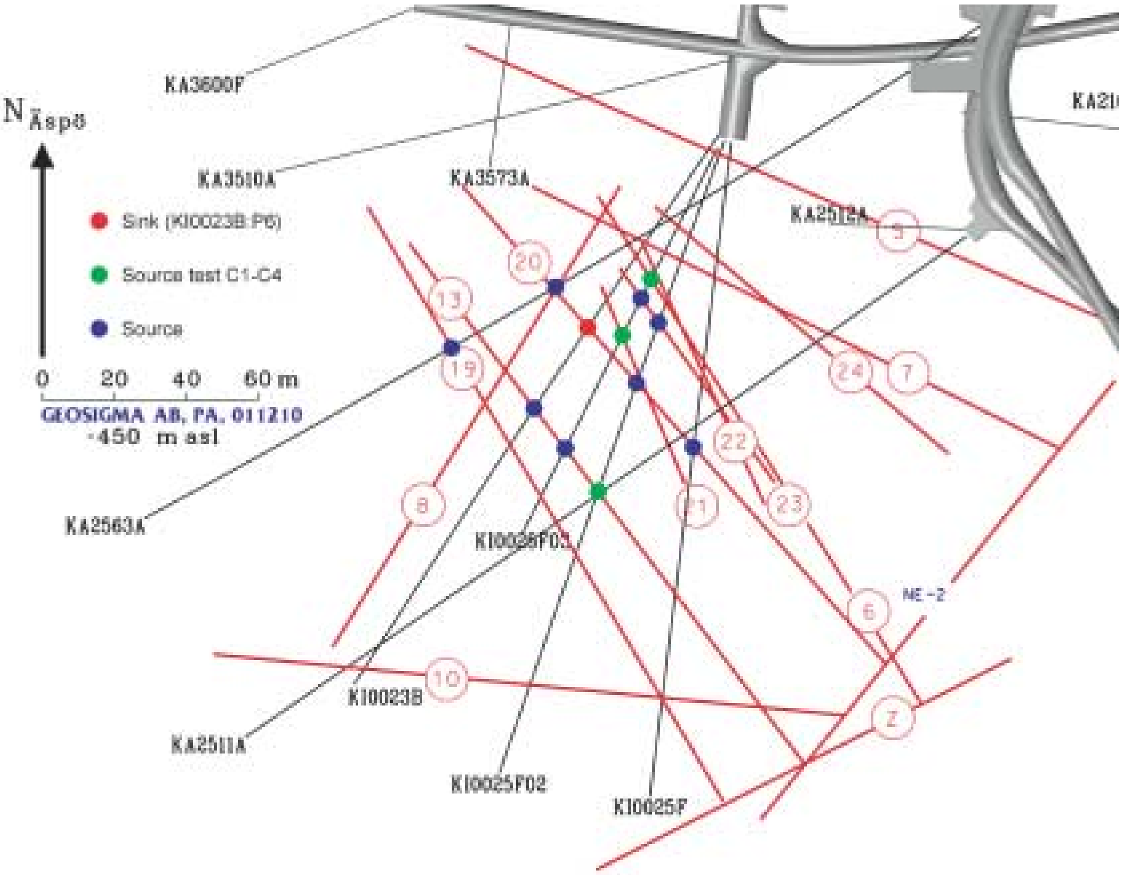


***Figure 3-4**. Detail of March 2000 Hydrostructural Model showing the layout of pumping section and injection sections used in the Phase C tests.*

Results

Evaluation modelling

During the year the Phase C tracer tests have been evaluated on an individual basis by the five modelling teams using the approaches mentioned above.

The Enresa/UPV-UPC team concludes on the basis of their analysis that retention plays an important role to interpret the tracer tests with sorbing tracer tests. Among the retention mechanisms, matrix diffusion is considered the most important one.

The Nirex/Serco Assurance team identifies that it is impossible to explain sorbing breakthrough curves with equilibrium surface sorption alone. It is also noted that the parameters governing the matrix diffusion differ from those from the laboratory, there is need of a more porous material than an intact unaltered rock with a porosity of 0.4%.

The JNC/Golder team evaluates sorption parameters about 1.3–100 times higher than the corresponding values for intact rock matrix. The physical nature of the increased sorption is attributed to an increased area for diffusion along the transport path, either through multiple reactive surfaces within the fracture, or by an increased width of the transport path.

The Posiva/VTT team identify the surface sorption and matrix diffusion to fault gouge as the main retention mechanisms for the sorbing tracers. In the case of the non-sorbing tracers the main retention mechanism is attributed to stagnant zones along the flow paths. Indications are that stagnant regions may be of importance for the retention of the least sorbing tracers too. The Posiva/VTT team also presented a conceptualisation of the transport channels where a spatial correlation of the velocity fields was in the order of centimetres. This was identified as mutually supportive to the interpreted interdistance of stagnant zones in the order of 2–5 cm.

The SKB/WRE team focused their analysis on the effects of variability in retention parameters (porosity) perpendicular to the fracture surfaces and longitudinally along the flow path. The results indicated that an increase in longitudinal variability (standard deviation) in porosity (assuming lognormal distribution) had an equivalent effect as an increase in average porosity. This fact was found to significantly affect estimates of the slope *k* in the τβ-relationship /e.g. Cvetkovic et al, 2000/. The implication being that ignorance/neglect of the longitudinal variability in porosity could entail uncertainty in the estimates of *k* within a factor 6. Similarly a variability in porosity normal to the fracture, going from high porosity at the surface and decreasing with distance within the first few centimetres to the background porosity of the intact unaltered matrix rock, could result in uncertainty in the K_d estimate for the strongly sorbing tracers. The SKB/WRE team provided evaluation tables with in-situ estimates of K_d's and effective diffusivities for a set of assumed porosity intervals.

In the compilation and comparison of the modelling results /Poteri et al, 2002/ it was demonstrated that the modelling concepts/approaches for transport share the same common conceptual basis. The ability to demonstrate this kinship, despite obvious differences in how macro-scale conductive structures are represented, constitutes an important step towards a de-dramatisation of the overall differences between modelling approaches. It is further shown that the actual differences lie mainly in a) how many of the immobile retention zones that are included and b) the way in which heterogeneity in retention parameters is accounted for (if accounted for at all). Additional tools for the comparison are water residence times obtained from calculation of Dirac pulses (for differentiation of effects of flow-fields) and comparative tabulations of evaluated/assigned retention parameters.

In addition, a basic evaluation of the Phase C tests using a 1D advective-dispersive model has been carried out by SKB/GEOSIGMA /Andersson et al, 2002b/. The latter evaluation was also presented at the Migration '01 conference. In the latter evaluation the retention is lumped into a matrix diffusion/sorption parameter (A). It was noted that the evaluated in-situ retention was significantly higher than what could be projected on the basis of the available laboratory data on the rock matrix. In addition it was noted that the retention in the Flow path I was equitable to that seen in the TRUE-1 Feature A /Winberg et al, 2000/. The retention noted in the Flow paths II and III, for the tracers that showed breakthrough, is interpreted to be somewhat higher (within a factor 2) compared to that seen for Flow path I. Overall Flow path III seems to show the highest retention. Of interest is also the evaluated dispersivities which suggest that Flow path III is much more complicated than suggested by the assumed 33 m long single structure flow path. Similarly, the Flow path II is assumed to have a length somewhere midway between the Euclidean distance (17 m) and the distance interpreted on the basis of the hydrostructural model (97 m).

Final reporting

During the past year work started up on the first three of a series of four final reports that will present the results, findings and conclusions of the TRUE Block Scale project. The four volumes and their main conclusions are:

I) Characterisation and model development /Andersson et al, 2002a/

- The main set of tools for determining the conductive geometry is combined borehole television (BIPS), flow logging (Posiva difference flow metre), and pressure responses from drilling/cross-hole interference tests.
- The developed hydro-structural model combined with the understanding of the hydraulic behaviour obtained from cross-hole and tracer dilution tests made it possible to identify a target area for well-controlled tracer experiments.
- The validity of the hydro-structural model, which should be regarded as a hypothesis in it-self, will be subject to further testing as part of the evaluation of the performed Phase C tracer tests.

II) Tracer tests in the block scale /Andersson et al, 2002b/

- The tracer tests performed cover a very large span of distances (11–130 m) and travel times (1.5 > 2000 hours), providing a unique transport data set for fractured crystalline bedrock.
- The interpretation and evaluation of the tracer breakthrough curves indicate responses of a heterogeneous system, both in single and multiple structure source-sink pairs.
- In-situ retention, expressed as the ratio ($R_{50\%}$) between the time at which 50% of the sorbing tracer has arrived relative to the corresponding time of the conservative tracer, indicates a similar degree of retention in Flow path I (tested by injections C1 and C4) and the Feature A in TRUE-1. The Flow paths II and III tested by injections C2 and C3 show a somewhat increased retention, with the highest retention noted for Flow path III.

III) Modelling of flow and transport /Poteri et al, 2002/

- The observed retention of radioactive sorbing tracers cannot be explained by equilibrium surface sorption alone.
- It is concluded that the hydrostructural model developed of the TRUE Block Scale rock volume has provided a satisfactory geometrical basis for the evaluation of the TRUE Block Scale tracer tests.
- All modelling groups assign matrix diffusion as an important (and dominant) retention mechanism.
- Parameter groups (flow field, immobile zone diffusion properties and sorption) govern retention. It is difficult to fully discriminate between the individual basic retention processes, hence difficult to come up with unambiguous in-situ values on retention parameters.
- Heterogeneity in immobile zone properties may have important influence on interpretation of results. Possibly most important is heterogeneity perpendicular to fracture surface. Kinetic effects and effective properties may provide partial explanation of differences between laboratory and in-situ retention parameters.

- No new phenomena/processes have been observed in the block scale (network of fractures/structures) from a retention standpoint compared to what has been seen in the detailed scale (single fracture).
- The results from the tracer tests with (radioactive) sorbing tracers performed at the TRUE Block Scale and TRUE-1 sites indicate equitable retention for the tests performed on a 5m (TRUE-1) and 14 m length scale (TRUE Block Scale). In addition, the results from the two longer flow paths at the TRUE Block Scale site 33 m and 17(97) m respectively indicate a slightly higher retention (< than a factor 2). The implications of this finding is that transport modelling over a length scale of 100 m (equivalent to the safety distance between the repository and the closest major fracture zone) may not be overly complicated by needs for scaling of retention properties.
- It is demonstrated that the various transport approaches share the same conceptual basis for transport. The ability to demonstrate this kinship is important for the de-dramatisation of the differences between the modelling approaches. The actual differences between the transport approaches lies manly in how many immobile zones that are included in the analysis, and the way heterogeneity in retention parameters is accounted for.

IV) Synthesis of flow, transport and retention in the block scale /Winberg et al, 2002/

- Conclusions are pending.

3.2.2 TRUE Block Scale Continuation

Background

Already midway during 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.

The TRUE Block Scale Continuation is divided into two separate phases, BS2A and BS2B. The former includes complementary model analyses and formulation of additional hypotheses to be tested by subsequent in-situ experiments. BS2B comprises additional in-situ tracer experiments, possibly including tests with radioactive sorbing tracers.

The overall experimental concept is described by /Winberg, 1997/. The basic results from the TRUE Block Scale Project are presented in Section 3.2.1.

Objectives

The specific objectives of BS2A are to:

- Collect tail-end tracer breakthrough data from Phase C of the TRUE Block Scale Tracer Test Stage.
- Verify non-breakthrough of moderately to strongly sorbing tracers noted for the longer and more complex flow paths.

- Formulate a generalised context for comparison and evaluation of numerical models describing transport and retention in the block scale.
- Perform complementary modelling with the purpose of covering yet unfinished modelling tasks to be defined, thereby paving the way for formulation of new hypotheses to be tested in-situ.

The specific objectives of the next phase, BS2B, are dependent of the outcome of the first phase of the TRUE Block Scale project and the complementary modelling performed in the first phase, BS2A, and new questions and hypotheses formulated to be addressed by new experimental set-ups.

Results

Pending.

3.2.3 TRUE-1 Continuation

Background

The First TRUE Stage, TRUE-1, was completed mid 2000 /Winberg et al, 2000/. The project team evaluation 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, see Section 3.8.1.

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, 2001c/. 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, 2002/ 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.

- 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:

1. 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.
2. Complementary laboratory tests co-ordinated with TRUE Block Scale Continuation, see Section 3.2.2. The activities include estimation of the sorption characteristics of fine grained gouge material. In addition an attempts will be made to measure the in-situ porosity of fine-grained fault gouge material using some type of resin.
3. 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 3.3. The time prior to application will be devoted to refinement of the technology.

Results

A preliminary compilation of time series of hydraulic head, selected groundwater chemistry and inflow to the tunnel has been performed. The time series covered the time period from termination of TRUE-1 to present. In addition an assessment of the needs for re-instrumentation was made. This resulted in separation of the interpreted Feature A and one likely splay fracture in a borehole (KXTT4).

Groundwater sampling for the purpose of assessing the distribution of radon concentration in the groundwater in piezometer sections at the TRUE-1 site has indicated clear differences between various interpreted features.

3.3 Long Term Diffusion Experiment

3.3.1 Background

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

3.3.2 Objectives

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

3.3.3 Experimental concept

The original test plan /Byegård et al, 1999/ presented an experimental concept based 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, see Figure 3-5. 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 scooping 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 performance assessment 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 adverse effect of an advective flow component (towards the tunnel). This was to be resolved by using a multi-packer system, which effectively would shield off the gradient

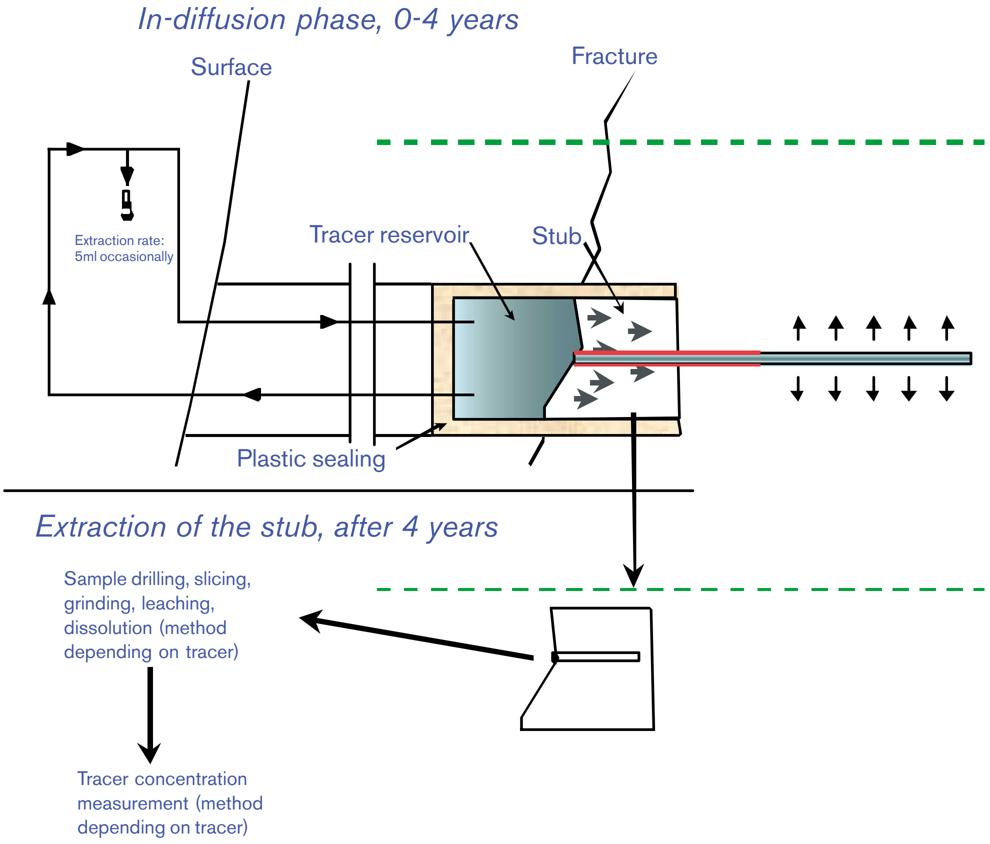


***Figure 3-5.** Schematic of modified LTDE experimental concept including injection in a section in contact with an exposed natural fracture surface and in a slim hole section in intact Äspö diorite, combined with excavation and penetration profile studies.*

from the area of interest. 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 measurements with various geophysical logs (BIPS). In addition, the core will be analysed using mineralogical, petrophysical and geochemical methods.

Drilling and site characterisation

A suitable target fracture was identified in borehole KA3065A02 at a depth of 9.81 m. This structure constitutes a chlorite splay (141/81) to a main fault, the latter on which slicken lines on the surface are evident. It shows mylonitic character in diorite/greenstone with an increasing alteration towards the fault centre. The total groundwater inflow at this zone in borehole KA3065A02 is about 16 l/min. The target structure constitutes the delimiting structure of the zone and is followed by a > 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. 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 300 mm, see Figure 3-6. However, due to poor visibility due to degassing (which partly 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.

Assessment of core stub stature

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 implications of this result are:

- 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; (i) stress concentrations associated with the advancing drill bit, and (ii) unloading of stress acting on 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.

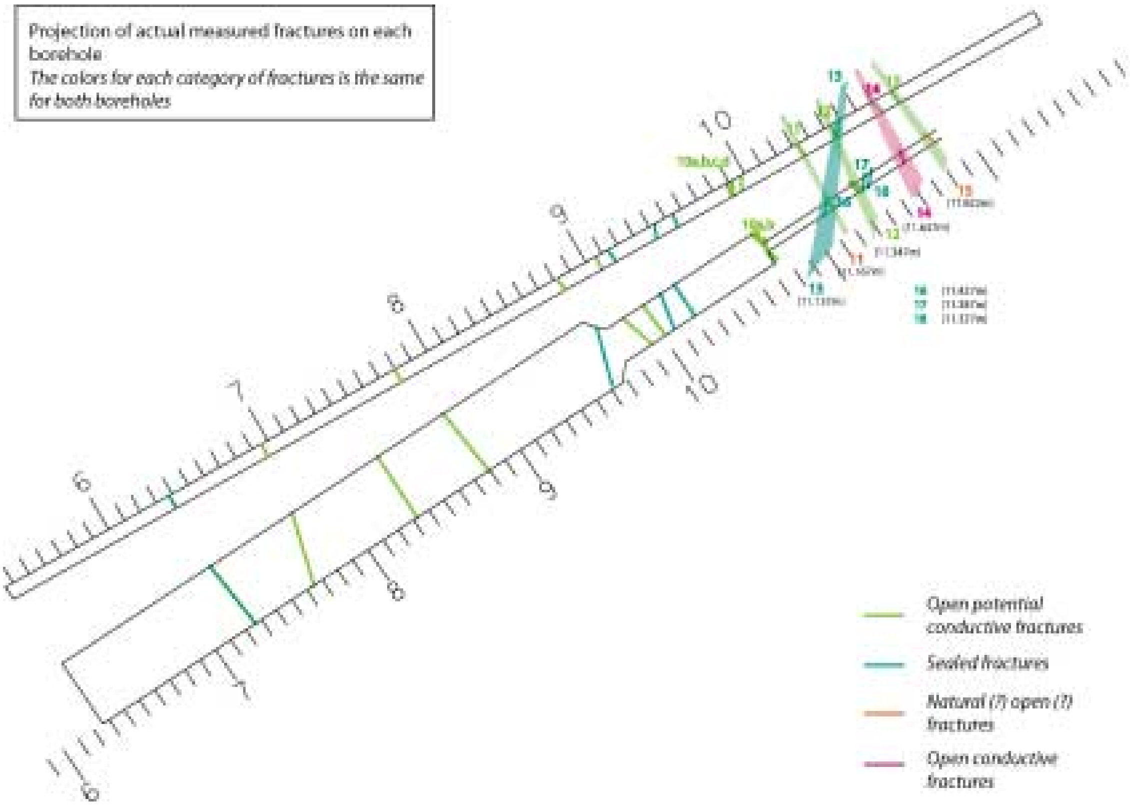


Figure 3-6. *Basic structural model of the LTDE rock volume.*

To investigate the effects noted under the first item above, a series of in-situ and laboratory measurements have been conducted during 2001 that have been compared with existing in-situ Äspö data/results and data/results found in the literature. The performed in-situ measurements included endoscope video imaging of the walls of the core stub in the 9.75 mm cylindrical slot around the core stub. In addition, the experimental borehole and the stub surface have been documented by a video mounted on a remote controlled vehicle. The results showed that no macroscopic fractures could be seen on the walls of the stub. Second, the inflow points along the boreholes could be established in a tentative way from the video recordings. The location of inflow points was subsequently established in more detail using single packer flow logging. The laboratory work, apart from basic mineralogy and geochemistry along the pilot and experimental boreholes, included micro-seismic measurements on drill cores and thin sections analyses in various directions, the latter two measurements aimed at quantifying the degree of sample disturbance on the core. The seismic work on a 177 mm core specimen indicated a 2–4% reduction in seismic velocity compared to what is attributed to intact unfractured Ävrö granite. The results of the thin section work showed that the mapped fractures are primarily radial (parallel to core axis) and that they diminish in number when moving towards the interior of the core. The background frequency of micro-cracks is approximately 1 fracture/mm in the interior of the studied 177 mm core, whereas the frequency in the outer 3 mm is in the order of 1.7–3.3 fractures/mm /Li, 2001/.

In addition, existing /Hakala, 1999/ and new experiment-specific rock mechanical modelling have been used to assess the effects of drilling and stress relaxation on the core and its environment. 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 leads to discarding the core stub for in-situ estimation of diffusivity.

Modified experimental concept

Given that the stub is mechanically disturbed plus the possibility that diffusion of weakly sorbing species through the stub may not reach the intact rock beyond the core root, analysis of alternative concepts were performed. The concept eventually put forward was one where the intact rock is accessed using a small diameter borehole through the centre of the core stub, see Figure 3-5.

3.3.4 Results

Site characterisation

The preparations for the drilling of the slim hole extension included a comprehensive update of the structural model of the investigated site. This included not only the area beyond the core stub but also the area between the target area and the collars of boreholes KA3065A02 and KA3065A03. A projection was specifically made of the structures to be expected in the slim hole extension on the basis of the pilot borehole information. It was identified that the volume of interest would not be free of fractures, but that the conditions were favourable. The drilling was made employing careful drilling in two separate uptakes and a total length of about a metre. The core was logged and the borehole was logged using a forward-looking TV-camera. The resulting structural model is shown in Figure 3-6. The basic result was that the borehole extension with the exception of its end was essentially dry. A series of flow tests were conducted in order to establish a) whether the identified discontinuities were conductive, and b) whether the noted conductive fracture in the bottom of the borehole could be used to bleed off 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 that 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.

Equipment

The new components in the equipment are made up of a mechanical double packer and a docking device connecting the new packer system with the old packer system, see Figure 3-5.

CE-marking of equipment set-up

The LTDE constitutes training set for SKB for how to CE-mark an actual experimental set-up. A new safety and risk analysis of the borehole equipment has been performed in light of the modified down-hole equipment.

Preparations for the borehole installations

One thing that was brought up during the risk analysis was the noted minor leakage through a small diameter de-airing borehole associated with the casing. Potentially this leakage, on the basis of exploratory hydraulic tests, is interpreted as being superficial but can potentially make the outer borehole section depressurised. This would entail that the hydraulic gradient along the experimental borehole would become higher than what the original design projects. It was therefore decided to make a focused grouting effort on the junction between the casing foot and the rock using a combination of a single component polyurethane and ordinary fine cement grout mix.

Preparations for container installation

A container will host the main surface equipment. The main equipment related to the injection/sampling/chemical monitoring and pressure regulation, respectively, will be hosted in two plexi-glass boxes, the former being a glove box. In addition, computers, auxiliary power supplies and detectors are hosted in the container. An extensive list of the various purchases and preparations needed to realise the experiments has been prepared. Once the borehole has been installed, the container will be fitted with the equipment. Parts of the pre-tests will be performed parallel to the container dressing.

Preparations for experiment start up

After a series of pre-tests and equipment tests the actual experiment will be started up.

3.4 Radionuclide Retention Experiments

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

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

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

3.4.2 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.

3.4.3 Experimental concept

CHEMLAB is a borehole laboratory built into a probe, in which in-situ experiments can be carried out under ambient conditions with respect to pressure and temperature, and with the use of natural groundwater from the surrounding rock. Initially one "all purpose" unit, CHEMLAB 1, was constructed in order to meet any possible experimental requirement. At a later stage, a simplified version, CHEMLAB 2, was designed to meet the requirements by experiments where highly sorbing nuclides are involved. Figure 3-7 illustrates the principles of the CHEMLAB 1 and CHEMLAB 2 units.

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

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

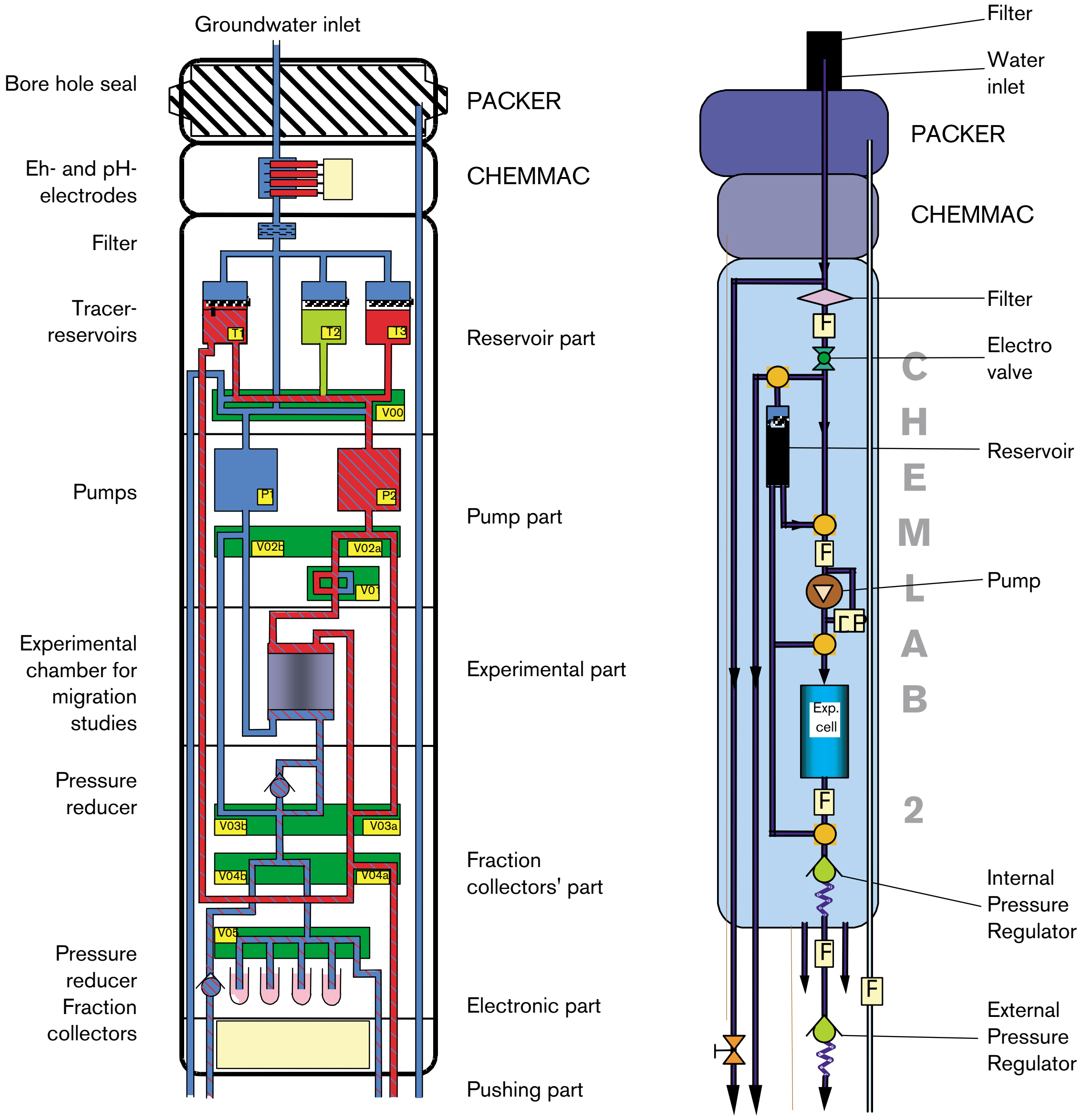


Figure 3-7. *Schematic illustrations of CHEMLAB 1 and CHEMLAB 2.*

3.4.4 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

In the radiolysis experiment the influence of primary and of secondary formed water radiolysis products on the migration of the redox-sensitive element technetium will be studied. Reduced technetium will be placed in a diffusion cell containing bentonite.

In the study with primary formed water radiolysis products the technetium will be placed on an irradiation source at the bottom of the cell. In the study with secondary formed products the technetium will be placed inside the cell while an irradiation source will be placed outside the cell.

The radiolysis experiment was planned to be conducted and completed 2001. Due to delays in the final evaluation of the previous experiment, diffusion in bentonite, and a water leakage in CHEMLAB 1 (which demanded service and modifications of CHEMLAB 1), the radiolysis experiments are to be conducted during 2002.

Migration of Actinides

The first experiment carried out in CHEMLAB 2 was the migration of actinides, americium, neptunium and plutonium, in a rock fracture. Pre-studies have been performed at Institut für Nukleare Entsorgung at Forschungszentrum Karlsruhe (INE) using cores taken from Äspö HRL. During fall of 2000 INE carried out a first of several actinide migration experiments at Äspö HRL in co-operation with SKB staff and Nuclear Chemistry at the Royal Institute of Technology. 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 results obtained for the first actinide experiments performed on drillcores in laboratory (Core #1) and in CHEMLAB 2 (Core #2) at Äspö HRL showed individual behaviour of each core. Core #1 had an open fracture and was used for several successive actinide migration experiments in laboratory. Core #2 was applied for one single experiment in CHEMLAB 2 at Äspö HRL. In this experiment, breakthrough of Np followed the tendency of the measured HTO curve, see Figure 3-8. Np was detected in the effluent migrated with hardly any retardation. Np breakthrough resulted in a recovery of about 40%. This type of breakthrough cannot be explained by a simple sorption mechanism. Flow path analysis by cutting Core #2 showed only partly open fractures, wide parts of the core had healed fractures, which could not be related to a flow path (see also Section 6.2.1).

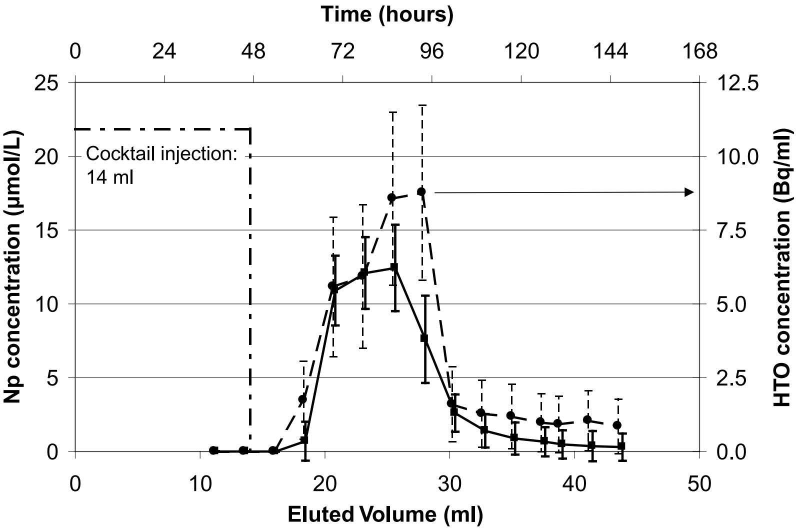


Figure 3-8. Breakthrough of Np and HTO determined in the CHEMLAB experiment (Core #2).

The second actinide experiment in Äspö HRL was started in the end of 2001 and will be completed in 2002. The analysis of the second experiment is yet not completed.

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

- The design of the drillcores 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.
- Post-mortem analyses resulted in different specific patterns of the flow paths. In the case of open fractures (Cores #1 and #2), application of fluorescent epoxy resin, cutting, and scanning of slices allowed to quantify the volumes and the inner surfaces of the fracture.
- 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 $\leq 40\%$. Breakthrough of Am(III) and Pu(IV) was not detected in the effluent.
- Improved analytical methods, such as laser ablation techniques and micro α-radiography will provide more information about the longitudinal and transversal distribution of sorbed actinides.

Modelling of the actinide migration and the correlation of observed batch sorption data with the results of migration experiments are currently carried out.

3.5 Colloid Project

3.5.1 Background

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

It has been argued that e.g. plutonium is immobile owing to its low solubility in groundwater and strong sorption onto rocks. Field experiments at the Nevada Test Site, where hundreds of underground nuclear tests were conducted, indicate however that plutonium is associated with the colloidal fraction of the groundwater. The $^{240}Pu/^{239}Pu$ isotope ratio in the taken samples indicate 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 planned to continue until December 2003. The results from the project will be used mainly in the future development of safety assessment modelling of radionuclide migration.

3.5.2 Objectives

The objectives of the Colloid Project are to:

- Study the stability and mobility of colloids.
- Verify the colloid concentration in groundwater at Äspö HRL.
- Study the role of bentonite clay as a source for colloid generation.
- Investigate the potential for colloid formation/transport in natural groundwater.

The work will also make it possible to verify that the colloid concentration is generally low at Äspö HRL, and that the chemical conditions at that site are such that the potential for colloidal uptake and transport of radionuclides is low compared to for example the Nevada Test Site. In addition, the work gives SKB a possibility to test new and improved techniques for in-situ determination of colloid concentrations.

Similar projects are ongoing or planned to be performed in for instance Switzerland. The aim is to co-operate with internationally recognised scientists and institutes to exchange information and experiences.

3.5.3 Experimental concepts and results

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

Laboratory experiments

The role of the bentonite clay as a source for colloid generation at varying groundwater salinity and temperatures has been studied in laboratory experiments conducted at KTH (Royal Institute of Technology, Stockholm).

In the experiments /Wold and Eriksen, 2001/ dry prepared or wet prepared bentonite was mixed with a sodium perchlorate ($NaClO_4$) solution of an ionic strength between 0 and 1 M in a 250 ml cylinder of the type shown in Figure 3-9. The suspensions were standing for at least one week in a thermostat box set to 20°C or 60°C before the solutions were analysed. In the case of colloid formation the solutions were filtered through 800 and 200 nm filters for analysis, otherwise unfiltered solutions were analysed. The particle size distribution was measured by light scattering.

The experiment has been extended to investigate in detail the chemical changes and the size distribution associated with colloid generation. These results will be compared with the parallel experiments conducted at the company Claytec. In addition, a “washed” bentonite is used in order to avoid interference from the clay on the solution. The chemical changes in the solution and formation of small particles have been studied in detail during the time period August-December 2001.

Figure 3-9. *The salinity of the water affects the colloid generation. The experiment shows different degrees of sedimentation of bentonite clay dependent of the ion content in the water. The experimental conditions: Dry bentonite, 10 g/250 ml in contact with 0.01, 0.1 and 1 M solution at 20°C after 1.5 weeks.*

The results from the laboratory experiments /Wold and Eriksen, 2001/ indicate that the bentonite colloid formation is strongly correlated with the ionic strength of the solution. Very low concentration of colloids formed in suspensions with ionic strengths 0.1 and 1 M. This is valid for experiments both with dry, see Figure 3-9, and wet prepared bentonite. At 0 and 0.01 M colloids were formed in the experiments with wet prepared bentonite. In the case with dry prepared bentonite, where the solutions are shaken initially, the sedimentation is slow and no measurements were possible. At high ionic strength the colloid formation is minor. At ionic strength 0.01 M, where colloid formation is favourable, the colloid formation seems to increase at a temperature of 60°C in the solution compared to a solution of 20°C.

The results from detailed investigation of the chemical changes and the size distribution associated with colloid generation are being analysed, and will be reported during 2002.

Background measurements

To verify the natural background concentration of colloids in Äspö HRL measurements are performed from eight different boreholes along the Äspö tunnel. The boreholes represent different types of water, since the colloid stability can change with the ion content of the groundwater. The measurements were performed by teams from Germany (INE), Finland (Posiva) and Sweden (SKB) during the time period October-November 2001.

The colloid content was measured on-line from the boreholes by using a modified laser based equipment LIBD (Laser-induced Breakdown-Detection) developed by INE in Germany (see also Section 6.2.2). The advantage of this equipment is that the resolution is higher compared to standard equipment. It is therefore possible to detect the colloid contents at much lower concentrations than previously possible. The results of these experiments have been compared with standard type measurements such as particle counting by using Laser Light Scattering (LLS) on pressurised groundwater samples.

Standard type of filtration and ultra filtration were performed on-line/at-line of the groundwater in the boreholes in order to compare and transform these results to all the earlier colloid sampling campaigns at Äspö HRL. In addition, groundwater samples to measure the content of microbes and humic materials 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 also can affect the colloid stability.

Borehole specific measurements

The aim of the measurements is to determine the colloid generation properties of the bentonite clay in contact with groundwater at the conditions prevailing at Äspö HRL. For the borehole specific measurements three boreholes along the Äspö tunnel will be investigated. The boreholes are selected so that the natural variation in the groundwater composition at Äspö 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 the groundwater is brought in contact with the bentonite clay, by using LIBD/LLS and conventional filtering. This activity will be performed in field during the time period April-August 2002.

The results of these experiments are planned to be reported in the second half of 2002.

Fracture specific experiments

Fracture specific experiments are planned within the Colloid Project. The design of the experiments is, however, dependent of the results from the other experiments in the project and a final judgement will be taken during the summer of 2002. The experiments are foreseen to take place in January-June 2003.

For the fracture specific measurements two nearby boreholes at Äspö HRL will be selected. One of the boreholes will be used as an injection borehole and the borehole downstream will be used as a monitoring borehole. The boreholes intersect the same fracture and have the same basic geological properties. After assessing the natural colloid content in the groundwater, bentonite clay will be dissolved in ultra pure water to form colloidal particles. The colloids are labelled with a lanthanide (i.e. europium) and the fluid is labelled with a water conservative tracer. The mixture will be injected into the injection borehole Figure 3-10. From the monitoring borehole the colloidal content will be measured with laser (LIBD/LLS), the water will be filtered and the amount of tracers will be measured.

The result of interest is to monitor the changes in the colloid content prior and after the transport. The outcome of the experiment is used to check the calculations in the safety assessment reports such as /Allard et al, 1991/ and to use the results in future colloid transport modelling. If the experiment is perform according to the plan, the results can be reported in the second half of 2003.

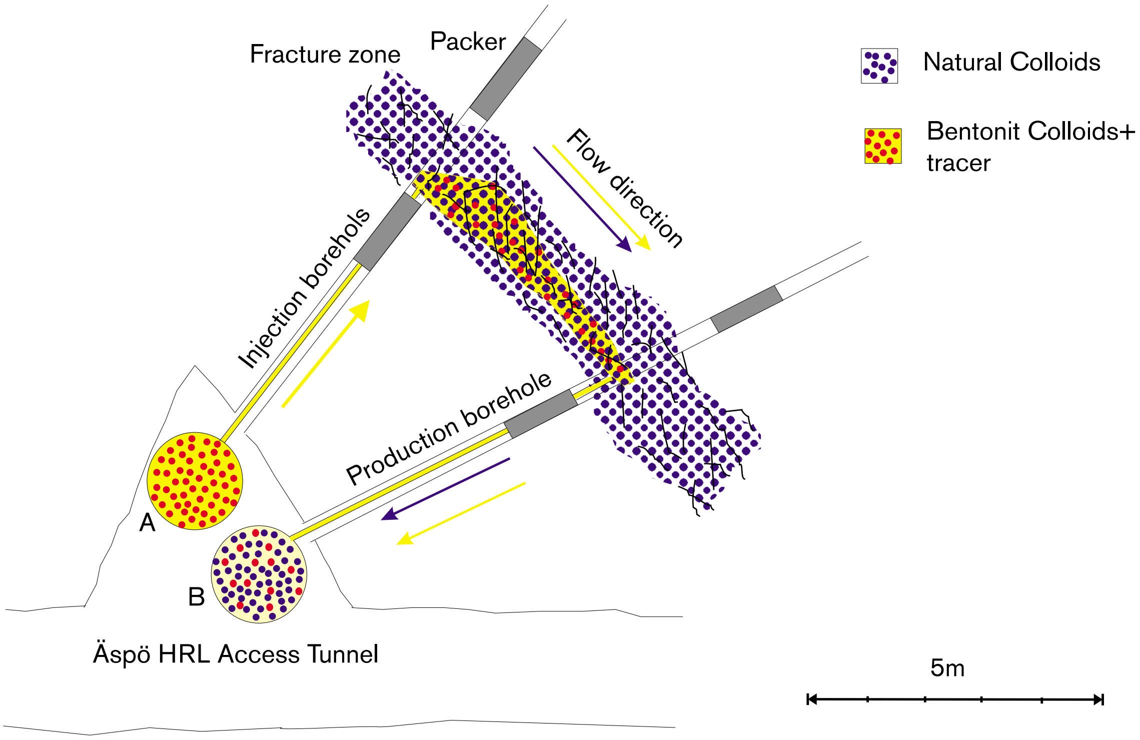


Figure 3-10. *Injection of bentonite colloids and monitoring of the injected and natural colloids in the production borehole.*

3.6 Microbe Project

3.6.1 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 nuclear fuel. Interactions with a potential for study at the experimental sites in the Äspö HRL are:

Bio-mobilisation of radionuclides. To what extent can bacterial dissolution of immobilised radionuclides and production of complexing agents increase radionuclide migration rates?

Bio-immobilisation of radionuclides. What are the retention effects from microbial biofilms forming on groundwater conducting fracture surfaces and in the biological iron-oxidising systems (BIOS) forming in ground surface outflow of groundwater?

Microbial corrosion of copper. Bio-corrosion of the copper canisters, if any, will be a result of microbial sulphide production. Two important questions arise: 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?

Biogeochemical cycling of sulphur in deep groundwater is poorly understood. Biological fractionation of stable sulphur isotopes is a process that may give important information. Biological formation of sulphide in groundwater is significant, but rates and mass balance is unknown.

Microbial effects on the chemical stability. Microorganisms can have an important influence on the chemical situation in groundwater. Especially, they may execute reactions that stabilise the redox potential in groundwater at a low and, therefore, beneficial level for the repository. Another very important bio-effect is the microbial reduction of oxygen with hydrogen, methane and organic carbon. In-situ data are required for proper modelling.

These tasks have been addressed in a range of projects, of which several are ongoing. Important conclusions have been obtained based on laboratory and field data. While some results seem very solid with general applicability, others are pending inspection at in-situ conditions. This is especially true for data generated at the laboratory only. In-situ generated data must be obtained for microbial activities in the far- and near-field environment at realistic repository conditions. This can only be achieved at underground sites, developed for microbiological research, using circumstantial protocols for contamination control during drilling and operation. An in-situ site allows experiments at high pressure with a proper gas content and biogeochemical situation. This is of great importance for modelling true subterranean microbial activity and very difficult to obtain in vitro.

3.6.2 Objectives

The major objectives for the experimental sites in Äspö HRL within the Microbe Project are:

- To provide in-situ conditions for the study of bio-mobilisation of radionuclides.
- To present a range of conditions relevant for the study of bio-immobilisation of radionuclides.
- To enable investigations of bio-corrosion of copper under conditions relevant for a deep repository for spent nuclear fuel.
- To offer proper circumstances for research on the effect of microbial activity on the long term chemical stability of the repository environment.

3.6.3 Experimental concept

The deepest Microbe site is on the 450 m level and consists of three core drilled boreholes, KJ0050F01, KJ0052F01 and KJ0052F03, intersecting water conducting fractures at 12.7, 43.5 and 9.3 m respectively. Each borehole is equipped with metal free packer systems that allow controlled sampling of respective fracture. An underground laboratory, approximately 7 x 2.5 m is installed close to the boreholes and is equipped with a large anaerobic chamber and basic laboratory equipment. Tubing connects those boreholes with the laboratory.

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

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

3.6.4 Results

During 2001 most activities have been focussed on planning, equipping and preparing for experiments that will start during 2002 and run for several years.

Bio-mobilisation of radionuclides. Biofilm build-up in KJ0052F03 has been investigated. The number of attached microorganisms was 10^7 cells cm^2 after 65 days, see Figure 3-11.

Bio-immobilisation of radionuclides. The vault roof in the 2200A site has been secured and the BSP borehole has been equipped with a packer.

Microbial corrosion of copper. The results obtained are consistent with earlier results. Microbial production of sulphide ceases under full bentonite swelling pressure (2 g/cm^2). Migration of sulphide producing microorganisms through bentonite does not occur at repository density (2 g/cm^2).

Biogeochemical cycling of sulphur. The 1127B site vault has been secured and an artificial pond has been constructed.

Microbial effects on the chemical stability. The equipment is under construction. This investigation will start during 2002.

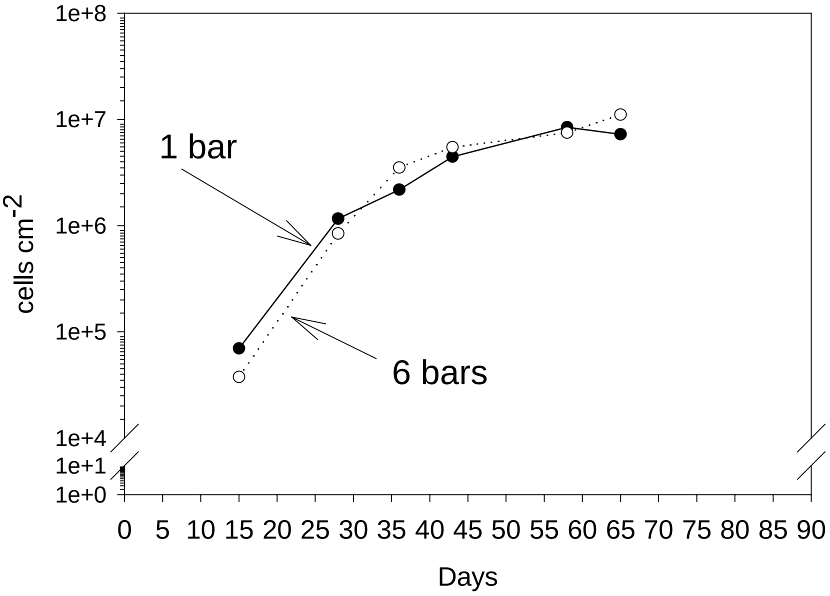


Figure 3-11. *Biofilm build-up is studied in KJ0052F03. The experiment started 26 September 2001 and will be closed 24 January 2002. Two pressure levels were analysed.*

3.7 Matrix Fluid Chemistry

3.7.1 Background

Knowledge of matrix fluids (i.e. accessible pore 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 will facilitate migration of matrix fluids. Therefore the matrix fluid chemistry will be related to the chemistry of groundwaters present in hydraulically conducting minor fractures (K= 10^{-10}–10^{-9} ms^{-1}). This is important 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.

3.7.2 Objectives

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

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

3.7.3 Experimental concept

The Matrix Fluid Chemistry experiments comprise:

- Feasibility study carried out on drillcore material. The mineralogy and major tracer element geochemisty is investigated to generally characterise the rock mass.
- Leaching and permeability experiments including crush/leach experiments to indicate the nature of the matrix fluid.
- 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 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 is designed to sample matrix fluids from predetermined, isolated borehole sections. The borehole was selected on the basis of: (a) rock type, (b) mineral and geochemical homogeneity, (c) major rock foliation, (d) depth in the tunnel, (e) presence and absence of fractures, and (f) existing groundwater data from other completed and on-going experiments at Äspö HRL.

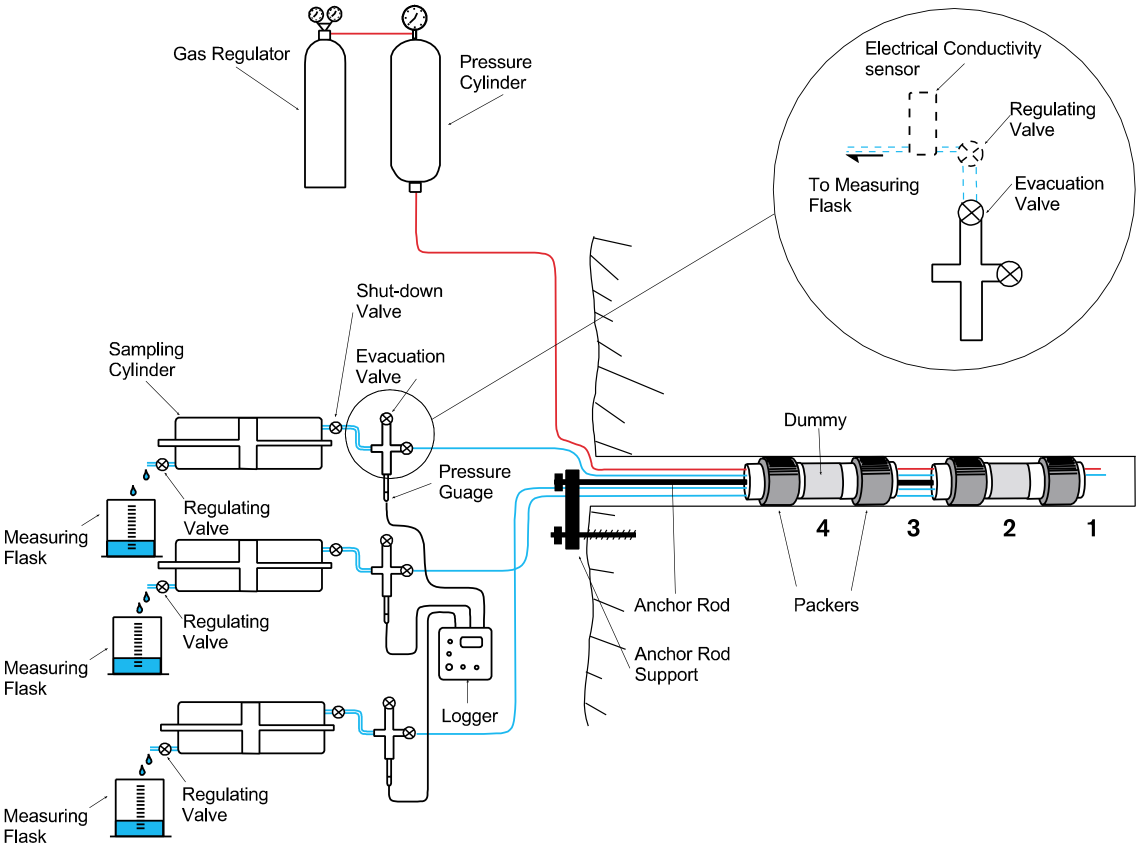


***Figure 3-12.** Matrix Fluid Chemistry experimental set-up. Borehole sections 2 and 4 were selected to collect matrix fluid; sections 1–4 are continuously monitored for pressure.*

Special equipment, see Figure 3-12, has been designed to sample the matrix fluids ensuring: (a) an anaerobic environment, (b) minimal contamination from the installation, (c) minimal dead space in the sample section, (d) the possibility to control the hydraulic head differential between the sampling section and the surrounding bedrock, (e) in-line monitoring of electrical conductivity and drilling water content, (f) the collection of fluids (and gases) under pressure, and (g) convenient sample holder to facilitate rapid transport to the laboratory for analysis.

3.7.4 Results

The most important activities during 2001 have been the sampling and analysis of the matrix groundwaters from the sectioned-off borehole KF0051A01 in October, the completion of the pore water diffusion experiments, the results of a pilot study on geological evidence of in- and out-diffusion processes which may influence the pore water chemistry, and the Final Matrix Fluid Workshop held in October in Stockholm. The final sampling campaign marked the end of field activities and the Workshop represented the last opportunity to present and discuss results prior to the scheduled end of the project in December 2001. Otherwise most input to the project has been the compilation of data and reporting in the form of International Technical Documents. Greater effort has been put into producing two synthesis reports (in preparation), since these help to form the basis to the final report that is presently in draft form.

Sampling of matrix fluids

Following a duration of almost two years since the previous sampling, the pressure monitoring curves, see Figure 3-13, indicated that Section 4 (blue) in the Äspö diorite (previously sampled and represented by the break in the curve in December 1999) appeared to have recovered, and Section 2 (green) in the Ävrö granite (unopened since the commencement of the experiment) continued to show a steady, although small, pressure increase with time. Section 1 (red) also opened previously, showed no change as might be expected because of the large borehole section volume, and Section 3 (yellow), located between the packed-off Sections 2 and 4, showed only a very slight pressure increase over the 3.5 year period.

Sampling was attempted in all four sections and resulted in the following:

Section 1: No water or gas; underpressure in section! (Previous sampling in Dec 1999 gave only gas.)

Section 2: Some gas and small water volume (34.74 ml); only water sampled.

Section 3: Gas and water (321.19 ml); both gas and water sampled.

Section 4: Gas and water (195.02 ml); both gas and water sampled. (Previous sampling in Dec 1999 gave 160 ml water.)

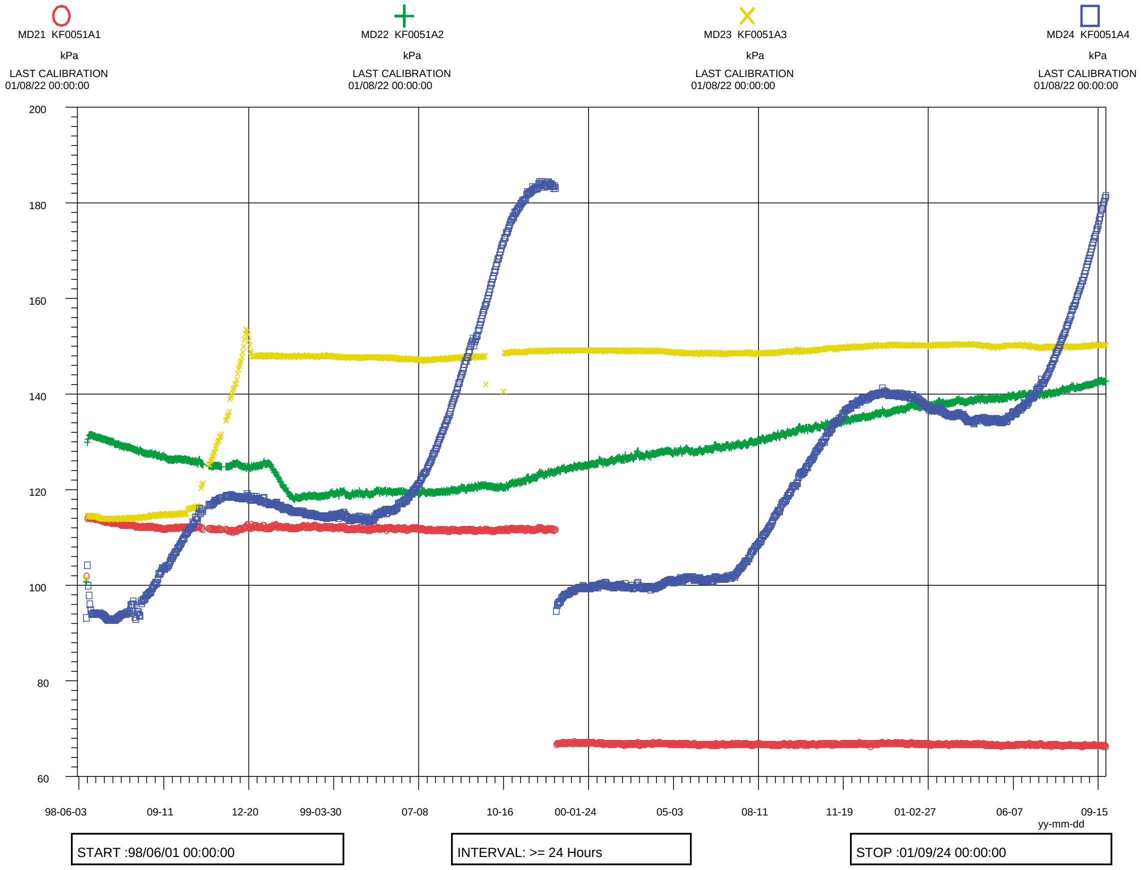


Figure 3-13. Pressure monitoring curves for each of the four isolated borehole sections: 1 (red), 2 (green), 3 (yellow) and 4 (blue). Sections 2 and 4 are specially equipped for matrix fluid sampling.

Adequate water was collected from Sections 3 and 4. Section 2 produced a small but important volume, which took several attempts to remove using evacuated glass vials. Surprisingly, Section 1 was underpressurised and nothing was collected. In the Sections 2, 3 and 4 H_2S was detected

Of the three water samples, only Section 2 (because of the small volume available) had to be prioritised as to what chemical species to be analysed. Analysis covered major cations and anions, stable isotopes (^{18}O, ^{2}H), strontium isotopes (^{86}Sr, ^{87}Sr) and ^{37}Cl. In addition, samples collected from Sections 3 and 4 included measurements of pH (field and laboratory), alkalinity, ^{13}C and ^{14}C, and ^{10}B. Gas volumes extracted from Sections 3 and 4 were sent for analysis (normal suite: N_2, O_2, CO_2, H_2, CH_3, CH_4 etc) but unfortunately still remain in storage due to analytical instrument problems.

The chemistry of the sampled matrix groundwaters, see Table 3-1, allowed certain trends and differences to be examined:

- Time-series (22 months duration) exhibited by comparing Section 4(1) collected in 1999 with Section 4(2).
- Chemical variation between Sections 2 (Ävrö granite) and 4 (Äspö diorite); due to differences in transmissivity and/or rock chemistry.
- The character of Section 3 located at the contact between the Ävrö granite and Äspö diorite.

With respect to Section 4, the passing of 22 months resulted in minimal differences in chemistry; a more significant increase in SO_4 was attributed to microbial activity. In contrast, Section 2 showed major differences in chemistry compared to Sections 3 and 4 even to the extent of suggesting some influence from younger drawdown groundwaters. Although this appears contrary to the low transmissivity of the Ävrö granite, it may indicate the near-vicinity location (some decimetres away?) of a water-conducting fracture of similar hydraulics and chemistry to the Prototype samples which are most influenced by drawdown effects. Both groundwater types might influence Section 3, since it straddles the contact between the Äspö diorite and the Ävrö granite. However, the data showed that the chemistry was dominated by the type of groundwater found in Section 4, which probably reflects the greater transmissivity of the Äspö diorite.

Pore water diffusion experiment

At the University of Bern, a feasibility study of simple pore water out-diffusion experiments was performed on three core samples from borehole KF0093-A0 to explore the in-situ pore-water composition. Borehole KF0093-A0 is located nearby the matrix fluid experimental in the same matrix block and was drilled for rock stress measurements. Given appropriate time, diffusion of the components dissolved in the pore water of the rock into the double de-ionised water was expected to reach steady state. With knowledge of the water content of the rock samples, the concentrations of non-reactive (free) solutes can be calculated to pore-water concentrations. For reactive (controlled) solutes, the concentration changes induced by rock-water interactions can be estimated utilising geochemical modelling strategies.

The out-diffusion experiments involving three drillcore samples commenced on August 8th, 2001, and continued until October 10th, 2001 for sample KF93-3, and until January 16th, 2002, for samples KF93-1 and KF93-2.

Table 3-1. Chemistry of the matrix groundwaters.

Element	Matrix Section 2 (mg/l)	Matrix Section 3 (mg/l)	Matrix Section 4(1) (mg/l)	Matrix Section 4(2) (mg/l)
Li	0.244	0.320	0.274	0.321
Na	1 760	2 460	2 200	2 480
K	16.3	14.5	11.4	9.28
Mg	17.4	8.3	7.8	4.2
Ca	568	916	964	908
Fe	–	1.19	0.24	0.029
Si	–	8.2	7.6	8.7
F	98.8	57.8	–	11.1
Cl	2 900	4 780	5 160	5 020
Br	24.1	36.7	43.16	32
SO_4	2.7	1.5	26	84
Alkalinity	–	303	approx. 170–200	371
pH	6.17	6.08	6.7	7.01
^{3}H (TU)	–	–	–	–
δ ^{18}O (‰ SMOW)	–7.8	–11.7	–11.6	–12.2
δD (‰ SMOW)	–63.6	–89.7	–87.9	–92.4
^{13}C (‰)	–	–21.9	–	–
^{14}C (pmc)	–	57.3	–	–
δ ^{37}Cl (‰ SMOC)	+0.46/44	+0.48/43	+0.61/59	+0.58/60
^{10}B (‰ CDT)	–	–	47.23	–
^{34}S (‰ CDT)	–	–	–	–
^{87}Sr/^{86}Sr	0.715635	0.714764	0.714516	0.714300

The three samples were placed in individual vessels, covered with double de-ionised water and stored under controlled inert conditions. After 2 months of equilibration time, one sample solution was analysed initially for pH and alkalinity and then for major ions and stable isotopes. For the two other samples, equilibration was allowed to continue. After 3, 4, and 5 months, small amounts of solution (about 7 ml) were removed from the samples for Cl-analysis. After 5 months, the samples were analysed for pH, alkalinity, major ions and stable isotopes.

The analysed solutions are of the Na-(Ca)-Cl-HCO_3 type with total dissolved solids between 68–125 mg/l. Unfortunately, close comparison of the chloride concentrations between the analysed samples suggested that the solutions were not homogenised in the reaction vessels and concentration gradients existed in the solution between the top and bottom of the vessels. Consequently, based on existing chloride data, it cannot be concluded if steady-state conditions had been reached after 150 days of experimental time.

Geochemical modelling showed that all three solutions were undersaturated with respect to calcite when using the measured alkalinity and pH-values. Of interest is, however, the fact that the calculated partial pressure of CO_2 ($\log pCO_2 = -4.12$) was below that of the atmosphere (log $pCO_2 = -3.5$) for sample KF93-3 and equal to that of the atmosphere for samples KF93-1 and KF93-2, which were stored overnight prior to analysis. Such conditions are consistent with those observed from the earlier reported crush/leaching experiments.

Small amounts of calcite are present as alteration products in the investigated rocks. Considering the experiment time, it can therefore be assumed that the solutions have reached calcite equilibrium. By doing so, pH-values between 8.9 and 9.2 and log pCO_2 values between –4.3 to –5.0 were obtained for the three solutions. At calcite equilibrium, the solutions are undersaturated with respect to all other minerals.

The solutions sampled from the reaction vessels after 60 and 150 days, respectively, show $\delta^{18}O$ and $\delta^{2}H$ values that indicated a slight tendency towards less negative values compared to the de-ionised water used in the experiment (i.e. –11.19 ‰ ^{18}O and –80.0 ‰ ^{2}H V-SMOW for de-ionised water compared to –11.12 to –11.14 ‰ ^{18}O and –79.1 to –79.4 ^{2}H V-SMOW for the samples). This could indicate that the stable isotope signature of the in-situ pore water is enriched in the heavy isotopes of water compared to the de-ionised water used in the experiments. However, the deviation lies for all samples within the analytical uncertainty so that the changes in isotopic composition between de-ionised water and experiment solutions are not significant.

Since the pore-water fraction that will mix in such experiments with the experiment solution is very low, to obtain a significant change in the final experiment solution the initial isotopic composition of the latter should be chosen to be strongly enriched in the light isotopes (i.e. very negative delta values).

All three core samples were weighed immediately after removal from the solution and dried until stable weight conditions were achieved (168 hours). Comparison of the rock wet weight measurements made before and after the experiments showed that the degree of saturation, is larger than 99.96% for all three samples, i.e. the samples were essentially received in a saturated state. The calculated water content and connected porosity for the Äspö diorite (0.144–0.159 volume-% (wet weight) and 0.40–0.44 volume-% respectively) overlapped with the range obtained for the matrix experiment drillcore samples. While the aplite sample of the KF93 drillcore displays a significantly higher water content and connected porosity (0.169–0.184 volume-% (wet weight) and 0.47–0.51 volume-% respectively).

In conclusion, since steady-state conditions were most probably not attained in the out-diffusion experiments, no final conclusion can be drawn with respect to the pore-water composition of the investigated rock samples. Comparison with the borehole waters sampled in the matrix fluid experimental borehole was further inhibited by the fact that the core samples used came from a different borehole with partially different lithologies which may also lead to compositional differences in water sampled in-situ even if only a few metres apart. Therefore, no further geochemical modelling exercises were performed on the present data.

Nevertheless, certain statements can be made about the feasibility of such experiments for pore-water characterisation of crystalline rocks of low-permeability. It appears that out-diffusion experiments are well suited to obtain valuable information about dissolved components in the pore water, at least about the non-reactive (free) ones. Thus, the impact of fluid contributed by mineral fluid inclusions is (almost) excluded and insignificant. A significant contribution would otherwise negate the value of all the different leaching techniques used to characterise the in-situ pore water. Success, however, depends on a proper design of the diffusion experiments where the rock samples size, the rock-water ratio, and experimental conditions (atmosphere) and time (steady state) are optimised.

Geological evidence for in- and out-diffusion mechanisms

A Pilot Study was initiated in September 2001 to study an identified small-scale microfracture some 56.5 cm from Section 4, already sampled for matrix groundwaters in December 1999. The purpose was to analyse a series of rock slices representing a profile across the microfracture in the Äspö diorite, with the objective to assess the nature of in- and out-diffusion processes around the fracture using microscopic studies, porosity measurements, bulk rock chemistry and U-decay series isotopes. Evidence of diffusion gradients may help to further understand the evolution of the pore water chemistry. The main observations were:

- *Fracture Coating:* Irregular layer of calcite and chlorite (0–0.3 mm thick).
- *Wall Rock:* Biotite preserved, no increase in alteration of plagioclase; no red staining (i.e. no evidence of increased oxidation).
- *Porosity:* Increase in porosity in the outermost 1 cm sample (0.61 volume-% compared with approx. 0.4 volume-% in the rock matrix).
- *Major and Trace Element Chemistry:* No clear trends; appears to reflect mineralogical heterogeneity.
- *Isotopes:* $^{234}U/^{238}U$ in secular equilibrium apart from the outermost sample closest to the fracture.

The results show no chemical evidence of alteration or chemical gradient and any variation can be explained by mineralogical heterogeneity. In contrast there was an increase in porosity adjacent to the microfracture edge corresponding to $^{234}U/^{238}U$ disequilibrium. This isotopic disequilibrium suggests that water/rock interaction has and/or is occurring marginal to the microfracture. Although the sensitivity of the sampling has not revealed any obvious diffusion gradients, the uranium disequilibrium data indicate that matrix groundwater is actively reacting and moving along the microfracture and is a likely source for the matrix waters sampled from borehole Section 4.

Final Matrix Fluid Workshop

The Final Matrix Fluid Workshop was held in Stockholm to provide a last opportunity to present the status on-going projects and to receive input from the participants prior to the conclusion of the project scheduled for December 31, 2001.

Final reporting

The Final Report is available in draft form and it is hoped that a final version will be completed by October 2002.

3.8 Modelling of groundwater flow and transport of solutes

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

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

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

3.8.1 The 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. Nine organisations, see Chapter 6, in addition to SKB have participated in the Äspö HRL during 2001. One of the organisations, Nirex, has left the co-operation during the year. A Task Force delegate represents each participating organisation and the modelling work is performed by modelling groups. Together these organisations involve twelve modelling groups. The Task Force meets regularly about once to twice a year.

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

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

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

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

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

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

Task 6: Performance Assessment 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. 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.

During 2001, all work by the modelling teams has been completed. The evaluation of the modelling done in sub-tasks 4E and 4F have been undertaken and reported by /Elert and Svensson, 2001/.

The TRUE-1 experiment that formed the basis for this modelling task is reported in /Winberg et al, 2000/ and /Cvetkovic et al, 2000/. Still on-going is the overall evaluation of Task 4 with the purpose to address understanding, methodologies and motivation/expectations from the viewpoint of the participating organisations.

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. Work is underway to compile results and summarise approaches, executions and conclusions of Task 5 into one summary report. A preliminary summary of the results obtained by the different modelling teams are compiled and presented in Appendix E in /Morosini, 2001/. It is for example remarked on the benefit of bringing together hydrogeologists and hydrochemists.

Task 6

A new task, Task 6, was initiated this year. 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 programs from a PA perspective (i.e. provide support for site characterisation program 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.

Modelling has been performed for sub-tasks 6A and 6B. In the former task 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 the latter 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.

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

Modelling concept

The modelling of groundwater flow and transport in sparsely fractured rock is made with three different concepts: Stochastic Continuum (SC), Discrete Fracture Network (DFN) and Channel Network (CN). The last modelling approach has similarities with the SC approach. Experiences gained from international modelling tasks within the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes have shown that the different concepts are all useful but there are needs to develop the codes both in terms of data handling and visualisation. It is also necessary to continue developing and testing the concepts /Gustafson and Ström, 1995; Gustafson et al, 1997/. The model code used 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 major part of the activities within Part 1 of NUMMOD was finalised during 2001. The work was reported in two reports; DarcyTools – Concepts, method, equations and tests, DarcyTools – Software description and documentation. The second report may later on be developed into a full User's Guide.

The transport algorithm PARTRACK in DarcyTools was presented in /Svensson, 2001a/. In this report the main features and implementation of the multi-rate mass transfer approach is described. PARTRACK can handle simulations of channelling in fracture planes, branching at fracture intersections, Taylor dispersion, matrix diffusion, and sorption. PARTRACK constitutes a powerful tool specifically for the analysis of tracer tests performed in sparsely fractured rock.

Within the NUMMOD project the porosity concept is discussed. A method to introduce porosity and connectivity structures in continuum methods is proposed. The method is based on defining properties such as conductivity, porosity and diffusion coefficient for conductive elements that represent fractures and fracture zones in a fracture network.

The method provides an improved description of the various porosities (kinematic porosity and stagnant storage volumes) associated with fractured rock.

Discretization errors in space and time have been considered and it has been shown that solutions produced by DarcyTools are quite insensitive to chosen discretization if a criterion on minimum grid spacing relative to domain size is fulfilled. Thus, the presented methodology for transforming a fracture network to a stochastic continuum is shown to provide a useful and powerful tool for modelling of groundwater flow since up-scaling problems to a certain extent are avoided.

In /Svensson, 2001b/ a number of modelling techniques are developed. Specifically, the new solver MIGAL is tested, visualisation using EXPLORER is tested, modelling using embedded grids is performed, and an explicit treatment of tunnels is developed. The MIGAL solver was proven a major improvement and is now included in DarcyTools. The use of embedded grids and the possibility to include tunnels are important features for future use of DarcyTools in the site characterisation programme.

3.9 Hydrochemical Stability

3.9.1 Background

The chemical properties of the groundwater affect the canister and buffer stability and the dissolution and transport of radionuclides. It is therefore important to know the possible changes and evolution of the groundwater chemistry during the repository lifetime. It is important to understand the processes that influence and control the pH, the redox properties and the salinity of both saline and non-saline groundwaters.

In the past five years this topic has been studied within the framework of the Äspö agreement between SKB and Posiva in a project named Hydrochemical Stability. The focus of the work has been on granitic-rock sites in Sweden and Finland. In addition, modelling work has been performed within the EC-project EQUIP and the framework of the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes (Task 5).

3.9.2 Results

EQUIP and PADAMOT

The EQUIP project has had as specific objective to trace the past hydrochemical conditions by investigating fracture filling minerals (calcite). The outcome has been compared with the results from the hydrological and hydrochemical models providing an independent check of the long term stability of the groundwater flow and chemistry. The EQUIP project has been finalised and the work carried out is reported in a complete report to EC /Bath et al, 2000/.

The EQUIP project is followed by a new three year EC-project named PADAMOT that started late 2001. The main task will be to optimise analyses of fracture fillings in order to get palaeohydrogeological information combined with age constraints. New analytical methods will be tested.

Task 5

The aim of Task 5 of Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes is to compare and ultimately integrate hydrochemistry and hydrogeology, see Section 3.8.1. The impact of the tunnel construction on the groundwater system at Äspö has been studied. A conclusion from the Äspö Task Force was that there is a need to obtain information on both hydrological and hydrochemical properties from the same location at the same time. Even though there is a huge database on hydrochemistry, many modellers still would have needed more time series data from more observation points. In general there was an agreement that the hydrochemical information assisted in constraining the groundwater flow models.

Conclusions and implications to repository performance

Work performed on the hydrochemical stability of groundwaters surrounding a spent nuclear fuel repository in 100 000 year perspective has been reported /Puigdomeneck, 2001/. The main conclusions from the work are that the present hydrochemistry is and has been affected by present and past hydrodynamic conditions. Past groundwater changes are still traceable in the bedrock. The groundwater at repository depth has and will be affected by extreme waters such as brine, seawater, as well as glacial and precipitation waters in various proportions. The cyclic changes are determined by the changing climate. A compositional variability in groundwaters similar to what is observed in the samples collected at various depths today has been predicted by modelling. However, despite these hydrodynamic changes the buffer capacity of the rock is such that hydrochemical stability and favourable chemical conditions can be sustained in the perspective of thousands of years. Radical climatic changes causing high flow (such as quick glacial meltdown) can cause short-term hydrochemical instability in the more conductive parts of the rock. The low conductive parts will probably be less affected during such conditions.

4 Disposal technology

4.1 General

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

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

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

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

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

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

The main experiments that are installed or under way are:

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

4.2 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 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 Canister Retrieval Test. After some modification the same equipment is used for the deposition of buffer material and canisters in the 5 m diameter TBM tunnel of the Prototype Repository.

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

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

4.3 Prototype Repository

4.3.1 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 and including seven participating organisations 2001.

4.3.2 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, possibly 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.

4.3.3 Experimental concept

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

The test location chosen is the innermost section of the TBM tunnel at 450 m depth. The layout involves altogether six deposition holes, four in an inner section and two in an outer, see Figure 4-1. 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 and a second plug will separate the two sections. This layout will in practice provide two more or less independent test sections. Canisters with dimension and weight according to the current plans for the deep repository and with heaters to simulate the thermal energy output from the canisters will be positioned in the holes and surrounded by a bentonite buffer. The deposition holes are with a centre distance of 6 m. This distance is evaluated considering the thermal diffusivity of the rock mass and the fact that the maximum acceptable surface temperature of the canister is 90°C.

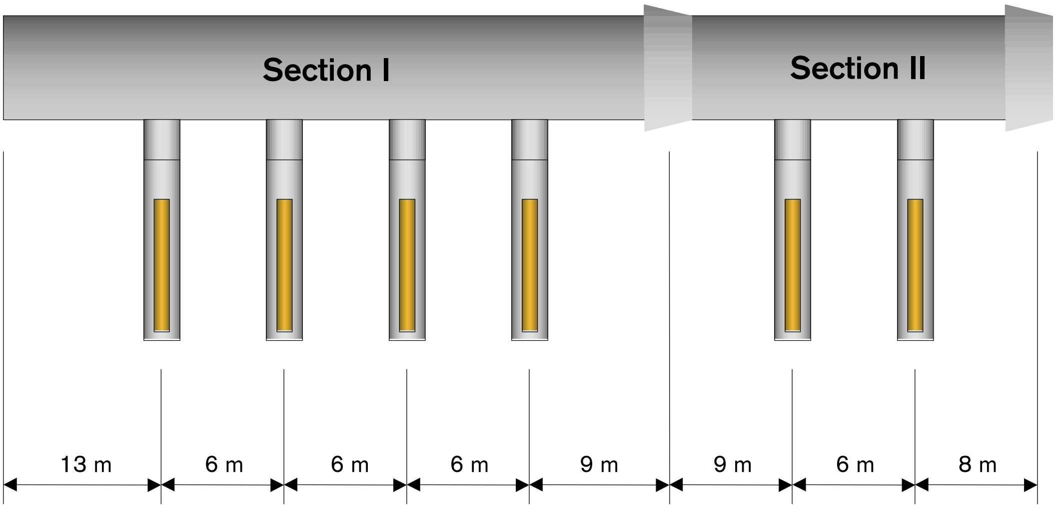


Figure 4-1. Schematic view of the layout of the Prototype Repository. (not to scale)

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.

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.

4.3.4 Results

Construction

The boring of the canister holes started in accordance with the overall plan and the inner four holes where completed in July 1999. The boring of the two outer holes started in August 1999 and where completed in September the same year. The boring machine performed satisfactory and all six holes fulfil well the requirements regarding verticality, straightness and wall smoothness.

Installation

Cement mortar was cast for making the central part of the bottom of the six deposition holes even and horizontal and the walls of the deposition holes in Section I was temporally covered with plastic in order to avoid wetting of the bentonite before start.

The buffer and canisters have been installed in the four deposition holes in Section I during the period May to August 2001 in accordance with the time schedule. The buffer was built up by 14 pieces of 0.5 m high bentonite blocks with the diameter 1.65 m and emplaced one by one with a gantry crane built for this purpose. The canisters were placed with the deposition machine after emplacement of all bentonite blocks except the uppermost 3 blocks. Holes 1 and 3 have been instrumented with gauges placed in the bentonite blocks for measuring THM processes. The canisters were equipped with internal heaters and optical fibre cables applied in grooves on the surface for measuring temperature.

The emplacement of the buffer and canisters were successful. The only problem occurred in relation to the emplacement of the canister in hole 2, since the canister had to be retrieved, the lid removed and the malfunction of the electrical heating system repaired. It was very important to keep the bentonite dry before blowing pellets into the slot between the blocks and the rock. The plastic cover turned out to work well, see Figure 4-2.

The backfill material consists of 70% crushed rock from the TBM drilling and 30% Greek bentonite converted from Ca- to Na-bentonite by treatment with sodium carbonate. The backfill was stored in tents on ground. Before installation the backfill was mixed and water added to yield an average water ratio of 12%. As part of the preparation before the start of the backfilling the compaction equipment was complemented and tested.

The backfilling started late in August and the backfilling of Section I was finished on November 2001. About 1225 tons of backfill material was compacted in 104 layers in the tunnel and about 80 tons were backfilled in the top of the deposition holes. A wall of prefabricated concrete beams was built to keep the backfill in place for the casting of the plug. The final space left between the roof and the plug was filled with bentonite pellets and compacted blocks made from a mixture of 20% bentonite and 80% sand.

The heaters in all the four installed canisters were turned on (the first on September 17 and the fourth on October 22) with the initial power of 1800 W. The power will be decreased in accordance to the decay curve of 40 years interim stored spent fuel.

All planned instruments in buffer, backfill and rock, except for temperature gauges in one borehole, have been installed as well as bentonite blocks and canisters in the inner Section I, see Figure 4-3. At total of 480 measuring points sensors and other monitoring instruments have been installed. A summary is presented in Table 4-1.

The last gauge was installed in the backfill on November 20. Directly arguer installation were the gauges, with only a few exceptions, yielding reliable values.

Table 4-1. Sensors and instruments installed in Section I of the Prototype Repository.

Measuring quantity	Buffer		Backfill	Rock	Canister			
	Dep. hole 1	Dep. hole 3			1	2	3	4
Displacement							6	
Temperature	32	32	20	37	2	2	2	2
Total pressure	27	27	21					
Pore pressure	14	14	22	65				
Relative humidity	37	37	45					
Resistivity			36					

Figure 4-2. *The canister is placed in the deposition hole. The gripping device has been made free from the lid and is being hoisted. The plastic covering the walls is installed for protection of the bentonite, since there is a long time between deposition of the bentonite blocks and backfilling of the tunnel.*

Figure 4-3. *Installed led-throughs with cables and instruments in the Prototype Repository tunnel ready to be placed in the bentonite blocks in deposition hole 3.*

Monitoring

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

The following variables will be measured to study THM processes in buffer and backfill: temperature, water content, pore water pressure, and total pressure.

Measurement of hydraulic regime in the rock comprise recording of piezometric heads has been made from early 2001 and the hydraulic regimes in the near-and far-fields are defined. The hydraulic characterisation of the rock has been made by use of a large number of boreholes, see Figure 4-4. These boreholes will be used for long-time monitoring of the Prototype Repository. Packers, 1–5 in each borehole, have been installed to facilitate monitoring of the water pressure and water chemistry in borehole sections. Temperature sensors are fixed in some of the boreholes. Tubes and cables from the borehole sections are led to a nearby G-tunnel where the pressure and temperature are recorded and the water samples. The inflow of water in the test drift and deposition holes was recorded and evaluated prior to the installation of canisters, buffer and backfill. Very low flows have been noted into the deposition holes, the maximum flow has been measured in deposition hole 1 ($8{\cdot}10^{-2}$ litre per minute) and minimum in deposition hole 4 ($7{\cdot}10^{-4}$ litre per minute). The holes are numbered from the tunnel front, i.e. from left to right on Figure 4-1.

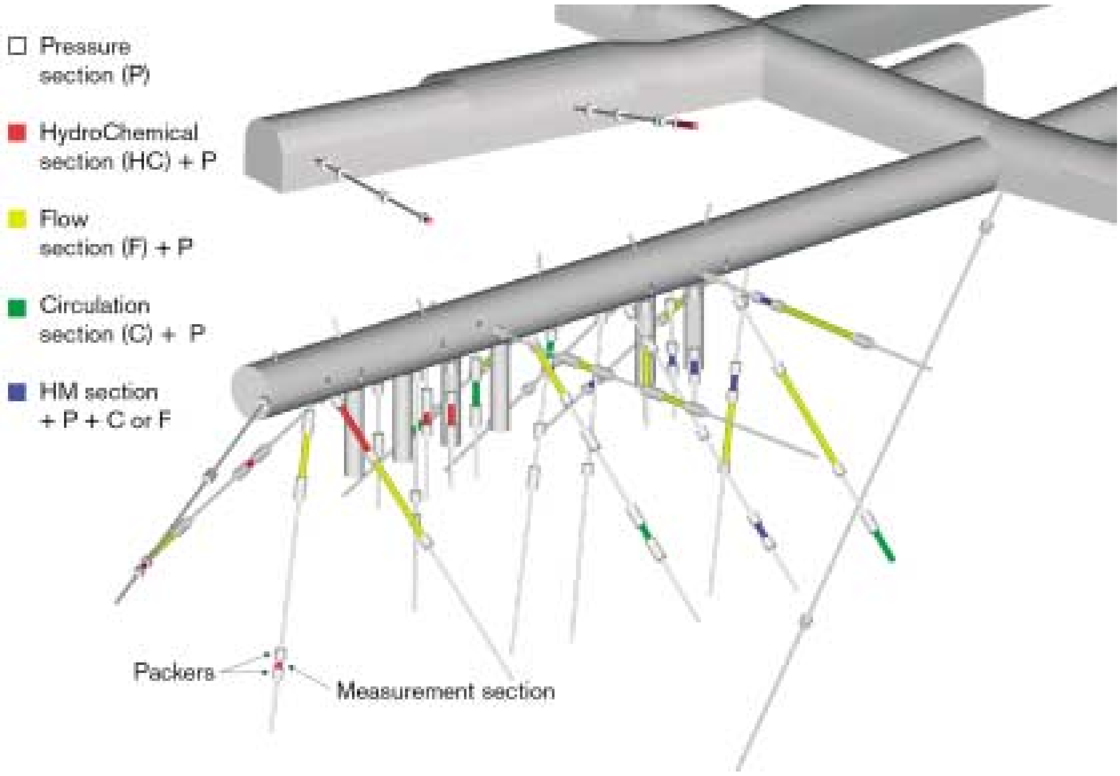


Figure 4-4. *View of the drilled core holes in the Prototype Repository. The diameter of the core holes is 76 mm except for the core holes in the roof of the TBM tunnel.*

An important issue is to characterise the rock structure with special respect to the hydraulic conductivity. Statistical analysis of measured data validates the common understanding that larger volumes (3 m intervals) give appreciably higher conductivity's than smaller ones.

Measurement of mechanical conditions in the rock have been performed to determine the rock stress conditions at various places in the rock mass yielding the average magnitudes and orientations given in Table 4-2. The data together with the material properties determined prior to the project indicate that stable conditions prevail. In addition, geophysical measurements have been made for determination of the local stress fields around the six deposition holes. This has been made by use of acoustic emission technique. The outcome of a comparison of the stress conditions and acoustic signals, indicating comprehensive overstressing up to a few decimetres distance from the periphery. It is reasonable to believe that the strength dropped and the hydraulic conductivity increased in these regions.

The objectives of the research for geochemistry, gas and biology of buffer and backfill is to identify and quantify changes in pore water composition in the buffer and backfill and to investigate the nature and extension of gas formation and biological activities. It involves sampling and analysis of pore water and gas. The main sampling will be made after excavation of the buffer at the termination of the test. However, some collectors are located in the backfill just deposition holes 1 and 3 so those samples can be taken in the course of the experiment.

A system for measuring the electrical resistivity of the buffer and backfill has been applied and is currently recording data for evaluation of water uptake in the buffer and backfill and possible desaturation of the rock between deposition holes 5 and 6.

Recording of possible tilting and vertical displacement of the canisters is made through a set of fibre optic units. The lack of commercially available technique required development of new components that can sustain high effective pressure and temperature. The system was applied in deposition hole 3 in June 2001 and is planned to be applied also in deposition hole 6.

Modelling

The modelling work within the Prototype Repository comprise conceptual modelling of the function of the engineered barrier system (EBS) and application and development of theoretical models for describing important EBS processes and integrated EBS performance.

Table 4-2. Averaged rock stress magnitudes in MPa and orientations.

Parameter	σ_1	σ_2	σ_3
Principal stress	29	21	10
Trend/plunge	133/19	049/42	234/33

The processes recorded in the Prototype Repository Project and predicted by use of theoretical models are:

1. Thermal evolution in the buffer and backfill.
2. Development of pore water pressure and water pressure in the near-field rock.
3. Redistribution of initial pore water in the buffer and uptake of additional water.
4. Development of swelling pressure.
5. Expansion of the buffer yielding displacement of the canisters and overlying backfill.
6. Dissolution of minerals and precipitation of chemical compounds in the buffer.
7. Changes in water chemistry and microbiology.

The evolution of the buffer and backfill is being 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 participants 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 basis for selection and development of these numerical tools for predicting and evaluating the processes in these engineered barriers is a simplified conceptual model.

The modelling work will continue with finalising the predictive modelling of the evolution of the buffer and backfill and near-field rock and for testing the applicability of conceptual and theoretical models.

EC-project

An EC project, which concerns the Prototype Repository, with the duration of 42 months, from September 2001 through February 2004 is ongoing. The participating organisations are:

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

The contributions from the international organisations participating in the Prototype Repository are described in more detail in Chapter 6.

4.4 Backfill and Plug Test

4.4.1 Background

The Backfill and Plug Test includes tests of backfill materials and emplacement methods and a test of a full-scale plug. It is a test of the integrated function of the backfill material and the near field rock in a deposition tunnel excavated by blasting. It is also a test of the hydraulic and mechanical functions of a plug. The test is partly a preparation for the Prototype Repository, see Section 4.3.

The entire test set-up with backfill, instrumentation and building of the plug was finished in autumn 1999 and the wetting of the 30/70 backfill mixture through permeable mats started in late 1999. Wetting of the backfill from the filter mats and the rock has continued during the years 2000 and 2001 and data from transducers has been collected and reported.

4.4.2 Objectives

The main objectives of the Backfill and Plug Test are:

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

4.4.3 Experimental concept

The test region for the Backfill and Plug Test is located in the old part of the ZEDEX drift. A 3D visualisation of the experimental set-up is shown in Figure 4-5. The test region can be divided into the following three test parts:

- The inner part (six sections) filled with a mixture of bentonite and crushed rock (30/70 sections).
- The outer part (four sections) filled with crushed rock and bentonite blocks and pellets at the roof (0/100 sections).
- The concrete plug.

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

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

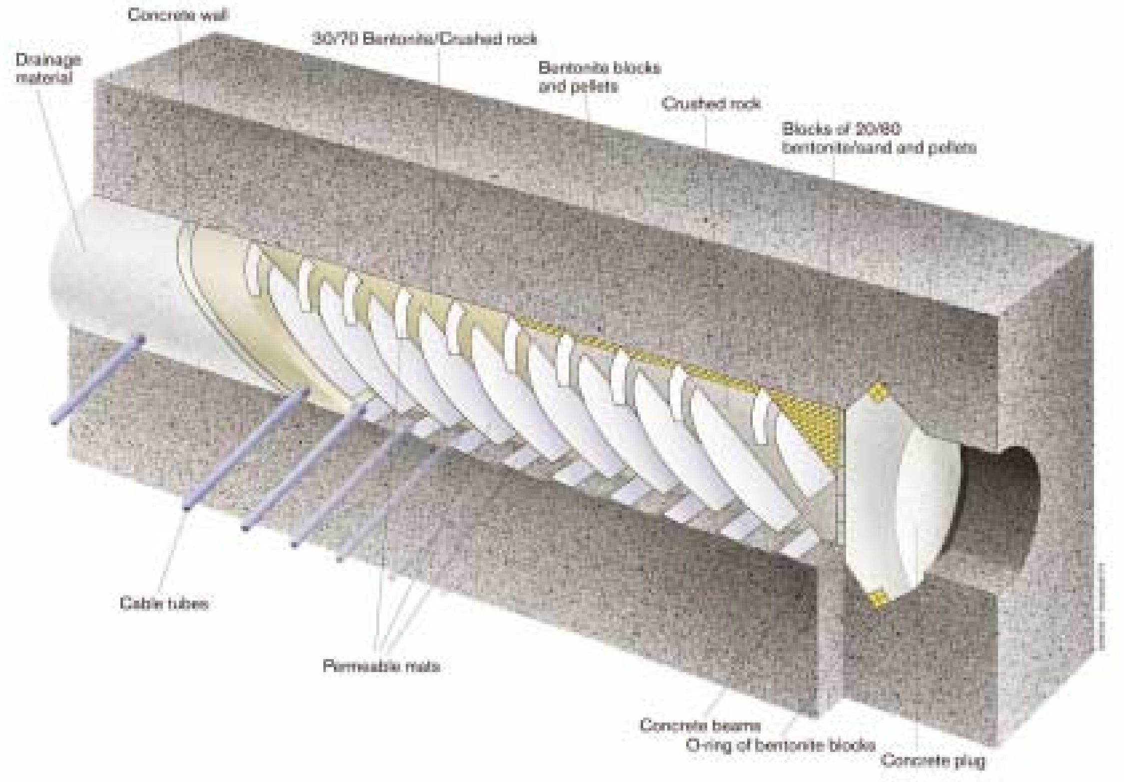


Figure 4-5. *An illustration of the experimental set-up of the Backfill and Plug Test.*

The test region is about 28 m long and it is divided into sections by drainage layers of permeable mats in order to apply hydraulic gradients between the layers and to study the flow of water in the backfill and the near-field rock. The mats are also used for the water saturation of the backfill. The mats were installed in both sections with a distance of 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 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 plug is designed to resist water and swelling pressures that can be developed. It is equipped with a filter on the inside and a 1.5 m deep triangular slot with an "O-ring" of highly compacted bentonite blocks at the inner rock contact, see Figure 4-5.

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

4.4.4 Results

Modelling of the wetting rate of the 30/70 sections with calibrated material models show that the time to full saturation will be more than 5 years with the water pressure 100 kPa in the mats and that a water pressure of 500 kPa is required to reduce the remaining time until full saturation to 1–2 years. With these results as basis, it was decided to increase the tightness of the plug by grouting and then increase the water pressure in the mats.

The interface between the concrete plug and the rock was grouted in the last week of June 1999. The grouting was made through three perforated plastic tubes that were installed on the rock wall before casting of the plug. The three tubes are running tangentially in the slot at different distances from the outer intersection between the slot and the tunnel. The inner and outer tubes were injected with cement and the central tube was injected with polyurethane-based grout.

The grout was allowed to rest for a few months. The permeable mat behind the plug, which had been partly emptied, was then refilled and the water pressure re-established.

Measurement of water leaking from the mat through the rock and plug interface indicated a decrease in leakage with a factor 4 compared with the leakage before grouting.

The water pressure in the permeable mats and the drained inner part of the drift was then increased to 400 kPa in steps of 100 kPa at the following dates: 2001-10-03, 2001-11-14, 2001-11-28, and 2001-12-10.

The amount of water passing through the plug and the surrounding rock has been measured during this period by collecting water outside the plug. Figure 4-6 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 increased from 0.02 l/min to 0.06 l/min when the pressure was increased from 100 kPa to 400 kPa. The leakage is not higher than what could be accepted for future flow tests.

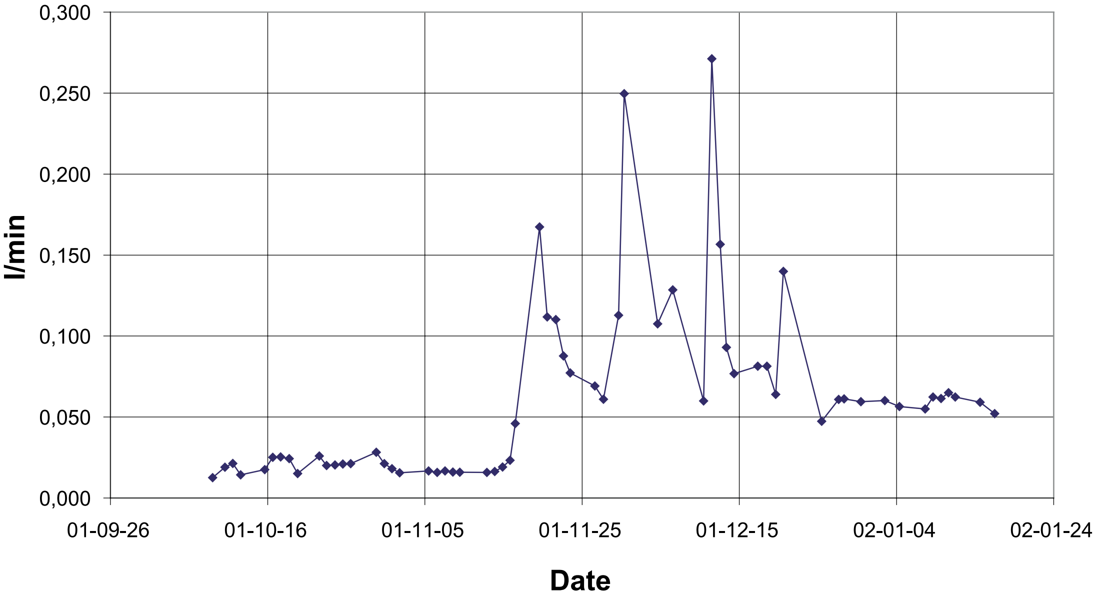


Figure 4-6. *Water flow through the plug and its surroundings. The first peak corresponds to the pressure increase from 100 to 200 kPa, the second to 300 kPa and the third to 400 kPa.*

Water saturation, water pressure and swelling pressure in the backfill and water pressure in the surrounding rock have been continuously measured and recorded. Figure 4-7 and Figure 4-8 show example of measured results. Figure 4-7 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 recent water pressure increase after grouting. Figure 4-8 shows the suction (negative pore water pressure) measured in the centre of different layers of 30/70. Only the sensors placed in the first layers (about 20 cm from the mat) have been clearly water saturated. Decrease in suction in transducers W17 and W20 (about 40 cm from the mat), which started in September 2000, has continued and can from July 2001 also be seen for the central transducers W19 and W22 (about 60 cm from the mats).

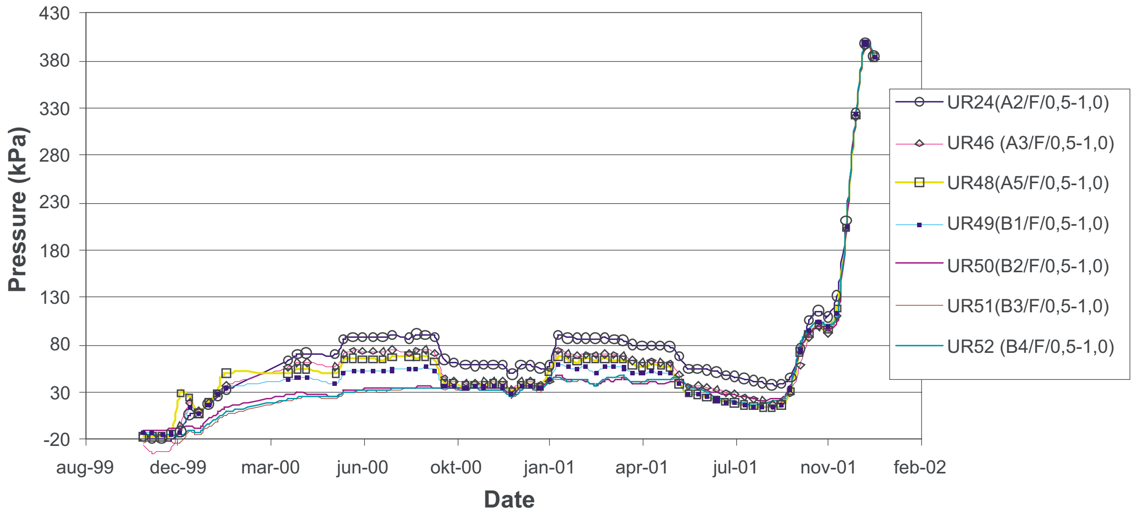


***Figure 4-7.** Water pressure measured in the floor 30 cm below the rock surface. UR24, 46, 48 and 49 are placed in the 30/70 sections and the rest in the 0/100 sections.*

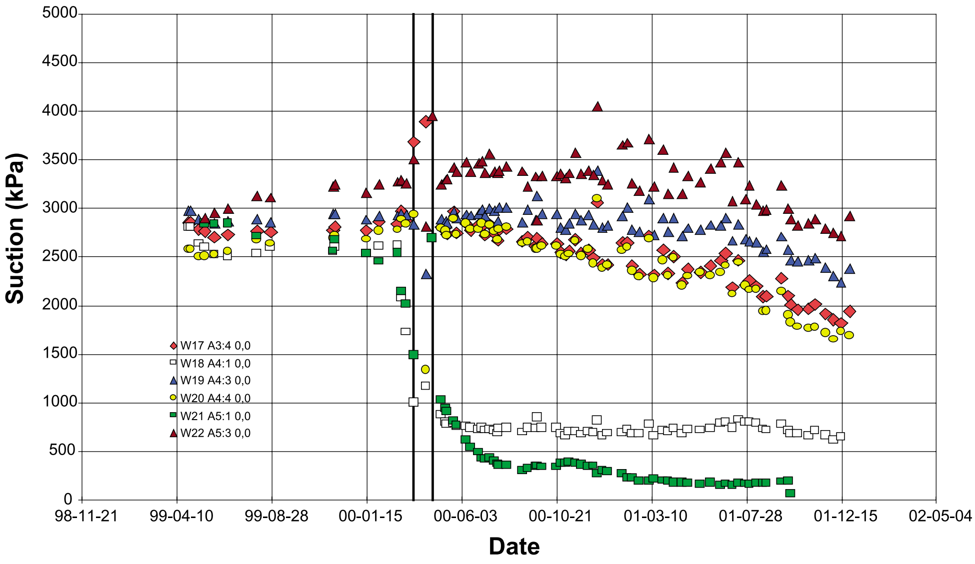


***Figure 4-8.** Suction measured in the centre of different layers in the 30/70 sections. W18 and W21 are placed in the first layer about 20 cm from the mats. W17 and W20 are placed 40 cm and W19 and W22 are placed 60 cm from the mats.*

4.5 Canister Retrieval Test

4.5.1 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 the canister 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.

4.5.2 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 in accordance to conditions planned for the real repository. However, for different reasons only one of these deposition holes has been used for implementation of the Canister Retrieval Test.
- Saturation and swelling of the buffer under controlled conditions, which are monitored.
- Preparations for testing of canister retrieval.

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

4.5.3 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 holes and installation of bentonite blocks and canisters with heaters. The holes are covered in the top with a lid of concrete and steel.

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

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

The buffer was installed in the form of blocks of highly compacted Na-bentonite, with a full diameter of 1.65 m and a nominal height of 0.5 m. When the stack of blocks was 6 m high the canister equipped with electrical heaters was lowered down in the centre. Cables to heaters, thermocouples and strain gauges are connected, and further blocks are emplaced until the hole was filled up to 1 m from the tunnel floor. On top the hole was sealed with a plug made of concrete and a steel plate as cover. The plug was secured against heave caused by the swelling clay with cable anchored to the rock. The tunnel will be left open for access and inspections of the plug support. The experimental set-up is shown in Figure 4-9.

Figure 4-9. *Experimental set-up in 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 about two-three years in the 350 mm thick buffer along the canister and about 5 years in the buffer below and above the canister. Decision on when to start the retrieval tests is dependent on 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.

4.5.4 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.

The alarm for low temperature level (80 degrees) went off on November 6, 2001. Readings from the measurements showed that a short circuit had occurred (November 4) in two of the heaters. The two failed heaters were disconnected and resistivity measurements were performed on all parts going into the canister. The resistivity measurements showed that the values were extremely low in all cases, in the order of 0.05–0.1 MΩ compared to more than 5 MΩ before heating. An investigation to determine the source of error and to locate the failed "area" was initiated immediately.

Measurements

A number of parameters are measured during the test to provide a basis for modelling purposes. Measurements covering the period 2000-10-26 to 2001-10-31 have been reported in /Goudarzi and Börgesson, 2001a,b; Goudarzi et al, 2001/. The next sensor data report is expected to be issued in May 2002. Table 4-3 shows which parameters that are measured and includes comments to the figures. Selected characteristic values from 2000-10-26 until 2001-12-30 is shown in Figure 4-10 to Figure 4-14. Values of temperature, humidity, and total pressure are picked at mid-height of the canister. The discontinuities in the temperature curves correspond to increase in effect at start-up, increases from 1700 W to 2600 W, and the heater failure in November 2001.

Table 4-3. Measurements during Canister Retrieval Test.

Type of measurement	Status and comments
Temperature inside canister (°C).	Ongoing, see Figure 4-12.
Temperature on canister surface (°C)	Ongoing, see Figure 4-12. The early dip of the curve starting at September 17 is due to dropouts of the readings.
Temperature in the buffer (°C)	Ongoing, see Figure 4-12.
Temperature in the rock (°C)	Ongoing, see Figure 4-12.
Rock stresses (Pa)	Ongoing. Output is not adjusted for temperature effects and is therefore not shown.
Total pressure in buffer (Pa)	Ongoing, see Figure 4-10.
Pore pressure in buffer (Pa)	Ongoing.
Relative humidity in buffer pores (%)	Ongoing, see Figure 4-11.
Strain in canister (mm/m)	Ongoing.
Heater effect (W)	Ongoing.
Artificial watering volume (l)	Ongoing.
Artificial watering pressure (Pa)	Ongoing.
Vertical displacement of plug (mm)	Ongoing, see Figure 4-13. The divergent curve indicates that the plug is in contact with the borehole wall.
Forces in rock anchors (kN)	Ongoing, see Figure 4-14. The discontinuity in the curves corresponds to distribution of forces on six more anchors.

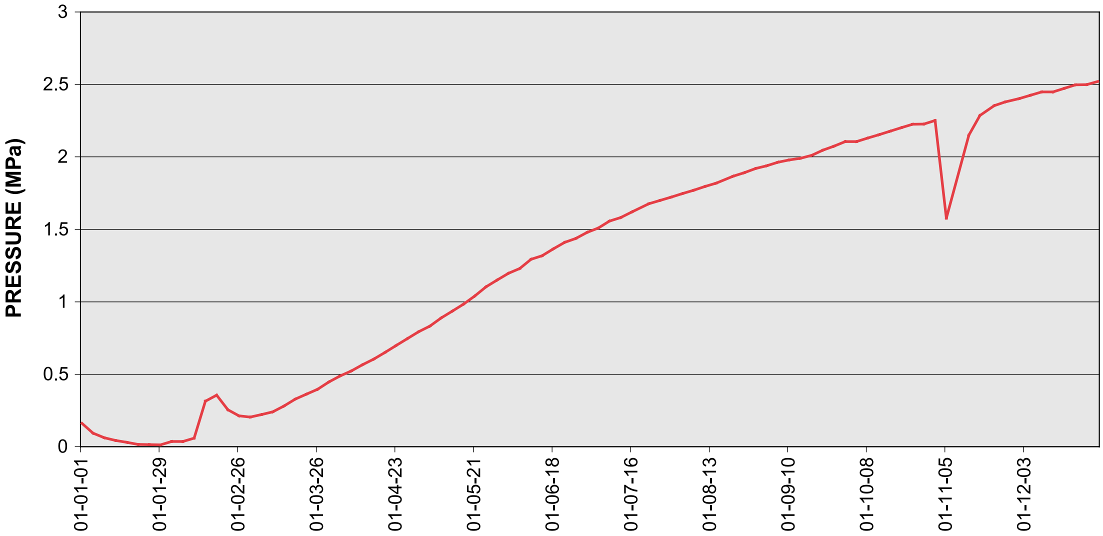


Figure 4-10. *Total pressure in buffer.*

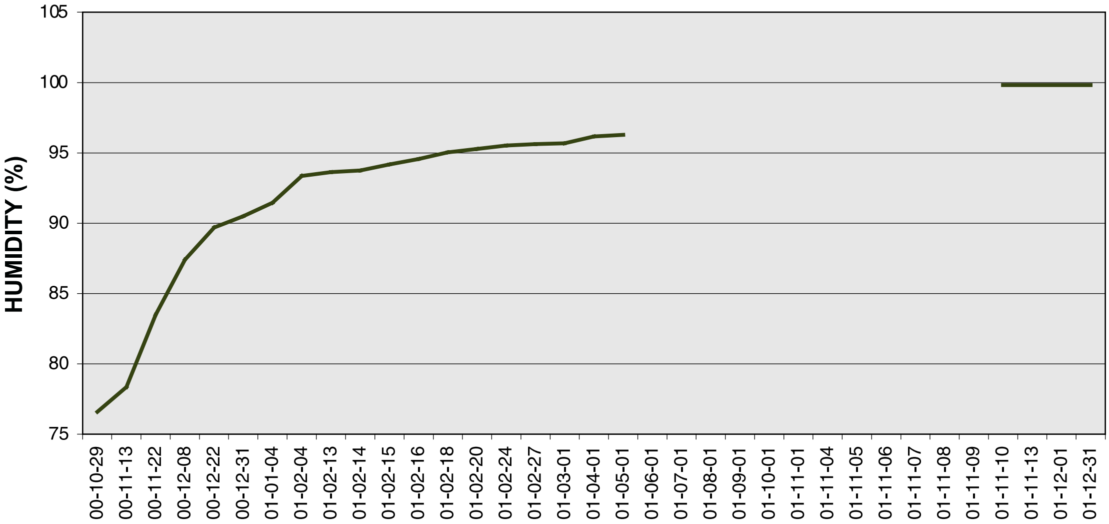


Figure 4-11. *Humidity in buffer.*

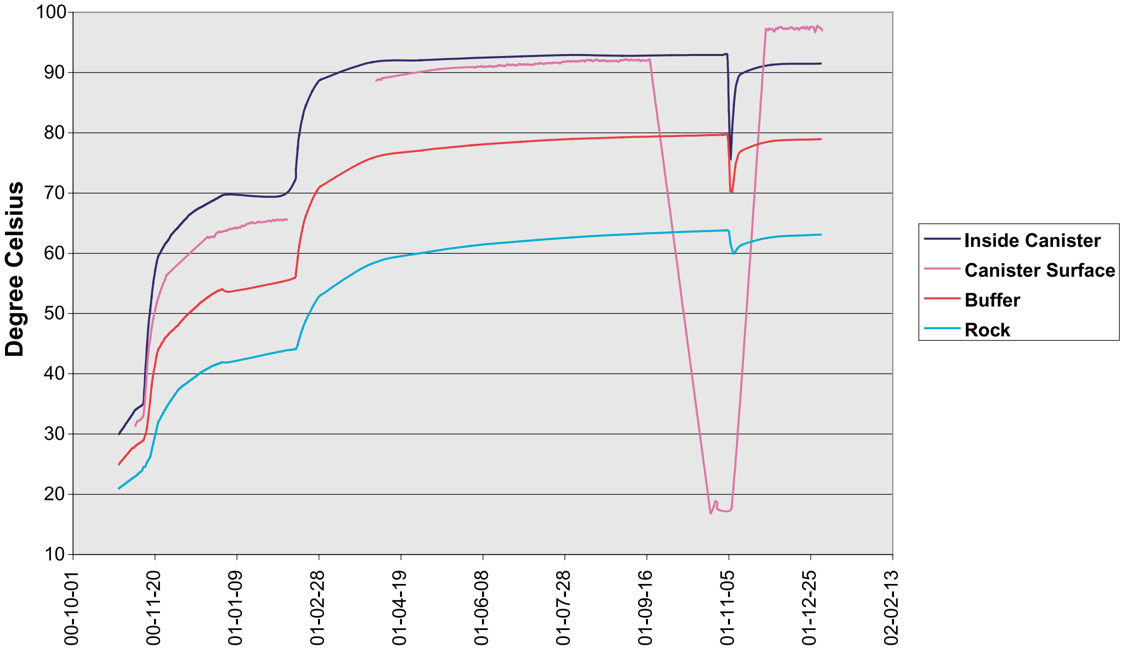


Figure 4-12. *Temperatures at mid-height of the canister.*

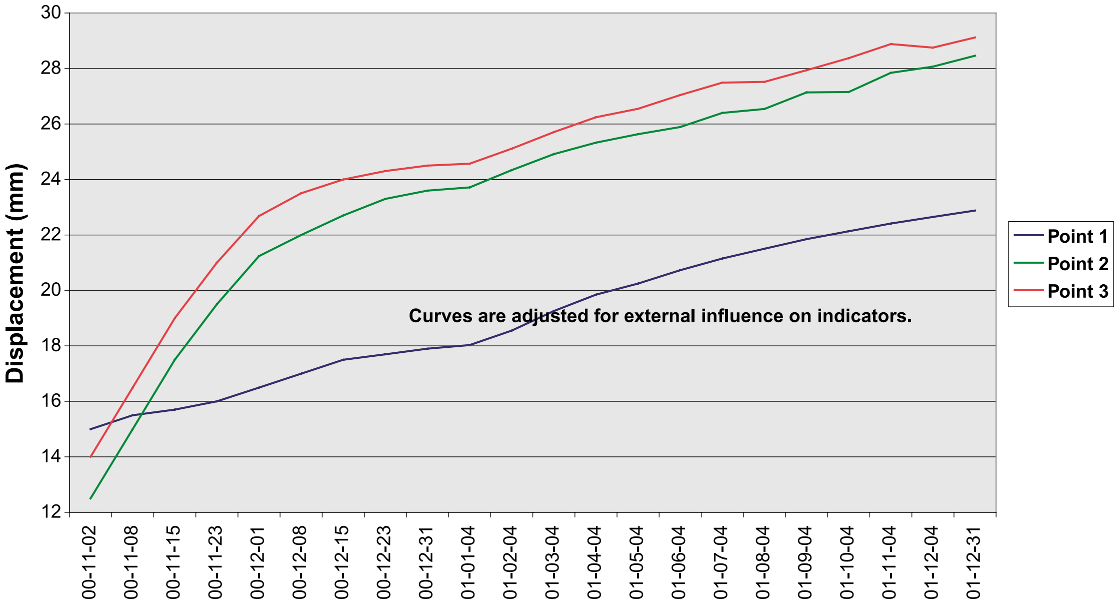


Figure 4-13. Vertical displacement of retaining plug.

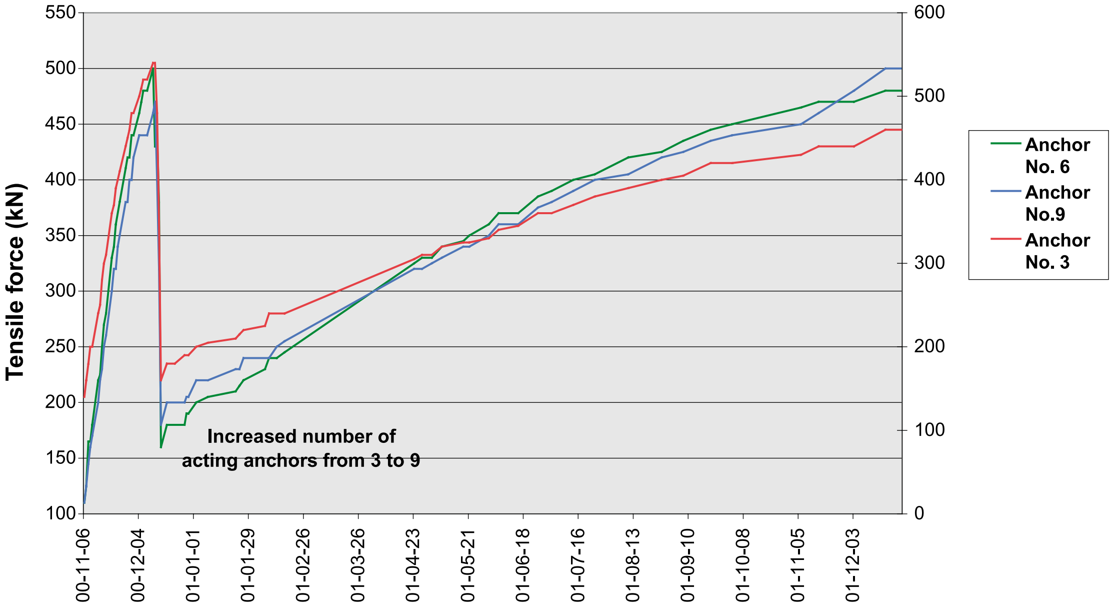


Figure 4-14. Tensile forces in rock anchors for retaining plug.

4.6 Long Term Test of Buffer Material

4.6.1 Background

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

4.6.2 Objectives

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

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

4.6.3 Experimental concept

The testing principle for all planned tests is to emplace "parcels" containing heater, central tube, pre-compacted clay buffer, instruments, and parameter controlling equipment in vertical boreholes with a diameter of 300 mm and a depth of around 4 m, see Figure 4-15. The test series, given in Table 4-4, concern realistic repository conditions except for the scale (size) and the controlled adverse conditions in some tests (A0–A3).

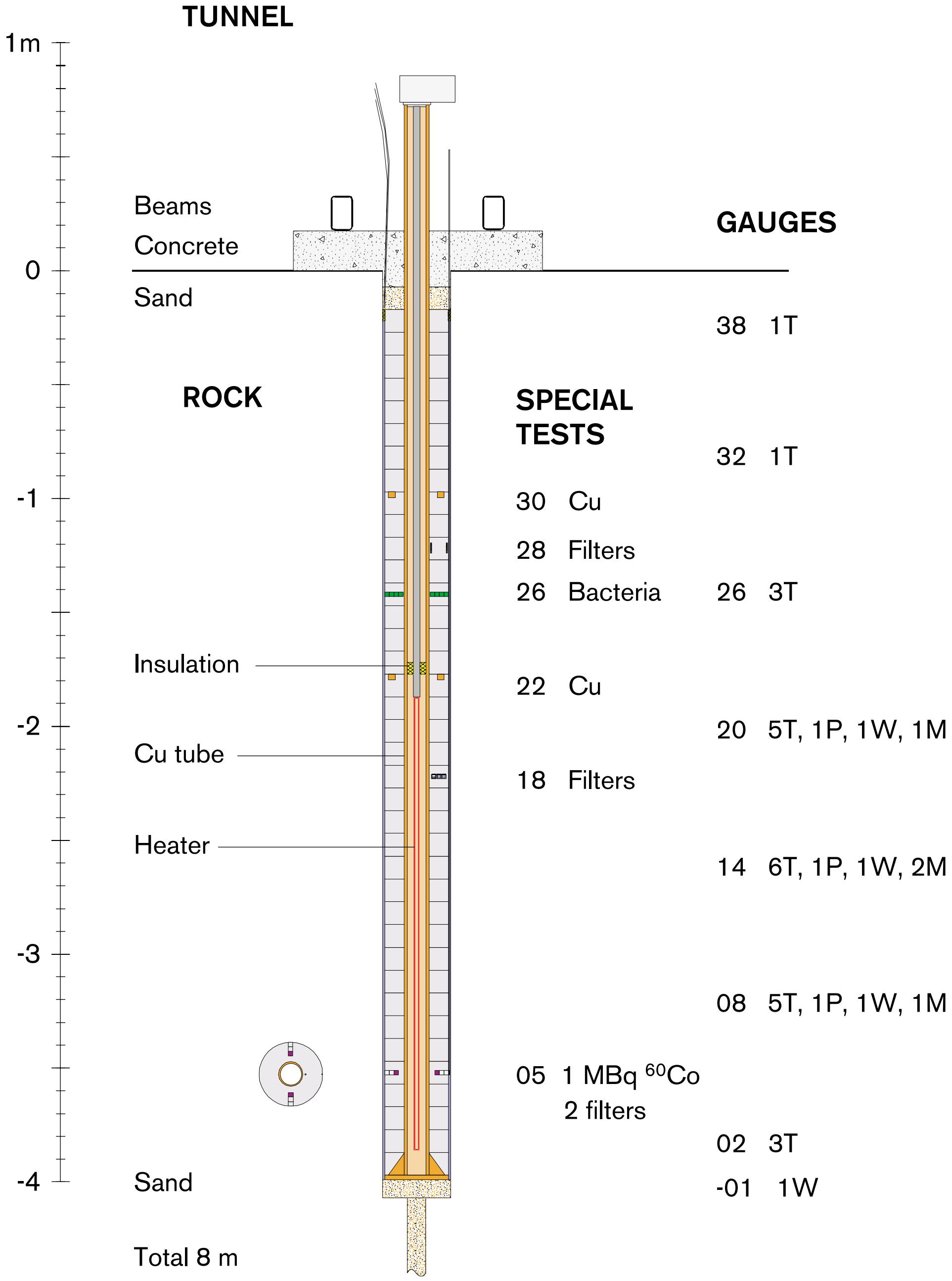


Figure 4-15. Cross-section view of an S-type parcel. The first figures in column denote block number and second figures denote the number of sensors. T denotes thermocouple, P total pressure sensor, W water pressure sensor, and M moisture sensor.

Table 4-4. Lay out of buffer material 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, reported
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
[K$^+$] = potassium concentration
am = accessory minerals added
S = standard conditions

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

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

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

4.6.4 Results

A system for online registration of possible copper corrosion has been connected to the preinstalled electrodes in the A2 parcel. The system is functioning well and has delivered expected data for the first year.

The power in the 1-year A0 parcel was turned off October 18, 2001, and the uptake operation was started in November. The overlapping core drilling around the parcel was made without water in order not to affect the bentonite in the parcel. The parcel was brought up November 27, and immediately split for delivery to the involved laboratories, see Figure 4-16.

Figure 4-16. *First check of radioactivity from tracer elements in the A0 parcel just after uptake and removal of the covering rock.*

The remaining ongoing four long term test parcels have been functioning without any major problems and temperature, total pressure, water pressure, and water content have been continuously measured and registered every hour. Figure 4-17 shows the temperature evolution in the warmest section of parcel A0. The shaky part of the lowest curve is due to contact problems and represents the kind of minor problems that has occurred in a few of the more than 200 sensors in the system.

The incoming data from the four ongoing parcels are automatically monitored with respect to overheating, and all recorded data are followed up monthly. In case of full water-saturation in one of the two S-parcels a first gas test will be initiated. The various laboratory analyses of the A0 parcel material have started and are planned to be reported during the fall 2002. The radioactive tracer (^{57}Co and ^{134}Cs) distribution are measured at the Nuclear Chemistry department at KTH, Stockholm, pore water analyses are made at Reactor department at VTT, Helsinki, copper corrosion by Rosborg Consulting/Studsvik Material, Nyköping, and the clay mineralogical and physical properties are studied at Clay Technology AB and the Geological department at Lund University.

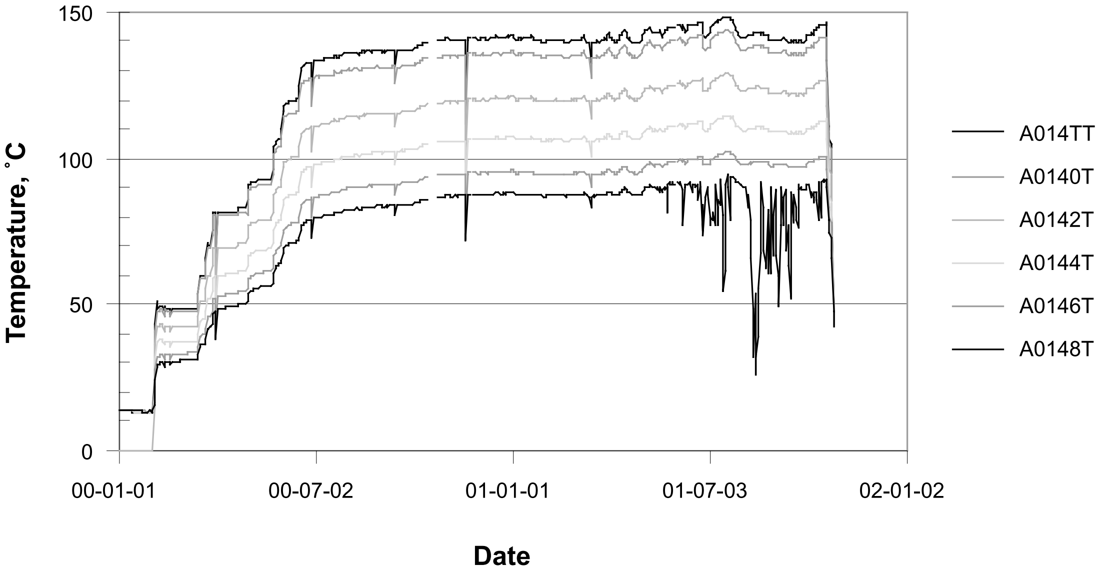


Figure 4-17. *Temperature evolution in six thermocouples, radially distributed in the warmest level of the A0 parcel. Uppermost curve represents the copper tube temperature, and the lowest the curve represents the temperature close to the rock.*

4.7 Pillar Stability Experiment

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

4.7.2 Objectives

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

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

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

The project is divided into four different phases:

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

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

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

4.7.4 Results

The project was initiated in late 2001 with a feasibility study.

4.8 Task Force on Engineered Barrier Systems

The Task Force is presently focusing on modelling of THM processes taking place in the bentonite buffer during saturation, which also is the prime modelling objective in the Prototype Repository. The work is therefore conducted under the umbrella of the Prototype Repository having the Task Force in a stand by position.

5 Äspö facility

5.1 Facility operation

5.1.1 Introduction

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 2001.

The service and maintenance agreement with the main contractor, OKG has been revised since the costs have increased and a reorganisation of OKG has meant that their service capacity has decreased. 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.

5.1.2 Surface activities

To meet the need for additional office space to host the staff of the site investigation in Oskarshamn a temporary barrack was built. The building accommodates 16 offices and two conference rooms. An application for planning permission for additional extension of the Äspö facility has been submitted.

The building of a new store at the portal of the tunnel began in November 2001 and is estimated to be completed in April 2002.

The parking lot with room for 32 cars and 2 busses, which was built during last year, has been surrounded with plantations and lawns in order to harmonise with the environment.

The refurbishing of the road has been completed with a coating of tarmac during the summer.

5.1.3 Underground activities

An extensive rock reinforcement programme was finalised in February 2001. The programme comprises complementary shotcreating, injections, bolting and mounting of mesh.

A facility operation monitoring system (ALFA) was taken into operation in 2001. The system facilitates the operation considerably and gives valuable information for maintenance. The knowledge of running hours for pumps, ventilation, and energy consumption enables optimisation of the different systems.

A system for hands-free registration when going underground has been installed. The installation of the software and the hardware throughout the underground facility was done in October. At present the function of the system is tested and bugs in the software are being identified. The hands-free registration system will be taken into operation during spring 2002, and the whole project will be finalised in September 2002.

A project with the aim to decrease the risk of fire and accidents underground but also above ground. The project comprises additional fire detection system at the 420 m level with voice alarm at strategic places, education in fire protection, and fire drill.

Replacement of corroded light equipment in the deeper half of the tunnel, 220–450 m level, and replacement of sealing on the water pipes in the shaft, 350–450 m level, have been completed.

5.2 Information and public relations

5.2.1 Background

SKB operates three facilities in Oskarshamn municipality, the Äspö HRL, CLAB and the Canister Laboratory. The evaluation of the six feasibility studies for siting a deep repository has indicated Oskarshamn as one municipality with high potential for hosting a deep repository.

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

5.2.2 Visitors and special events

During the year 2001, the Äspö HRL had 12 348 visitors, see Figure 5-1. The groups have represented the general public, communities where SKB has performed feasibility studies, teachers, students, politicians, journalists and visitors from foreign countries. 5420 visitors represented the six communities where SKB has performed feasibility studies.

The total amount of visitors to all SKB facilities in Oskarshamn is 21 200. The information group at Äspö has administrated the visitors.

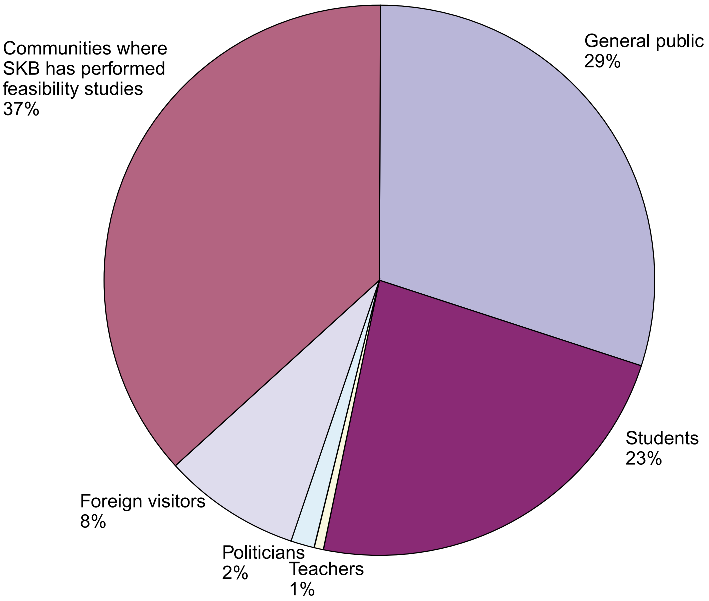


Figure 5-1. *Visitors Äspö HRL during 2001.*

The U500 summer tours for the general public started on June 8 and finished in August. The tours generated 2400 visitors which was 400 visitors more than SKB had planned to attract.

An annual event "The Äspö Day" took place on May 6. About 400 people took part in the underground tours.

On December 9 an open house with the theme "Christmas in the Hard Rock Laboratory" was arranged. The open house generated more than 300 visitors.

5.2.3 Other activities

During 2001 the following improvements have been performed:

- The common booking system has been ordered and is under construction. Start of running test in early 2002.
- A video of the history of the Äspö HRL has been produced. The video presents the history from the very beginning in 1986 with site investigations, tunnel construction and research up till today.
- A film to demonstrate the deposition machine has been produced.
- The information boards underground have been updated.

5.3 Hydro Monitoring System

5.3.1 Background

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

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.

5.3.2 Results

Improvements, new installations and other measures carrie out during 2001 are:

- The weirs in the tunnel have been calibrated.
- An on-line presentation system has been installed for the Canister Retrieval Test. Radio modems have been installed at the boreholes KAS 08 and KAS 12 for data collection.
- A new HMS computer has been installed in the G-tunnel to take care of data from hydro-sections in the Prototype Repository.
- Renovation has been made at the measuring station at 3007 m in the tunnel.

5.4 Monitoring of groundwater head and flow

5.4.1 Background

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

The monitoring of water levels started in 1987 while the computerised HMS was introduced in 1992. The number of boreholes included in the network has gradually increased. The tunnel construction started in October 1990 and the first pressure measurements from tunnel drilled boreholes were included in the HMS in March 1992. To date the monitoring network comprises a total of 62 boreholes most of which are equipped with inflatable packers, measuring the pressure by means of pressure transducers. The measured data is relayed to a central computer situated at Äspö village through cables and radio-wave transmitters. 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. Water seeping through the tunnel walls is diverted to trenches and further to 21 weirs where the flow is measured.

Construction of the hard rock laboratory began in October 1990 and was completed during 1995. However the tunnel excavation began to impact on the groundwater head during the spring 1991.

5.4.2 Objectives

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

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

5.4.3 Results

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

Table 5-1. Type of measurement and number of measurement points.

Type of measurement	Number of measurement points
Groundwater pressure in surface boreholes	80
Groundwater pressure in tunnel boreholes	174
Groundwater level in surface boreholes	15
Flow of tunnel water	21
Electric conductivity of tunnel water	11

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 5-1.

5.5 Monitoring of groundwater chemistry

5.5.1 Background

During the Construction Phase of the Äspö Hard Rock Laboratory, 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 the cored boreholes drilled from the ground surface and from percussion and cored boreholes drilled from the tunnel.

5.5.2 Objectives

At the beginning of the Operational Phase, sampling was replaced by a groundwater chemistry-monitoring program, aiming to sufficiently cover the hydrochemical conditions with respect to time and space within the Äspö HRL. This program should provide information for determining where, within the rock mass, the hydrochemical changes are taking place and at what time stationary conditions have been established.

The monitoring program should provide the data necessary to check that the pre-investigation and the Construction Phase models are valid, as well as it should provide new data for further development of the hydrogeochemical model of Äspö.

5.5.3 Results

Groundwater samples were taken at one occasion during 2001, 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 will be presented in a Technical Document in the beginning of 2002.

5.6 Geo-scientific modelling

5.6.1 Background

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

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

5.6.2 Objectives

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

6 International co-operation

6.1 General

Nine organisations from eight countries have participated in the Äspö Hard Rock Laboratory during 2001. Table 6-1 shows the scope of each organisation's participation under the agreements.

The co-operation is based on separate agreements between SKB and the organisations in question. Nirex has left the co-operation work during 2001. The participation by JNC and CRIEPI is regulated by one agreement and one delegate in the International Joint Committee represents the two companies.

Table 6-1. International participation in Äspö HRL.

Organisation	Participation
Agence Nationale pour la Gestion des Déchets Radioactifs, **ANDRA**, France	Tracer Retention Understanding Experiments (TRUE Block Scale) Task Force on Modelling of Groundwater Flow and Transport of Solutes Prototype Repository
Bundesministerium für Wirtschaft und Technologie, **BMWi**, Germany	Radionuclide Retention Project (Migration of actinides) Colloid Project Microbe Project Task Force on Modelling of Groundwater Flow and Transport of Solutes Prototype Repository
Empresa Nacional de Residuos Radiactivos, **ENRESA**, Spain	Tracer Retention Understanding Experiments (TRUE Block Scale) Task Force on Modelling of Groundwater Flow and Transport of Solutes Backfill and Plug Test Prototype Repository
Japan Nuclear Cycle Development Institute, **JNC**, Japan	Tracer Retention Understanding Experiments (TRUE Block Scale) Task Force on Modelling of Groundwater Flow and Transport of Solutes Prototype Repository
The Central Research Institute of the Electronic Power Industry, **CRIEPI**, Japan	Task Force on Modelling of Groundwater Flow and Transport of Solutes Prototype Repository Voluntary project on groundwater dating – Validation of groundwater dating methods and evaluation of stability in groundwater environments after tunnelling.
Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle, **NAGRA**, Switzerland	Task Force on Modelling of Groundwater Flow and Transport of Solutes
Nirex Limited, **Nirex**, United Kingdom	Tracer Retention Understanding Experiments (TRUE Block Scale)
Posiva Oy, **Posiva**, Finland	Tracer Retention Understanding Experiments (TRUE Block Scale) Colloid Project Matrix Fluid Chemistry Task Force on Modelling of Groundwater Flow and Transport of Solutes Prototype Repository Long Term Test of Buffer Material Pillar Stability Experiment
United States Department of Energy, Carlsbad Field Office, **USDOE CBFO**/ Sandia National Laboratories,**SNL**, USA	Task Force on Modelling of Groundwater Flow and Transport of Solutes

ANDRA, Posiva, ENRESA, JNC and SKB are co-operating under a special multilateral agreement regarding the TRUE Block Scale experiment.

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

In the following sections some of the work performed by the international participants during 2001 is described in more detail.

The ongoing experiments at Äspö HRL are described in Chapter 3 and 4

6.2 BMWi

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

In the following contribution, studies related to actinide migration and in-situ measurement of colloids in the Äspö groundwater are presented.

6.2.1 Radionuclide Retention Experiment – Migration of actinides

The FZK/INE investigations are focusing on sorption and migration of radionuclides, especially actinides, in fractured rock. To guarantee conditions as realistic as possible, the experiments are designed to be compatible with the CHEMLAB 2 probe. The objectives of the experiments 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 of americium, neptunium and plutonium.

Experiments

In a first step, the experimental set-up was designed and some preliminary sorption experiments with fracture filling material and granite, respectively, and with groundwater from the area of CHEMLAB 2 were conducted in the laboratory at INE. For the in-situ migration experiments, a drill core sample with a fracture concealed in an autoclave was placed in CHEMLAB 2. The first experiment was conducted in 2000 and the second was started in November 2001.

The hydraulic properties of fractured rock samples were investigated at INE. HTO was used as inert tracer and dependencies of the breakthrough from the applied flow rates were recorded. The actinide breakthrough and the actinide recovery were measured as a function of the eluted groundwater volume.

Different techniques were applied in order to investigate the retention of the actinides along the flow path. After termination of the migration experiments, a fluorescent epoxy was injected and the cores were cut perpendicular to the cylinder axis. The geometry of the flow path was analysed by scanning the slices optically and by discrimination of colours with respect to the fluorescent resin. The volumes and the inner surface areas of the fracture were determined from the scans by means of pixel counting and numerical evaluation. Additional information on the flow path was obtained by 3D visualisation of the fracture.

The actinide concentrations on each surface of the slices were analysed by spatially resolved α-radiography and by coupled laser ablation ICP-MS techniques. The abraded material gained by cutting the slices was dissolved and actinide concentrations were measured by ICP-MS.

Results

In laboratory and in the in-situ experiment, a non-retarded breakthrough of ^{237}Np was observed. Total recovery of Np was between 20 and 40%. Breakthrough of Am and Pu was not measured. The open fracture of Core #1 (used in a laboratory migration experiment) was analysed. Its cross sections varied between 38 and 87 mm^2 (mean value 53 mm^2) and the circumferences of the fracture at top and bottom of each slice were determined between 72 and 96 mm (mean value 80 mm). In contrast to Core #1, no continuous flow path was detected in Core #2. Structures, which could be seen in the scans of Core #2 slices, were attributed to a healed fracture system. Volumes filled with fluorescent resin were generally too small to be identified by the scanning technique, however, single spots of fluorescent resin were identified visually throughout many slices of the core.

In the abraded material gained by cutting the slices of Core #1, ^{237}Np was found by ICP-MS measurements between $9\cdot10^{-3}$ and $2\cdot10^{-2}$ nmol/g. The Np concentrations varied between $6\cdot10^{-3}$ and $7\cdot10^{-2}$ nmol/g in Core #2. Pu was in the range of the detection limit ($3\cdot10^{-4}$ nmol/g) in both Core #1 and Core #2. ^{234}Am was detected in Core #1 only, its concentration was between $6\cdot10^{-4}$ and $2\cdot10^{-3}$ nmol/g.

For Core #1, it was possible to combine measured Np and Am distributions with the geometrical information of the fracture obtained by evaluation of the slices. Spatially resolved α-radiography showed clearly that the actinides were sorbed onto the surfaces of the fractures. The surface loading of the fracture was calculated. For Np, a continuous decrease of the loading from the injection to a distance of 23 mm was found. At a distance of 4.35 mm from the injection plane, the Np loading was about $4\cdot10^{-4}$ nmol/mm^2. Between 23 and 56 mm, the Np loading was found to scatter between about $2\cdot10^{-4}$ and $1\cdot10^{-4}$ ng/mm^2. Integration over the surface loading of Np yielded in average 1.1 nmol/mm^2 which reflected the amount the of totally injected ^{237}Np and the observed recovery.

A similar analysis was carried out for ^{243}Am. Am recovery in all experiments was below the detection limit indicating that almost the total amount of Am injected remained in the core. A first maximum of the Am loading was determined at a distance of 18.5 mm from injection ($4\cdot10^{-5}$ nmol/mm^2). The Am loading dropped to $2\cdot10^{-5}$ nmol/mm^2 at 37.3 mm. The Am distribution over this distance showed a well-pronounced peak. Comparing the groundwater velocity with the migration velocity of Am, a retardation of Am against water of approximately 40 was calculated.

6.2.2 Colloid Project – Background measurements

In safety assessments for a radioactive waste repository, 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 is determined. The aim is to directly investigate the colloid occurrence in different groundwater types without any interference by sampling.

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 set-up built for in-situ measurements, equipped with a new high-pressure detection cell is used for the background colloid detection in natural groundwater along the access tunnel.

Experiments

The principle of LIBD is based on the generation of a dielectric breakdown in the focus region of a pulsed laser beam. As the threshold energy (irradiance) to incite breakdown for solids is lower than for liquids or gas, the breakdown can be generated selectively on particles dispersed in solution at suitable pulse energy. A pulsed laser beam with a frequency of 15 Hz at 532 nm wavelength from a small Nd: YAG-laser is focused into the centre of a flow-through detection cell. A microscope equipped with a CCD monochrome camera triggered by the incident laser pulse and recorded by a PC-controlled image processing system monitors the plasma generated at a breakdown event.

A new flow-through detection cell had to be developed (Figure 6-1) constraining a water pressure of 32 bar for the investigations in the Äspö tunnel, down to a depth of –416 m. Because of its different optical and geometrical properties, the LIBD system had to be re-calibrated completely.

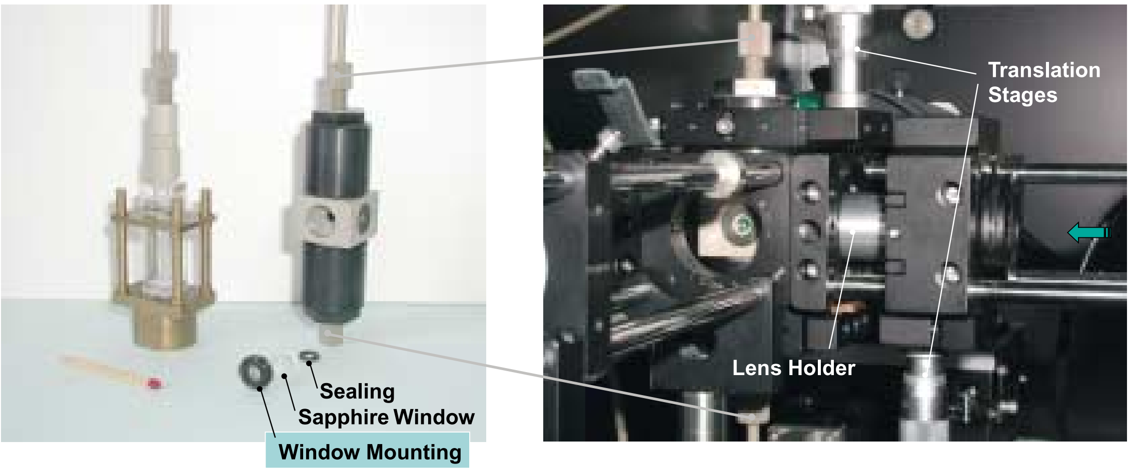


Figure 6-1. *LIBD high-pressure flow-through detection cell (left: flow-through silica detection cell).*

Along the 3.6 km long access tunnel at depths from –70 m down to –416 m eight sampling locations with lined boreholes were selected by SKB. Each borehole contains one representative type of groundwater, which can be characterised as a mixture of water of different origin, e.g. meteoric, Baltic Sea, brine, glacial. The instrumented van is installed close to the sampling boreholes, mostly on a ramp to guarantee a horizontal orientation of the set-up (Figure 6-2).

Results

The LIBD data for the different groundwaters are summarised in Table 6-2. At each borehole position, the groundwater flow rate adjusted at a bypass valve was varied between 4 ml/min and the maximum flow rate given by completely opened valves. Groundwater properties arising from visual inspection at the sites, such as "gas generation" (gas bubbles in the dispersion) and "coloured dispersion", give some casual information about pressure fluctuations and the amount of colloids.

In order to investigate the influence of 100 m external tubing between the bypass valve and the borehole, the colloid concentration was measured in groundwater in borehole KA1755A both with and without the external tubing.

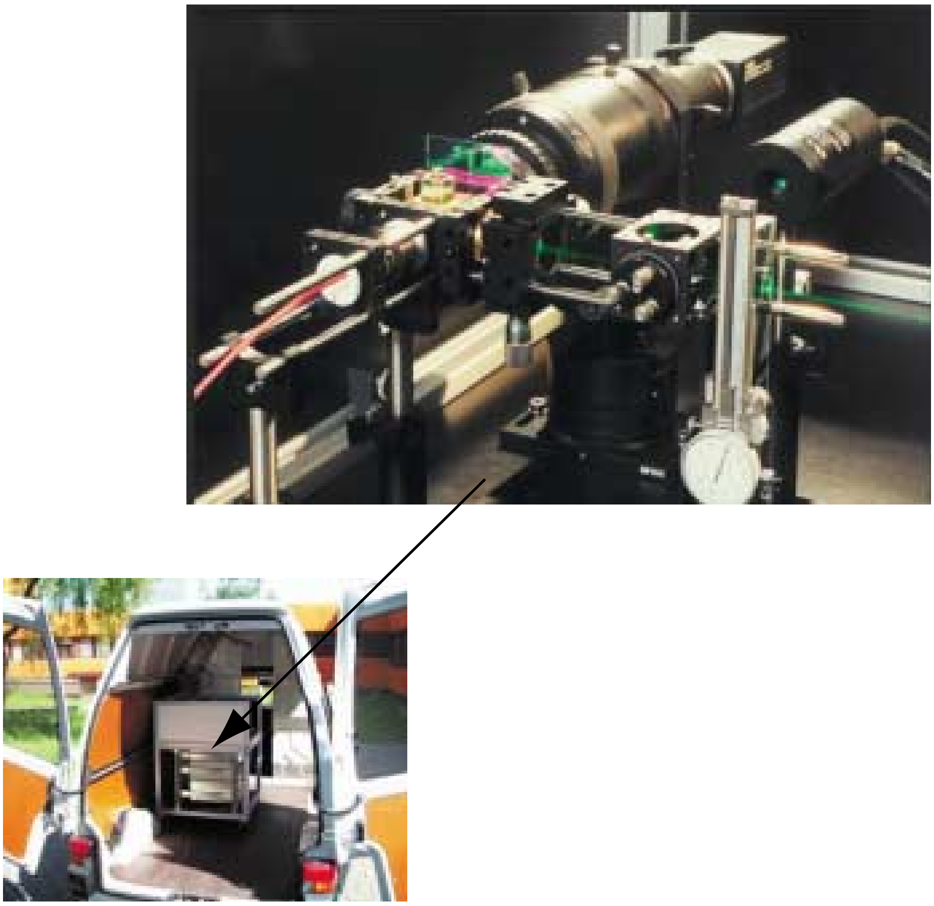


Figure 6-2. *LIBD instrumentation used in the Äspö Hard Rock Laboratory.*

Table 6-2. Summary of LIBD results.

Borehole ID	Elevation m	Tubing Length m	Flow Rate ml/min.(1)	Visual Inspection Gas-Gen.	Visual Inspection Colrd. Disp.	LIBD Data Evaluation Bd. Prob. %	LIBD Data Evaluation Colloid Diameter nm	LIBD Data Evaluation Colloid Conc. ppb
1 KR0012B	−69	0	4	no	yes	100	~404(2)	~300(2)
			222			100	~600(2)	~600(2)
2 SA1229A	−168	40	4	no	yes	92	~600(2)	~190(2)
			930			100	~300(2)	~110(2)
3 HA1330B	−182	55	4	no	yes	100	~993(2)	~1 000(2)
			125			100	~404(2)	~100(2)
4 KA1755A	−235	100	4	yes	no	69.5	631(3)	630(3)
			550			3.0	281(3)	4.1(3)
		0	12			0.2	<19(2), 57(3)	<0.01(2), 0.014(3)
			1 400			0.4	129(3)	0.15(3)
5 SA2074A	−282	0	4	no	yes	100	~600(2)	~600(2)
			190			38.8	354(3)	99(3)
6 SA2273A	−306	75	4	no	yes	14.5–26.0	175(3)–263(3)	9.2(3)–35.5(3)
			900			46.0	218(3)	53(3)
7 HA2780A	−370	70	4	yes	no	2.3–18.0	165(3)–296(3)	1.2(3)–19(3)
			11			28.5	456(3)	102(3)
			20			63.1	627(3)	525(3)
			920			14.5	244(3)	16.5(3)
			1 100			17.2	245(3)	19.6(3)
8 KA3110A	−416	0.5	4	no	yes	9.9	365(3)	22(3)
			2 400			9.4	333(3)	18(3)

(1) Flow rate adjusted at bypass valve.
(2) Data s-curve evaluated.
(3) Data evaluated with constant laser pulse energy.

The different groundwaters were sampled by SKB one week before the LIBD detection (Table 6-3) and the analysis was carried out at INE four weeks later. It is evident that the low Fe-content (compared to SKB analysis, obtained directly after sampling) in the samples is caused by contact with oxygen. Initially dissolved Fe(II) is oxidised to form FeOOH, which is mostly found as precipitated red brown flocs at the bottom of the glass bottles.

Table 6-3. Groundwater composition (INE chemical analysis, sampling by SKB, date: Oct 2001).

Borehole ID	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	PO_4 mg/l	F mg/l	Si mg/l	Fe_{tot} mg/l	Mn mg/l	Li mg/l	Sr mg/l	DOC mg/l	Pre.(1)
Measurement uncertainty⇒	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	50%	5%	5%	5%	0.1 mg/l	
1 KR0012B	167	2.1	44	9.4	136	30.7	<0.1	<0.1	0.5	6.75	0.11600	0.141	0.031	0.76	15.7	no
2 SA1229A	1560	32.9	295	128.0	3381	234.2	<0.1	<0.1	5.4	6.15	0.00296	0.714	0.115	4.60	7.0	yes
3 HA1330B	1590	20.8	348	120.0	3496	305.2	<0.1	<0.1	5.7	4.89	0.00283	0.766	0.117	4.86	6.2	yes
4 KA1755A(2)	2940	8.6	3900	32.2	11044	565.7	31.3	28.7	19.3	4.06	0.11300	0.250	2.240	4.06		no
5 SA2074A	1400	11.2	414	84.6	2913	234.3	<0.1	<0.1	4.7	5.70	0.00249	0.464	0.172	5.80	5.4	no
6 SA2273A	1620	18.6	719	105.0	4234	260.9	<0.1	<0.1	7.1	5.22	0.00344	0.774	0.421	10.60	4.3	yes
7 HA2780A	3400	21.2	4510	48.3	15470	620.4	<0.1	3.7	22.3	4.11	<det.limit	0.250	4.730	66.20	1.5	no
8 KA3110A	1490	45.1	277	133.0	3193	257.9	<0.1	<0.1	4.5	5.09	0.00208	0.737	0.100	3.81	6.3	yes

(1) Precipitation in 3 l sampling bottle (red brown flocs).
(2) Sampling date: Jan 2002.

Colloid concentrations determined by LIBD vary from less than 0.1 ppb to 1000 ppb. They do not only vary in samples taken at different locations, they also depend on flow rates and the lengths of the tubing from the borehole to the LIBD flow-through cell at each sampling site. In the case of borehole KA1755A, a clear decrease of colloid concentrations appeared when the tubing length was considerably shortened from 100 m to direct coupling. A decrease of the measured colloid population was also achieved by increasing the flow rate in the long tubing. Both facts indicate colloid generation by in-diffusion of O_2 through the polyamide tube walls. Dissolved Fe(II) is successively oxidised to form colloidal FeOOH. Both, shortening the tubing length and increasing the sample flow rate diminishes the O_2 input and thus the colloid formation. Increasing the flow rate to very high rates of 1400 ml/min and direct connection of the LIBD to the borehole entails slightly increased colloid concentration. The reason for this finding is most likely a wash out of colloidal material in the water-conducting fractures as a consequence of the shear forces due to the high flow rates (mechanical erosion). As a conclusion it is assumed that the lowest value for the colloid concentration analysed at this sampling location is considered to be least of all affected by artefacts. Similar relationships regarding the colloid concentration for different water flow rates can also be found in other sampling boreholes.

The dependence of colloid concentration on the groundwater salinity is shown in Figure 6-3. A clear decrease of the colloid concentration with increasing salinity (indicated by the respective Cl^--concentration) is stated. This observation is in agreement with findings of other investigations. The ionic strength dependence of the colloid concentration proves the presence of charge stabilised particles at low ionic-strength conditions. At high ionic-strength conditions, colloids appear to be destabilised and, therefore, only low concentrations are found.

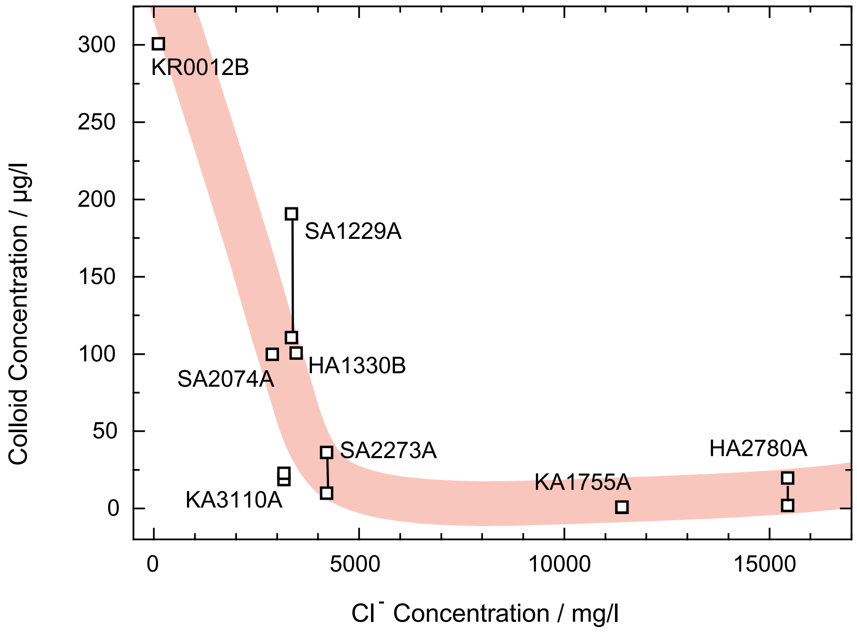


Figure 6-3. LIBD analysed colloid concentration as a function of the Cl-concentration (SKB analysis) as an indicator for salinity.

Conclusions

The present study proves the appropriateness of the mobile LIBD for sensitive in-situ colloid analysis in groundwater. The necessity for an in-situ colloid analysis taking as much as possible care to prevent possible artefacts is also demonstrated. O_2 access to the groundwater and degassing has to be excluded and moderate constant flow rates have to be applied, in order to be sure that only the genuine groundwater colloids are analysed and possible artefacts are minimised. Measured colloid concentrations so far show the influence of low salinity on colloid stability in groundwater. Scooping thermodynamic calculations suggest the supersaturation with regard to mainly carbonates as a possible source for colloid formation.

6.3 ENRESA

Within the frame of collaboration agreement signed between ENRESA and SKB the demonstration projects Backfill and Plug Test and Prototype Repository are of especial interest to ENRESA. Both projects pertain to crucial issues related to the global performance assessment of a repository in granite, the KBS-3 concept. Although the Spanish reference concept differs from the Swedish in some aspects, mainly configuration and site specific characteristics, the two 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 test 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 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.

6.3.1 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.

To measure hydraulic conductivity of the backfill when saturated 13 DPP sensors were installed in 1999, in areas of section A4 of the backfill where a higher density gradient may be expected (i.e. rock proximity), see Figure 6-4. A map of local permeability values will be obtained and compared with the global value estimated by back-analysis from the flow test to be performed when saturation is attained.

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

The entire measurement sequence will be carried out manually, although some of the operations are automated (specially valves control) to simplify the process, making it more accurate and repetitive, and to avoid miss functioning. Data will be 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. The system is connected to AITEMIN's office in Madrid by a standard telephone line.

Figure 6-4. *DPP sensor installed close to the rock face.*

Results

During the year 2001, due to the delay in the backfill saturation, only maintenance and supervision work, as well as remote monitoring have been carried out. The system is working properly and sensor data are recorded to follow the evolution of the pressure in 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 solved. The temperature is assumed to be constant. The gas phase has not been taken into account. The main processes considered in the modelling 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 composition of the hydration water used in the test is given in Table 6-4 and Table 6-5 shows the scheme of the geochemical model solved for the backfill hydration.

Table 6-4. Composition of the hydration water used in the Backfill and Plug Test.

Cl^- (mols/l)	Ca^{2+} (mols/l)	Na^+ (mols/l)	pH
0.2807	0.0720	0.1367	7.3

Table 6-5. Scheme of the geochemical model solved in the analysis.

Primary aqueous species:	H_2O, Ca^{2+}, Na^+ and Cl^-
Species in the solid phase:	NaX and CaX_2
Exchangeable cations reaction:	$CaX_2 + 2Na^+ = 2NaX + Ca^{2+}$

The analysis required some additional information to express the coupling between hydraulic conductivity and salt concentration. The influence of salt concentration on the saturated hydraulic conductivity has been studied by means of oedometer tests carried out in Rowe cells. Figure 6-5 shows the interpretation of the oedometer tests and includes a relationship between intrinsic permeability (obtained from the interpretation of the tests) and salt concentration in the injected water. 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). Figure 6-6 shows the water retention curves in drying and wetting paths measured on the bentonite/sand mixture. Figure 6-7 presents the wetting water retention curve, in terms of degree of saturation, and includes the corresponding van Genuchten fitting curve. In this case, matrix and total suction have been represented. According to these results, a constant value of 1.16 MPa has been adopted for the osmotic suction in all the analyses.

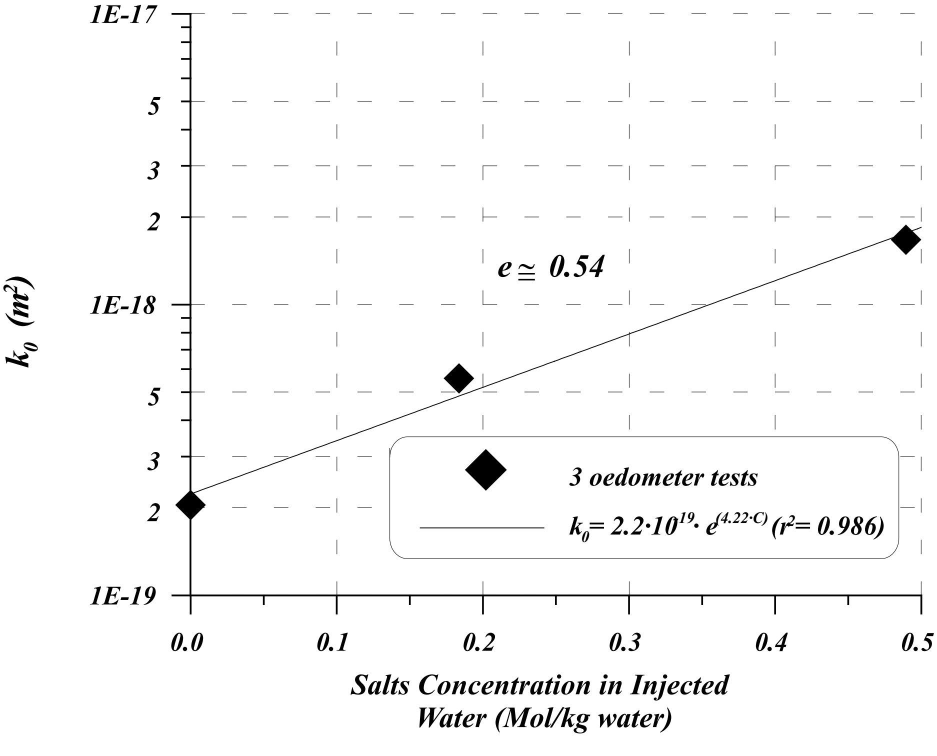


Figure 6-5. *Variation of intrinsic permeability with molar concentration of salts estimated from three oedometer tests.*

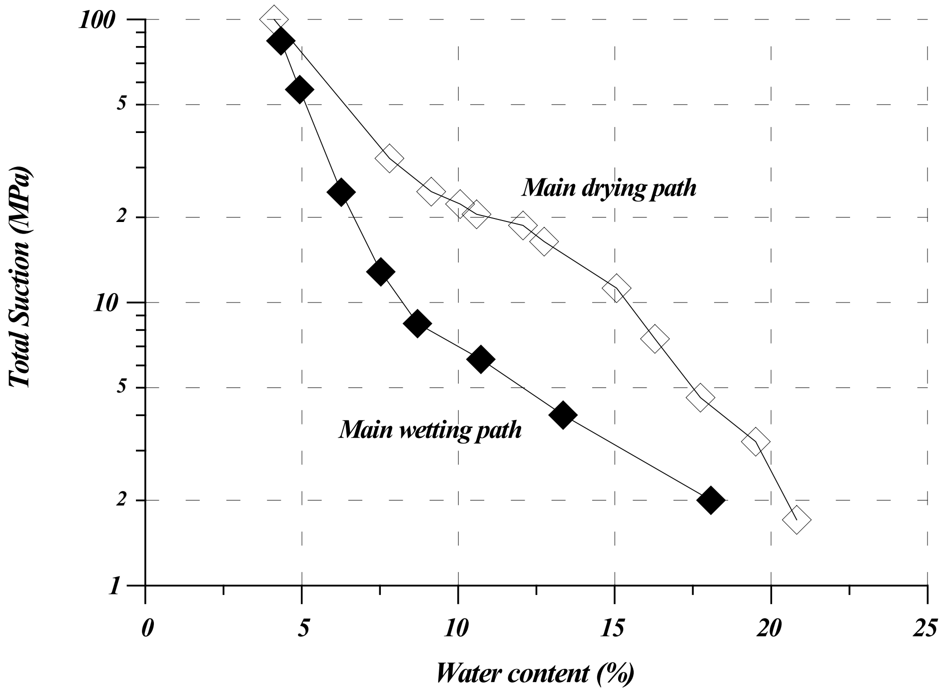


Figure 6-6. Main drying and wetting retention curves for a 30/70 bentonite and sand mixture.

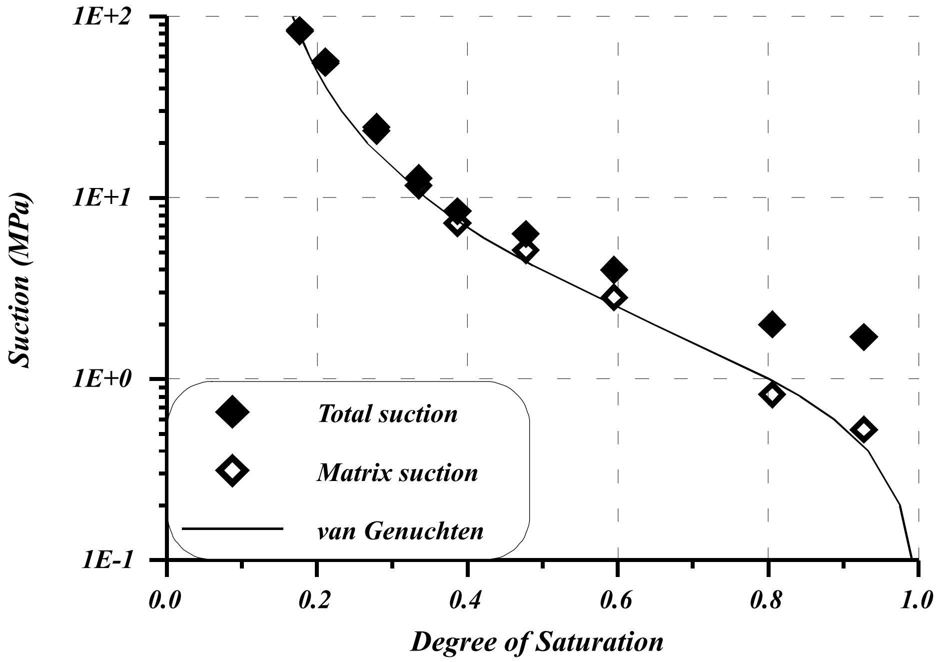


Figure 6-7. Matrix suction (wetting path) for the bentonite sand mixture and the interpolation using van Genuchten model. Osmotic suction was assumed constant (1.16 MPa).

Apart from the tests indicated above, the Swedish company Clay Technology performed some water uptake experiments using different salt concentrations for the hydration water. Figure 6-8 reproduces some results indicating that for high salt concentrations the hydration process becomes faster.

It is important to point out that the experimental results present some scatter due to the heterogeneity of the samples and the process of sample preparation. In general, dynamic compaction was used for preparing the samples of water uptake tests. The dry density obtained was 17.1 kN/m^3 which is consistent with the value measured in the field, in the central part of the backfilled tunnel.

The initial geochemical conditions in the field are very important when analysing the hydro-chemical coupled problem, but difficult to establish. The initial exchangeable cation and solute contents in the bentonite are necessary for the simulation of geochemical problems in bentonite-water systems, The initial backfill pore water conditions have been obtained interpolating experimental data from compacted MX-80 bentonite with fresh and salt water published by /Muurinen and Lehikoinen, 1998/, see Figure 6-9.

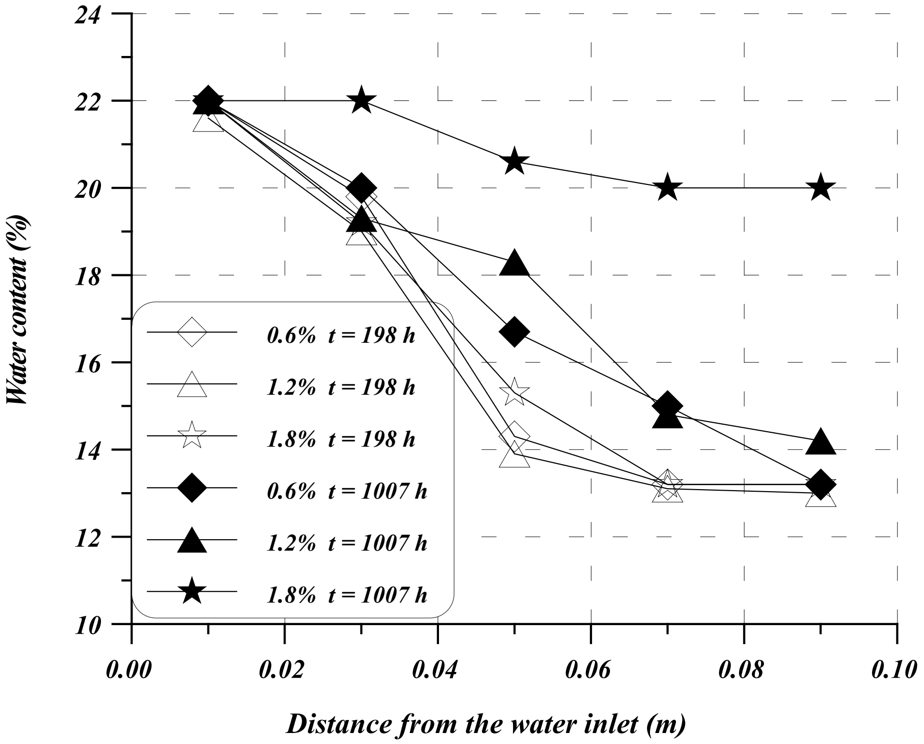


Figure 6-8. *Results of the water uptake tests performed by Clay Technology using different salt concentrations (%) for the hydration water.*

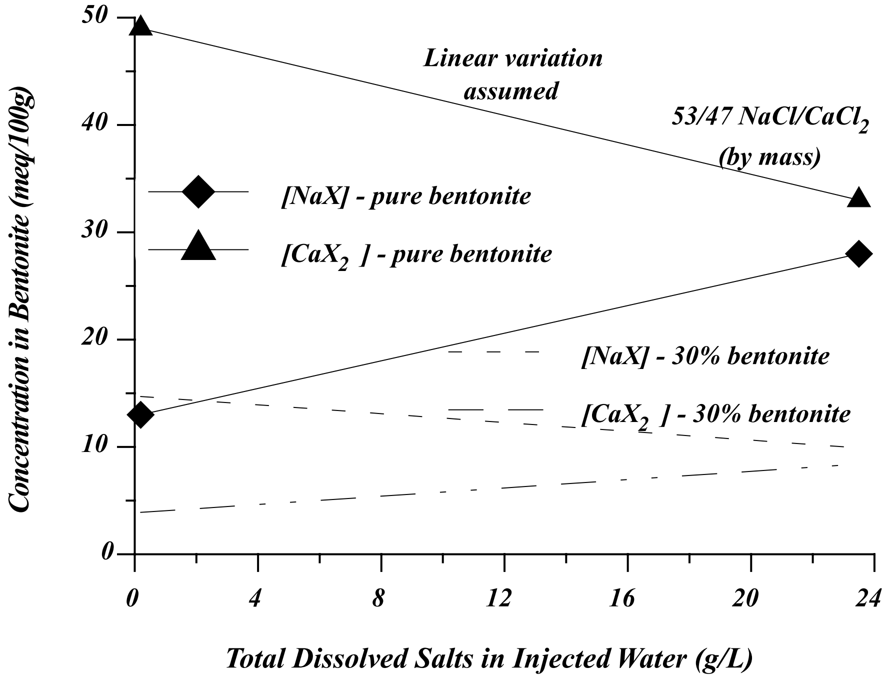


Figure 6-9. *Equilibrium concentrations of NaX and CaX_2 in MX-80 bentonite for two total dissolved salt concentrations in hydration water, for a bentonite/water ratio of 510 kg/m^3 /after Muurinen and Lehikoinen, 1998/.*

Results

During year 2001, the hydration process has continued in the backfill at a slow rate due to unexpected leakage through the plug. The work performed included:

- Laboratory analyses done on the 30/70 material to improve the knowledge of its mechanical behaviour and the effects of salinity on hydration. The experiments are still being carried out. They will be completed by March 2002.
- Modelling work seeking the simulation of the backfill hydration, incorporating the effect of different salt concentrations. So far, only a preliminary approach has been adopted. In fact, the series of laboratory tests being performed will be used to understand the coupling between hydraulic properties and salt concentration of water in the backfill. The effect of this coupling has been considered very important, after realising that in Äspö, water with different salt concentrations can be mixed in the backfill and this might influence the hydraulic processes. Some details of the modelling work performed during 2001 are presented in the following sections.

An initial attempt has been made to simulate the water uptake tests for calibration purposes. Figure 6-10 shows the comparison between measured and computed water content profiles for a salt content in the water of 16 g/l (1.6%). The agreement seems reasonable, although the complexity of the problem may explain why there are different combinations of parameters that provide similar results in terms of water content changes. The intrinsic permeability used in that simulation was $4{\cdot}10^{-20}$ m^2 and the potential exponent n, of the unsaturated permeability ($k_{unsat} = k_{sat} \cdot S_r^n$, where S_r is the degree of saturation), was found to be close to 4. The final value of the intrinsic permeability after saturation was

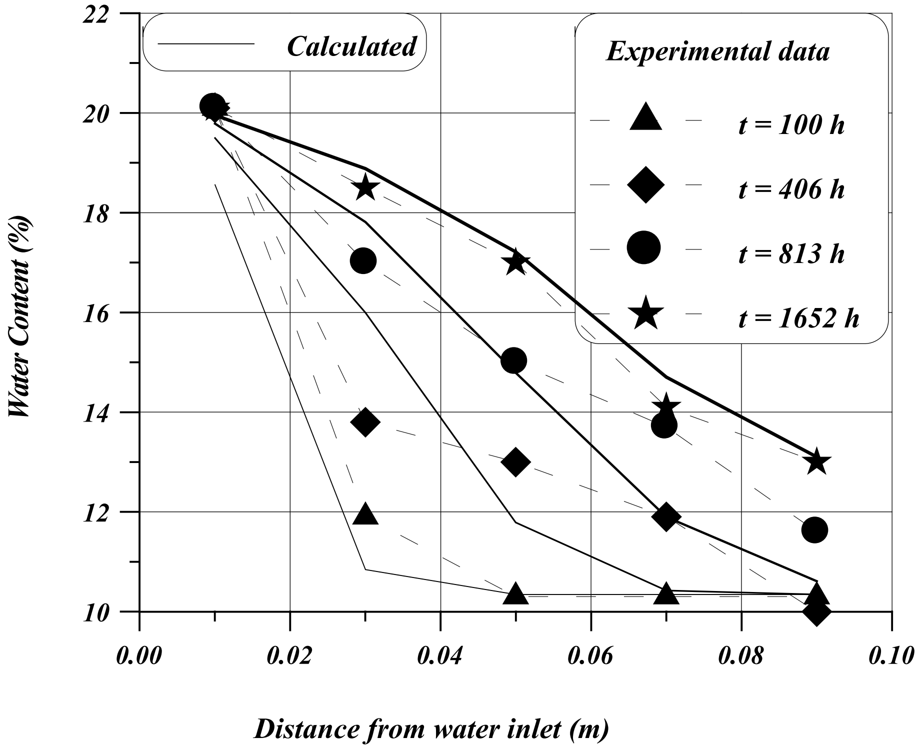


Figure 6-10. *Numerical simulation of the water uptake tests performed on the backfill hydrated with a salt content of 16 g/l.*

$8 \cdot 10^{-20}$ m^2 due to the chemical coupling. This value is significantly lower than the value obtained from oedometer tests ($1.7 \cdot 10^{-18}$ m^2). A few reasons that could explain this difference are being investigated. The sample preparation in the oedometer was performed using static compaction, whereas dynamic compaction was employed for water uptake tests; the interpretation of these hydration tests depends on many parameters and, therefore, the estimation of saturated hydraulic conductivity becomes much more difficult. Moreover, the data available refers to water contents far from saturation and an extrapolation is being performed when estimating backfill properties under saturated conditions.

On a second stage, a simulation of the hydration of the ZEDEX gallery was carried out. During 2001 the hydration process has been very slow with a water injection pressure in the mats of only around 0.06 MPa, to avoid hydraulic fracturing and because of the leakage through the plug observed. The sections analysed are A3 and A4 (Figure 6-11). The water pressure applied to the mats and the corresponding simplified values used in the simulation are respectively depicted in Figure 6-12 and Figure 6-13.

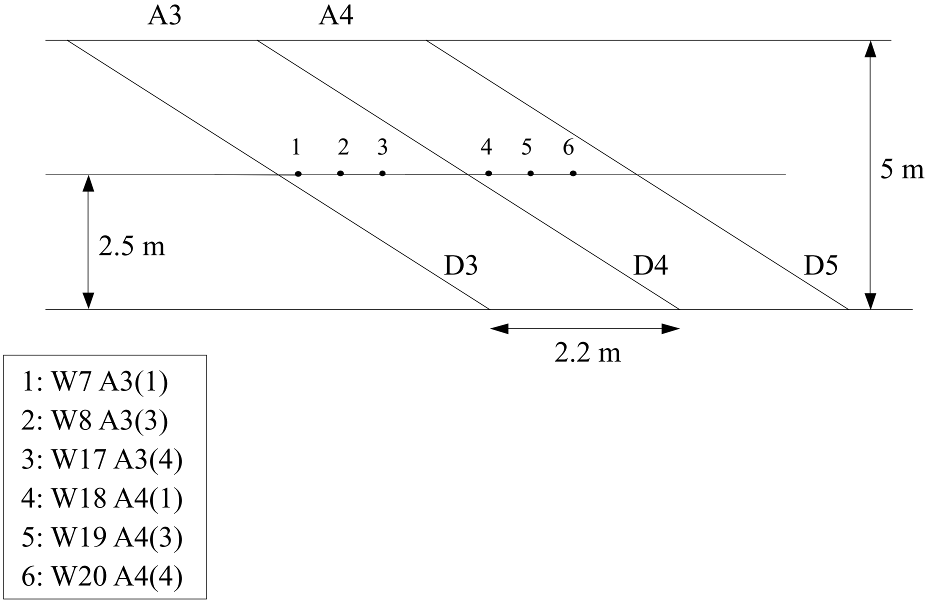


Figure 6-11. Geometry considered, including section s A3 and A4. Central points indicate the location of 6 psychrometers analysed in the simulations.

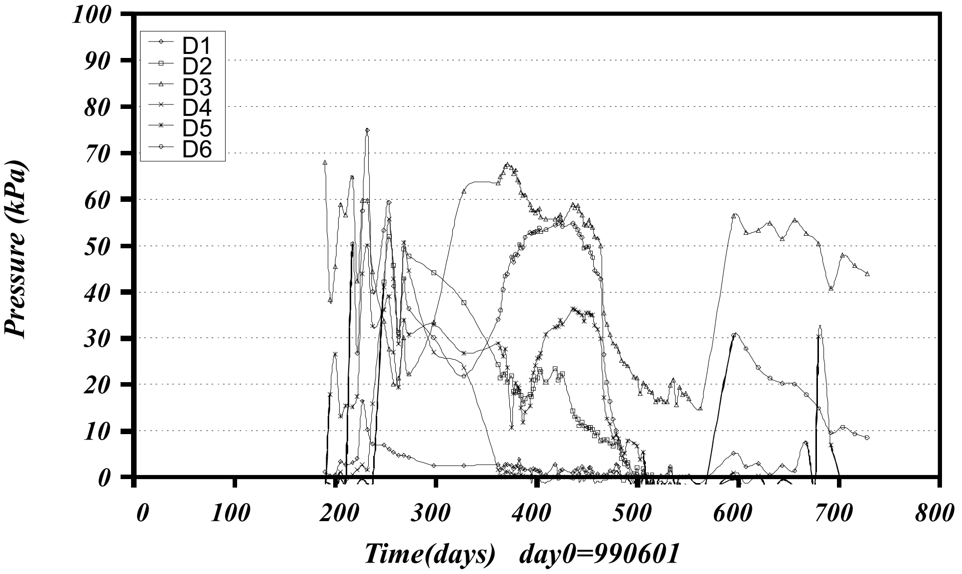


Figure 6-12. Water injection pressure in the permeable mats D1–D6 (data provided by Clay Technology).

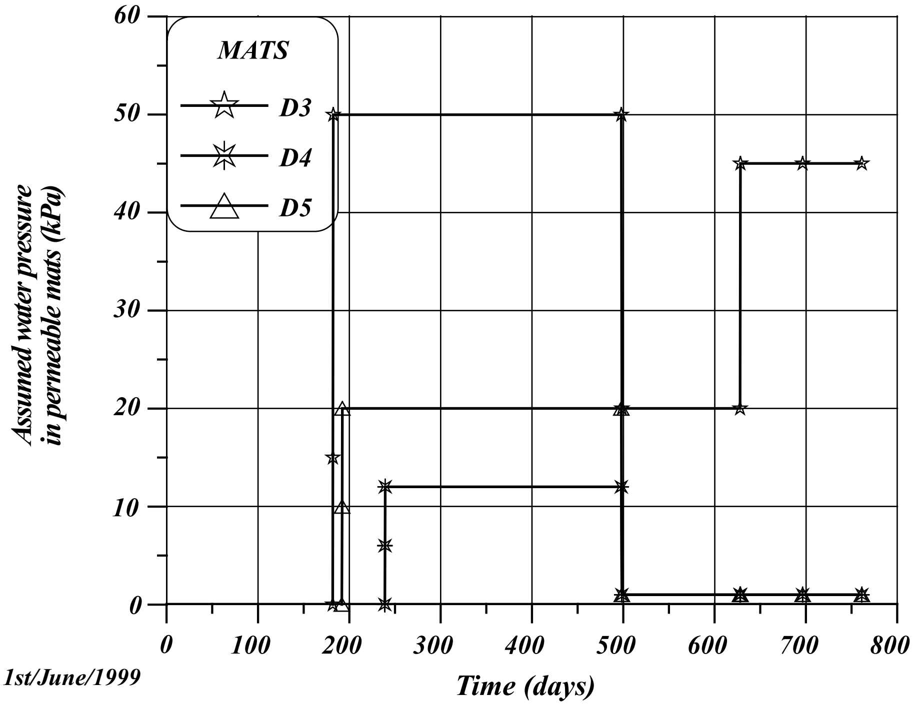


Figure 6-13. *Assumed evolution of the water injection pressure in the mats considered in the simulations.*

Two-dimensional simulations of the hydration process were carried out using the information collected from the laboratory and the indicated boundary conditions. Two families of parameters were used. The first one corresponded to the intrinsic permeability obtained in the interpretation of the water uptake tests ($4{\cdot}10^{-20}$ m^2). The second one, obtained by means of trial and error fitting, resulted in a value of intrinsic permeability of $9.6{\cdot}10^{-20}$ m^2, slightly higher than the previous one. This increment allows a better fitting with the measured suction values. A complete description of all the parameters involved in the simulations can be found in /Mata et al, 2001/.

Figures 6-14 and 6-15 show the suction computed and measured values in the psychrometers 1 to 6, for these two families of parameters. The instruments located near the mats indicate that saturation has been already reached while the psychrometers located in the central part of the section are still far from saturation.

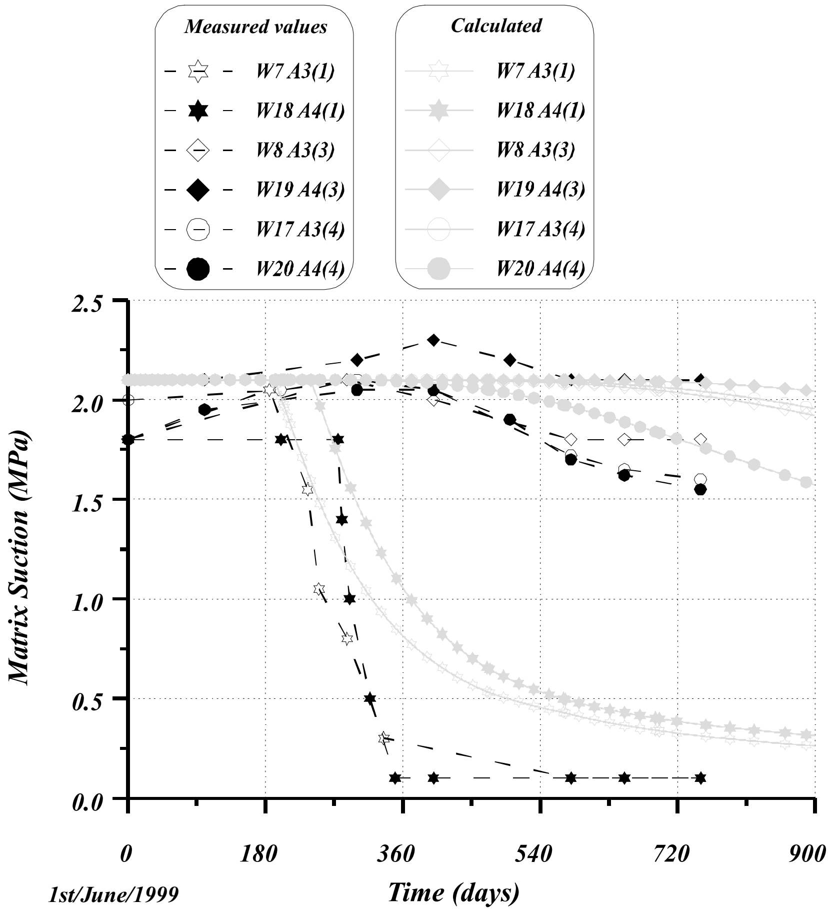


Figure 6-14. *Comparison between the computed and measured values in 6 psychrometers in the ZEDEX gallery using the parameters calibrated from the water uptake test.*

The simulations done reproduce the field measurements but the errors for future predictions could be important, because the hydration process has proceeded very slowly and any extrapolation for saturated conditions could be unrealistic. If the water injection pressure in the mats is increased in a step wise (i.e. 100 kPa every week) until 1 MPa is reached the simulations indicate that, in approximately one year, the degree of saturation will be over 95% in all points of the sections. This result could be used as an estimation of the period of time required for proceeding with the test.

As indicated in Modelling and supporting laboratory tests, the drying and wetting retention curves used for this analysis were obtained in a mixture of bentonite and sand due to the big size of the crushed granite. A typical vapour transfer technique was used to estimate the main drying and wetting paths. The curves under free shrinkage conditions were measured by means of transistor psychrometers. The main wetting curve was determined by vapour transfer in a suction controlled atmosphere (by means of different salt

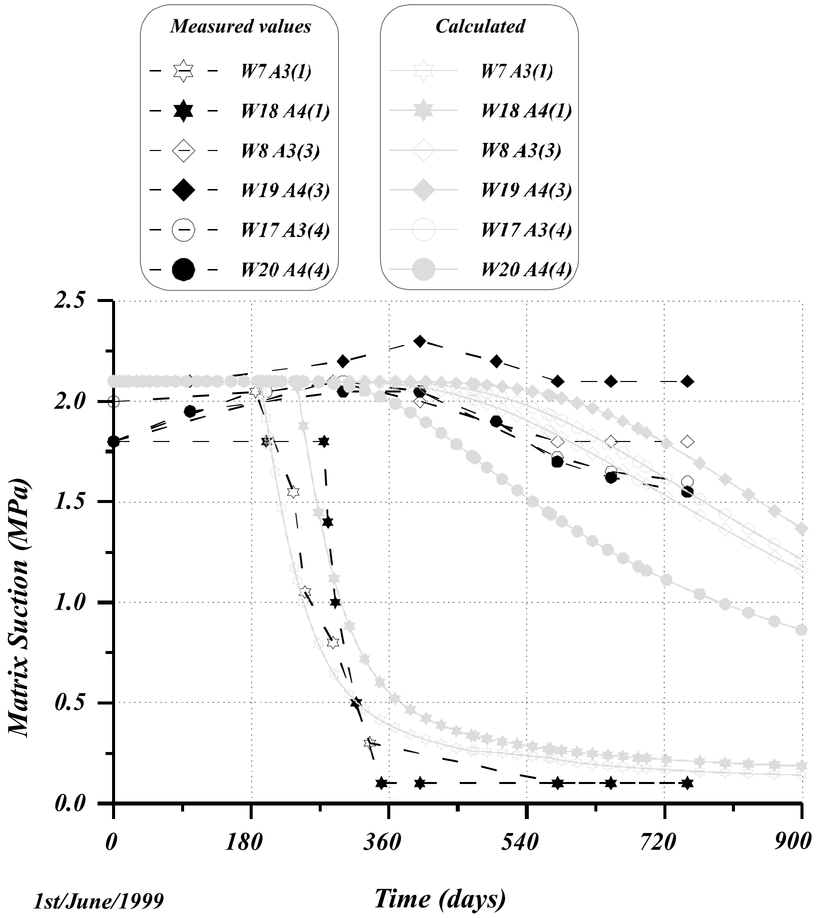


Figure 6-15. Comparison between computed and measured values in 6 psychrometers in the ZEDEX gallery, fitting the measured results.

solutions) after a long period to reach equilibrium. Therefore, the determination of the osmotic suction was performed on this bentonite-sand mixture. Details of the experimental procedure are described in /Mata et al, 2001/.

6.3.2 Prototype Repository

The Prototype Repository layout involves six deposition holes, four in an inner section (No 1 – No 4) and two (No 5 and No 6) in an outer section. The two sections are separated with a concrete plug.

Canister displacement sensors

Six displacement sensors, grouped into one single measuring section, are planned at the bottom of each canister, in deposition holes No 3 and 6.

Three of those sensors are placed horizontally on the upper face of the bentonite block, close to the bottom 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 that 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.

Remote monitoring from the main offices of AITEMIN in Madrid does the supervision and data management. This system connects via modem periodically with the site for data transmission. A master database will be created with the data gathered and periodic reports, including graphical representation of the evolution of the displacements, will be issued.

Results

The displacement sensors for the deposition hole No 3 and the corresponding measurement system were installed in June 2001. The evolution of the movement tracking system is being monitored from Spain since then.

Modelling and supporting laboratory tests

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.

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 densities 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.

Results

T and TM problems have been solved for six different geometry cases, as shown in Figure 6-16 and Figure 6-17 involving one, two and six heaters, and different assumptions regarding symmetry. All cases have been used as a tool for comparison. The assumptions made were:

Case (1) 1D case considering a single deposition hole. First node is on the heater, and last node is in the rock, far away (70 m) from the heater. Total symmetry is assumed. (35 nodes and 34 elements).

Case (2) Quasi 3D geometry. One single deposition hole is considered with axis-symmetry. The tunnel over the deposition hole becomes a sphere because of the rotation. (1740 nodes and 1640 elements).

Case (3) 2D geometry considering two heaters. A cross section of the deposition holes with two symmetry axes has been considered. (1440 nodes and 1352 elements).

Case (4) 3D geometry considering two heaters. Two symmetry planes are considered. (7302 nodes and 35576 elements).

Case (5) 2D geometry with 6 heaters. A cross section of all the deposition holes assuming only one axis of symmetry. (6484 nodes and 6168 elements).

Case (6) 3D geometry with 6 heaters. Fully actual geometry, assuming one plane of symmetry. (13510 nodes and 63033 elements).

Case (1) will be used mainly for THM highly non-linear approaches and quick checking purposes. Case (6) can not be used in a systematic way for THM analyses with complex elasto-plastic models because each run would require very long computing time.

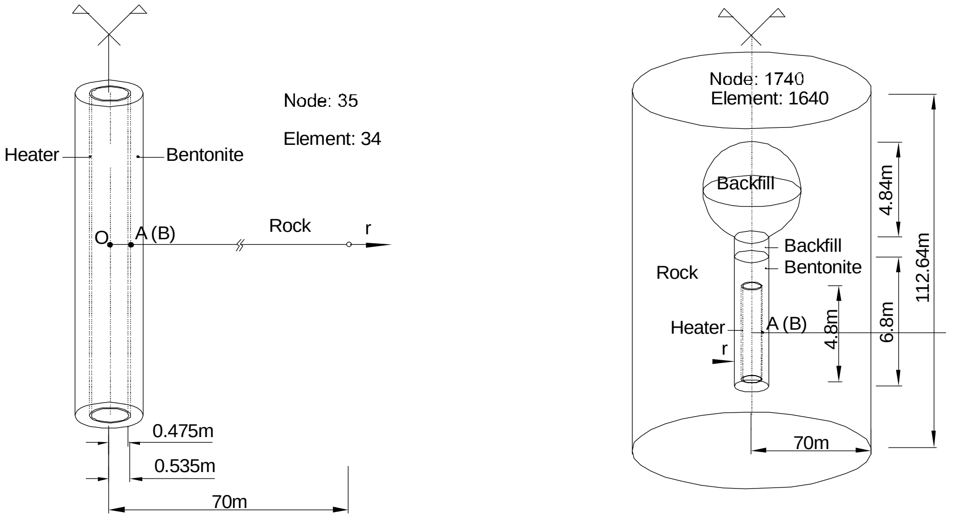


Figure 6-16. *Two cases considered for the T and TM analyses.*

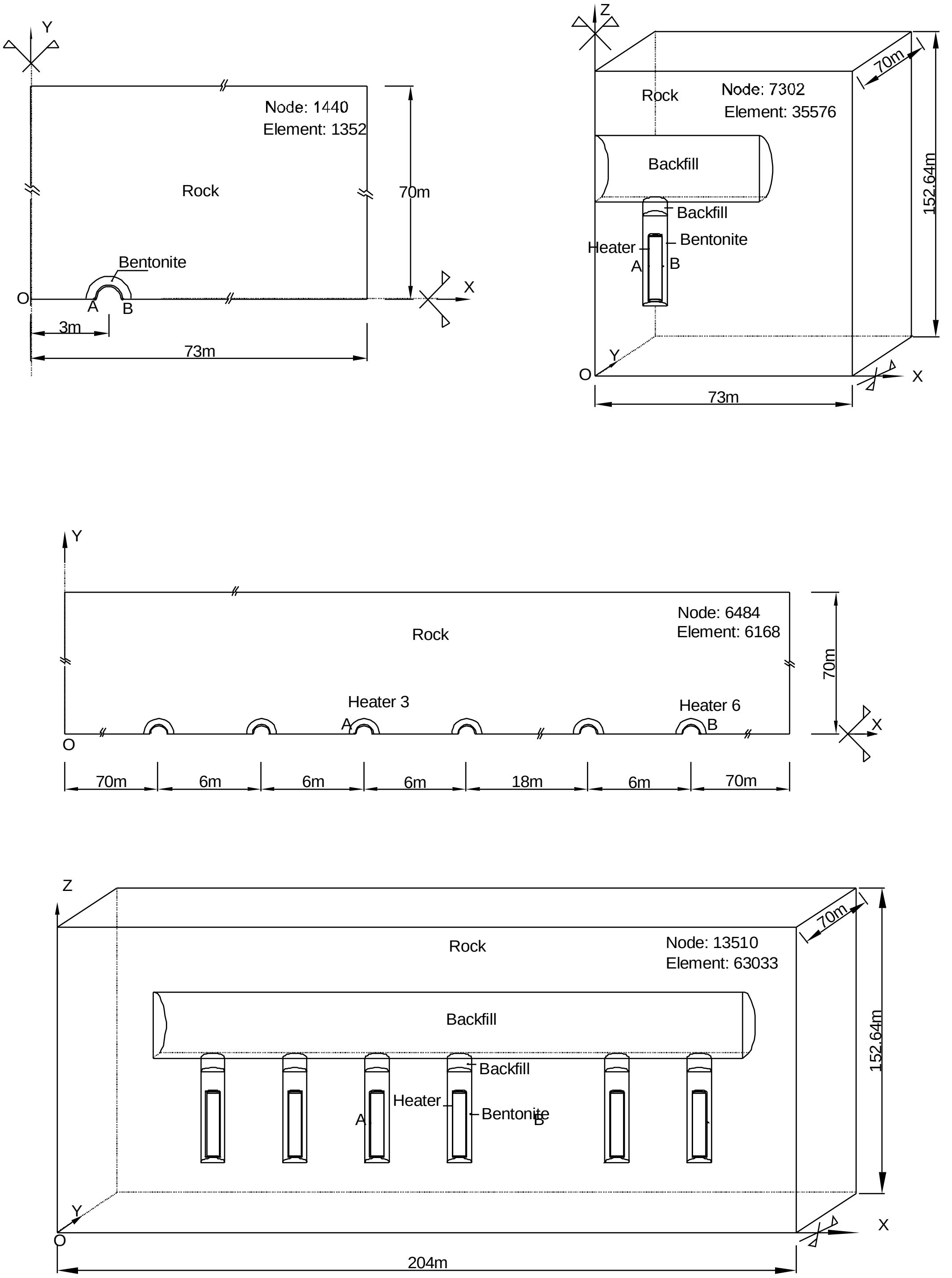


Figure 6-17. Four cases considered for the T and TM analyses.

No special features of the rock have been taken into account in these previous analyses, i.e. fractures crossing the deposition holes.

When comparing the modelling results, it could be concluded that the axis-symmetric Case (2) provides a good approximation when the central zone of the deposition hole is analysed. This is the case for the T and TM analyses in which the position of the boundary controls the final temperature values. The hydraulic analyses could change slightly that pattern, especially when conductive rock fractures are introduced in the geometry. However, as a general rule, the axis-symmetric Case (2) is suitable for many of the low cost analyses that will be required in the project. Fully 3D Case (6) would be expensive or even not possible in terms of computing time, when very complex constitutive laws are used. Additionally, for a highly non-linear problem the number of elements and nodes should be even greater than those considered in Case (6).

Therefore, the comparison between these 6 cases proposed will be useful when assumptions regarding geometry simplifications are considered in the future.

On the other hand, with respect to the thermal problem, it can be stated that maximum temperature in the central part of the heaters is expected to reach 80°C for the heat flux of 1800 W/heater. Also stresses will increase around 0.1 MPa in that zone, and the maximum displacements expected are below 1 mm. According to the figures presented, the maximum values are practically reached after the first year of operation.

A **preliminary THM** analysis including all the typical couplings, but using simple mechanical models, has been performed, as a first step in the simulation process of the Prototype Repository problem. A one-dimensional geometry has been adopted, as in Case (1), with only one deposition hole and assuming total symmetry. First node is in the heater, and last node is in the rock, far away (70 m) form the heater. Using this simple geometry, it is easy to try different models and parameters, in order to understand the processes involved in the problem.

Figure 6-18 presents the geometry used in this analysis. Material A corresponds to the heater, B refers to bentonite blocks, C to the bentonite pellets and D to the rock. The numbers indicated refer to node numbers or to element numbers, and they are used in further graphics.

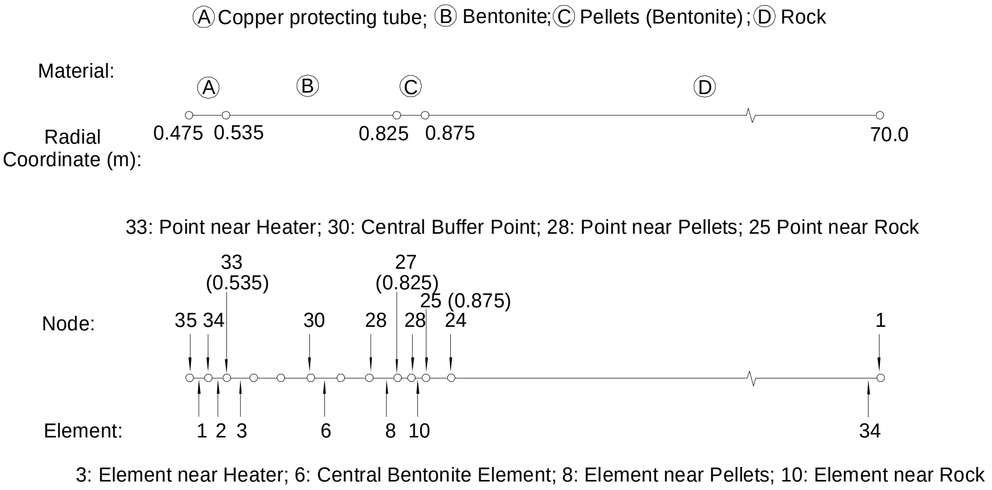


Figure 6-18. *Geometry of the THM one-dimensional analysis.*

The parameters have been selected from Äspö data available, and are also based on the experience of the group in the FEBEX Project. Future analyses will improve the definition of the parameters, as more information becomes available.

The results of the simulations are summarised in Figure 6-19 and Figure 6-20. In the case presented here, a heat flux of 1344 W/heater has been adopted, in order to reach a final temperature distribution similar to that obtained in the 3D simulations of the T and TH analysis. Comparisons between fully 3D analysis and 1D analysis for the T and TM problem indicate that 1D case overestimated temperature distributions. To reduce that effect, heat flux has been decreased in the heater node accordingly.

Figure 6-19a shows the evolution of the temperature at some specific nodes in the bentonite surrounding the heater. There is a general temperature increment, although for a node close to the heater, a reversal is observed after 100 days of heating. This is due to the couplings between the thermal and the hydraulic problem, and this pattern is similar to that obtained in the FEBEX Project.

Figure 6-19b presents the saturation degree computed for some selected elements. The elements close to the heater become initially less saturated, but reach saturation in about 200 days. This should not be considered as definite, but provides an interesting value to be considered in further comparisons. It should be pointed out that recent experience from FEBEX Project indicates that saturation may be slower than predicted with conventional THM models. That experience will be considered in future simulations of the Prototype Repository. The analysis presented here should be considered as preliminary.

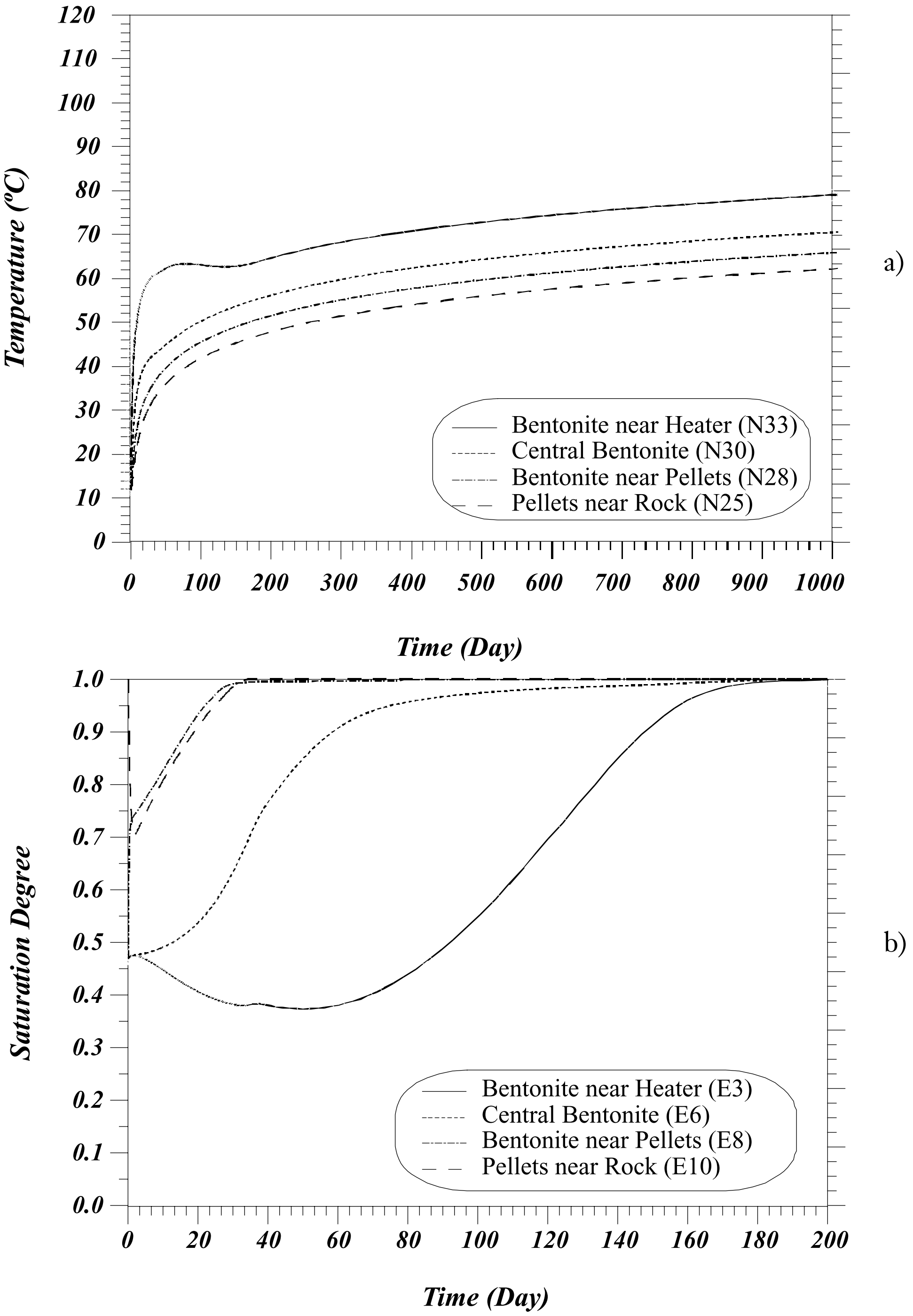


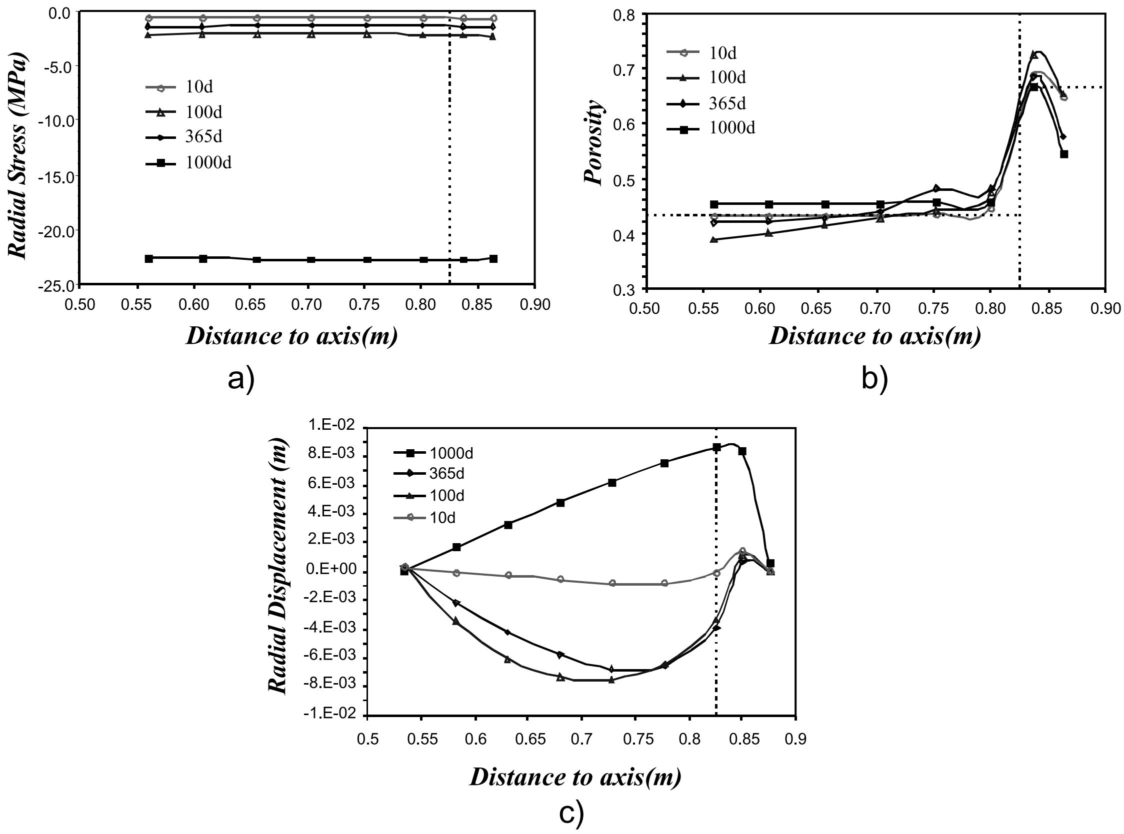
Figure 6-19. *a) Variation of temperature with time (1344W/Heater); b) Variation of degree of saturation with time (1344W/Heater).*

The radial stress on the bentonite (blocks and pellets) is depicted in Figure 6-20a. The initial stress used in the simulation, 0.5 MPa, increases with time. Negative values mean compression. That compression is due to different mechanisms involving thermal, hydraulic and mechanical effects that finally lead to a general compression of the block.

Figure 6-20b presents the variation of porosity in the bentonite. Initial values are assumed different for the blocks and for the pellets, though the differences are small.

Finally, Figure 6-20c shows the evolution of radial displacements for the nodes of the bentonite (blocks and pellets). Positive values indicate displacements away from the heater. In the initial stage there is shrinkage of the bentonite due to heating. Immediately afterwards the hydraulic coupling becomes important, as saturation progresses, giving rise to partial saturation and swelling of the bentonite. That effect changes the sign of the displacements.

These results show the main aspects involved in a THM simulation of this kind. The results are preliminary and should be taken with caution, as the computational results are very sensitive to small changes in the parameters. In any case, they constitute the first step and will be improved during the development of the project.



a) b) c)

***Figure 6-20.** a) Bentonite and pellets stress distribution (1344W/Heater). b) Bentonite and pellets porosity distribution (1344W/Heater). c) Bentonite and pellets displacement distribution (1344W/Heater).*

CIEMAT has performed some **laboratory determinations** using MX-80 clay provided in April 1996 by Clay Technology AB. The MX-80 powder had a hygroscopic water content of around 8% and a specific weight of the solid particles (determined with pycnometers using distilled water as suspension medium) of 2.82 g/cm^3.

For saturation of the samples either distilled water or saline water are being used. The saline water is obtained in the laboratory by mixing $CaCl_2$ and NaCl at a relationship 32/68% to provide a solution with 0.5 g/l.

A method for the measurement of **hydraulic conductivity** in expansive soils through the determination of the coefficient of permeability (k_w) has been developed at CIEMAT. The method is based on the theoretical principle of the fixed load permeameter.

The results obtained are plotted in Figure 6-21. Exponential relations between dry density and hydraulic conductivity have been drawn for each kind of permeant.

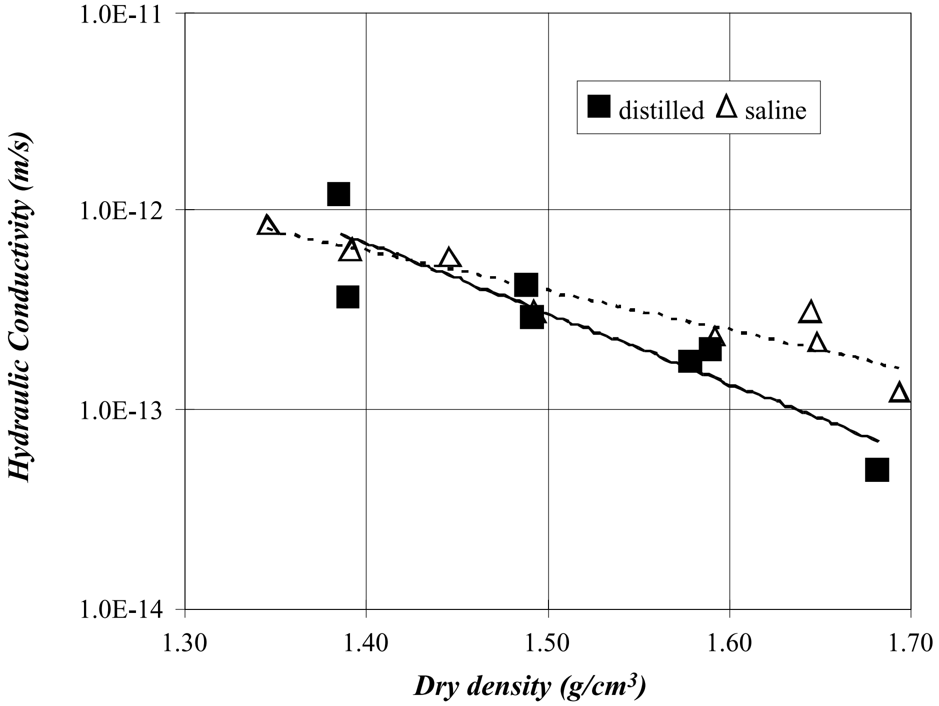


Figure 6-21. *Results of the hydraulic conductivity tests with compacted MX-80.*

To determine the **retention curve at laboratory temperature** at constant volume, as a function of the salinity of the interstitial water, a new method has been devised. It consists in the compaction of a bentonite block with the clay previously mixed with the desired quantity and kind of water.

Four dry densities, 1.50, 1.60, 1.70 and 1.80 g/cm^3, have been investigated, with water contents from 8 (the hygroscopic one) to 25%. The target water contents were obtained by mixing previously the clay with distilled or saline water. The results obtained are plotted in Figure 6-22 and Figure 6-23. The compaction technique does not allow manufacturing blocks with a degree of saturation larger than 80%. For this reason no results on suction are available for such high humidity. It neither allows to compact blocks with a water content below the hygroscopic one, as the material been cohesionless crumbles easily. Consequently, there are no results for the lowest degrees of saturation.

The results clearly show the dependence of suction on the degree of saturation, being the suction of a block for a given degree of saturation is higher the higher the dry density of the block.

With the results available it has not been possible to evaluate the influence of the salinity of the interstitial water on the value of suction. In fact, the suctions measured for a given dry density and water content of the clay are the same regardless the salinity of the water added.

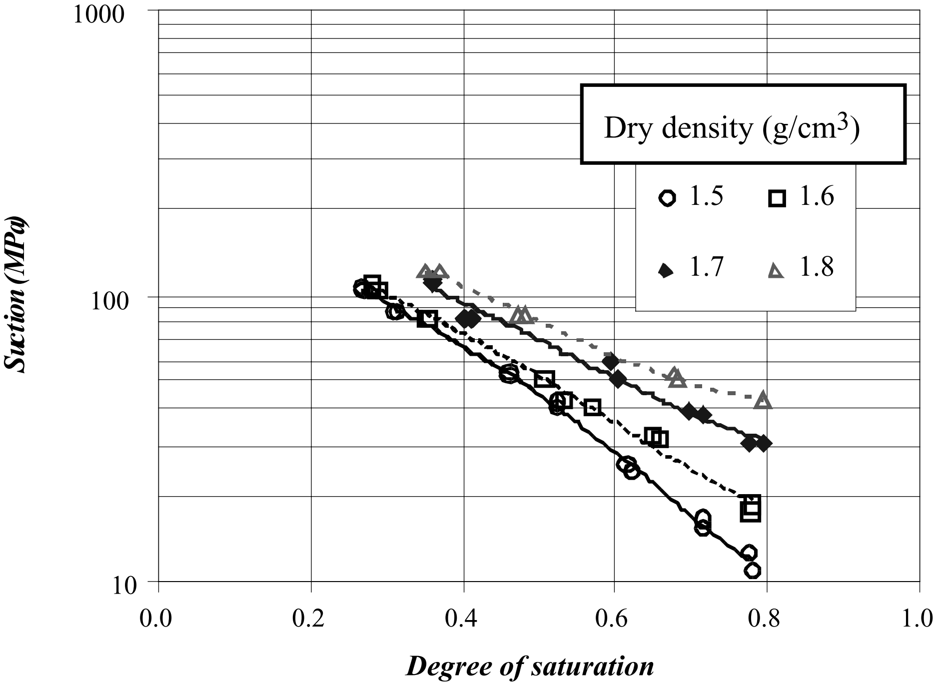


Figure 6-22. *Retention curve for MX 80 clay compacted at different dry densities and water contents (distilled water).*

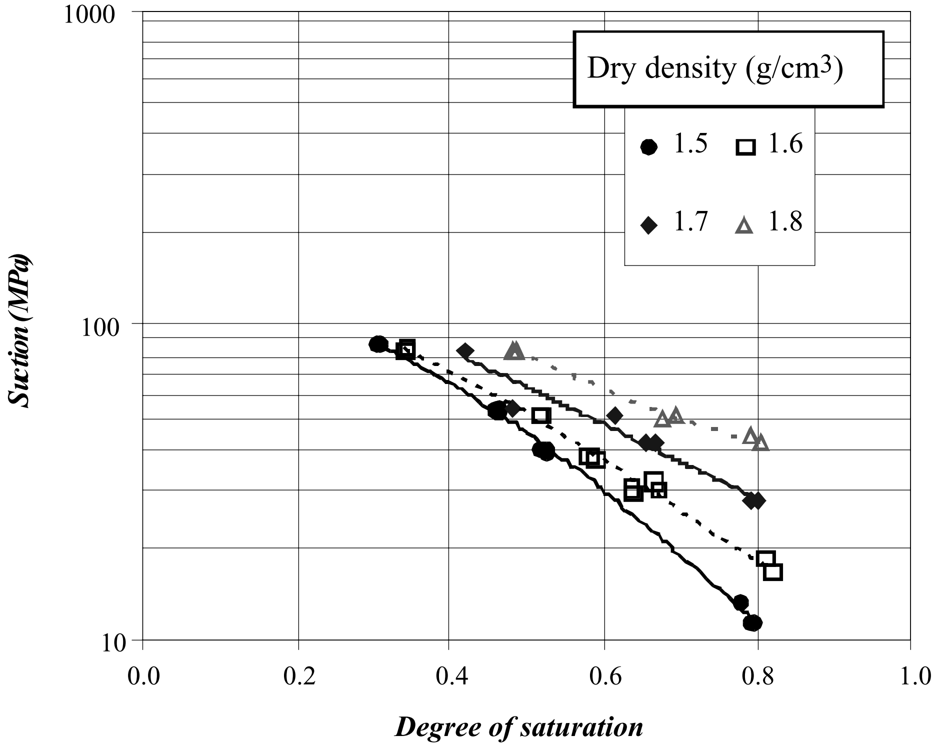


Figure 6-23. Retention curve for MX-80 clay compacted at different dry densities and water contents (saline water).

In order to check the performance of this new methodology, a retention curve at 20°C is also determined in non-deformable cells, according to a method that has been thoroughly tested in the context of the FEBEX Project.

With this aim, a wetting/drying path for dry density 1.60 g/cm^3, from an initial water content of 9% (the hygroscopic one, approximate suction 110 MPa) is being performed in a non-deformable cell.

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

- Wetting/drying paths for dry density 1.79 and 1.60 g/cm^3, with initial water content of 17% (approximate suction 40 MPa).
- Wetting paths for dry density 1.30 g/cm^3, with 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 **suction controlled oedometer tests** include suctions up to 40 MPa and vertical loads of up to 9 MPa. The samples will be subjected to saturation under a low vertical load and, once saturated, they will be loaded. The initial dry density and water content of the clay in these tests are: dry density 1.79 and 1.69 g/cm^3, 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 is 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 between 0.1 and 14 MPa, and by solutions of sulphuric acid for values between 3 and 500 MPa.

The time required for stabilisation of each suction step is very long, more than 40 days, as a result of which the duration of each test will be longer than one year. The evolution of the strain as a function of time of one of the tests is shown as example in Figure 6-24.

The results already obtained in the four oedometric tests are shown in Figure 6-25. A good agreement is found between the two methods of suction control, what again would be indicative of the lack of influence of the osmotic suction on the behaviour of the clay. The huge swelling developed for the lower suctions attenuates the initial difference in void ratio of the specimens.

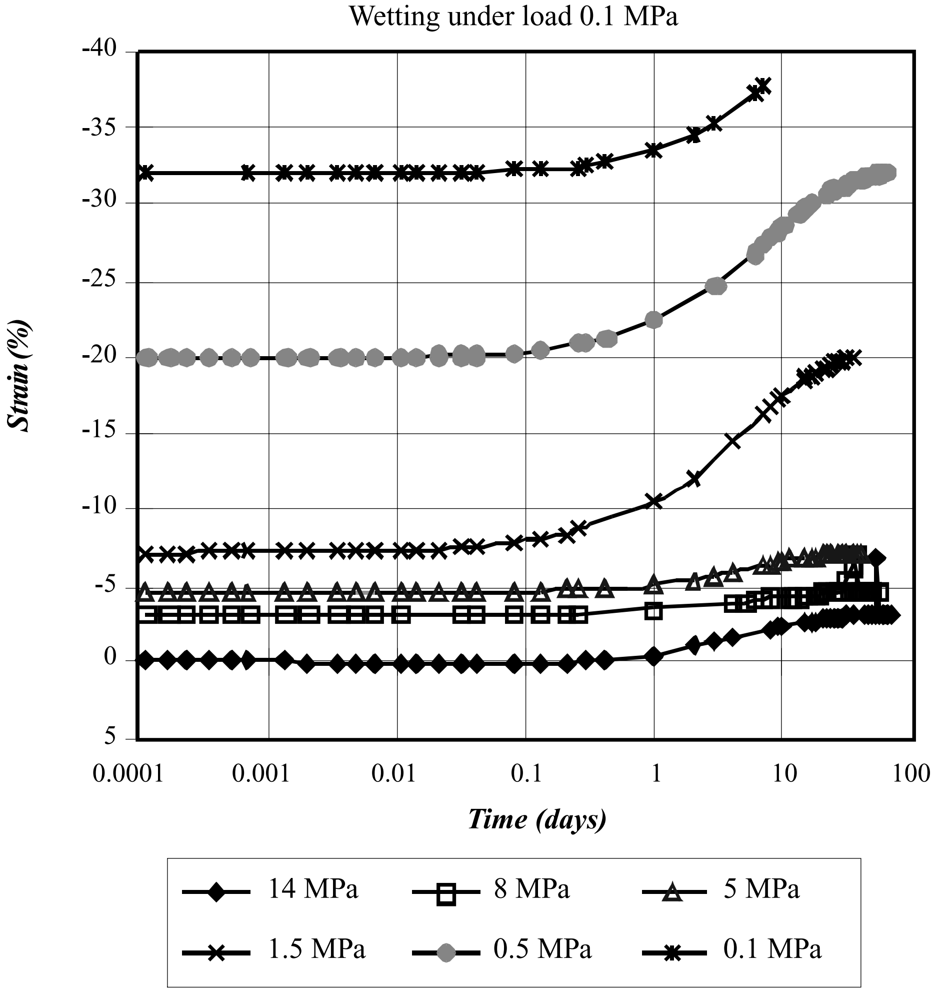


Figure 6-24. Evolution of strain in the different steps of the wetting stretch (test EDN4_10) (MX-80 compacted at ρ_d 1.69 g/cm^3).

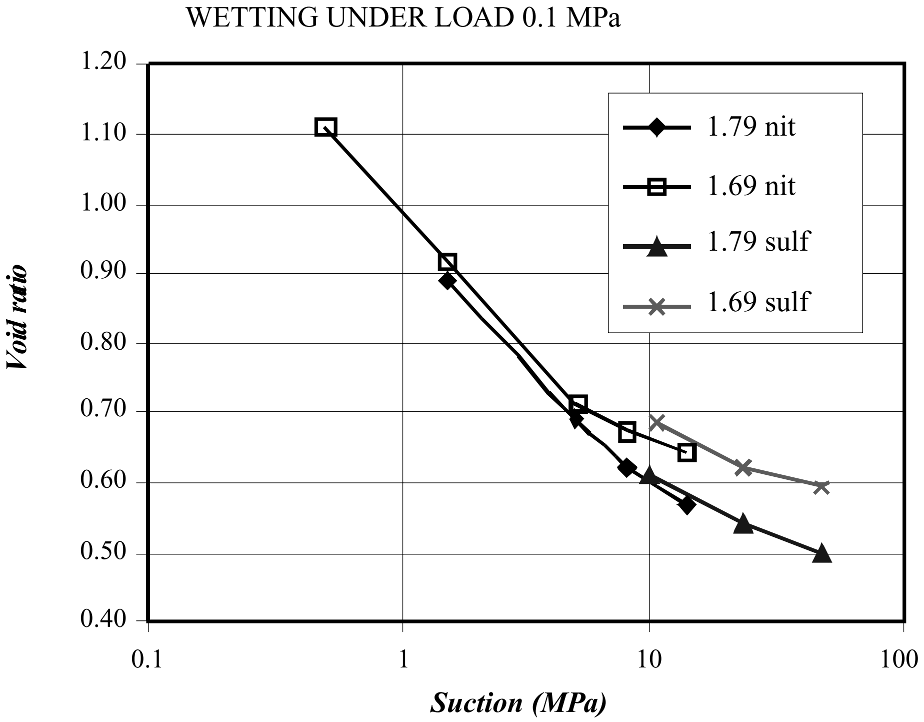


Figure 6-25. *Preliminary results of the suction controlled oedometer tests (dry densities indicated in g/cm^3).*

6.4 JNC

Japan Nuclear Cycle Development Institute (JNC) actively participated in the Äspö Task Force on Modelling Groundwater Flow and Transport of Solutes and in the TRUE Block Scale experiment during 2001. The primary activities for the Task Force involved development of the specifications of Task 6 (Performance Assessment Modelling Using Site Characterisation Data), together with initial simulations and demonstration calculations. In addition, JNC completed reporting of Task 4 (TRUE-1 solute transport experiments /Dershowitz et al, 2000/), and of Task 5 (Integrated Hydrogeochemical Modelling /Wikberg, 1998; Dershowitz et al, in print/).

During 2001, JNC activities for the TRUE-Block Scale experiment focused on analysis of the results of the TRUE Block Scale Phase C tracer experiments and 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.

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

Task 6 (Performance Assessment Modelling Using Site Characterisation Data) attempts to bridge the gap between site characterisation and performance assessment modelling approaches using data sets derived from TRUE-1 and TRUE-Block Scale experiments. During 2001, JNC assisted in the development of the technical specification of Task 6, and carried out preliminary simulations using the GoldSim performance assessment code and MAFIC/LTG solute transport code.

The objective of the JNC/Golder activities on Task 6 during 2001 was to improve the understanding of the use of site characterisation data for performance assessment calculations. In particular, JNC efforts focused on quantifying the propagation of uncertainties in parameters derived from in-situ experiments to time and distance scales used in performance assessment calculations.

The JNC/Golder team used a combination of performance assessment and site characterisation modelling for this task. Over 5000 stochastic simulations of the GoldSim performance assessment code were performed to evaluate the ranges of physical transport parameters, which gave values consistent with TRUE-1 tracer transport experiments. The resulting uncertainty ranges were then propagated to PA time and distance scales through benchmark PA simulations. The conceptual model used for solute transport is illustrated in Figure 6-26. Parameter uncertainties were assessed for:

- Advective velocity.
- Transport aperture.
- Transport path width.
- Breccia/gouge immobile zone porosity and thickness.
- Altered wall rock immobile zone porosity and thickness.
- Rock matrix immobile zone porosity and thickness.
- Sorption coefficients (K_d and K_a).

For each parameter, a "physically possible" range was assessed based on the geological conceptual model /Bossart et al, 2001/ and the values obtained from the MIDS database. The "physically possible" values were then constrained by comparing simulated and measured tracer breakthrough.

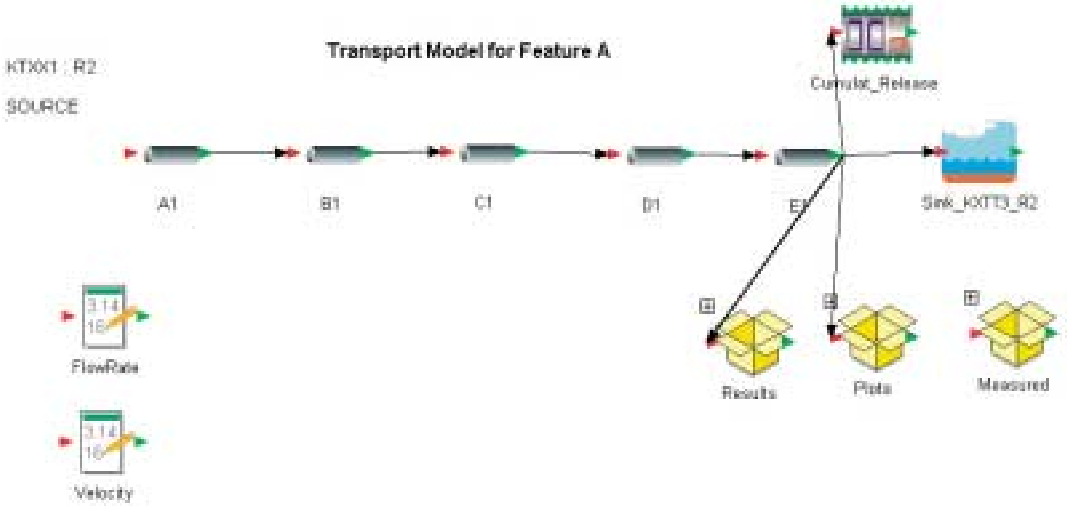


Figure 6-26. Solute transport conceptual model for site characterisation experiments and performance assessment simulations.

Results

Task 6A simulations of the TRUE-1 tracer experiment (STT-1b) demonstrated that the physical parameters controlling transport such as transport aperture and immobile zone porosity are poorly constrained by tracer testing. Due to the nature of the solute transport equations, parameter groups such as the "β-factor" or "F-factor" are better constrained, and in turn provide better constraints on solute transport at PA time scales. Figure 6-27 illustrates solute transport simulations constrained to match the STT-1b tracer breakthrough.

Constrained results based on parameter groups such as the "β-factor" or "F-factor" consistent with STT-1b sorbing tracer experiments were then used in 1 million year simulations for the PA demonstration case (sub-task 6B). This case was based on a 1000 times reduction in advective velocities relative to experimental conditions. These results demonstrated that for the geometry and boundary conditions considered, the sorbing tracer transport experiments could provide a fairly good constraint on long term transport. This is because the key parameters for long term immobile zone transport, reactive surface area is constrained by in-situ experiments, while the intact rock porosity is well constrained by laboratory testing of rock samples. Poorly constrained PA result occur, however, in cases where sorption parameters were not derived by in-situ experiments (Figure 6-28).

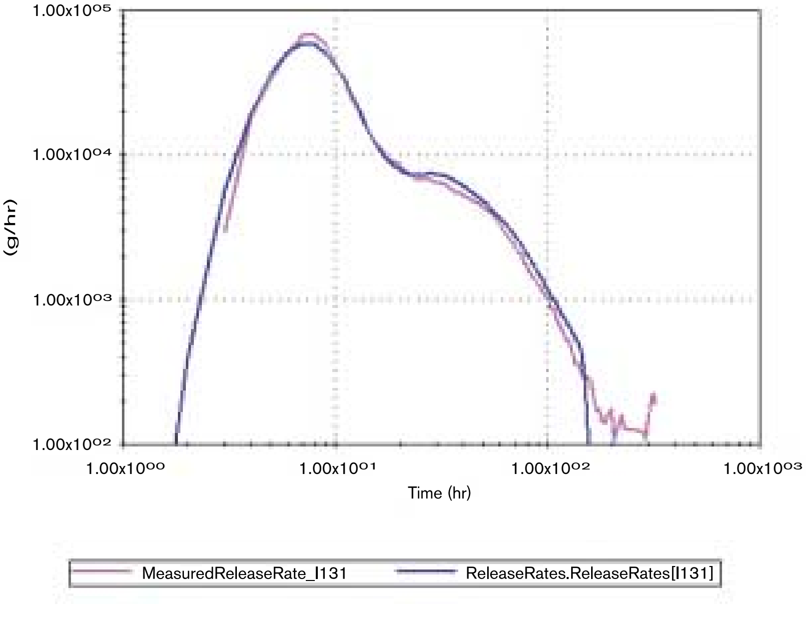


Figure 6-27. *Simulations (blue line) using PA transport conceptual model to match TRUE-1 STT-1b experiments with ^{131}I (purple line).*

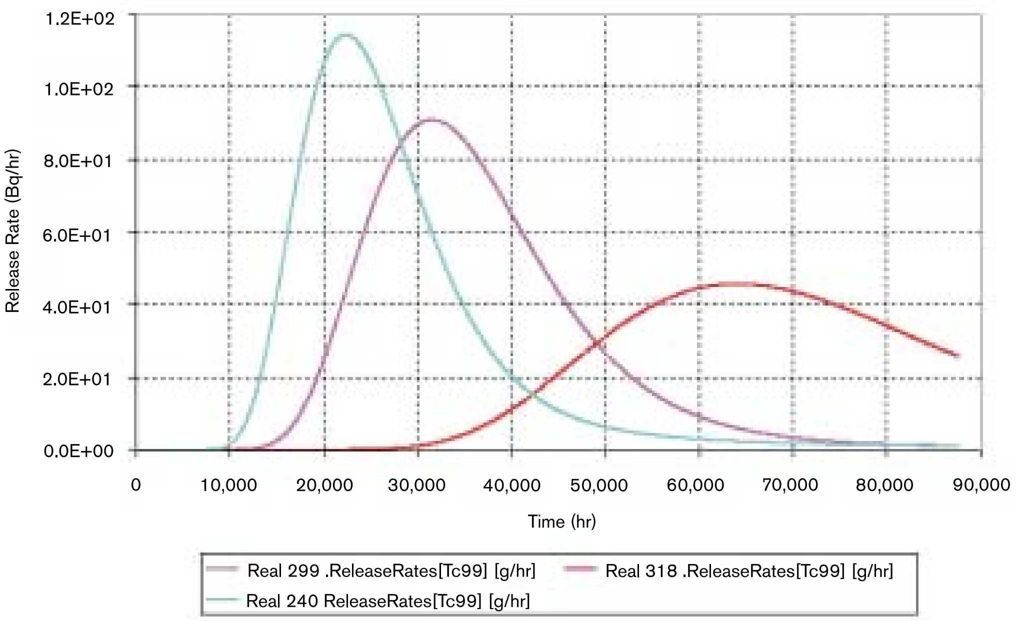


Figure 6-28. *PA time scale simulations not constrained by in-situ tracer experiments (^{99m}Tc).*

In addition to the site characterisation and PA time scale simulations carried out using the GoldSim PA code, a series of demonstration simulations were carried out for 2D transport in a heterogeneous fracture at PA time scales using the MAFIC/LTG code which is generally used for simulation of in-situ experiments.

6.4.2 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 2001 concentrated on analysis of experimental results and reporting of simulations and analyses.

JNC's objective within the TRUE Block Scale Project during 2001 was to advance the understanding of the nature of flow and transport in fracture networks at 50 to 100 m scales. JNC participated in the project at all levels from the definition of hypotheses to be tested, support to experimental design, development of the hydrostructural model, and hydraulic and tracer test interpretation. In addition, JNC participates in the TRUE Block Scale Project as channel network (CN) modelling team.

During 2001, JNC carried out channel network modelling to test each of the four project hypotheses related to sorbing tracer transport in fractured rock. Work was carried out to study the hydrostructural conceptual model, the range of possible tracer transport processes and parameters, and the fracture intersection zone (FIZ) hypothesis.

Results

During 2001, the JNC/Golder team implemented a simplified CN model for the experimental transport pathways, based on an assumption of series linear pathways due to a radial flow boundary condition. Transport pathways of 20 tracer were studied and visualised. These pathways had experimental mass recoveries varying from 0 to 100%. Figure 6-29 illustrates for example the pathway of one tracer experiment (A4c), which had very low mass recovery. Based on this simplified model, a range of transport parameters was identified for each pathway consistent with the laboratory measurements and the hydrostructural conceptual model.

To study the fracture intersection zone effect, the in-situ recovery for pathways incorporating multiple fractures was compared to that for single fracture pathways. Table 6-6 summarises the results of this study. There is a clear correlation between the number of FIZ encountered on a pathway and the mass recovery, indicating that fracture intersections may play some role in mass loss. No correlation was found, however, between effective dispersion or normalised advective velocity and the number of FIZ encountered.

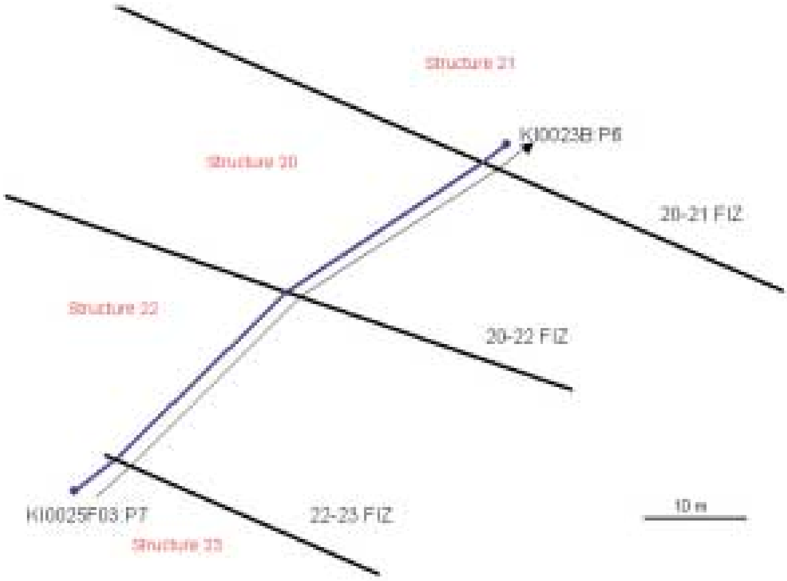


Figure 6-29. Visualisation of A4c tracer experiment pathway in hydrostructural model.

Table 6-6. Projected ultimate mass recovery from in-situ tracer experiments.

	5 pathways NOT involving FIZ	15 pathways involving FIZ
Average	94%	58%
St. Dev	13%	34%
Min	70%	0%
Max	100%	100%

The hydrostructural model was evaluated using a 500 m scale discrete fracture network model. Using this model, hydraulic interference measurements were compared with simulations for a range of variations to the hydrostructural model including increased compartmentalisation, removal of sub-horizontal structures, and removal of background fracturing. Models including background fractures were generally over-connected relative to hydraulic interference measurements, indicating that the background fracture intersections with the hydraulic structures may not be completely connected.

6.4.3 Prototype Repository

JNC participated in the Prototype Repository project during 2001. JNC participated in 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

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

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

Results

In the last annual report, JNC described the governing equations of the coupled THM analytical code THAMES. THAMES was originally developed by /Ohnishi et al, 1985/. The governing equations were extended to calculate the coupled behaviour of the buffer material by /Chijimatsu et al, 2000/. In this report the analytical results of the prediction analysis A are summarised.

JNC has prepared the preliminary analysis of the Prototype Repository project. Preliminary analysis (two-dimensional axial-symmetrical analysis) is used for the prediction analysis A.

Almost all parameters except for the hydraulic conductivity, thermal vapour flow diffusivity and swelling pressure parameter are the same as those used in the simulation conducted by SKB /Börgesson and Hernelind, 1999/. The parameters used in THAMES were refined based on the results of laboratory tests /Börgesson and Hernelind, 1999/.

Analysis is carried out by two-dimensional model. The model geometry is shown in Figure 6-30 where (a) shows a whole geometry and (b) shows the geometry of engineering barriers. The analysis region is 11 m wide and 74 m high. The finite element mesh for prediction A and the initial and boundary conditions for the simulation is shown in Figure 6-31.

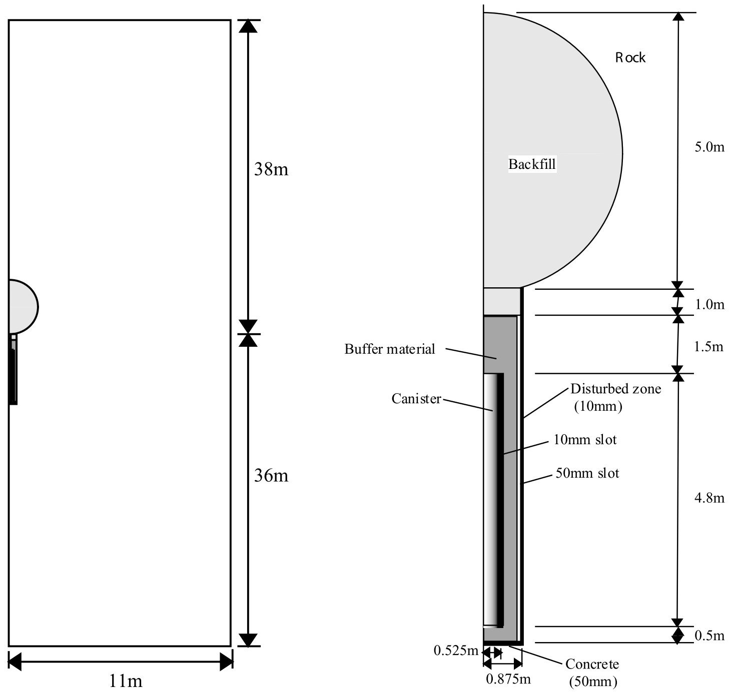


Figure 6-30. *Model geometry. (a) Whole geometry. (b) Geometry of engineered barriers.*

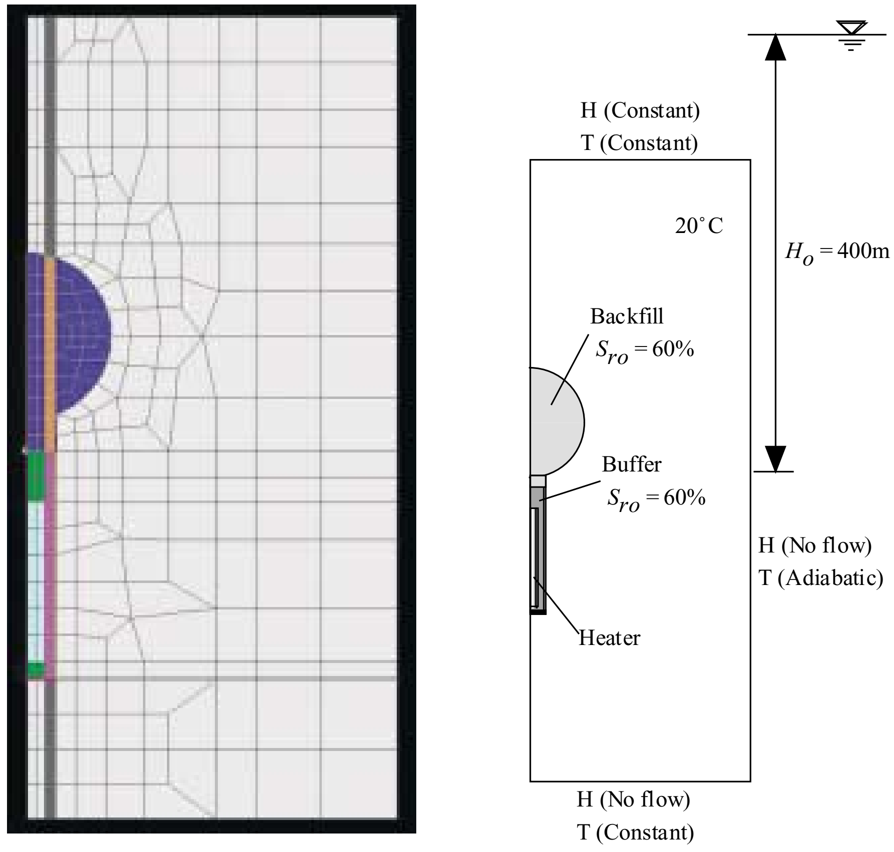


Figure 6-31. *(a) Finite element mesh. (b) Initial and boundary conditions.*

Table 6-7 shows the analysis cases. Case0-1 and Case0-2 are cases with the aim to examine the effect of different boundary conditions at the heater. In Case0-1, the temperature is held constant at the heater and in Case0-2 the heat flux from the heater is held constant. The initial void ratio of the buffer material is 0.77. The gaps between the heater and the buffer and between the rock and the buffer are not considered. This void ratio value in buffer material corresponds to that after saturation. The hydraulic conductivity of the rock mass is 10^{-10} m/s. Effects of different permeabilities in the rock mass are examined in Case1-1, Case1-2 and Case1-3. The hydraulic conductivity in the rock mass is 10^{-10}, 10^{-12}, and 10^{-14} m/s, respectively. The initial void ratio of the buffer material is 0.64. This value corresponds to the bentonite block before installation in the test pit. The gaps between the heater and the buffer and between the rock and the buffer are not considered. Since the bentonite in Case1-1 corresponds to that before installation and the bentonite in Case0-1 corresponds to that after saturation (after swelling). In Case2-1, with constant temperature at the heater, the gaps between the heater and the buffer and between the rock and the buffer are considered. The thermal properties of the gaps are the same as in pure water. Case3-1, Case3-2 and Case3-3 are cases to examine the effects of different thermal vapour flow diffusivity in the buffer. The thermal vapour flow diffusivity in the buffer is $4 \cdot 10^{-13}$, $6 \cdot 10^{-13}$, and $10 \cdot 10^{-13}$ m^2/s K, respectively.

Figure 6-32 shows the time history of the degree of saturation in the buffer with different permeabilities in the rock mass. Closed legends are the saturation in the buffer near the rock mass, and open legends are the saturation in the buffer near the heater. Figure 6-33 shows the time history of temperature both in the buffer and in the rock. The figures show that different permeabilities in the rock mass has insignificant effect on the saturation and temperature distributions in the buffer.

Table 6-7. Analysis cases.

Case	Boundary condition of heater	Initial void ratio of buffer material	Hydraulic conductivity of rock mass (m/s)	Consideration of gap	Thermal vapour flow diffusivity (m^2/s K)
Case0-1	Temperature constant	0.77	10^{-10}	No	$2.0 \cdot 10^{-13}$
Case0-2	Heat flux constant	0.77	10^{-10}	No	$2.0 \cdot 10^{-13}$
Case1-1	Temperature constant	0.64	10^{-10}	No	$2.0 \cdot 10^{-13}$
Case1-2	Temperature constant	0.64	10^{-12}	No	$2.0 \cdot 10^{-13}$
Case1-3	Temperature constant	0.64	10^{-14}	No	$2.0 \cdot 10^{-13}$
Case2-1	Temperature constant	0.64	10^{-10}	Yes	$2.0 \cdot 10^{-13}$
Case3-1	Temperature constant	0.64	10^{-10}	No	$4.0 \cdot 10^{-13}$
Case3-2	Temperature constant	0.64	10^{-10}	No	$6.0 \cdot 10^{-13}$
Case3-3	Temperature constant	0.64	10^{-10}	No	$10.0 \cdot 10^{-13}$

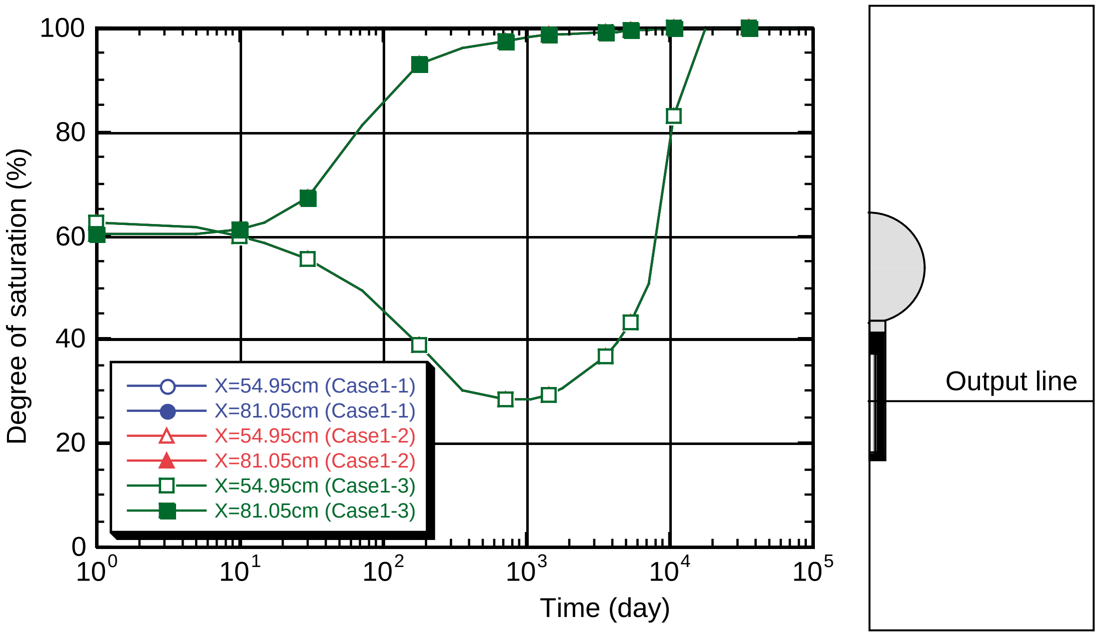


Figure 6-32. *Comparison of degree of saturation with different permeability of rock mass.*

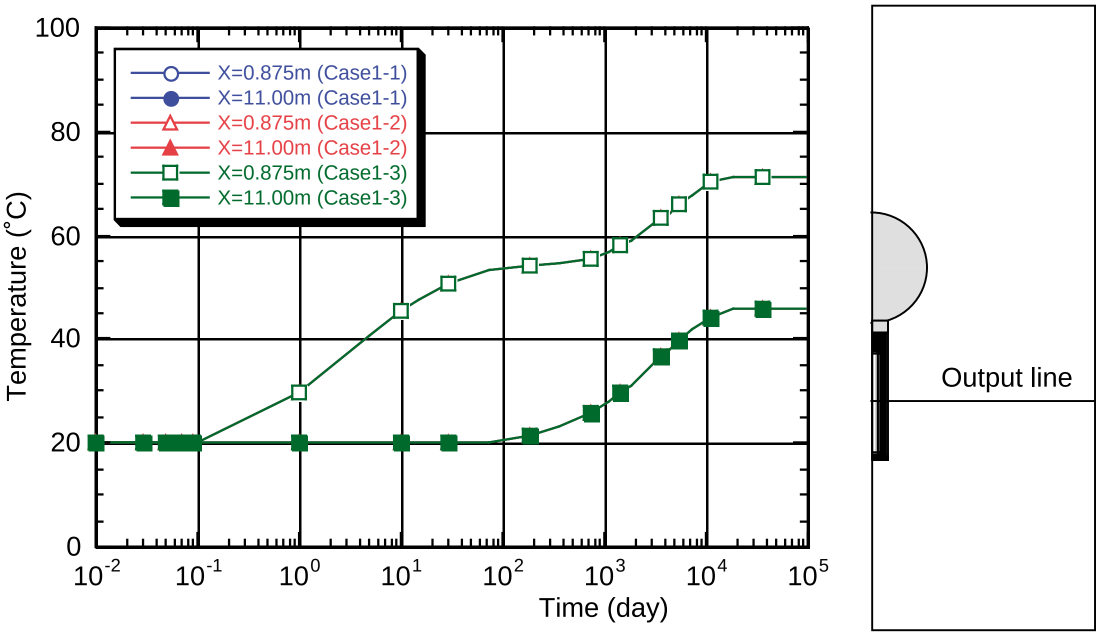


Figure 6-33. *Comparison of temperature with different permeability of rock mass.*

The effects of different thermal vapour flow diffusivities in the buffer are shown in Figure 6-34 and Figure 6-35. Figure 6-34 shows the time history of the degree of saturation. As compared with Figure 6-32, there is a large difference in degree of saturation between the cases shown because of different thermal vapour flow diffusivities. Figure 6-35 shows the time history of temperature with different thermal vapour flow diffusivities. Since the degree of saturation in the buffer decreases with increasing thermal vapour flow diffusivity, the temperature at the outer part of the model decreases due to decrease in thermal conductivity in the buffer. In this analysis, the boundary condition at the heater is a constant temperature. Therefore, the maximum temperature in the buffer becomes lower as the thermal vapour flow diffusivity of the buffer is high, as shown in Figure 6-35. However, a real canister is better simulated with a constant heat flux than a constant surface temperature. At that situation, the maximum temperature in the buffer may increase with increasing thermal vapour flow diffusivity.

Figure 6-36 shows the time history of the degree of saturation in the buffer with different assumptions concerning the gap between buffer and rock mass. At the inner part of buffer where it will take the longest time to reach saturation, the re-saturation time of Case2-1 is between the results of Case0-0 and Case1-1. Figure 6-37 shows the time history of the temperature with different model for the gap between buffer and rock mass. Regarding temperature distribution, there is little difference between these calculations.

From the analysis, the following results are obtained:

- Re-saturation phenomena in the buffer are not dependent on the permeability of the rock mass if the hydraulic conductivity of rock mass is in between 10^{-10} and 10^{-14} m/s.
- The re-saturation time of the buffer depends on the initial void ratio and the thermal vapour flow diffusivity in the buffer.
- There are only relatively small differences in the temperature distribution between the cases with different modelling assumptions for the gaps. The differences in distribution of degree of saturation in the buffer differ more.
- It is important to evaluate the water movement due to thermal effects in order to estimate the re-saturation phenomena in the buffer mass.

In this analysis, JNC investigated the effect of void ratio and thermal vapour diffusivity in the buffer and the effect of the permeability in surrounding rock on the re-saturation phenomena in the buffer by a two-dimensional model. JNC plans to investigate the effect of adjacent boreholes with a three-dimensional model.

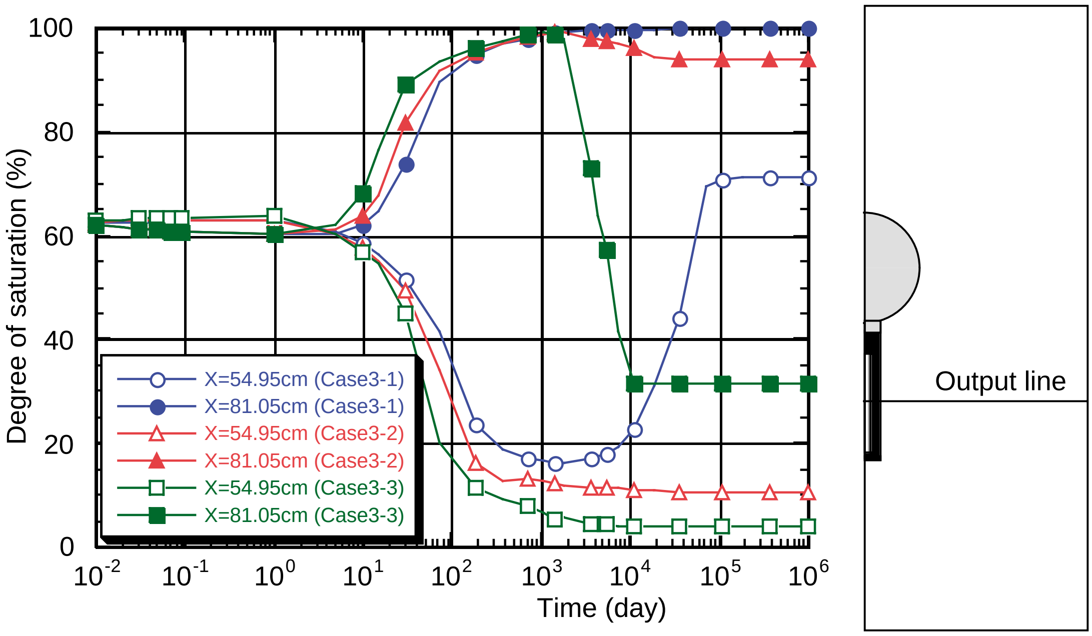


Figure 6-34. *Comparison of degree of saturation with different thermal vapour flow diffusivity.*

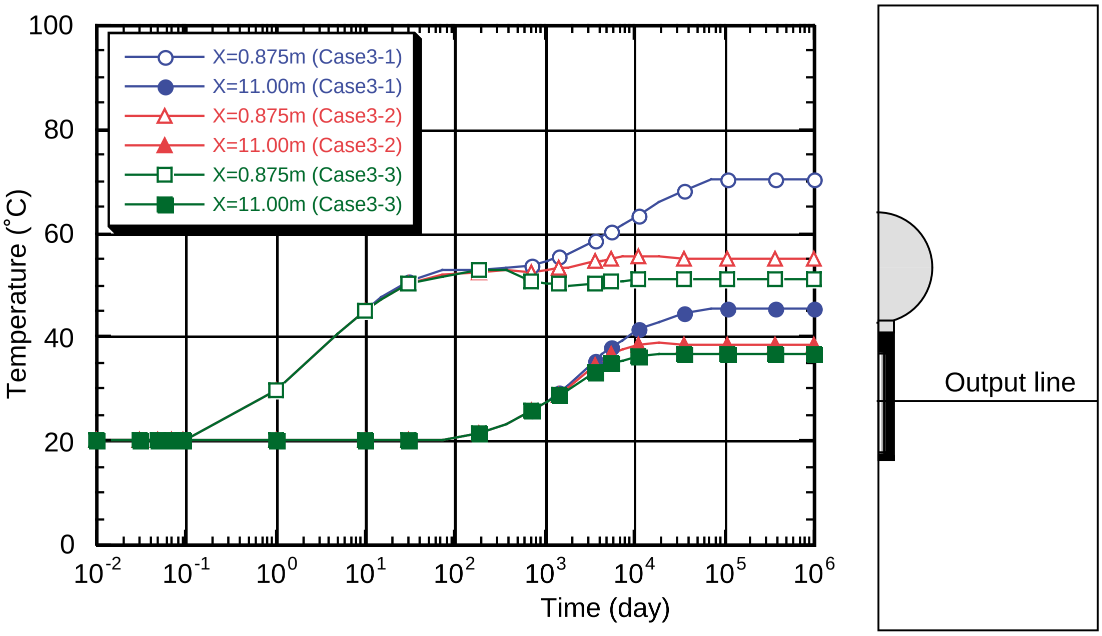


Figure 6-35. *Comparison of temperature with different thermal vapour flow diffusivity.*

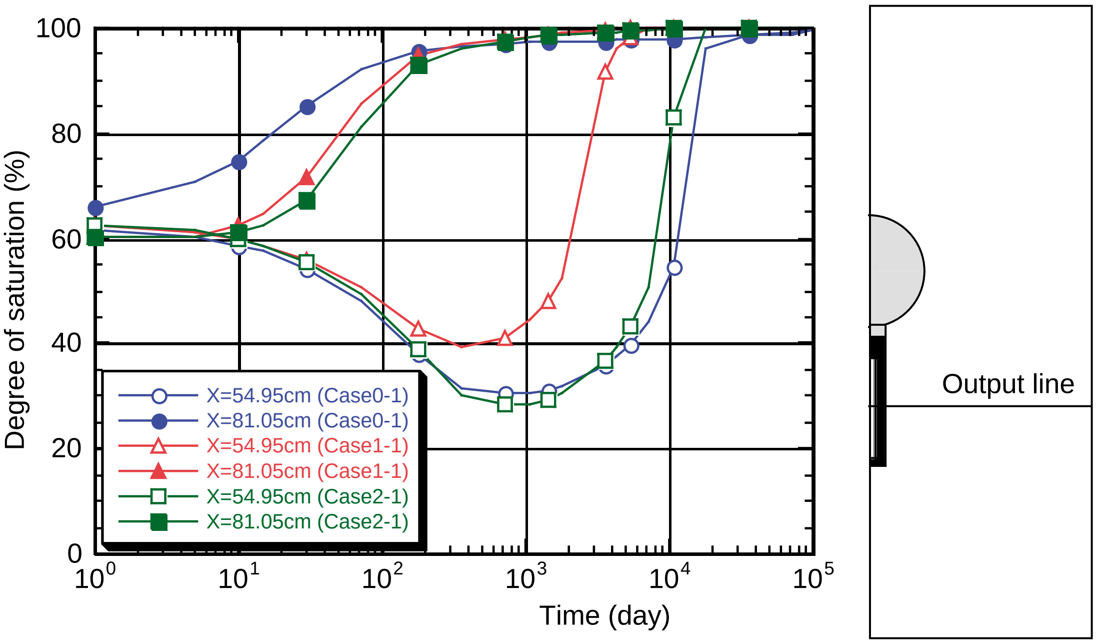


Figure 6-36. Comparison of degree of saturation with different model for gap.

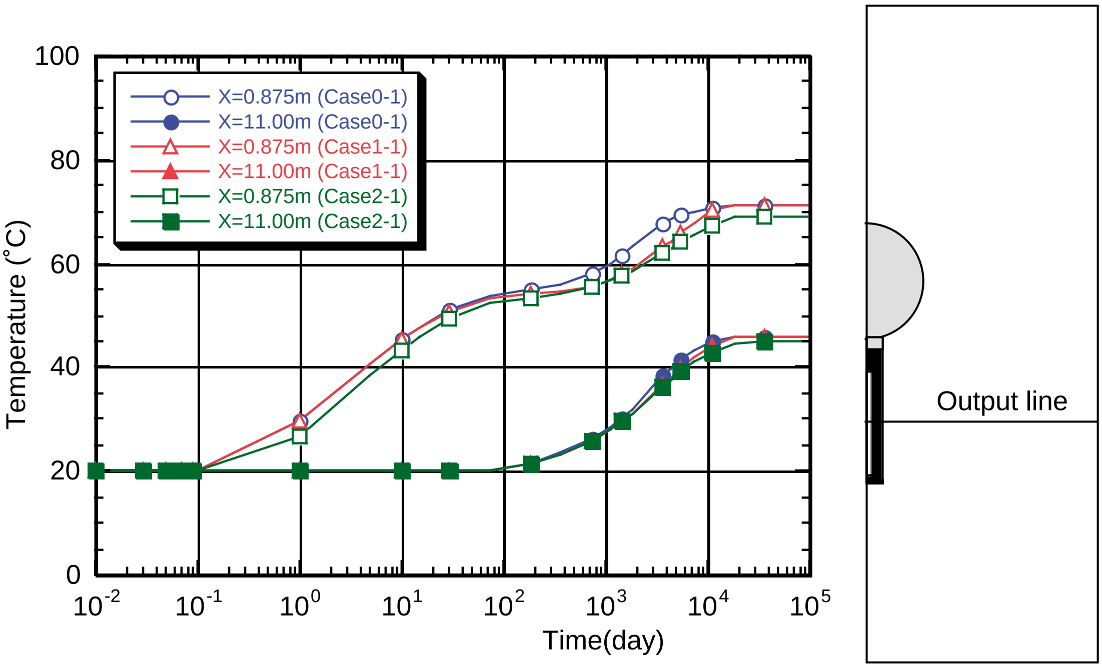


Figure 6-37. Comparison of temperature with different model for gap.

Chemistry (C) modelling of buffer, backfill and groundwater

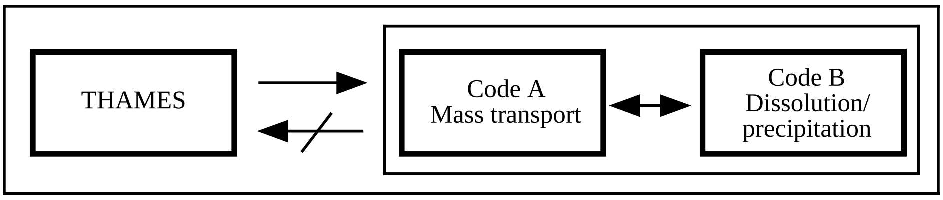
Chemical processes are significant processes for assessing the migration of radionuclides from HLW in performance assessment (PA). JNC believes that THM analysis has to be evolved to THMC analysis. However, chemical processes are not simple. We have to select the significant chemical processes to be considered. We also need a database for selected chemical processes. Therefore, JNC has just started the studies of coupling between chemical processes and THM modelling.

Results

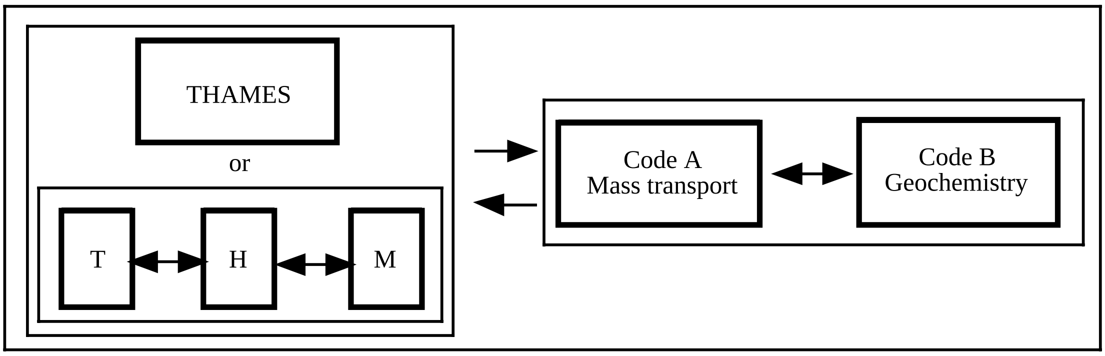
JNC has discussed a development of a concept and has decided upon the approach and procedure to follow. Firstly, JNC will develop the primitive (prototype) THMC code, secondly, JNC will develop the flexible THMC prototype code. The development concept of each step is as follows.

In the development of the primitive THMC code, JNC will link a simple chemical model with the mass transport model and THM model in the code THAMES, see Figure 6-38.

In the near future JNC is planning to develop a fully coupled THMC code. In the THMC analysis different kinds of codes are needed and the control of each code and data transfer among the codes have to be handled. JNC is planning to test the performance of a platform for coupling the mass transport with geochemistry, see Figure 6-38.



Primitive THMC code



Flexible THMC prototype code

Figure 6-38. *Concept of the THMC numerical code.*

6.5 CRIEPI

CRIEPI joined the Äspö HRL Project with JNC and has participated in the task of demonstrating modelling and analytical methods for groundwater flow and radionuclide migration. CRIEPI also conducted groundwater sampling at the Äspö site to demonstrate groundwater dating methods.

CRIEPI has taken part in two international co-operation activities and in a voluntary work to evaluate the performance of natural barriers.

a) Task Force on Modelling Groundwater Flow and Transport of Solutes, Task 6.

b) Task Force on Modelling Groundwater Flow and Transport of Solutes, Task 5.

c) Voluntary Groundwater Dating Project.

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

CRIEPI performed numerical analyses for sub-task 6A. Numerical codes developed by us for groundwater flow and solute transport in rock formations, i.e. FEGM and FERM, were used in these analyses.

In sub-task 6A, the results of a TRUE-1 tracer test (STT-1b) were analysed, which was conducted using absorbing solution in the TRUE-1 experiments and a three-dimensional model. In the model, Feature A was represented as a single flat square of non-uniform aperture with a side length of 30 metres. The surrounding rock matrix is represented as a porous media block of 10 cm thickness on either side of Feature A. Before analysing STT-1b, we calibrated our model of Feature A using the data set for the tracer tests performed previously. The calibrated parameters were distribution of transmissivity in Feature A, and hydraulic gradient under natural conditions. According to the results of the calibration, the transmissivity in Feature A was 10^{-8} or 10^{-9} m^2/s in the order of magnitude, except for the surrounding of one borehole section (KXTT3 R2) where the transmissivity was extremely large. The average magnitude of hydraulic gradient was estimated to be 0.17.

First numerical simulations of the breakthrough curve of HTO in the pumping section were performed. In these simulations, the degree of separation (f) of Feature A was assumed to be 0.8 and the aperture of Feature A at any point was determined from the transmissivity at the point according to cubic law. By introducing a correction factor, and assuming the value of the correction factor to be $1.65 \cdot 10^{-4}$, we were able to reproduce the breakthrough curve (Figure 6-39). Next we tried to simulate the breakthrough curve of Sr. When we used the estimated value of the surface-related sorption coefficient evaluated from a 14-day contact time and a geometrical surface of $8.0 \cdot 10^{-6}$ m, which was recommended by SKB as the input data to the modelling, the peak value of the calculated breakthrough curve was larger and occurred earlier than in the measured breakthrough curve. When we used $1.4 \cdot 10^{-4}$ m as the surface-related sorption coefficient, the calculated breakthrough curve was in close agreement with the measured breakthrough curve, see Figure 6-40. In our view a future study on how to evaluate the values of sorption coefficients based on the results of indoor experiments is critical. Finally we tried to simulate the breakthrough curve of Co. When we used the value of the surface-related sorption coefficient recommended by SKB, $8.0 \cdot 10^{-3}$ m, the peak value of the calculated breakthrough curve was 7.5 times larger and the peak hour occurred earlier

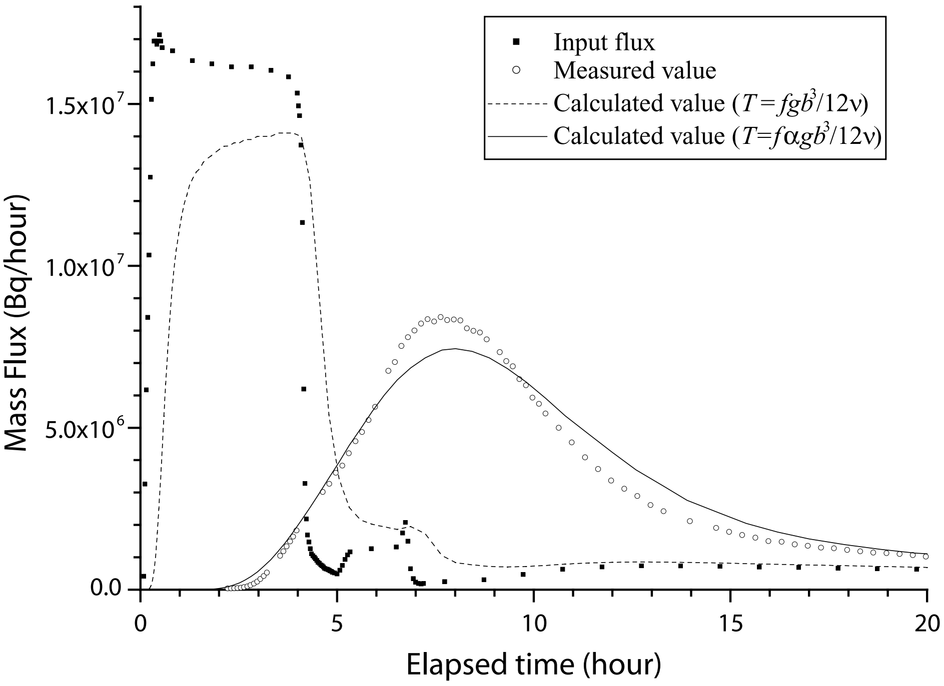


Figure 6-39. *Breakthrough curves of HTO at the pumping section, KXTT3 R2, during STT-1b experiments.*

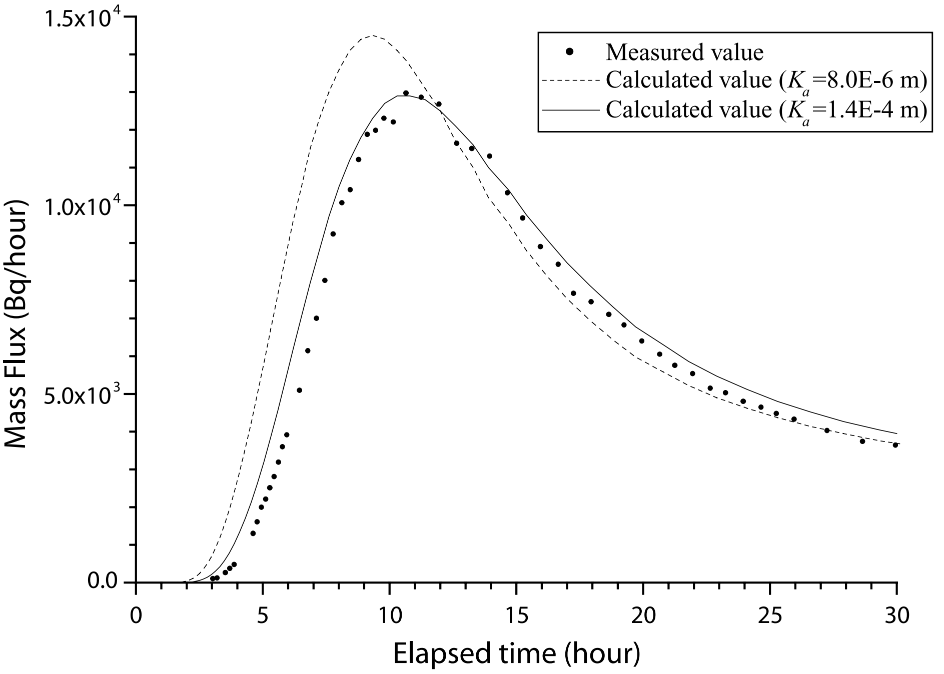


Figure 6-40. *Breakthrough curves of Sr at pumping section, KXTT3 R2, during STT-1b experiments.*

than the measured breakthrough curve. When we used the value of the surface-related sorption coefficient, 0.02 m, the peak hour of the calculated breakthrough curve agreed with that of the measured breakthrough curve, however the peak value of the calculated breakthrough curve was 4.6 times larger than in the measured breakthrough curve. When we conducted calculations taking into consideration the irreversible process of adsorption, the peak value and the peak hour of the calculated breakthrough curve agreed with the results from measuring.

6.5.2 Task Force on Modelling Groundwater Flow and Transport of Solutes, Task 5

CREPI is participating in Task 5 modelling work as part of the modelling team. Task 5 concerns the integration of hydrodynamics with hydrochemistry to investigate changes in groundwater systems during tunnel construction. The objectives are to check the consistency between groundwater flow and geochemical distribution, and to develop a procedure for evaluating groundwater flow systems.

We applied the FEGM-B, which is the FEM code for groundwater flow and solute transport, to the change of groundwater flow during tunnel construction at Äspö, and conducted a simulation of the draw down change at the borehole section, mixing portion of end member, geochemical reaction and helium concentration.

Main results

The progress of tunnel construction and changes in draw down over time are of use in understanding the hydrogeological models, because these relationships clarify impact and response. Changes in draw down over time were represented broadly by proper modelling of the geometric relationship between tunnel, shaft, hydraulic conductor domains, and monitoring borehole section.

The simulated mixing proportions were almost the same as those measured at the shallow section of the tunnel, however at the deeper section the proportions of Baltic sea water and Meteoric water were different. The effects of mixing rate and geochemical reaction may be expected to be of importance in determining the mixing portions at the deeper section.

Figure 6-41 shows the measured and simulated mixing portion during tunnel construction at the shallow part.

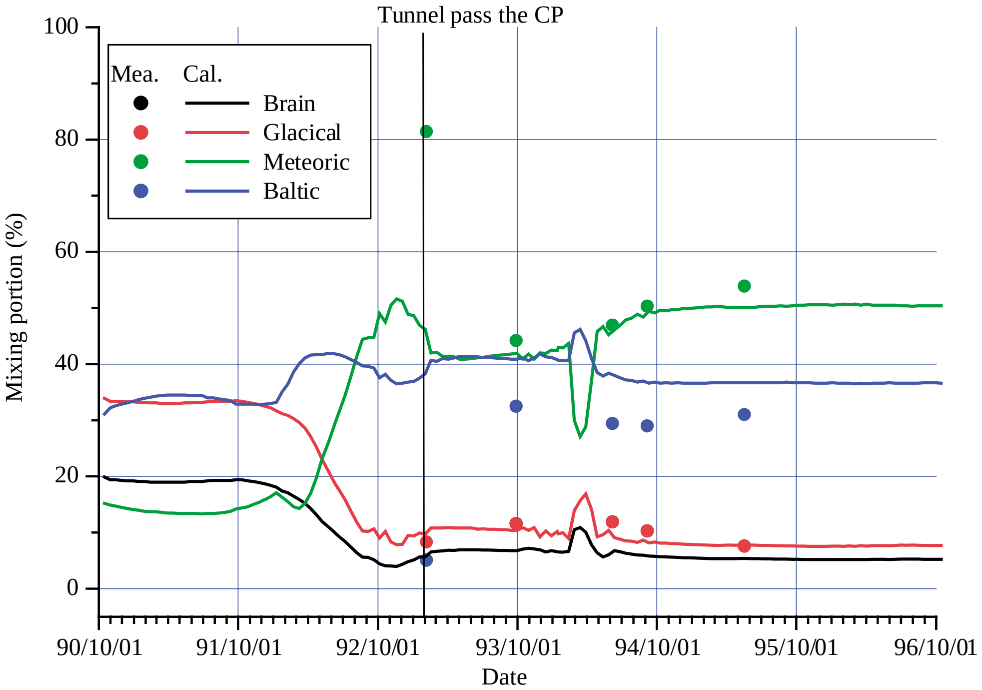


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Figure 6-41. *Measured and simulated mixing portion during tunnel construction at monitoring point. The portion of meteoric water has peak at the tunnel passing, after that it is gradually increasing with time.*

The simulated helium concentrations were generally consistent with the measured concentrations as shown in Figure 6-42. Since measured and simulated results reflect the hydraulic properties of the hydraulic conductor domains, this is a potentially useful method for verifying the hydrogeological model.

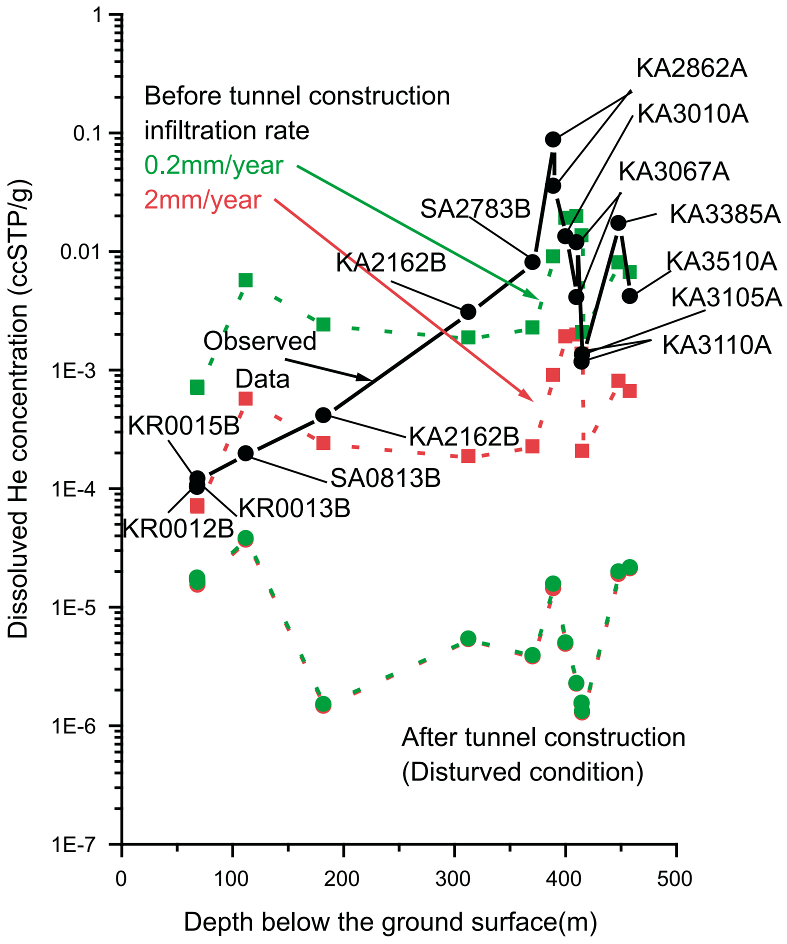

Figure 6-42. *Measured and simulated helium concentration along the tunnel. The black line shows helium concentrations measured in 1995 and 1997. The dot lines show the simulated results before and after tunnel construction by changing infiltration rate. The trends of the result before tunnel construction agree with the measured concentration.*

6.5.3 Voluntary Groundwater Dating Project

CRIEPI has collected groundwater samples at Äspö HRL every two years since 1995, for the purpose of investigating the origins and residence time of groundwater and the stability of groundwater environments in response to disturbances caused by tunnel excavation. Investigations have been conducted in noble gas hydrology, isotope hydrology, and chemical hydrology.

Results and discussions

Judging from the distribution of stable isotopes in the past six years, groundwater mixing has almost reached a stable condition (Figure 6-43). Three different mixing lines have the same single crossing point characterised by the isotope ratio of Baltic seawater. This indicates the intrusion of Baltic seawater through fractures in the tunnel. Furthermore, approximately ten years passed after excavation of the tunnel commenced before pumping out groundwater from the tunnel offset the intrusion of Baltic seawater.

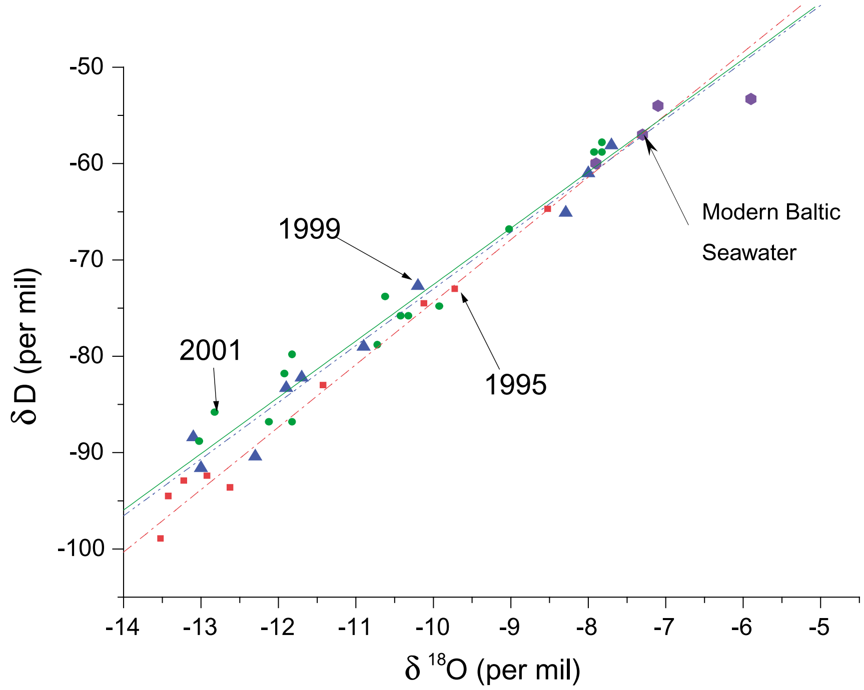

Figure 6-43. *Variation of stable isotopes ratio in the past 6 years.*

^{36}Cl content and He content were measured to estimate groundwater residence time. As the in-situ ^{36}Cl production is not negligible, groundwater residence time can not simply be estimated from a decrease in cosmogenic ^{36}Cl. We observed the correlation between ^{36}Cl grow-up and accumulation of helium (Figure 6-44). We can roughly estimate a helium accumulation rate for $3.01 \cdot 10^5$ years equivalent to the apparent ^{36}Cl half-life. The residence time is predicted to be more than two million years.

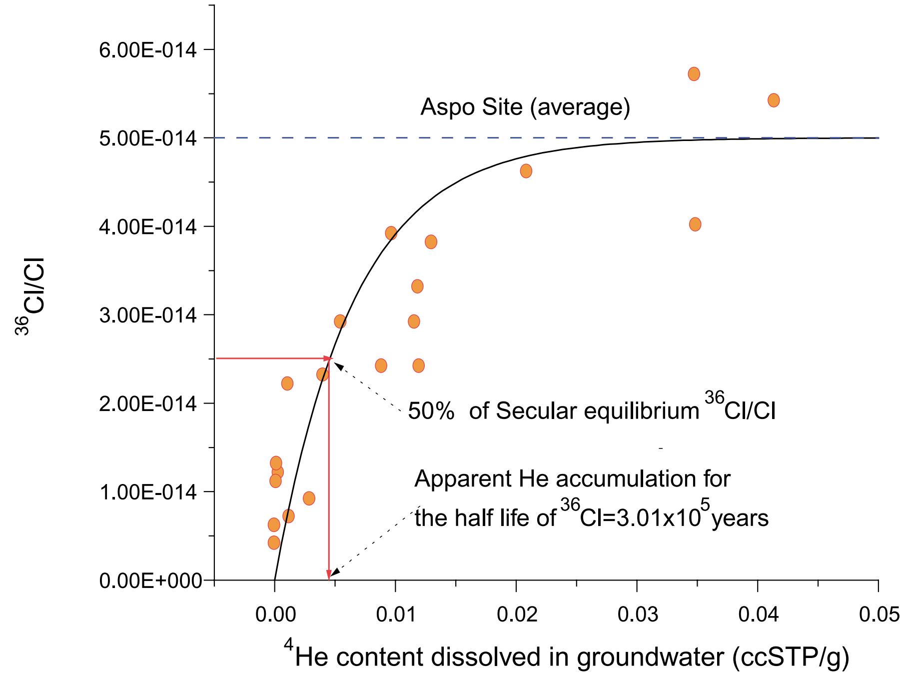

Figure 6-44. *Correlations between He accumulation and ^{36}C1/C1 grow-up curve.*

6.6 Nirex

United Kingdom Nirex Limited has been supported by Serco Assurance (formerly AEA Technology) to provide modelling for the international TRUE-1 Block Scale project.

6.6.1 TRUE Block Scale

The TRUE Block Scale project is in its final reporting stage. The phases consisted of a progressive campaign of hydraulic interference testing, point dilution measurements and finally tracer testing of progressively more reactive tracers, culminating in a series of sorbing radioactive tracer tests. The activities this year supported by Nirex have been principally focussed on reporting the predictive modelling of the Phase C. Phase C consists of a series of sorbing radioactive tracer tests.

There have been various modelling concepts used by the partners in the project. Nirex (supported by Serco Assurance) is using the discrete fracture network (DFN) approach to predict the outcome of the various phases of the project.

Overall Nirex's modelling support has been used to develop a:

- Site-model, that includes the influence of the HRL, tunnel system, and Äspö Island to capture the overall water balance, establish the distribution of salinity and to provide appropriate boundary conditions for sub-models.
- Local scale model of the TRUE Block on a 100 m scale to capture the features of the March 2000 hydrostructural model (this model encompasses the current knowledge of the structures in the TRUE Block).
- Detailed sub-scale model to describe variability of the components (structures) of the structural model.
- Detailed transport model based on particle tracking.

Site-scale model

A site-scale model has been established that includes both the discrete features of the site (fracture zones) and the distribution of salinity. The purpose of this model was to study the influence of the larger scale flows on the local scale model of the TRUE Block and provide self-consistent boundary conditions for the local-scale models.

Local-scale model

A basic local model of the TRUE Block site has been constructed based on the so-called March 2000 hydrostructural model. This includes a parameterised structural model (primarily based on transmissivity measurements arising from the pre-testing of the key structures) of the basic hydrostructural model. This has been implemented using the discrete fracture network software NAPSAC. Figure 6-45 shows the March 2000 model with transmissivity correlation length on a 10 m scale.

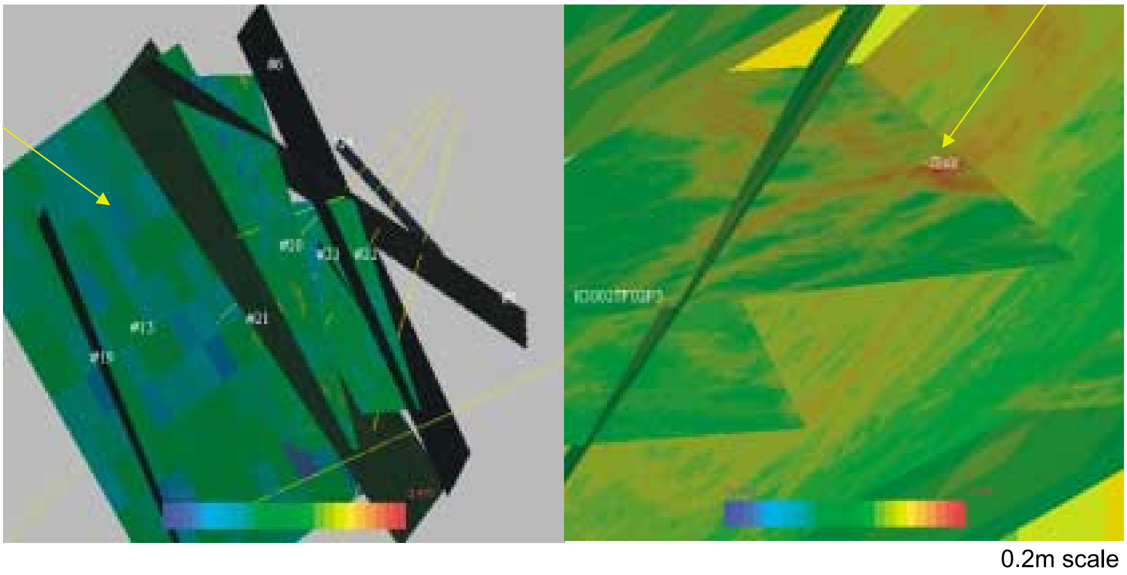

***Figure 6-45.** March 2000 Hydrostructural Model (10 features) with heterogeneity in transmissivity (T) on a 10 m scale and on a 0.2 m scale. The colour shading indicates the scale of variability in T.*

Detailed sub-scale model

The discrete fracture network software NAPSAC has been used to include variability on a sub-scale, as illustrated in Figure 6-45, to enable small-scale variability, potentially down to a scale commensurate with the dimensions of a borehole diameter, to be included. Figure 6-46 shows a simulation of the release of tracer for tracer tests C3 and C2.

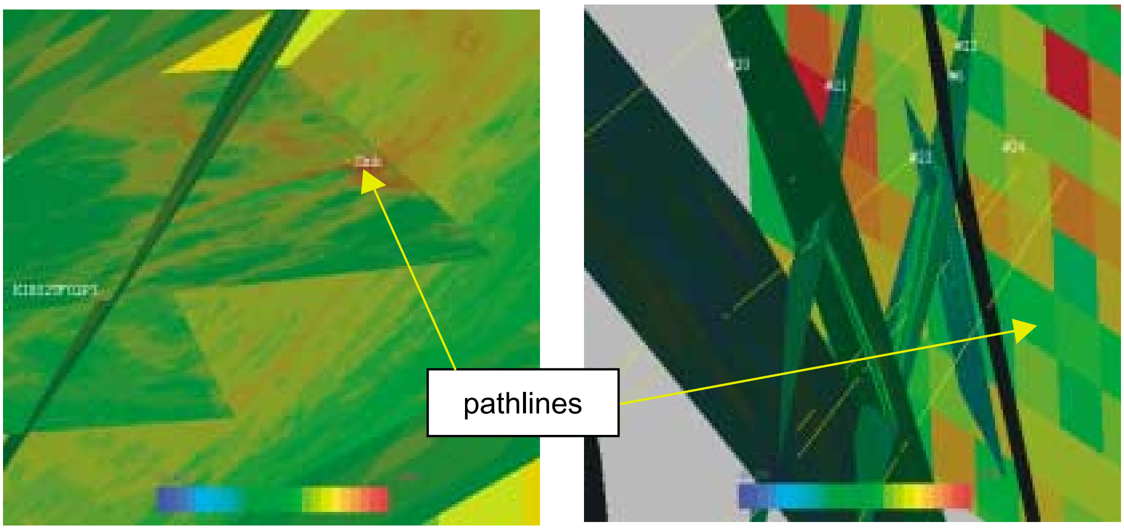

***Figure 6-46.** The path-lines indicated in light green indicate the flow path in the case of tracer test simulations for (a) C3, and (b) C2. It is apparent that the C3 test is within the same structure whereas the C2 testing consists of multiple paths.*

Transport calculations

Tracer transport calculations have been performed in both a predictive phase and an evaluation phase as part of the Phase C tracer testing. These have revealed a series of interesting observations.

- Heterogeneous models based on variability derived from transmissivity estimates are generally inadequate to explain the dispersion observed in the C1 and C3 tracer tests. This was apparent in the predictions in which typically the simulations show inadequate dispersion. The fit to the breakthrough data can be improved by introducing additional dispersion.
- In the case of the C2 tracer test, the simulations, based on the March 2000 hydrostructural model, predicted large spreading of tracer at the injection interval (and poor mass recovery). This was largely due to poor connectivity of the feature intersecting the injection interval, and hence reflected an inadequacy in the hydrostructural model. The additional effect of this lack of connectivity gave rise to multiple flow paths, making the transport paths appear to be more like a dipole rather than a passively released tracer. Interestingly, this had the effect of producing significant dispersion, longer breakthrough times, and some tracer loss, as illustrated in Figure 6-47 and Figure 6-48. However, in the evaluation phase of the simulation work, the injection interval feature was made more extensive (and therefore more connective), resulting in much of this apparent dispersion disappearing. The results then resembled the C1 and C3 tracer test simulations in which the fit to the breakthrough data was improved by introducing additional dispersion (an example of the calibration is shown in Figure 6-47 and Figure 6-48).
- The tracer test predictions based on laboratory derived retention parameters generally resulted in an under prediction of their effect in all of the tests. The evaluation phase of the modelling demonstrated that fits to some of the breakthrough curves (with the exception of the strongly sorbing tracers) was possible by enhancing these parameters. It is plausible that this is justifiable, because it is related to increased retention due to the presence of gouge material, or the enhanced porosity of a rim zone in the vicinity of the fracture surface.
- The methods illustrated above demonstrate why it is important to use both the flow and transport information when trying to derive parameters from tracer tests and not to rely solely on fitting the breakthrough curves.

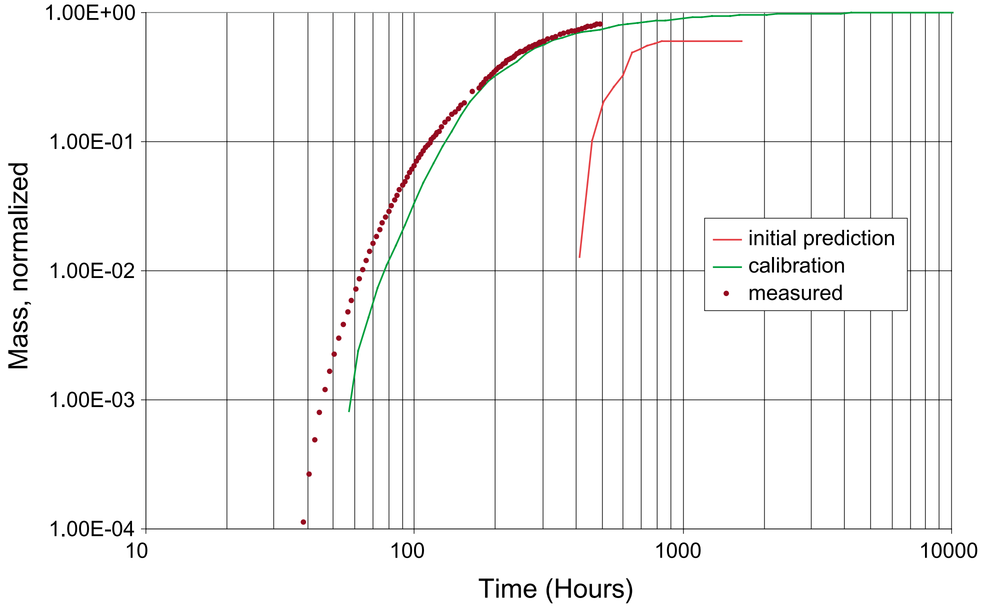

Figure 6-47. *Cumulative breakthrough curves (simulated prediction and evaluation results) compared to the measured conservative tracer result (Re) for tracer test C2.*

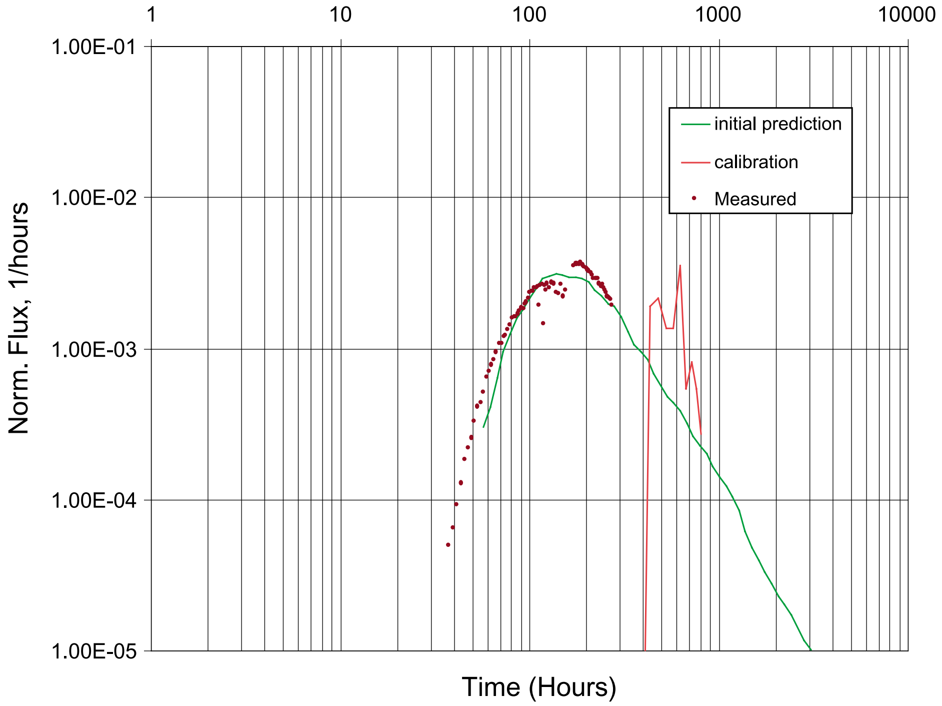

Figure 6-48. *Breakthrough curves (simulated prediction and evaluation results) compared to the measured conservative tracer result (Re) for tracer test C2.*

6.7 Posiva

The Project Agreement between SKB and POSIVA covered the co-operation at Äspö HRL until the end of May, 2001. The work within the Joint Project comprised two main areas:

- Testing of models for description of the barrier function of the host rock.
- Demonstration of technology for and function of important parts of the repository system.

Posiva and SKB signed a new co-operation agreement in June 2001. The agreement covers the co-operation in the areas of scientific and technical programmes and commercial services. Research and development into canister and encapsulation techniques, into repository technology and site evaluation are included. Work at Äspö HRL belongs mainly to the research and development of repository technology and site evaluation. According to a specific agreement Posiva is participating in TRUE Block Scale.

The following text comprises the work done during 2001 according to the Joint Project.

6.7.1 TRUE Block Scale

The TRUE Block Scale project is an international project that is part of the Tracer Retention Understanding Experiments (TRUE). The TRUE Block Scale experiments have been performed in a network of fractures with varying transport lengths of about 16–95 m.

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

The experiment is designed to study transport of tracers through a network of 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 to test potential flow paths using non-sorbing tracers. Phase C included three different flow paths and variety of different sorbing and non-sorbing tracers in transport tests.

Results

During the year 2001 the breakthrough curves of the Phase C tracer experiment were predicted. Predictions are based on a semi-analytical 1D-transport channel model. The same model with a modified advective part was applied to the evaluation of the Phase C tracer experiments at the end of 2001. Reporting of the Posiva-VTT predictions and evaluation of the modelling of the Phase C tracer tests started in 2001. The Posiva-VTT team has also participated in the writing of the final report of the TRUE Block Scale project.

6.7.2 TRUE Block Scale Continuation – Investigation of porosity and micro-fracturing in granitic rock using the ^{14}C-PMMA technique

The objective of the work was to analyse the porosity and micro-fracturing of ten samples from interpreted deterministic structures at the TRUE Block Scale Site using the ^{14}C-PMMA method. The work comprised an analysis of three categories of rock samples: Fault breccia fragments and pieces as well as wall rock samples. The work was reported in /Kemppainen et al, 2001/.

The ^{14}C-PMMA method involves the impregnation of rock samples with ^{14}C-labelled methylmethacrylate (^{14}C-MMA) in a vacuum, polymerisation by irradiation, sample preparation and partitioning, autoradiography, optical densitometry and porosity calculation routines using digital image processing techniques. In the work ^{3}H-labelled methylmethacrylate was used for some of the fragment samples. The advantage of ^{3}H is its low beta energy (18 keV) allowing autoradiography of very thin rock samples.

Methylmethacrylate (MMA) intruded into dark minerals of the fault breccia fragment samples taken from two intercepts; structure #22 in KI0025F02:66.7 m and structure #20 in KI0023B:69.9 m. Porosity levels of several percent were determined. According to the visual inspection of the autoradiographs MMA had distributed homogeneously inside the dark mineral grains. When MMA had intruded into the feldspar mineral grains, porosity distribution was heterogeneous, even cracks and fissures could be distinguished on the autoradiograph from the 1–2 mm size fragments. Some of the feldspar grains were nonporous in the sense of the ^{14}C-PMMA method.

Results

A total amount of four samples of fault breccia pieces were impregnated with ^{14}C-MMA. The samples were taken from two intercepts: structure #22 in KI0025F02:66.7 m and structure #20 in KI0023B:69.9 m. The total porosity of a piece from structure #22 in KI0025F02:66.7 m was around 0.6% and that of a piece from structure #20 in KI0023B:69.9 m around 0.7%. Fault breccia pieces contained plenty of cracks and fissures having apertures between 10 to 20 µm.

Six wall rock samples were impregnated with ^{14}C-MMA. The porosity pattern of samples taken from intercepts from structure #22 in borehole KI0025F02:66.7 m and structure #20 in KI0023B:69.9 m included cracks and fissures. Dark and altered minerals had the highest porosities, around 6 to 8%. The very tight altered mineral phases proved to be nonporous with the ^{14}C-PMMA method. Wall rock samples of intercepts from structure #23 in borehole KI0025F03:56.8 m and structure #21 in borehole KI0023F:71.1 m had total porosities of around 0.3% with the ^{14}C-PMMA method. Porous mineral grains and open mineral grain boundaries form connected migration pathways. The feldspar grains are slightly porous; a few micro-cracks and fissures intersect large potassium feldspar phenocrysts. The porosity pattern of the sample taken from the intercept of structure #20 in KI0025F02:74.6 m contained porous veins (porosity around 1%) cutting the core sample parallel to the fracture surface. The MMA did not intrude completely into the wall rock sample taken from the intercept of structure #20 in KA2563:188.7 m. Contrary to the conditions seen in the other wall rock samples, feldspars here showed a porosity of 0.35%. A strongly altered mylonitic phase adjacent to the fracture surface was not impregnated with MMA.

6.7.3 Task Force on Modelling of Groundwater Flow and Transport of Solutes, Task 5

Task 5 (Impact of the tunnel construction on the groundwater system at Äspö, a hydrological-hydrochemical model assessment exercise) aimed at the comparison and ultimate integration of hydrochemistry and hydrogeology. The task was broken down into two sub-tasks: studies of groundwater chemistry and hydrogeological simulations. VTT Energy and VTT Building and Transport did the work. Task 5 was also part of the Hydrochemical Stability project.

The groundwater chemical studies done in VTT aimed at an independent comparison of the SKB's M3 method described in /Laaksoharju and Wallin, 1997/. The geochemical inverse modelling calculations attempted to take several aspects contemporaneously into account during calculations. The Calculations were performed using reference water types that were identified based on: 1) the analyses of geochemical data, 2) the interpretations of the Quaternary history of the Äspö HRL, see Figure 6-49 and 3) the calculated geochemical mole-transfers that were assumed to confirm the geochemical steady-state conditions. As key results of the modelling calculations the mixing fractions were obtained.

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

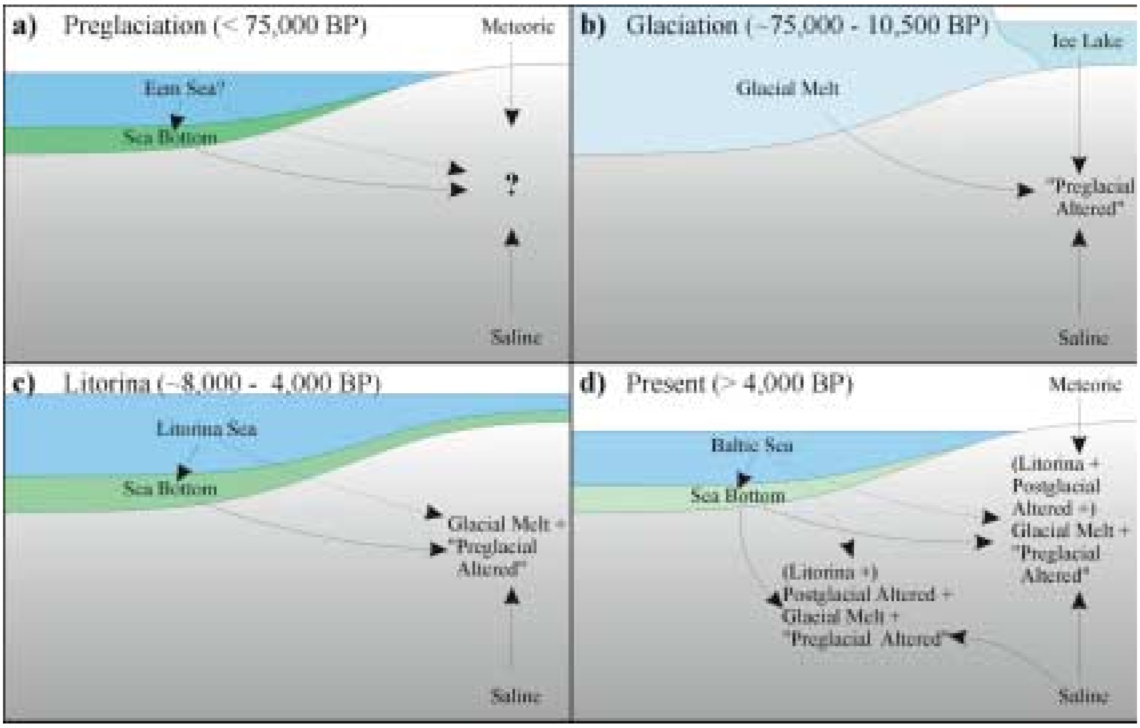

Figure 6-49. Quaternary history of the Äspö area, based on analyses of geochemical data and interpretations of the Quaternary history of the Fennoscandian Shield /e.g. Eronen, 1988; Laaksoharju and Wallin, 1997/. Only periods considered significant for groundwater evolution at the Äspö site are presented.

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

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

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

Results

POSIVA contributed to Task 5 with three reports, one on the geochemical inverse modelling method and two on the hydrological simulations, to be published in 2002. The whole hydrological simulation process was done twice because there were two sets of geochemical modelling results available for the simulations. The M3 based geochemical results were given by the Task 5 organisation but the inverse modelling based geochemical results were calculated in the VTT.

As regards the M3 based simulated mixing fractions in the control points, the future condition of the brine water seems steady, except in the prediction section (tunnel length > 3000 m), where it is mildly increasing. The glacial water decreases, because it is a relic component in the present-day groundwater conditions. The meteoric water generally slightly increases as a function of time. The overall future condition of the Baltic water seems quite steady. As a summary, the simulated results conform fairly well with the given M3 mixing fraction results. According to the given M3 results, changes in the HRL volume are moderate as a result of excavations. This piece of work showed the essential role of the dispersion lengths as regards to the simulated mixing fractions at the control points. Also, the infiltration from the sea had to be restricted.

In the geochemical inverse modelling the calculation results for the undisturbed conditions form the basis for disturbed sample calculations. Furthermore, the detected depth distributions of mixing fractions in undisturbed samples form geochemical boundaries necessary in hydrological simulations. An example of results of disturbed condition calculations is given in Figure 6-50 that illustrates how mixing fractions evolve in time in a control point, and how large CaX_2 mole-transfers has to be taken into account as a function of fresh Baltic Sea fraction intruding into a control point.

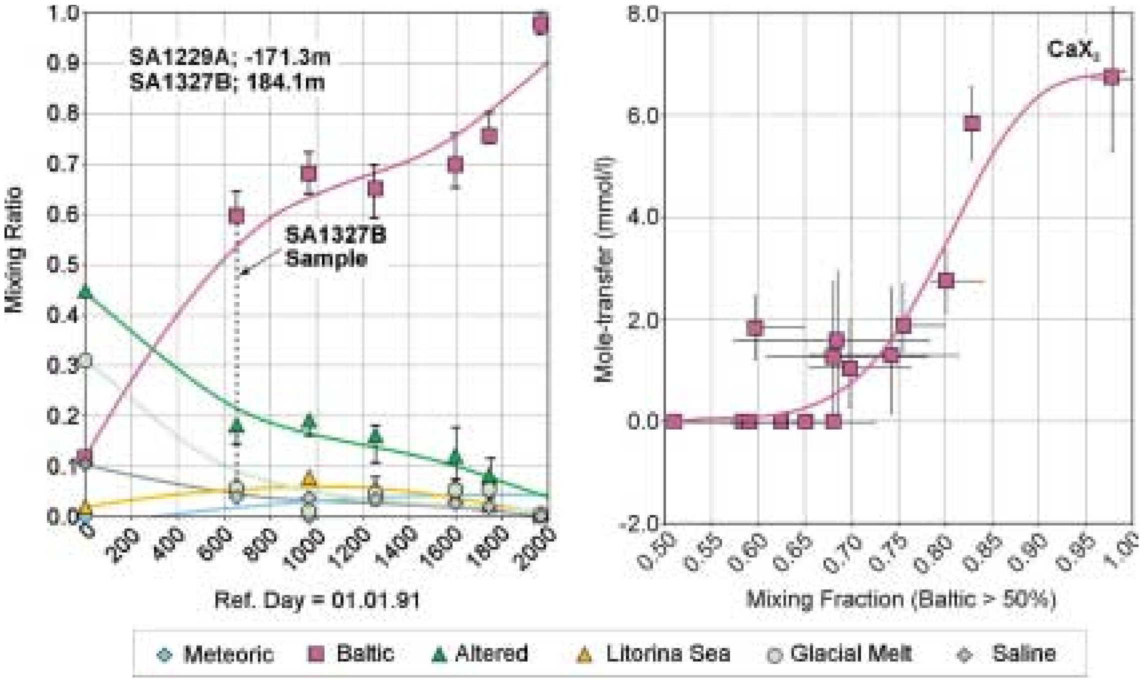

Figure 6-50. *Reference water-type mixing fractions in the control points SA1229A and SA1327B as a function of time, and CaX_2 mole-transfer as a function of the fresh Baltic Sea fraction. Cumulative maximum errors in mixing fractions and maximum errors related to mole-transfers are shown with error bars. Drawn regressions are visual approximations.*

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

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

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

Task 6 (Performance assessment modelling using site characterisation data) started at the end of the year 2000. Task 6 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 programs.

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 a single feature over a transport distance of about 5 m using simple flow geometry and both conservative and sorbing tracers.

Results

In year 2001 preliminary results were presented for the sub-tasks 6A and 6B. According to the preliminary results the effect of the matrix diffusion is greater in site characterisation tracer tests than in the performance assessment flow conditions. The reason for this could be that high porosity fault gouge and stagnant zones dominate retention in tracer test flow conditions but in the performance assessment conditions they get saturated and matrix diffusion takes place only to the rock matrix.

6.7.5 Hydrochemical Stability

Posiva and SKB initiated in 1997 a joint project with the aim to investigate the hydrochemical stability of deep groundwater in crystalline bedrock. This project has been carried out within the Äspö agreement between SKB and Posiva. It also covers the technical parts of the participation in the modelling Task 5 (within the framework of the Äspö Task Force on modelling of groundwater flow and transport of solutes) and re-sampling and analysis of groundwater from KLX02. The project was finalised in 2001 and reported in /Puigdomeneck, 2001/. The effects of climatic changes on the chemical composition of deep ground waters were evaluated, especially the effects on salinity, oxygen content and redox conditions at potential repository sites in Finland and Sweden. Groundwater salinities will change due to future climatic variations due to shoreline movements, permafrost and continental ice-sheets. In most sites the present reducing redox conditions will remain undisturbed during glacial cycles. Posiva contributed to the over-all evaluation of the sites and estimates on the implications for repository performance. Posiva performed modelling of the hydrodynamic effects from climatic changes at Olkiluoto, and evaluation of redox conditions and oxygen intrusion/uptake at investigation sites in Finland.

6.7.6 Matrix Fluid Chemistry

The fluid inclusions, thought to be a reservoir of salinity in crystalline rocks, contribute essential geochemical evidence. The fluid inclusion studies of the experiment in the Äspö HRL have been divided between four laboratories (University of Bern, University of Waterloo, Stockholm University and Kivitieto Oy, Oulu).

The Finnish studies performed by S. Gehör (Kivitieto Oy), aims 1) to find out the fluid inclusion appearance in Äspö diorite 2) to distinguish the chemical characteristics of the fluid inclusions and 3) to evaluate the value of Laser Ablation ICP MS methods in determination of compositions.

The results of the work at Kivitieto Oy are weighted against the analytical data given by Raman spectrometer (analyses carried out by Dr Sten Lindblom at Stockholm University). Double polished thin sections, 200 µm in thickness, were prepared from seven rock samples at Stockholm University. All the samples were selected from drill core sample KF0051A01. The analytical methods consist of petrographic microscope, microthermometry (Reynolds Fluid Inc) and Laser Ablation ICP-MS equipment (Cetah-Perkin Elemers 6000).

Results

According to the studies performed at Kivitieto Oy most of the fluid inclusions occur in quartz, only few of them were detected in apatite and in sphene. The fluid inclusions in coarse-grained quartz and in plebby quartz of Äspö diorite bear record of repeated fracturing, recrystallization and refracturing episodes. Three types of inclusions were found; vapour, vapour-liquid and liquid. Moreover in one sample a vapour-liquid-solid fluid inclusion was detected. The fluid inclusions appear as: 1) small clusters in crystals, 2) isolated, and 3) related to intragranular fractures. The last type is the most common and it carries the majority of the fluid inclusions. The fluid inclusion trails in these fractures are aligned in several cross cutting directions, which tend to continue directly though the section.

The dominant fluid inclusion population belongs to the H_2O-NaCl-$CaCl_2$-CO_2 system; the data suggests also a probable incidence of $MgCl_2$ within solution but this could not be verified. Carbon oxide compounds comprise a prominent fraction of the constituents in the inclusion trails. The trails, which have been formed late within the quartz host, have a lower salinity and the major part of this population belongs to the H_2O-CO_2-NaCl system.

The concentrations of aluminum, alkaline and alkaline rare-earth elements are found to be higher in inclusions within the intercrystalline spaces and trails in comparison to intracrystalline fluid inclusion clusters. The analytical data imply the occurrence of ^{88}Sr and ^{138}Ba in significant amounts in inclusion trails as well as within intercrystalline spaces and coatings. In several cases sodium seems to coincide with occurrence of Sr and Ba. Due to the small size of the inclusions it was not possible to make sure if these elements occur as compounds within aqueous inclusions, together with Na. Although the data suggest that the latter is evident in a small number of the analysis, it is also probable that these elements form independent inclusions. The determination of trace elements and REE:s (rare-earth elements) within inclusions on intercrystalline spaces was tested in one sample only. This analysis gives evidence of the existence of Pb and La in tiny inclusions.

The potential of the ablation method in fluid inclusion studies is apparent. For example, the ability to work within a three dimensional space with micron sized targets, being able to distinguish objects and focusing the beam are basic prerequisites for analytical success. The latest improvements on this area provide greater possibilities to focus the beam with high precision and to select the proper wavelength for study.

6.7.7 Colloid Project

In 2000 SKB decided to initiate the Colloid Project at Äspö HRL to study the stability and mobility of colloids. Posiva joined the project in autumn 2001. Posiva's aims in the Colloid Project is to get a comparison of the different sampling methods and analysis for QA-purposes and also to get experience in sampling of groundwaters from greater depth from underground facilities for planning of the ONKALO groundwater samplings.

Another aim is to gain experience in sampling of colloids from underground rock facilities for the ONKALO. A third aim is a comparison of colloid results collected under normal pressure and under the predominant hydrostatic pressure. Samplings of three groundwaters were performed in October 2001. Results are reported and they will be discussed in a workshop March 2002.

6.7.8 Long Term Test of Buffer Material

Posiva's task in the LOT project is to study pore water chemistry in bentonite. The task will be carried out at VTT Chemical Technology. Excavation of the one-year parcel (A0) was performed during the second half of the year 2001.

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

Results

The parcel A0 was successfully removed from the borehole during the year 2001 and the studies on the bentonite are underway. The preliminary results show that the water saturation has occurred far enough to allow the squeezing of the pore-waters. The studies will be completed in the year 2002.

6.7.9 Characterisation of excavation disturbance around full-scale experimental deposition holes and in-situ failure test

In a deep repository, rock in the excavation-disturbed zone adjacent to the walls of deposition holes for waste canisters is one potential pathway for the transport of corrosive agents and radionuclides. Rock characteristics in the excavation-disturbed zone also play a role in saturation of the bentonite buffer and in gas release. The stability of the deep repository is of great importance from the point of view of both safety and constructability. For the rock to be damaged, fracturing must occur and result in an unstable situation. A significant component of progressive failure is fracture propagation. The development of computers and associated modelling programs has made it possible to model the process of fracture propagation.

Results

The following activities: In-situ failure test, Characterisation of excavation disturbance around full-scale experimental deposition holes, Study of blast damage at Äspö, and Disturbance caused by TBM-boring at Äspö, which were part of the task "Demonstration of technology for and function of important parts of the repository system" have been transferred from Posiva-Äspö co-operation to be continued under an other project entity since middle of 2001. The work carried out in 2001 was concentrated on finishing the reporting of the Study of blast damage at Äspö and the Disturbance caused by TBM-boring.

6.8 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 Äspö HRL.
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 topics was conducted in calendar year 2001. A summary of the work conducted on each topic is provided below.

Sandia National Laboratories joined the Äspö Task Force in September of 1998 in order to be involved with the TRUE-1 tracer test planning and evaluation and better accomplish Topic 1. A single Task Force Meeting was held in 2001 in Goslar, Germany in September.

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

Topic 1

The objective of Topic 1 is to validate the multi-rate mass-transport model developed at the 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 comprised of the prediction and estimation of the STT-1, STT-1b and STT-2 tracer tests from the TRUE-1 program. These estimations and predictions were conducted under Task 4 of the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes.

In 2001, work on Task 4 was finalised and work began on Task 6. Task 6 is focused on the scaling of information from the tracer test scale to larger time and length scales. Work completed in 2001 included the prediction of breakthrough curves for Co, I, Tc and Sr transport within Feature A under assumed ambient conditions. 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, see Figure 6-51.

An offshoot of this 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.

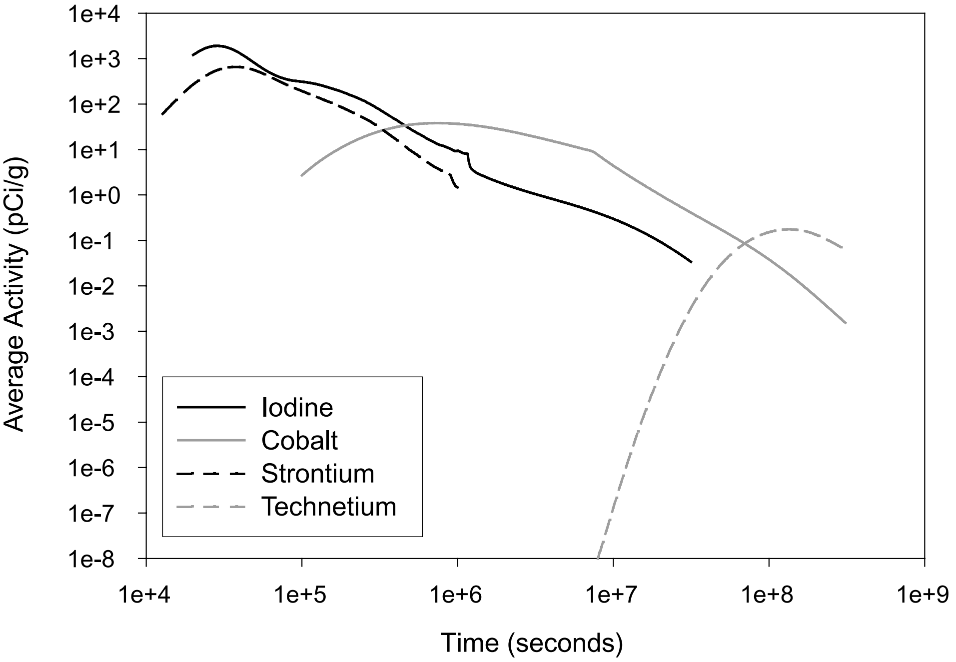

Figure 6-51. *Predicted breakthrough curves for the STT-1b tracer test under ambient (no-pumping) groundwater flow conditions. Each curve represents the average solute activity as calculated with the multi-rate mass-transfer model across 100 stochastic realisations of the Feature A transmissivity field.*

Topic 2

The objective of Topic 2 is to develop new techniques for the visualisation of mass-transfer processes in low porosity rock. Work conducted in 2001 focused on determining the resolution of computerised microtomography (CMT) and better quantification of (with the hope of reducing) the noise associated with CMT. Capillary tubes of known concentration of caesium and iodine (potential tracers for diffusion experiments) were imaged. The measured amount of X-ray absorption (as measured by the linear absorption coefficient, μ) was compared to the theoretical value, see Figure 6-52. The measured values approximately bracket the theoretical values. We are now developing software to quantify and hopefully reduce this noise and normalise the measured values to the theoretical values.

In order to determine the resolution of CMT, cores were created with known pore space. These cores were then imaged both dry and saturated with CsCl. The artificial pore space created ranged from 20 microns to 100 microns. With a voxel size of approximately 25 microns on a side, we could not see the 100-micron pore space in the dry core. Unfortunately, the X-ray absorbance was of the CsCl was too great to be able to image the saturated cores. Based on these results we have decided that we need to be imaging cores less than 1 cm in diameter in order to decrease the size of the voxels. This would also decrease the X-ray absorption of the solid core, allowing for the use of iodine as a tracer. Use of iodine as a tracer is preferable because of its conservative transport properties. In our next round of experiments, we will bring new cores with known pore space where hopefully the imaging will be more successful.

Results of this work to date /Altman et al, 2001/ was presented at the Spring American Geophysical Union Meeting in a session called "Pore to Continuum-Scale Transport and Fate Processes in Groundwater and Vadose Zone Environments". The meeting was held in Boston, Massachusetts in May 2001.

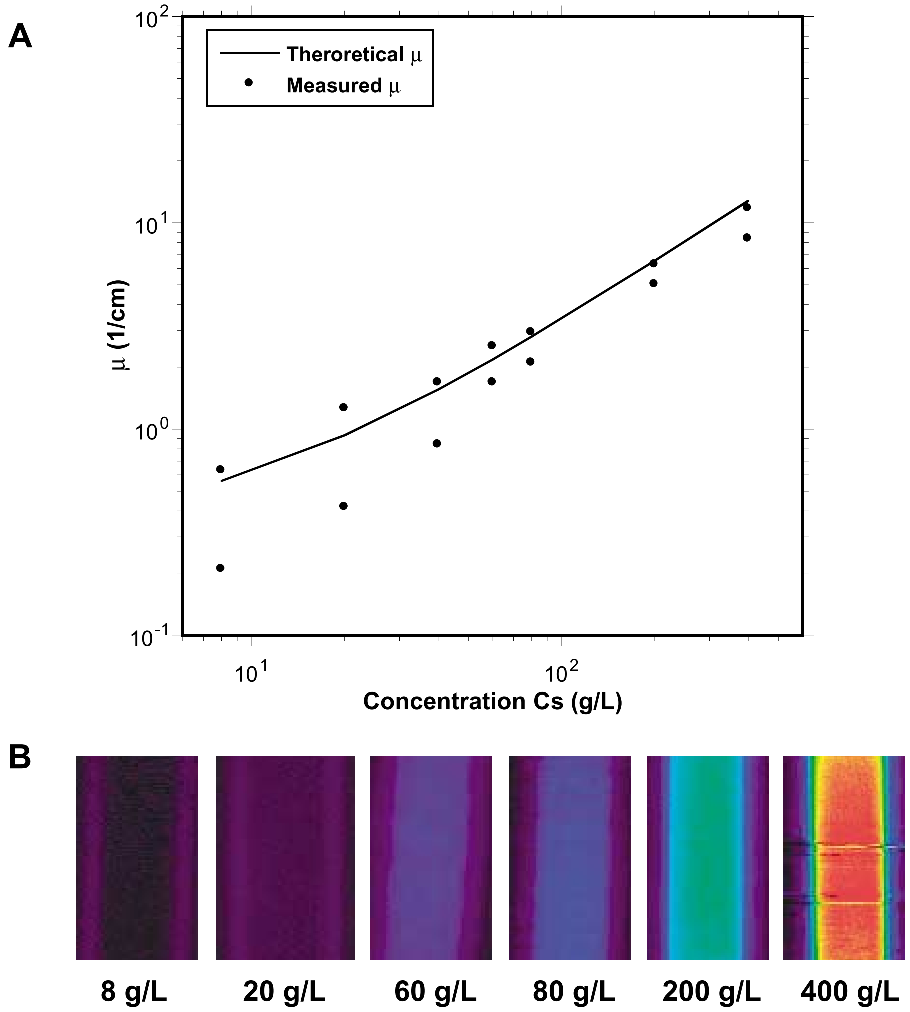

Figure 6-52. *Comparison of measured X-ray absorption (linear absorption coefficient, μ) to theoretical values for CsCl solutions (A). Images of the capillary tubes filled with CsCl solutions of different concentration (B). Two-dimensional slices taken from three-dimensional images obtained non-destructively using synchrotron source microtomography at the Advanced Photon Source at Argonne National Laboratory. Ranges of measured m values approximately bound theoretical value. Software is now being developed to reduce noise in the images and normalise measured values to the theoretical values.*

Topic 3

Work on Topic 3 in 2001 was focused on writing 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 (FARF-31). Significant findings from this work include the results that the FARF-31 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 article is entitled: Constraining Performance Assessment Models with Tracer Test Results: A Comparison of Two Conceptual Models by McKenna and Selroos will be submitted to the Hydrogeology Journal in early, 2002.

6.9 EC-projects

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

6.9.1 Prototype Repository

SKB's reference concept for deep disposal of spent nuclear fuel, the KBS-3 system, 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 will be 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.

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

6.9.2 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

6.9.3 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 project also includes an extension (until quite-saturation) of the heating phase of a mock-up test, design and construction of a geochemical mock-up, and some complementary laboratory tests, as well as modelling works.

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

Start Date: 1999-07-01	**End Date:** 2003-12-31
Co-ordinator: Empresa Nacional de Residuos Radiactivos, Spain	**Participating countries:** Belgium, Czech Republic, Finland, France, Germany, Spain, Sweden, and Switzerland

6.9.4 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 EU Member States on how to incorporate THM processes into Performance Assessment.

BENCHPAR – Benchmark tests and guidance on coupled processes for performance assessment of nuclear repositories

Start Date: 2000-10-01	**End Date**: 2003-09-30
Co-ordinator: Royal Institute of Technology (Dep of Civil and Environmental Engineering), Sweden	**Participating countries:** Finland, France, Spain, Sweden, and United Kingdom

6.9.5 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

6.9.6 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 micro-seismic 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

6.9.7 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 experiments. 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

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