Technical Report

TR-07-10

Äspö Hard Rock Laboratory

Annual report 2006

Svensk Kärnbränslehantering AB

June 2007

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

Äspö Hard Rock Laboratory

Annual report 2006

Svensk Kärnbränslehantering AB

June 2007

Abstract

The Äspö Hard Rock Laboratory (HRL) is an important part of SKB's work with the design and construction of a deep geological repository for the final disposal of spent nuclear fuel. Äspö HRL is located in the Simpevarp area in the municipality of Oskarshamn. One of the fundamental reasons behind SKB's decision to construct an underground laboratory was to create opportunities for research, development and demonstration in a realistic and undisturbed rock environment down to repository depth. The underground part of the laboratory consists of a tunnel from the Simpevarp peninsula to the southern part of Äspö where the tunnel continues in a spiral down to a depth of 460 m. Äspö HRL has been in operation since 1995 and considerable international interest has been shown in its research, as well as in the development and demonstration tasks. A summary of the work performed at Äspö HRL during 2006 is given below.

Geo-science

Geoscientific research is a basic activity at Äspö HRL. The main aim of the current studies is to develop geoscientific models and increase understanding of the rock mass properties as well as knowledge of applicable methods of measurement. The main activities in the different fields have been: (1) Geology – mapping of rock surfaces and drill cores, (2) Hydrogeology – monitoring and storage of data in the computerised Hydro Monitoring System, (3) Geochemistry – sampling of groundwater in the yearly campaign and for specific experiments and (4) Rock Mechanics – reporting for the Äspö Pillar Stability Experiment.

Natural barriers

At Äspö HRL, experiments are performed under the conditions that are expected to prevail at repository depth. The experiments are related to the rock, its properties and *in situ* environmental conditions. The aim is to provide information about the long-term function of natural and repository barriers. Experiments are performed to develop further and test methods and models for the description of groundwater flow, radionuclide migration, and chemical conditions at repository depth. The programme includes projects which aim to determine parameter values that are required as input to the conceptual and numerical models.

A programme has been defined for tracer tests at different experimental scales, the so-called *Tracer Retention Understanding Experiments* (True). The overall objectives of the experiments are to gain a better understanding of the processes which govern the retention of radionuclides transported in crystalline rock and to increase the credibility of models used for radionuclide transport calculations. At the moment, work is being performed in the projects: *True Block Scale Continuation* (final reporting), *True-1 Continuation* and *True-1 Completion (*complementary tracer tests*)*.

The *Long Term Sorption Diffusion Experiment* complements the diffusion and sorption experiments performed in the laboratory, and is a natural extension of the True-experiments. The in situ sorption diffusion experiment was started in September 2006 and on-line measurement of the concentration of the gamma emitting tracers is ongoing. For the strongest sorbing tracers the concentration in the water phase decreased relatively fast, while the concentration of non-sorbing to slightly sorbing tracers levelled out at a more or less constant concentration.

The *Colloid Project* is comprised of studies of the stability and mobility of colloids, bentonite clay as a source for colloid generation, the potential of colloids to enhance radionuclide transport and the measurements of the colloid concentration in the groundwater at Äspö. Interactions of radionuclides with bentonite colloids have been studied in laboratory experiments. Colloid dipole experiments with latex colloids have been performed at the True-site in Äspö HRL.

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 repository for spent fuel. These interactions are studied in the *Microbe Projects*. The microbe laboratory located at the –450 m level in Äspö HRL has been functioning well during 2006. The project *Micored* has been started to investigate the contribution from microorganisms to stable and low redox potentials in groundwater. The project *Micomig* has been initiated to evaluate the influence from microbial complexing agents on radionuclide migration.

The project *Matrix Fluid Chemistry Continuation* focuses on the small-scale micro-fractures in the rock matrix which facilitate the migration of matrix waters. Understanding of the migration of groundwater, and its changing chemistry, is important for repository performance. Hydraulic testing of fracture-free and fracture-containing borehole sections in the matrix borehole have been performed during 2006.

Radionuclide Retention Experiments are carried out to confirm in situ*,* where the conditions with respect to groundwater properties are representative of those at repository depth, the results of laboratory experiments. Due to other priorities no activities have been performed in this project in 2006.

In the EC-project *Padamot* (Palaeohydrogeological Data Analysis and Model Testing) specific processes that might link climate and groundwater in low permeability rocks were investigated and analytical techniques and modelling tools to interpret data were developed. The EC part of the project was reported in 2005 and a continuation of the Swedish part was initiated in 2006. At the start-up meeting in July samples were taken from a drill core from Äspö and sent for uranium series analyses.

The basic idea behind the project *Fe-oxides in fractures* is to examine Fe-oxide fracture linings, in order to explore suitable palaeo-indicators and their formation conditions. At the same time, information about the behaviour of trace component uptake can be obtained from natural material as well as from studies in the laboratory under controlled conditions. The main activities have been reported and a continuation project to establish the penetration depth of oxidising waters below ground has been initiated.

The *Single well injection withdrawal (Swiw) test with synthetic groundwater* constitutes a complement to the tests and studies performed on the processes governing retention of radionuclides in the rock, e.g. the True experiments. A feasibility study is being carried out to evaluate the possibility of performing and evaluating Swiw-tests at a suitable site in Äspö HRL.

Important goals of the activities at Äspö HRL are the evaluation of the usefulness and reliability of different models and the development and testing of methods to determine parameter values required as input to the models. An important part of this work is performed in the *Task Force on Modelling of Groundwater Flow and Transport of Solutes*. The work in the Task Force is closely tied to on-going and planned experiments at the Äspö HRL. During 2006, the work in progress has been mainly on Task 6 (performance assessment modelling using site characterisation data) and Task 7 (long-term pumping test in Olkiluoto, Finland).

Engineered barriers

At Äspö HRL, an important goal is to demonstrate technology for and the 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 are conducted under realistic conditions and at an appropriate scale. A number of large-scale field experiments and supporting activities are therefore carried out at Äspö HRL. The experiments focus on different aspects of engineering technology and performance testing.

The *Prototype Repository* is a demonstration of the integrated function of the repository and provides a full-scale reference for tests of predictive models concerning individual components as well as the complete repository system. The layout involves altogether six deposition holes, four in an inner section and two in an outer. During 2006 the monitoring of relative humidity, total pressure and temperature in different parts of the test area has continued.

The *Long Term Test of Buffer Material (Lot-experiment)* 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. In the beginning of 2006 one of the long-term test parcels (> five years) was successively extracted by overlapping core-drilling. The results from on-going analyses of the test parcel will determine when the next of the three remaining long-term test parcels will be retrieved.

The *Backfill and Plug Test* is a test of the hydraulic and mechanical function of different backfill materials, emplacement methods and a full-scale plug. The inner part of the drift is backfilled with a mixture of bentonite and crushed rock and the outer part is filled with crushed rock. The wetting of the backfill started in 1999 and continued until autumn 2003. Flow testing between filter mats was finalised in 2005. The hydraulic conductivity evaluated from these measurements was somewhat higher than expected from laboratory results. During 2006, measurements in single points, using pressurising filter-equipped tubes, were made. The results yielded a hydraulic conductivity that is about a factor 10 lower than the results from the flow tests between the mats.

The *Canister Retrieval Test*, located in the main test area at the –420 m level, aims to demonstrate readiness for recovering emplaced canisters even after the time when the surrounding bentonite buffer is fully saturated. In January 2006 the retrieval phase was initiated and during the second quarter the canister was successively retrieved. The saturation phase had, at that time, been running for more than five years with continuous measurements of the wetting process, temperature, stresses and strains. Analyses of the canister are ongoing.

The *Temperature Buffer Test* aims at improving our current understanding of the thermo-hydro-mechanical behaviour of buffers with a temperature around and above 100°C during the water saturation transient. The experiment has generated data since the start in 2003. The current understanding is that only the bentonite buffer around the upper heater, which has a sand shield around it, has reached fully saturated conditions. In support of the field test a mock-up test has been performed by CEA in France.

SKB and Posiva are co-operating on a programme for the *KBS-3 Method with Horizontal Emplacement* (KBS-3H). Preparations for the full scale demonstration at Äspö HRL are in progress. The demonstration comprises two deposition holes: (1) one short hole (15 m) which will be used for construction and testing of a low-pH shotcrete plug and (2) one long hole (95 m) which will primarily be used for demonstration of the deposition equipment and for evaluation of the chosen excavation method. The tests on the plug in March 2006 showed a displacement of the plug when exposed to a pressure of about three MPa. The preparations of the niche were finalised at the beginning of the year and the deposition equipment for emplacement of the Supercontainer was delivered. However, problems with the balancing system have postponed the official site acceptance test to 2007.

The aim of the *Large Scale Gas Injection Test* is to perform gas injection tests in a full-scale KBS-3 deposition hole. The installation phase, including the deposition of canister and buffer, was finalised in 2005. Water is artificially supplied and the evolution of the saturation of the buffer is continuously monitored. The test has been in successful operation during 2006 and the saturation measured at both the rock/buffer interface and in individual clay blocks. The measurements indicate that the buffer above and beneath the canister is not fully saturated. The gas injection tests will start when the bentonite buffer is fully saturated.

The objective of the project *In situ Corrosion Testing of Miniature Canisters* is to obtain a better understanding of the corrosion processes inside a failed canister. In Äspö HRL in situ experiments with miniature copper canisters with cast iron inserts will be performed where the copper canisters will be exposed to both natural reducing groundwater and groundwater which has been conditioned by bentonite for several years. At the end of 2006, three canisters were installed and the remaining two canisters will be installed early 2007.

In the project *Cleaning and Sealing of Investigation Boreholes* the best available techniques are to be identified and demonstrated. In order to obtain data on the properties of the rock, boreholes are drilled during site investigations. These investigation boreholes must be cleaned and sealed, no later than at the closure of the repository. A complete sealing concept has been developed and a large-scale test was made in 2005 in a borehole at Olkiluoto in Finland. To simulate the sealing of the upper wider parts of boreholes, copper and quartz/cement plugs have been installed in two boreholes at the surface and preparations are made for testing at the –450 m level at Äspö HRL.

The objective of the project *Alternative Buffer Materials* is to study clay materials that laboratory tests have shown to be conceivable buffer materials. A number of blocks have been produced and three parcels with different combinations of materials were installed in boreholes at Äspö HRL in 2006. The parcels and the experimental set-up are similar to that used in the *Lot-experiment*. The experiment will run for about one year before the first package is retrieved and the other packages will be in operation for 2–5 years before retrieval.

The aim of the *Rock Shear Experiment* is to observe the forces that would act on a KBS-3 canister if a displacement of 100 mm were to take place in a horizontal fracture that crosses a deposition hole. The first phase, a pre-study, is complete. The conclusion is that the test is feasible. Planning and preparations for the test are underway.

The main objectives for the project *Earth Potentials* are to identify the magnitude of potential fluctuations and stray currents for geomagnetically induced and man-made stray current sources at repository depth, and thereby estimate any potential problems. The change in ion-exchange properties of MX-80 bentonite exposed to copper chloride solutions and the potential corrosion effects of voltage differences in a repository have been studied. In addition, measurements of earth potentials at Forsmark indicate that changes in the high voltage current in the cable between Sweden and Finland have an influence on the vertical magnetic field at Forsmark.

The *Task Force on Engineered Barrier Systems* was activated in 2004. The Task Force starts with a first phase of four years. This phase addresses two tasks: (1) THM processes and (2) gas migration in buffer material. The aim is to produce a state-of-the-art report. The focus is on the use of codes for predictions of the conditions in the buffer during specified milestones in the repository evolution. Two Task Force meetings have been held during 2006. The results from the modelling of the laboratory tests for Task 1 and 2 have been presented and discussed. In addition, the large scale field tests to be used for the modelling in the next benchmark are defined.

Äspö facility

An important part of the activities at the Äspö facility is the administration, operation, and maintenance of instruments as well as the development of investigation methods. The main goal of the operation is to provide a safe and environmentally sound facility for everybody working or visiting the Äspö HRL. The goal of an operational time of 98% for the laboratory during 2006 has been exceeded.

During 2006 a Bentonite Laboratory has been under construction. The laboratory is designed for studies of buffer and backfill materials. In the laboratory, buffer emplacement in deposition holes can be tested at full scale. In addition, techniques for backfilling the tunnels can be further developed.

The public relations and visitor services group is responsible for presenting information about SKB and its facilities. During the year 2006, the Äspö HRL and the "Äspö nature path" were visited by about 11,000 visitors and the guided summer tours "U500" set a new record with more than 2,800 visitors.

Environmental research

Äspö Environmental Research Foundation was founded 1996 on the initiative of local and regional interested parties. The aim was to make the underground laboratory at Äspö and its resources available for national and international environmental research. The Äspö Research School started in 2002 and has over the first years of research activities focused on chemical processes in the surface environment. Most of these studies will be included in Ph.D. theses and in May 2006 the second Ph.D. dissertation took place.

International co-operation

In addition to SKB, nine organisations from eight countries co-operated on the activities at Äspö HRL during 2006. Six of them; Andra, BMWi, CRIEPI, JAEA, OPG and Posiva together with SKB form the Äspö International Joint Committee which is responsible for the co-ordination of the experimental work arising from the international participation. Most of the organisations participating in the Äspö HRL co-operation are interested in groundwater flow, radionuclide transport and rock characterisation. Several of the organisations are participating in the experimental work at Äspö HRL as well as in the two Äspö Task Forces: (1) Task Force on Modelling of Groundwater Flow and Transport of Solutes and (2) Task Force on Engineered Barrier Systems.

Sammanfattning

Äspölaboratoriet nära Simpevarp i Oskarshamns kommun är en viktig del i SKB:s arbete med utformning, byggande (och drift) av ett slutförvar för använt kärnbränsle. Ett av de grundläggande skälen till SKB:s beslut att anlägga ett underjordslaboratorium var att skapa förutsättningar för forskning, utveckling och demonstration i en realistisk och ostörd bergmiljö på förvarsdjup. Underjordslaboratoriet utgörs av en tunnel från Simpevarpshalvön ner till södra delen av Äspö där tunneln fortsätter i en spiral ner till 460 meters djup. Äspölaboratoriet har varit i drift sedan 1995 och verksamheten har väckt stort internationellt intresse. Här följer en sammanfattning av det arbete som bedrivits vid Äspölaboratoriet under 2006.

Geovetenskap

Forskning inom geovetenskap är en viktig del av arbetet vid Äspölaboratoriet. Det huvudsakliga målet med de pågående studierna är att utveckla geovetenskapliga modeller samt att öka förståelsen för bergmassans egenskaper och kunskapen om användbara mätmetoder.

De huvudsakliga aktiviteterna inom de olika områdena har varit; (1) Geologi – kartering av bergytor och borrhål, (2) Hydrogeologi – övervakning och lagring av data i det datoriserade ”Hydro Monitoring System”, (3) Geokemi – den årliga provtagningen av grundvatten samt för specifika experiment och (4) Bergmekanik – rapportering av Pelarförsöket.

Naturliga barriärer

I Äspölaboratoriet genomförs experimenten vid förhållanden som liknar de som förväntas på förvarsdjup. Experimenten kopplar till berget, dess egenskaper och in situ förhållanden. Målen med de pågående experimenten är att ge information om säkerhetsmarginalerna i slutförvaret och de naturliga barriärernas funktion. Ett viktigt syfte med verksamheten vid Äspölaboratoriet är att vidareutveckla och testa beräkningsmodeller för grundvattenströmning, radionuklidtransport och kemiska/biologiska processer på förvarsnivå. I programmet för testning av modeller ingår att bestämma de parametrar som krävs som indata till konceptuella och numeriska modeller.

Bergets förmåga att fördröja transport av spårämnen studeras i olika skalor i *True-försöken*. Syftet är att öka förståelsen för de processer som styr fördröjningen av radionuklider i granitiskt berg samt att öka tillförlitligheten hos de modeller som används för beräkning av radionuklidtransport. För tillfället bedrivs arbete inom delprojekten: ”*True Block Scale Continuation*” (slutrapportering), ”*True-1 Continuation*” och ”*True-1 Completion*” (kompletterande spårämnesförsök).

LTDE-SD-försöket är ett komplement till de sorptions- och spårämnesförsök som genomförts i laboratorium och är också en utvidgning av de experiment som genomförts inom True-programmet. Sorptions- och spårämnesförsöket in situ startade i september 2006 och direkt-mätning av koncentrationen av gammastrålande spårämnen pågår. För de mest sorberande spårämnena sjönk koncentrationen i vattenfasen relativt snabbt, medan koncentrationen av icke-sorberande till lätt sorberande spårämnen planade ut på en mer eller mindre konstant nivå.

Kolloidprojektet omfattar studier av kolloiders stabilitet och rörlighet, bentonitens betydelse som källa för bildandet av kolloider, risken för att radionuklider transporteras med kolloider samt mätningar av kolloidkoncentrationen i grundvattnet i Äspö. Radionukliders interaktion med bentonitkolloider har studerats i laboratorieexperiment. Dipolexperiment med latex-kolloider har utförts på platsen för *True-försöken* i Äspö HRL.

Mikroorganismer samverkar med sin omgivning och kan i vissa fall ge stor påverkan på förhållandena där. Detta kan vara av betydelse för hur ett framtida förvar för använt bränsle fungerar och studeras därför inom *Mikrobprojekten*. På 450 meters djup i Äspö HRL finns mikroblaboratoriet som har fungerat bra under året. För att undersöka hur mikroorganismer bidrar till stabila och låga redoxpotentialer i grundvatten har projektet *Micored* startats och projektet *Micomig* har initierats för att utvärdera inverkan av mikrobiellt bildade komplexbildare på radionuklidtransport.

I *Matrisförsöket* är fokus på hur de småskaliga mikrosprickorna i bergmatrisen underlättar matrisvattnets rörelse. Förståelsen av grundvattnets rörelse och förändringar i vattenkemin är viktig för slutförvarets funktion. Hydrauliska tester av sprickfria och sprickiga sektioner i matrisborrhålet har utförts under 2006.

Radionuclide Retention Experiments genomförs in situ, där förhållandena med avseende på grundvattenbetingelserna är representativa för vad som gäller på förvarsdjup, för att befästa resultaten från laboratorieexperiment. På grund av andra prioriteringar har inget arbete utförts inom detta projekt under 2006.

EU-projektet *Padamot* (Palaeohydrogeological Data Analysis and Model Testing) hade som syfte att undersöka de specifika processer som beskriver hur klimatet påverkar grundvattenkemin i berg med låg permeabilitet. Inom projektet utvecklades även analysteknik och modelleringsverktyg för att utvärdera palaeohydrogeologiska data. EU-delen av projektet rapporterades under 2005 och en fortsättning av den svenska delen inleddes under 2006. Vid uppstartsmötet i juli togs prover från en borrkärna från Äspö som skickades iväg för att genomgå urananalyser.

I projektet *Järnoxider i sprickor* undersöks järnoxidbeklädda sprickytor för att hitta lämpliga palaeoindikatorer och beskriva under vilka förhållanden dessa bildas. På samma gång kan information inhämtas om beteendet av spårämnesupptaget både från naturliga material såväl som från studier i laboratoriet under kontrollerade förhållanden. Huvudaktiviteterna har rapporterats och för att klargöra penetrationsdjupet för oxiderande vatten under marknivå har en fortsättning av projektet startats.

Single well injection withdrawal (Swiw) test with synthetic groundwater utgör ett komplement till testerna och studierna som utförts rörande de processer som styr fördröjningen av radionuklider i berget, till exempel True-experimenten. En förstudie utförs för att utvärdera möjligheten att utföra och utvärdera Swiw-tester på en lämplig plats i Äspölaboratoriet.

Aktiviteterna vid Äspölaboratoriet omfattar projekt med syfte att utvärdera användbarhet och tillförlitlighet hos olika beräkningsmodeller. I arbetet ingår även att utveckla och prova metoder för att bestämma vilka parametrar som krävs som indata till modellerna. En viktig del av detta arbete genomförs i ett internationellt samarbetsprojekt ”*Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes*”. Arbetet i projektet har anknytning till pågående och planerade experiment vid Äspölaboratoriet. Under 2006 har arbetet huvudsakligen fortskridit inom ”Task 6” (användandet av data från platsundersökning i modellering för säkerhetsanalys) och ”Task 7” (pumptester under lång tid i Olkiluoto, Finland).

Tekniska barriärer

Verksamheten vid Äspölaboratoriet har som mål att demonstrera funktionen hos förvarets delar och visa att teknik finns för att bygga och driva ett framtida förvar. Detta innebär att vetenskapliga och teknologiska kunskaper används praktiskt i arbetet med att utveckla, testa och demonstrera de metoder och tillvägagångssätt som kan komma att användas vid uppförandet av ett slutförvar. Det är viktigt att möjlighet ges att testa och demonstrera hur förvarets delar kommer att utvecklas under realistiska förhållanden. Ett flertal projekt i full skala, liksom stödjande aktiviteter, pågår vid Äspölaboratoriet. Experimenten fokuserar på olika aspekter av ingenjörsteknik och funktionstester.

I *Prototypförvaret* pågår en demonstration av den integrerade funktionen hos förvarets barriärer. Prototypförvaret utgör dessutom en fullskalig referens för prediktiv modellering av slutförvaret och barriärernas utveckling. Prototypförvaret omfattar totalt sex deponeringshål, fyra i en inre tunnelsektion och två i en yttre. Under 2006 har fortsatta mätningar av relativ fuktighet, totalt tryck och temperatur i olika delar av testområdet genomförts.

I *Lot-försöket* genomförs långtidsförsök på buffertmaterial som syftar till att validera modeller och hypoteser som beskriver buffertens fysikaliska egenskaper och processer relaterade till mikrobiologi, radionuklidtransport, kopparkorrosion och gastransport under förhållanden som liknar dem i ett KBS-3-förvar. I början av 2006 togs ett av långtidsförsökets testpaket (> fem år) upp med hjälp av överborrningsteknik. Resultaten från de pågående analyserna av testpaketet kommer att avgöra när nästa av de tre återstående paketen från långtidsförsöket ska återtas.

I *Återfyllningsförsöket* undersöker man den hydrauliska och mekaniska funktionen hos olika återfyllningsmaterial. Försöket är också en demonstration av olika metoder för inplacering av återfyllning och installation av tunnelförslutning. Sektionens innersta del är återfylld med en blandning av krossat berg och bentonit medan den yttre delen är återfylld med krossat berg. I slutet av 1999 påbörjades bevätningen av återfyllningen och den pågick fram till och med hösten 2003 då flödestester startades. Flödestester har genomförts mellan filtermattor i två riktningar och dessa avslutades under 2005. Utvärderingen av den hydrauliska konduktiviteten från dessa mätningar gav något högre värden än de som utvärderats från laboratorieförsök. Mätningar av den hydrauliska konduktiviteten i enskilda punkter med trycksatta filterrör gjordes under 2006 och resultaten visade på en hydraulisk konduktivitet som är ungefär en tiondel av den som erhölls i flödestesterna.

Återtagsförsöket, ligger i försöksområdet på 420 meters djup och syftar till att prova teknik för att återta kapslar efter det att den omgivande bentonitbufferten har vattenmättats. Återtagsfasen påbörjades i januari 2006 och under andra kvartalet genomfördes ett lyckat återtag av kapseln. Vattenmättnadsfasen hade då pågått i mer än fem år med kontinuerliga mätningar av fukthalten, temperaturen och påfrestningar. Analyser av kapseln pågår.

Syftet med *TBT-försöket* är att förbättra förståelsen av buffertens termiska, hydrologiska och mekaniska utveckling under vattenuppmättnadsfasen vid temperaturer runt eller högre än 100°C, vilket behövs för att kunna modellera beteendet hos bufferten. Experimentet har genererat data sedan starten 2003. Den nuvarande förståelsen är att endast bentonitbufferten vid den övre värmaren, som har sand närmast värmaren, har uppnått full vattenmättnad. För att stödja fältförsöket görs ett ”mock-up” försök av CEA i Frankrike.

Ett forskningsprogram för ett *KBS-3-förvar med horisontell deponering* (KBS-3H) genomförs som ett samarbetsprojekt mellan SKB och Posiva. Förberedelser för en fullskaledemonstration av KBS-3H pågår nu i Äspölaboratoriet. Demonstrationen omfattar två deponeringshål: (1) ett kort hål (15 m) som ska användas för att installera och testa en betongplugg av låg-alkalisk cement och (2) ett långt hål (95 m) som huvudsakligen ska användas för demonstration av deponeringsutrustning men även för utvärdering av berguttagsmetod. Testerna av pluggen i mars 2006 visade på en förskjutning av pluggen när den utsattes för tryck på ungefär tre MPa. Förberedelserna av nischen avslutades i början av året och deponeringsutrustningen för placeringen av Superkontainern levererades. Problem med balanseringssystemet har gjort att det officiella platsgodkännandet har skjutits upp till 2007.

Syftet med ett *Gasinjekteringsförsök i stor skala* är att studera gastransport i ett fullstort deponeringshål (KBS-3). Installationsfasen med deponering av kapsel och buffert avslutades under 2005. Bufferten beväts på konstgjord väg och utvecklingen av vattenmättnadsgraden i bufferten mäts kontinuerligt. Försöket har drivits under 2006 och mättnaden både i berg/buffertgränssnittet och i individuella lerblock har mätts. Mätningarna visar att bufferten ovanför och under kapseln inte är helt mättad. Gasinjekteringsförsöken kommer att påbörjas när bentonitbufferten är helt vattenmättad.

Målet med projektet *In situ testning av korrosion av miniatyrkapslar* är att få en bättre förståelse av korrosionsprocesserna inuti en trasig kapsel. Vid Äspölaboratoriet kommer in situ experiment med miniatyrkopparkapslar med gjutjärnsinsats att genomföras där kopparkapslarna kommer att utsättas för både naturligt reducerat grundvatten och grundvatten som har jämviktats med bentonit under flera år. Vid slutet av 2006 installerades tre kapslar och ytterligare två kapslar ska installeras i början av 2007.

Ett projekt för att identifiera och demonstrera bästa möjliga tillgängliga teknik för *Rensning och förslutning av undersökningsborrhål* genomförs vid Äspölaboratoriet. I platsundersökningarna borras undersökningsborrhål och en noggrann karakterisering genomförs för att erhålla data på bergets egenskaper. Dessa borrhål måste rensas och pluggas senast när driften av slutförvaret avslutats. Ett fullständigt referenskoncept för förslutning av borrhål har utvecklats och ett storskaligt test i borrhål utfördes i Olkiluoto, Finland, under 2005. För att simulera förslutningen av de övre, vidare delarna av borrhål har koppar och kvartscementpluggar installerats vid ytan i två borrhål och förberedelser pågår för tester på 450 meters djup i Äspölaboratoriet.

Målet med projektet *Alternativa buffertmaterial* är att studera olika lermaterial som i laboratorietester har visat sig vara tänkbara buffertmaterial. Ett antal lerblock har framställts och tre paket med olika kombinationer av lermaterial har installerats i borrhål i Äspölaboratoriet under 2006. Paketen och experimentuppställningen liknar de som används vid Lot-försöket. Försöket kommer att pågå under cirka ett år innan det första paketet återtas och de återstående två paketen kommer att vara i drift i ytterligare 2–5 år innan de återtas.

I *Rose*-försöket är målsättningen att undersöka vilka krafter som påverkar en KBS-3 kapsel vid en jordbävning som resulterar i en förskjutning på 100 mm i en horisontell spricka som korsar ett deponeringshål. Den första fasen, en förstudie, har genomförts och rapporterats. Slutsatsen är att försöket är genomförbart.

Målet med projektet *Jordpotentialer* är att identifiera storleken av ändringar i potentialen och jordströmmar av geomagnetiskt inducerad och mänskligt tillverkade jordströmskällor på förvarsdjup, och därigenom uppskatta några eventuella problem. Förändringen i jonbytaregenskaperna för MX-80-bentonit som utsatts för kopparkloridlösningar och de eventuella effekterna av spänningsskillnader i ett förvar för korrosion har studerats. Tilläggsvis visar mätningar av jordpotentialer vid Forsmark att ändringar i högspänningskabeln mellan Sverige och Finland påverkar det vertikala magnetfältet vid Forsmark.

Ett internationellt samarbetsprojekt ”*Task Force on Engineered Barrier Systems”* återupptogs under 2004. Den första fasen av projektet, som beräknas pågå i fyra år, omfattar huvudsakligen två områden: (1) THM-processer och (2) gasmigration i buffertmaterial. Målet är att framställa en ”state-of-the-art” rapport. Projektet fokuserar på användandet av numeriska koder för att förutsäga förhållandena i bufferten under betydelsefulla skeden i förvarets utveckling. Två möten har hållits under 2006. Resultaten från modelleringen av laboratorietesterna för ”Task 1” och ”Task 2” har presenterats och diskuterats. De storskaliga fältförsöken, som ska användas för modelleringen i nästa ”benchmark”, har även definierats.

Äspöanläggningen

En viktig del av verksamheten vid Äspöanläggningen är administration, drift och underhåll av instrument samt utveckling av undersökningsmetoder. Målet med driften av Äspöanläggningen är att garantera säkerheten för alla som arbetar eller besöker anläggningen samt att driva anläggningen på ett miljömässigt korrekt sätt. Under 2006 var tillgängligheten i laboratoriet större än den satta målsättningen om en driftstid på 98 %.

Byggnationen av ett bentonitlaboratorium har pågått under 2006. Laboratoriet uppförs för studier av buffert- och återfyllnadsmaterial. I laboratoriet kan inplacering av buffert i deponeringshål studeras i full skala. Dessutom kan tekniker för återfyllnad av tunnlar utvecklas vidare.

Ansvarig för att presentera information om SKB och dess anläggningar är Information och besöksverksamheten vid Äspölaboratoriet. Under 2006 besöktes Äspölaboratoriet och Äspö-stigen av ungefär 11 000 besökare och de guidade sommarvisningarna ”Urberg 500” satte nytt rekord med mer än 2 800 besökare.

Miljöforskning

Äspö Miljöforskningsstiftelsen grundades 1996 på initiativ av lokala och regionala intressenter, med målsättningen att göra Äspölaboratoriet och dess resurser tillgängliga även för nationell och internationell miljöforskning. Äspö:s forskarskola startade 2002 och har under sina första forskningsår fokuserat på kemiska processer i ytmiljön. De flesta av dessa studier kommer att inkluderas i doktorsavhandlingar och i maj 2006 ägde den andra disputationen rum.

Internationellt samarbete

Förutom SKB har nio organisationer från åtta länder deltagit i det internationella samarbetet vid Äspölaboratoriet. Sex av dem, Andra, BMWi, CRIEPI, JAEA, OPG och Posiva utgör tillsammans med SKB ”Äspö International Joint Committee” vilken ansvarar för att koordinera det experimentella arbetet som uppkommer från det internationella deltagandet. Flertalet av de deltagande organisationerna är intresserade av grundvattenströmning, radionuklid-transport och bergkaraktärisering. Många organisationer deltar både i det experimentella arbetet i Äspölaboratoriet och i modelleringsarbetet inom de två ”Äspö Task Force”grupperna: (1) ”Task Force on Modelling of Groundwater Flow and Transport of Solutes” och (2) ”Task Force on Engineered Barrier Systems”.

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 with design and construction of a deep geological repository for final disposal of spent nuclear fuel. This work includes the development and testing of methods for use in the 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 concerned with processes of importance for the long-term safety of a future final repository and the capability to model the processes taking place. Demonstration addresses the performance of the engineered barriers, and practical means of constructing a repository and emplacing the canisters with spent nuclear fuel.

The underground part of the laboratory consists of a tunnel from the Simpevarp peninsula to the southern part of Äspö where the tunnel continues in a spiral down to a depth of 460 m, see Figure 1-1. The total length of the tunnel is 3,600 m where the main part of the tunnel has been excavated by conventional drill and blast technique and the last 400 m have been excavated by a tunnel boring machine (TBM) with a diameter of 5 m. 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 and rock-mechanical conditions to be observed during excavation of the laboratory. This phase also included planning for the Construction and Operational phases.

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

The *Operational phase* began in 1995. A preliminary outline of the programme for this phase was given in SKB's Research, Development and Demonstration (RD&D) Programme 1992. Since then the programme has been revised every third year and the basis for the current programme is described in SKB's RD&D-Programme 2004 /SKB 2004/.

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 as well as after closure.
4. *Demonstrate technology for and function of important parts of the repository system*. In full scale test, investigate and demonstrate the different components of importance for the long-term safety of a final repository and show that high quality can be achieved in design, construction and operation of repository components.

Stage goals 1 and 2 have been concluded at Äspö HRL and the tasks have been transferred to the Site Investigations Department of SKB which performs site investigations at Simpevarp/Laxemar in the municipality of Oskarshamn and at Forsmark in the municipality of Östhammar.

In order to reach present goals (3 and 4) the following important tasks are today performed at the Äspö HRL:

- Develop, test, evaluate and demonstrate methods for repository design and construction as well as deposition of spent nuclear fuel and other long-lived waste.
- Develop and test alternative technology with the potential to reduce costs and simplify the repository concept without sacrificing quality and safety.
- Increase the scientific understanding of the final 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 repository.
- Provide information to the general public on technology and methods that are being developed for the final repository.
- Participate in international co-operation through the Äspö International Joint Committee (IJC) as well as bi- and multilateral projects.

1.3 Organisation

SKB's work is organised into six departments: Technology, Nuclear Safety, Site Investigations, Operations, Environmental Impact Assessment (EIA) and Public Information and Business Support. The research, technical development and safety assessment work is organised into the Technology department, in order to facilitate co-ordination between the different activities. Within the Technology department a Technical-Scientific Council has been set up in order to prepare technical and scientific issues concerning the research and development of the KBS-3 method. The Council shall in different issues continuously judge the state of development and the need of further work as well as advice on on-going and planned new projects aimed at development and scientific verification of the different parts of the KBS-3 method.

The director of the Technology department is the chair of the Technical-Scientific Council and there is one executive secretary appointed responsible for the preparation of issues and the documentation and follow-up of standpoints taken by the council. Other members of the council are the managers of the units within the Technology department responsible for research and development as well as the director of the Site Investigations department of SKB.

The executive secretary in the Technical-Scientific Council act as a representative between on one hand the clients within the units Repository Technology and Safety and Science and on the other the performing organisation at Äspö HRL. The executive secretary is also responsible for the co-ordination of the research performed in the international co-operation.

The Äspö Hard Rock Laboratory is one of five units organised under the Technology department and is responsible for the operation of the Äspö facility and the co-ordination, experimental service and administrative support of the research performed in the facility. The Äspö HRL unit is organised in four operative groups and a secretariat:

- *Project and Experimental service (TDP)* is responsible for the co-ordination of projects undertaken at the Äspö HRL, for providing services (administration, planning, design, installations, measurements, monitoring systems etc) to the experiments.
- *Repository Technology and Geoscience (TDS)* is responsible for the development and management of the geo-scientific models of the rock at Äspö and the test and development of repository technology at Äspö HRL to be used in the final repository.
- *Facility Operation (TDD)* is responsible for operation and maintenance of the Äspö HRL offices, workshops and underground facilities and for development, operation and maintenance of supervision systems.
- *Public Relations and Visitor Services (TDI)* is responsible for presenting information about SKB and its facilities with main focus on the Äspö HRL. The HRL and SKB's other research facilities are open to visitors throughout the year.

Each major research and development task carried out in Äspö HRL is organised as a project that is led by a Project Manager who reports to the client organisation. Each Project Manager is assisted by an on-site co-ordinator with responsibility for co-ordination and execution of project tasks at the Äspö HRL. The staffs at the site office provide technical and administrative service to the projects and maintain the database and expertise on results obtained at the Äspö HRL.

1.4 International participation in Äspö HRL

The Äspö HRL has so far attracted considerable international interest. During 2006, nine organisations from eight countries in addition to SKB participated in the Äspö HRL or in Äspö HRL-related activities. The participating organisations were:

- 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.

- Japan Atomic Energy Agency (JAEA), Japan.
- Ontario Power Generation Inc. (OPG), Canada.
- Posiva Oy, Finland.
- Empresa Nacional de Residuos Radiactivos (Enresa), Spain.
- Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (Nagra), Switzerland.
- Radioactive Waste Repository Authority (RAWRA), Czech Republic.

For each partner the co-operation is based on a separate agreement between SKB and the organisation in question.

Andra, BMWi, CRIEPI, JAEA, OPG and Posiva together with SKB form the Äspö International Joint Committee (IJC), which is responsible for the co-ordination of the experimental work arising from the international participation.

Task Forces are another form of organising the international work. Several of the international organisations in the Äspö co-operation participate in the two Äspö Task Forces on (a) Modelling of Groundwater Flow and Transport of Solutes and (b) THMC modelling of Engineered Barrier Systems.

SKB also takes part in several international EC-projects and participates in work within the IAEA framework.

1.5 Allocation of experimental sites

The rock volume and the available underground excavations are 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 some of the experimental sites within the Äspö HRL is shown in Figure 1-2.

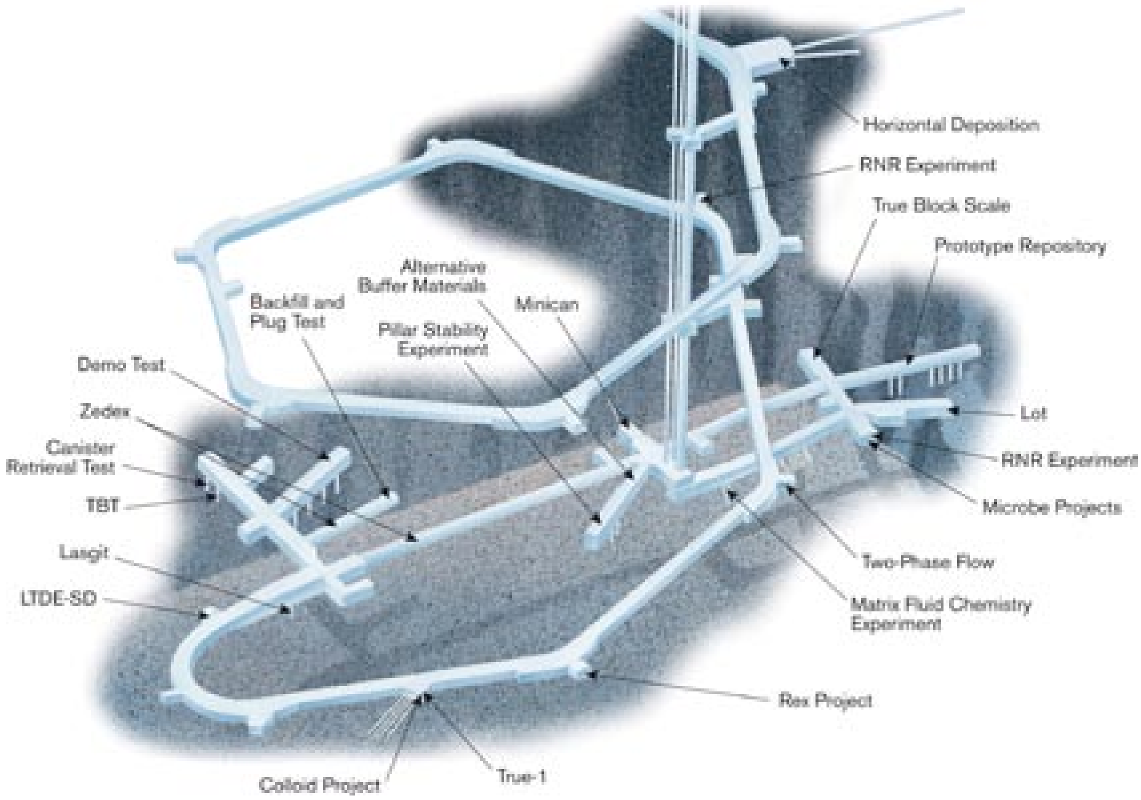


Figure 1-2. Allocation of experimental sites from –220 m to –450 m level.

1.6 Reporting

Äspö HRL is an important part of SKB's RD&D-Programme. The plans for research and development of technique during the period 2005–2010 are presented in SKB's RD&D-Programme 2004 /SKB 2004/. The information given in the RD&D-Programme related to Äspö HRL is detailed in the Äspö HRL Planning Report /SKB 2006/ and this plan 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 quarterly. This report describes the achievements during 2006.

Joint international work at Äspö HRL, as well as data and evaluations for specific experiments and tasks, are reported in Äspö International Progress Report series. 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	Executive secretary, technical-scientific council	SKB
Planning report – Detailed plans covering each calendar year	Contributors	Executive secretary, technical-scientific council
Annual report – Summary of work covering each calendar year	Contributors	Executive secretary, technical-scientific council
Status report – Short summary of work covering each 3 month period	Principal investigators or project managers	Executive secretary, technical-scientific council
Technical report (TR)	Project manager	Executive secretary, technical-scientific council
International progress report (IPR)	Project manager	Executive secretary, technical-scientific council
Internal technical document (ITD)	Case-by-case	Project manager
Technical document (TD)	Case-by-case	Project manager

1.7 Management system

SKB is since 2001 certified according to the Environmental Management System ISO 14001 as well as the Quality Management Standard ISO 9001. Since 2003 SKB is also certified according to the up-graded ISO standard 9001:2000.

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

The documentation can be accessed via SKB's Intranet where policies and quality assurance documents for SKB (SD-documents) as well as specific guidelines for Äspö HRL (SDTD-documents) can be found. Employees and contractors related to the SKB organisation are responsible that work is performed in accordance with SKB's management system.

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

The guiding principles of all SKB's activities and each employer's work are expressed in three key words:

- Safety.
- Efficiency.
- Responsiveness.

Project process

SKB has developed a project process for the implementation of projects. The aim of the process is to create an effective and uniform management of all projects and establishment of the requirements for initiation, implementation and delivery of projects.

According to the project process each project shall have a client within the SKB line organisation. The client initiates a project through the project decision document containing details for the project in terms of specifications, resources, time and budget. A project manager is chosen by the client and is responsible for preparation of the project plan containing details on implementation of the project, a risk analysis and a quality plan. The realisation of the project shall be done according to the project plan. As a delivery of the project the project manager puts together an evaluation report containing the clients' reflections on the project implementation and result, the project organisation experiences, evaluation of risk management and possible improvements for further projects.

Environmental management

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

SKB also makes every effort to minimise the impact of on-going operations and activities on the environment. This environmental work is goal-oriented and the progress versus goals is assessed every three months. Key assessment parameters for the selection of suppliers include security, environmental aspects and quality.

1.8 Structure of this report

The work performed at Äspö HRL during 2006 is in this report described in six chapters:

- Geo-science – experiments, analysis and modelling to increase the knowledge of the surrounding rock.
- Natural barriers – experiments, analysis and modelling to increase the knowledge of the repository barriers under natural conditions.
- Engineered barriers – demonstration of technology for and function of important engineered parts of the repository barrier system.
- Äspö facility – operation, maintenance, data management, monitoring, public relations etc.
- Environmental research.
- International co-operation.

2 Geo-science

2.1 General

During the pre-investigations for the Äspö Hard Rock Laboratory (HRL) in the late 1980's the first geoscientists came to Äspö. Most of them were consultants that mainly worked off-site. A new site organisation was developed when the rock laboratory was taken into operation 1995. Posts as site geologist and site hydrogeologist were then established. These posts have been broadened with time, and today the responsibility of the holder involves maintaining and developing the knowledge and methods of the scientific field, as well as scientific support to various projects conducted at Äspö HRL. Geoscientific research and activities are conducted in the fields of geology, hydrogeology, geochemistry (with emphasis on groundwater chemistry) and rock mechanics.

Geoscientific research is a part of the activities at Äspö HRL as a complement and an extension of the stage goals 3 and 4, see Section 1.2. Studies are performed in both laboratory and field experiments, as well as by modelling work. The overall aims are to:

- Establish and develop geoscientific models of the Äspö HRL rock mass.
- Establish and develop the understanding of the Äspö HRL rock mass material properties as well as the knowledge of applicable measurement methods.
- To provide basic geoscientific data and to ensure high quality of experiments and measurements related to geosciences.

From 2006 the work follows a yearly geoscientific programme. An important part of the programme is the development of the new Äspö site description. The integrated site description is planned to be published 2008 and to be updated every third year. The performed geoscientific work during 2006 is described in Section 2.2 to 2.5.

2.2 Geology

Geological work at Äspö HRL is focused on several main fields. Major responsibilities are mapping of tunnels, deposition holes and drill cores, as well as continuous updating of the geological three-dimensional model of the Äspö rock volume and contribution with knowledge in projects and experiments conducted at Äspö HRL. Also, development of new methods in the field of geology is a major responsibility. As a part of the latter, the Rock Characterisation System (RoCS) feasibility study is being conducted, see Section 2.2.2.

2.2.1 Geological Mapping and Modelling

Background and objectives

All rock surfaces and drill cores are mapped at Äspö HRL. This is done in order to increase the understanding of geometries and properties of rocks and structures, which is subsequently used as input in the 3D modelling, together with other input data.

Results

Geological mapping

A shallow niche (NASQ0036A) in the TASQ-tunnel has been excavated in 2006. The niche has been geologically mapped and partially digitised and the information entered into the rock characterisation system TMS (Tunnel Mapping System). Besides the niche, there are still some old mappings that have not yet been digitised and entered into TMS.

Although not yet put in place, signs have been made to mark out deformation zones in the Äspö tunnels.

The AMS (Anisotropy of Magnetic Susceptibility) test to establish the true width of deformation zones has been completed and the report has been printed /Mattsson 2006/.

Core logging

Some new 3–5 m long core holes have been drilled in the TASQ-tunnel. Three of them had a diameter of 300 mm and were drilled in the new niche NASQ0036A, as a part of the project "Alternative Buffer Material". The three boreholes have been documented by using BIPS (Borehole Image Processing System) and the 300 mm cores have already been logged.

New core loggings and BIPS measurements from Äspö HRL are now available on the SKB computer network (on the G-disk).

Modelling

The modelling work of the –450 m level has proceeded but has not been completed during the year of 2006. The aim of the model is to visualise water bearing structures around the –450 m level. As a result of the modelling work most of the geological mapping of the Äspö tunnels can now be found on 3D drawings (DGN format from MicroStation).

Miscellaneous guidance

The geologist group has participated in a number of projects as advisors on geological matters, e.g. in the projects Alternative Buffer Materials project (see Section 4.11) and KBS-3H Method with Horizontal Emplacement (see Section 4.7).

2.2.2 Rock Characterisation System

Background and objectives

A feasibility study concerning geological mapping techniques is performed beside the regular mapping and modelling tasks. The project Rock Characterisation System (RoCS) is conducted as an SKB-Posiva joint-project. The purpose is to investigate if a new system for rock characterisation has to be adopted when constructing a future final repository. The major reasons for the RoCS project are aspects on objectivity of the data collected, traceability of the mappings performed, saving of time required for mapping and data treatment and precision in mapping. These aspects all represent areas where the present mapping technique may not be adequate. In this initial feasibility study-stage, the major objective is to establish a knowledge base concerning existing and possible future methods and techniques to be used for a mapping system suitable for SKB's, and also Posiva's, requirements.

Results

The work with the feasibility report is almost completed but has required more time than anticipated. During the autumn 2006 adjustments have been made in the report after the first review by BGS (British Geological Survey). Just before Christmas 2006 the report was sent to Posiva for a last review. There has thus been a delay in the project time plan.

In connection with the excavation of the niche NASQ0036A laser scanning was performed in the TASQ-tunnel. The work, that only partly is a concern of RoCS, was executed by the firm Advanced Technical Solutions AB (ATS) in three stages; one before and one after excavation of the niche and one after the reinforcement of the niche. The first two scanning events covered only the niche while the last one covered the whole Q-tunnel. The results have only partly been presented but seem to be promising.

2.3 Hydrogeology

The major aims of the hydrogeological activities are to:

- Establish and develop the understanding of the hydrogeological properties of the Äspö HRL rock mass.
- Maintain and develop the knowledge of applicable measurement methods.
- Ensure that experiments and measurements in the hydrogeological field are performed with high quality.

One of the main tasks is the development of the integrated Äspö site description. The numerical groundwater flow and transport model is an important part of the site description. The groundwater model is to be continuously developed and calibrated. The intention is to develop the model to a tool that can be used for predictions, to support the experiments, and to test hydrogeological hypotheses.

Another task is to develop the more detailed model of hydraulically conductive structures below the –400 m level. The purpose of this model is firstly to grasp the important hydraulic structures in an area with many active experiments and secondly to develop the methodology of detailed hydro-structural modelling. The work during 2006 also comprised activities concerning the Seismic Influence on the Groundwater System (Section 2.3.1), Inflow Predictions (Section 2.3.2) and Hydro Monitoring Programme (Section 2.3.3).

2.3.1 Seismic Influence on the Groundwater System

Background and objectives

The Hydro Monitoring System (HMS) registers at the moment the groundwater pressure in about 275 positions in boreholes underground in the Äspö HRL. An induced change of the head with more than 2 kPa triggers an intensive sampling. All measured data are stored in a database.

The data in the database are assumed to bear witness of different seismic events in Sweden but also abroad, dependent on the magnitude of the event, as well as the position of the epicentre. The seismic events also include blasting activities in and around Äspö HRL. By analysing the data on changes in the groundwater pressure at Äspö, connections to specific seismic events are expected to be established. The work is a reference for the understanding of dynamic influences on the groundwater around a future final repository.

Results

The data registered by the hydro monitoring system during 2006 have been stored in SKB's site characterisation database (Sicada) pending analyses. The data comprise information about blastings in and around the Äspö HRL as well as earthquakes in Sweden and abroad. The registered data will be analysed during 2007.

2.3.2 Inflow Predictions

Background

SKB has conducted a number of large field tests where predictions of inflow into tunnels or depositions holes have been a component: (a) Site characterisation and validation test in Stripa /Olsson 1992/, (b) Prototype Repository /Rhén and Forsmark 2001/ and (c) Groundwater degassing and two-phase flow experiments in Äspö HRL /Jarsjö et al. 2001/. The results from these tests show that when going from a borehole to a larger diameter hole, the inflow into the larger hole is often less than predicted, and the explanation for this is not yet well understood. The ability of predicting inflow is of importance from several aspects:

- Evaluation of experimental results from Äspö HRL. A good understanding of the mechanisms controlling inflow would improve the possibilities for good experimental set-ups and accurate result interpretation.

- Evaluation of potential repository sites. It is desirable to be able to predict the inflow conditions into the excavations, already before the construction work starts, based on hydraulic measurements made in small diameter boreholes.
- Evaluation of the expected bentonite buffer behaviour. The amount of inflow into deposition holes will influence the time needed for saturation and also the expected performance of the buffer.
- Design and optimisation of the repository layout. Poor prediction of inflow could lead to less optimal design alternatives.

Objectives

The main objectives for this project are to:

- Make better predictions of the inflow of groundwater into deposition holes and tunnels.
- Confirm (or refuse) previous observations of reduced inflow into deposition holes and tunnels compared with boreholes.
- Identify the different mechanisms determining the inflow and quantify their importance.

Results

To better understand the data acquired during the hydro-mechanical data acquisition project at the Äspö Pillar Stability site /Mas Ivars 2005/, a three dimensional mechanical modelling study of the de-stressing of the rock pillar in the Äspö Pillar Stability Experiment (Apse) was carried out using the distinct element code 3Dec /Itasca 2003/. The results from this modelling exercise show the stress redistribution in the tunnel during the drilling of the de-stressing slot (Figure 2-1 and Figure 2-2). The report is finalised and is under revision for publishing.

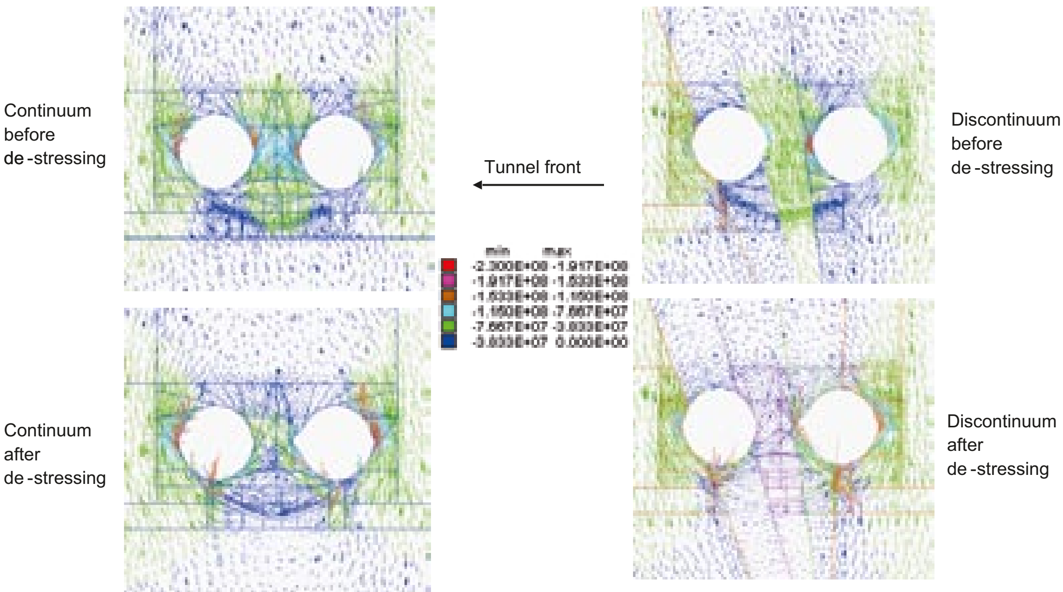


Figure 2-1. *Horizontal cross-section showing the projected principal stress at 1.5 m depth from the floor of the Apse tunnel before and after the de-stressing slot has been excavated (Colours by magnitude of σ_1).*

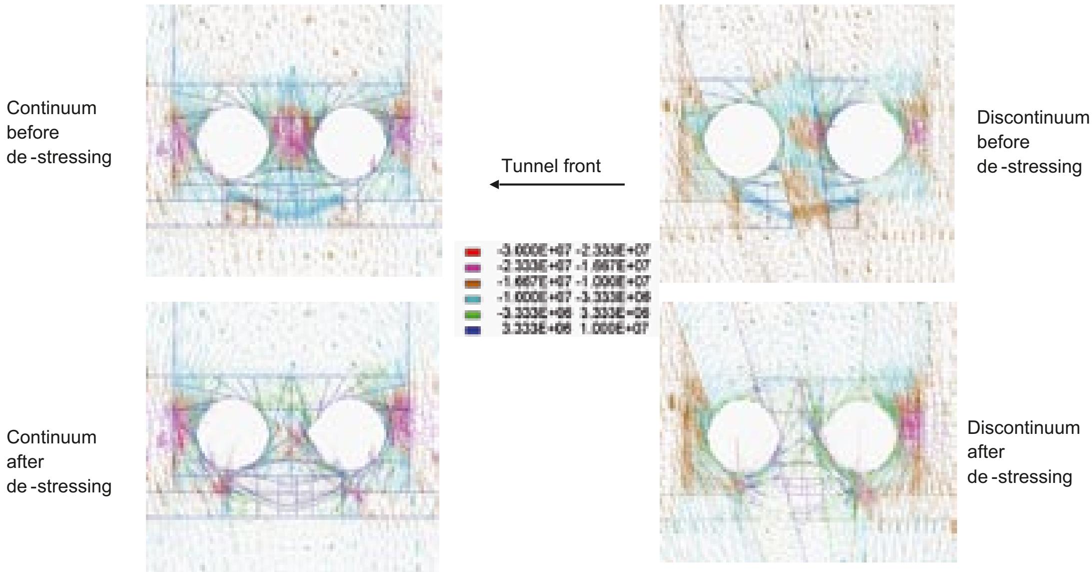


Figure 2-2. *Horizontal cross-section showing the projected principal stress at 1.5 m depth from the floor of the Apse tunnel before and after the de-stressing slot has been excavated (Colours by magnitude of σ_3).*

The next stage of the studies involved the drilling of two 30 mm diameter boreholes. These two boreholes intersected a very conductive fracture where flow and displacements were monitored during the de-stressing of the Apse pillar /Mas Ivars 2005/. Coupled stress-flow laboratory tests were conducted on three large fracture samples cut from the mentioned boreholes (Figure 2-3).

The surfaces of the fracture walls were scanned before and after the tests were conducted using a 3D-laser scanner and the geometrical properties of the fracture plane were characterised. Variograms and contour maps of the aperture were produced for each fracture sample (Figure 2-4). The results of the coupled stress-flow laboratory tests were analysed (Figure 2-5). The report on this project is under revision for publishing.

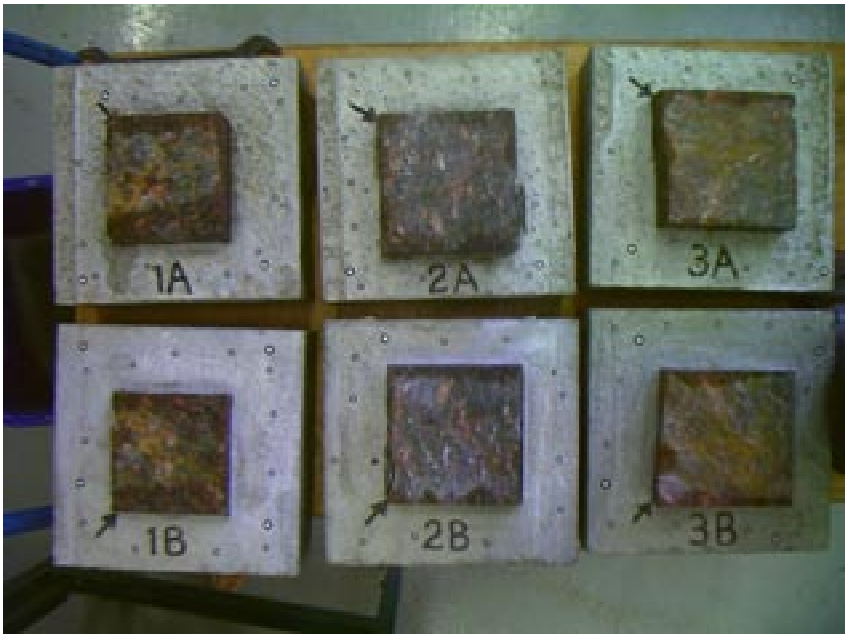


Figure 2-3. *Three fracture samples opened after the tests have been performed.*

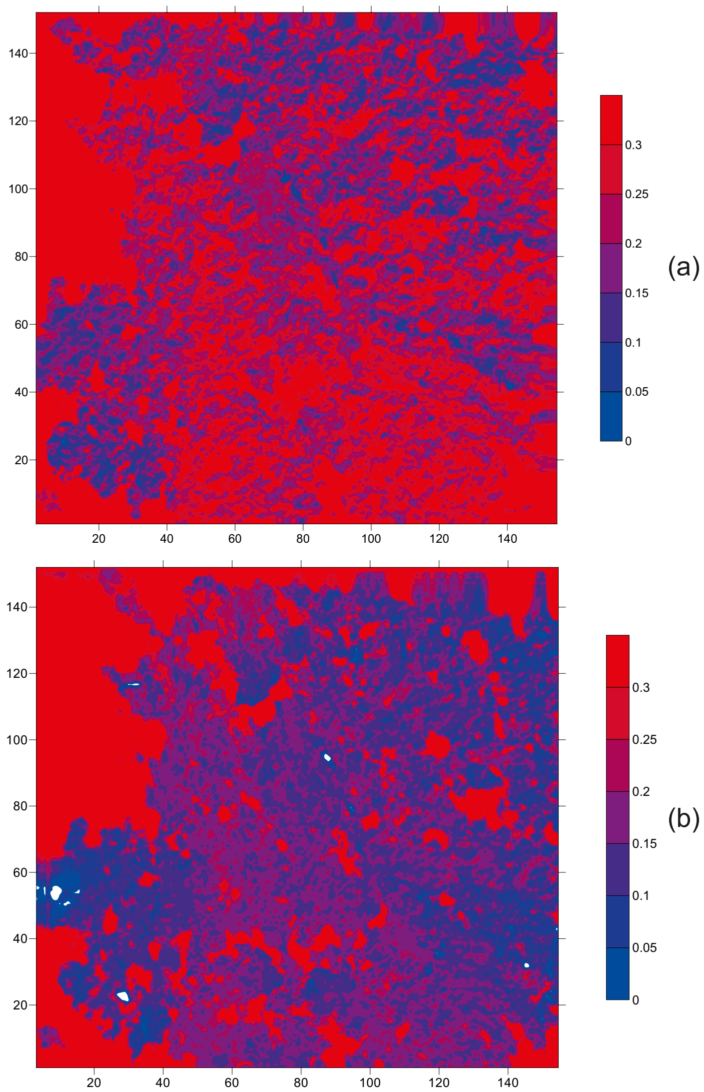


Figure 2-4. *Example of aperture contours in mm (sample 3 – short aperture range), (a) before the test and (b) after the test.*

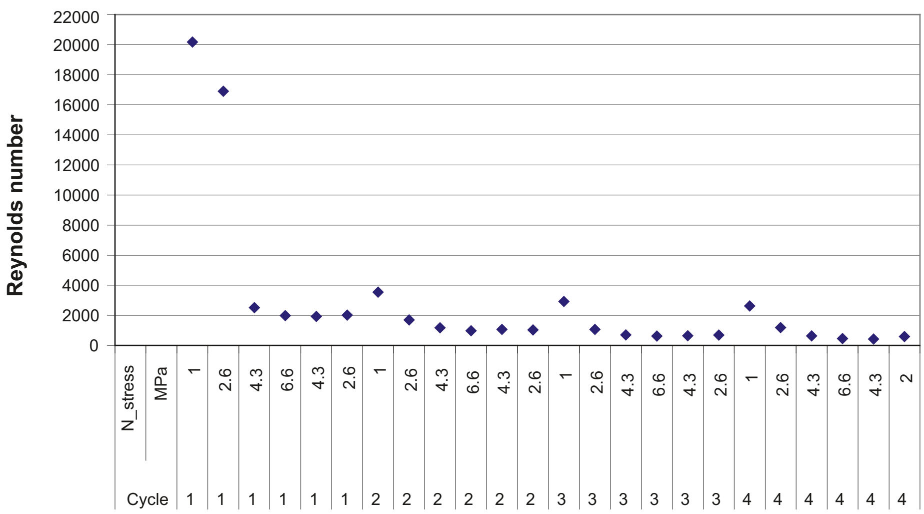


Figure 2-5. *Example of Reynolds number versus normal stress during the four cycles of normal loading/unloading (sample 1).*

2.3.3 Hydro Monitoring Programme

Background

The hydro monitoring programme is an important part of the hydrogeological research and a support to the experiments undertaken in the Äspö HRL. The programme also has had legal grounds. It was conditioned by the water rights court, when granting the permission to execute the construction work for the tunnel, that a monitoring programme should be put in place and that the groundwater head conditions should continue to be monitored until the year 2004.

The monitoring of water level in surface boreholes started in 1987 while the computerised Hydro Monitoring System (HMS) was introduced in 1992. The HMS implemented in the Äspö HRL and on the nearby islands collects data on-line of pressure, levels, flow and electrical conductivity of the groundwater. The data are recorded by numerous transducers installed in boreholes and in the tunnel. The number of boreholes included in the monitoring programme has gradually increased, and comprise boreholes in the tunnel in the Äspö HRL as well as surface boreholes on the islands of Äspö, Ävrö, Mjälen, Bockholmen, and some boreholes on the mainland at Laxemar. The tunnel construction started in October 1990 and the first pressure measurements from tunnel drilled boreholes were included in the HMS in March 1992. The tunnel excavation began to affect the groundwater level in many surface boreholes during the spring 1991.

Objectives

The scientific grounds of maintaining the hydro monitoring programme are:

- To establish a baseline of the groundwater head and groundwater flow situations.
- To provide information about the hydraulic boundary conditions for the experiments in the HRL.
- To provide data to various model validation exercises, including the comparison of predicted head with actual head.

Results

The system has been continuously maintained and calibrated. Transducers for temperature, humidity and pressure of tunnel air have been installed throughout the whole tunnel. This work will continue during 2007. However, automatic monitoring in surface boreholes is successively replaced by monthly manual levelling. A report describing instrumentation, measurement methods and summarising the monitoring during 2005 is available /Nyberg et al. 2006/. Preparations have been done for a semi-automatic transfer of data from the HMS to Sicada (SKB's site characterisation database) three to four times annually. A new management organisation for the HMS will also be established.

2.4 Geochemistry

Geochemistry is one of the fields included in the geoscientific programme for Äspö HRL. The main activities are related to the monitoring of changes in groundwater chemistry.

All active and on-going projects at Äspö HRL have the possibility to request additional sampling of interest for their projects in conjunction to the sampling campaign set to be performed around September–October each year.

2.4.1 Monitoring of Groundwater Chemistry

Background

During the Äspö HRL construction phase, different types of water samples were collected and analysed with the purpose of monitoring the groundwater chemistry and its evolution as the construction proceeded. The samples were obtained from boreholes drilled from the ground surface and from the tunnel. At the beginning of the Äspö HRL operational phase, sampling was replaced by a groundwater chemistry monitoring programme, aiming at a sufficient cover of the hydrochemical conditions with respect to time and space within the Äspö HRL.

Objectives

The monitoring programme is designed to provide information to determine where, within the rock mass, the hydrogeochemical changes are taking place and at what time stationary conditions are established.

Results

During the year, about 220 sampling occasions have been registered of which about 50 are within the monitoring programme and 20 are within the water control programme. The rest of the sampling activities (including microbial parameters and colloids sampled in the water phase) are performed within the active projects at Äspö HRL. The projects that have reported to have sampled groundwater (directly from boreholes) or experimental groundwater (groundwater affected by the actual experiment, tracers added etc) are Colloid Project, Microbe Projects, Long Term Diffusion Experiment, Long Term Test of Buffer Material and Prototype Repository.

Previous years sampling results of biogeochemical parameters (ATP) is being analysed with respect of the sampling preparation methodology and needs to be further analysed for better evaluation and comparison with other reference data. Unfortunately sample preparation gave unstable results using the same analytical measuring protocol (and instrument) performed at laboratory at the central interim storage facility for spent nuclear fuel (Clab) where this analysis is routine. Weather this analysis is interesting for the future is being discussed. The main dataset from last year is still subject for further quality assurance before release and therefore the data presented here is just a part of the sampled quota during 2006.

The yearly monitoring campaign proceeded as planned and with the same sampling programme as previous year, except sampling for ATP. Preliminary results from the sampling campaign 2006 indicate that the chloride and sulphate concentrations seem to be in the same range as 2005. However, the data set is not complete and nor other parameters may be used for comparison at the moment. Any further conclusions are difficult to make due to the lack of quality assured data. In Figure 2-6 the chloride concentrations measured in some sampling points at Äspö HRL at different occasions during 2006 are given.

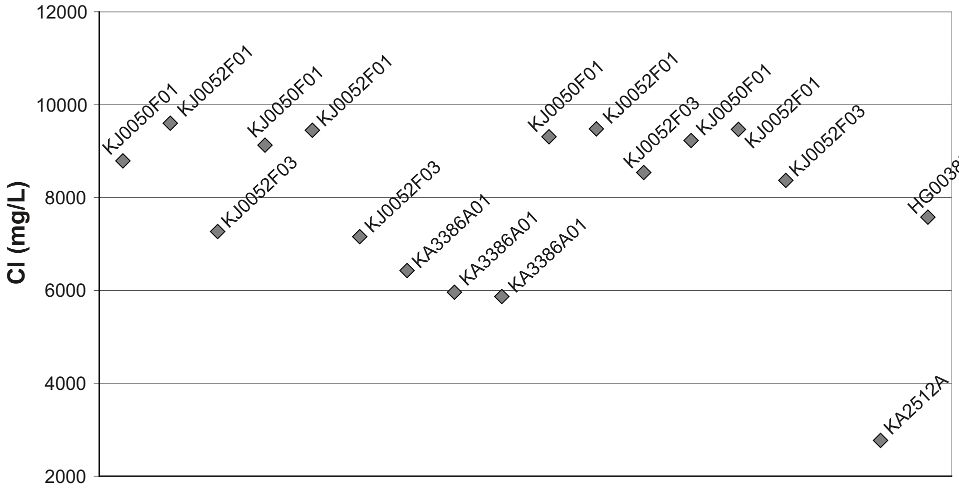


Figure 2-6. The chloride concentration in some sampling points at Äspö HRL during 2006.

2.5 Rock Mechanics

Rock Mechanic studies are performed with the aims to increase the understanding of the mechanical properties of the rock but also to recommend methods for measurements and analyses. This is done by laboratory experiments and modelling at different scales and comprises:

- Natural conditions and dynamic processes in natural rock.
- Influences of mechanical, thermal, and hydraulic processes in the near-field rock including effects of the backfill.

During 2006 work has mainly been focused on the reporting for Äspö Pillar Stability Experiment (Apse), see Section 2.5.2.

2.5.1 Stress Measurements Core Disking

Background and objectives

The purpose of the project is to study the conditions under which core disking occur by drilling in the vicinity of the area for Apse.

Experimental concept

A total of four holes were drilled vertically in the tunnel floor (KQ0062G05, KQ0062G06, KQ0061G10 and KQ0062G04). Core disking in solid and hollow cores was observed in the first three of these. Two successful installations of a Borre probe used for stress measurements were made.

Results

A three-dimensional RVS model of fracturing around the Apse volume has been developed with the purpose to better understand the possible displacements and stress re-distributions that may have occurred during the development of the Äspö Pillar Stability Experiment.

2.5.2 Äspö Pillar Stability Experiment

Background

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

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

Objectives

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

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

Experimental concept

To achieve the objectives a new drift was excavated in Äspö HRL to ensure that the experiment was carried out in a rock mass with a virgin stress field. In the new drift a vertical pillar was constructed in the floor between two large boreholes, each with a diameter of 1.8 m. The pillar was designed in such a way that spalling will occur in the walls of the boreholes when the pillar is heated.

The two large vertical holes were drilled in the floor of the tunnel so that the distance between the holes is one metre. To simulate confining pressure in the backfill (0.7 MPa), one of the holes was subjected to an internal water pressure via a liner. Convergence measurements, linear variable displacement transducers (LVDT), thermistors and an acoustic emission system were used to monitor the experiment. The experiment drift has a rounded floor, se Figure 2-7, to concentrate the stresses in the centre of the drift.

Results

The project was successfully finished during 2006. The results have been published both as a PhD thesis and as an SKB report /Andersson 2007/. Important findings are that the yielding strength of the rock mass has been successfully determined, low confinement pressures significantly affects the onset of yielding, the primary mode of fracture initiation and propagation is extensional, no significant time dependency of the yielding process was observed. The unloading studies also indicate that what appeared to be shear bands likely was a propagating zone of extensile failure that weakened the rock so that displacements in the shear direction could occur.

Figure 2-7. *The Apse experimental drift shortly after the excavation.*

3 Natural barriers

3.1 General

To meet Stage goal 3, experiments are performed to further develop and test methods and models for description of groundwater flow, radionuclide migration, and chemical conditions at repository depth.

The experiments are related to the rock, its properties and in situ environmental conditions. The programme includes projects with the aim to evaluate the usefulness and reliability of different conceptual and numerical models and to develop and test methods for determination of parameters required as input to the models.

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 final 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 final repository.
- Clearly present the role of the geosphere for the barrier functions: isolation, retardation and dilution.

The on-going experiments and projects within the Natural Barriers at Äspö HRL are:

- Tracer Retention Understanding Experiments.
- Long Term Diffusion Experiment.
- Colloid Project.
- Microbe Project.
- Matrix Fluid Chemistry Continuation.
- Radionuclide Retention Experiments.
- Padamot.
- Fe-oxides in Fractures.
- Swiw-test with Synthetic Groundwater.
- Äspö Task Force on Groundwater Flow and Transport of Solutes.

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 objective of the defined experiments is to increase the understanding of the processes which govern retention of radionuclides transported in crystalline rock, and to increase the credibility in models used for radionuclide transport calculations used in licensing of a repository.

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.

During 2001, it was decided to collect all future True work in two separate projects: True Block Scale Continuation and True-1 Continuation. Although the experimental focus is placed on the respective True experimental sites developed at the Äspö HRL, integration and co-ordination of experimental activities at and between the sites is emphasised.

Experimental concept

The basic idea 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. An option is to characterise the tested pore space and analyse tracer fixation using epoxy resin injection. Subsequently, the tested rock volume will be excavated and analysed with regards to flow-path geometry and tracer concentration.

Together with supporting laboratory studies of diffusion and sorption characteristics made on core samples, the results of the in situ tests will provide a basis for integrating data on different scales, and testing of modelling capabilities for radionuclide transport up to a 100 m scale, see Figure 3-1. A test of the integration and modelling of data from different length scales and assessment of effects of longer time perspectives, partly based on True experimental results, is made as part of Task 6 in the Task Force on Modelling of Groundwater Flow and Transport of Solutes, see Section 3.11.

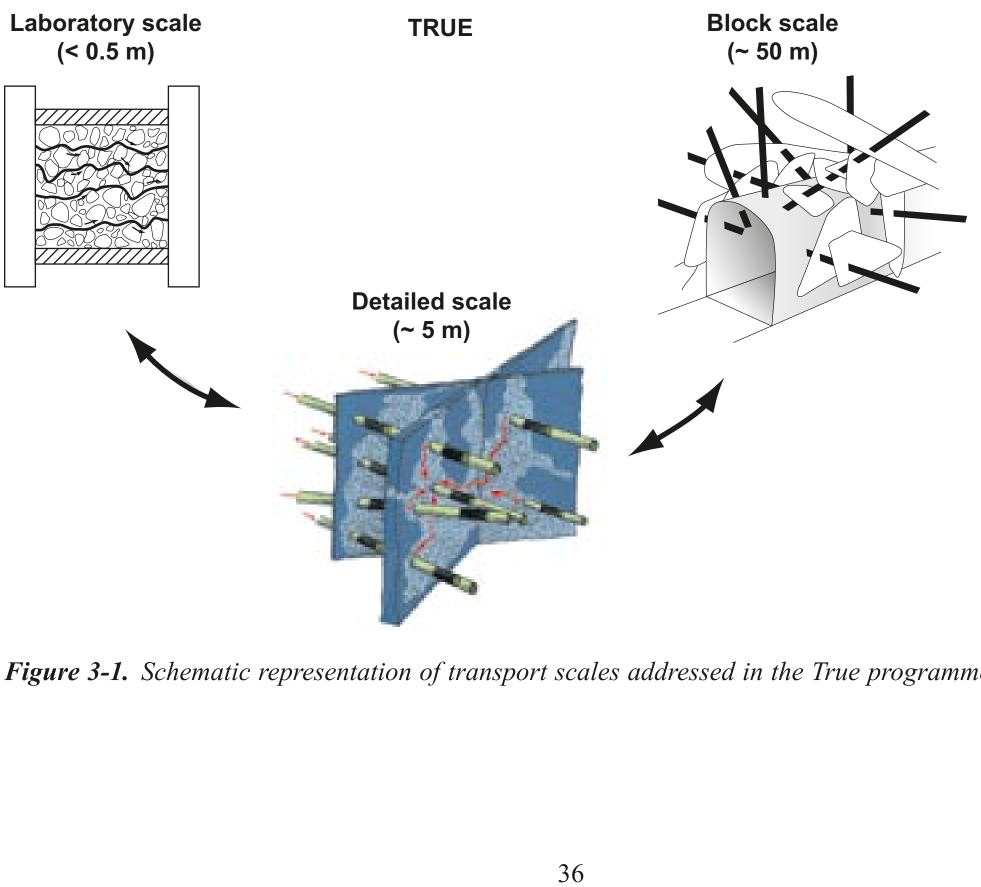


Figure 3-1. *Schematic representation of transport scales addressed in the True programme.*

3.2.1 True Block Scale Continuation (BS2)

The True Block Scale Continuation (BS2) project has its main focus on the existing True Block Scale site. The True Block Scale Continuation is divided into two separate phases:

BS2a Complementary modelling work in support of BS2 in situ tests. Continuation of the True Block Scale (phase C) pumping and sampling including employment of developed enrichment techniques to lower detection limits.

BS2b Additional in situ tracer tests based on the outcome of the BS2a analysis. In situ tests are preceded by reassessment of the need to optimise/remediate the piezometer array. The specific objectives of BS2b are to be formulated on the basis of the outcome of BS2a.

Objectives

The overall objective of BS2 can be summarised as: Improve understanding of transport pathways at the block scale, including assessment of effects of geometry, macro-structure and micro-structure. Special consideration is in this context put on the possibility to explore the role of more low-permeable parts of the studied fracture network, including background fractures, the latter without developed wall rock alteration and fault gouge signatures.

Results

The Block Scale Continuation deliverables accounted for below are about a year delayed and the results therein have already been accounted for in previous annual reports.

During the past year the four individual evaluation reports accounting for the predictive and evaluation modelling associated with the BS2b sorbing tracer tests have been completed and printed according to plan. These include results of the two discrete fracture network (DFN) and channel network based models /Billaux 2005/ and /Fox et al. 2005/ complemented by analysis using the Posiva streamtube approach /Poteri 2005/ and the Lasar concept /Cheng and Cvetkovic 2005/.

A complete draft of the final report of the Block Scale Continuation was completed late November and was distributed to the technical and steering committees. Minor revisions to the text are expected and the report will be finalised and printed during the second quarter of 2007 /Andersson et al. 2006/.

3.2.2 True Block Scale Continuation (BS3)

In the aftermath to the BS2 project a discussion has been in process to set up a second step of continuation of the True Block Scale (BS3). This step in the True Block Scale process aims at consolidation and integrated evaluation of all relevant True data to date, although with a particular focus on the True Block Scale and True Block Scale Continuation experimental results. This step does not include any experimental component.

Results

During the year plans have been drawn up resulting in a proposed sequence of scientific papers (5 papers altogether) directed at different audiences and spanning over a couple of years. The plans and their intent have been tentatively sanctioned by SKB.

A first two-part series of journal papers is intended to summarise the True Block Scale and True Block Scale Continuation results. Tentative titles of the two papers are; Sorptive tracer tests from single to multiple fractures in crystalline rock at Äspö Predictive modelling (Part 1) and Experimental results and effective retention properties (Part 2).

In these papers the results and interpretation are presented of the C1, C2 and C4 tests from True Block Scale and tests in flow paths I and II from True Block Scale Continuation. These tests cover the transport scale 10–20 m, they provide additional evidence for retention and most importantly provide (indirect) information about retention properties of background (non-fault, type 2,) versus (fault, type 1) fractures.

The first paper deals with predictive capability of current modelling tools with emphasis on retention properties of the rock and the possibility to arrive at reasonable estimates of the retention material property group (κ), including the effects of fractures and minor deformation zones.

In Part 2, experimental results are summarised and effective retention properties are estimated. A supporting collective model comparison paper focused on the True Block Scale Continuation modelling provide an account of the groundwater flow aspects and assessments of the flow dependent retention parameter β (corresponding to the F-factor).

3.2.3 True-1 Continuation

The True-1 Continuation project is a continuation of the True-1 experiments, and the experimental focus is primarily on the True-1 site. The continuation includes performance of the planned injection of epoxy resin in Feature A at the True-1 site and subsequent overcoring and analysis (True-1 Completion, see Section 3.2.4). Additional activities include: (a) test of the developed epoxy resin technology to fault rock zones distributed in the access tunnel of the Äspö HRL (Fault Rock Zones Characterisation Project), (b) laboratory sorption experiments for the purpose of verifying K_d values calculated for altered wall rock and fault gouge, (c) writing of scientific papers relating to the True-1 project. A previously included component with the purpose of assessing fracture aperture from radon data has been omitted due to changed priority of resources.

Objectives

The objectives of True-1 Continuation are:

- To obtain insight into the internal structure of the investigated Feature A, in order to allow evaluation of the pore space providing the observed retention in the experiments performed.
- To provide an improved understanding of the constitution, characteristics and properties of fault rock zones (including fault breccia and fault gouge).
- To provide quantitative estimates of the sorption characteristics of the altered rim zone and fault rock materials of fault rock zones.

The scope of work for the field and laboratory activities includes:

- Characterisation of a number of typical fault rock zones of variable thickness. Injection of epoxy resin and subsequent sampling. Assessment of pore space and quantification of in situ porosity of fault gouge material.
- Writing of three scientific papers accounting for the SKB True project team analysis of the True-1 experiments.
- Batch sorption experiments on rim zone and fault gouge materials from the True Block Scale site and from other locations along the access tunnel.
- Injection of epoxy resin into the previously investigated Feature A, with subsequent excavation and analyses.

Results

During the year progress has been made in the subproject True-1 Completion (see Section 3.2.4) and in the production of scientific papers accounting for the achievements of the True-1 project and associated modelling by the project team.

No or limited progress has however been made in conjunction with the reporting of the Fault Rock Zones Characterisation Project and the reporting of the complementary sorption experiments on fault gouge and rim zone materials. This is due to heavy engagements of the project participants in the Oskarshamn and Forsmark site modelling projects.

The first two in a series of three papers accounting for the results, modelling and synthesis of the True-1 experiments were submitted late June 2006. The papers account for the laboratory/experimental work and the associated modelling, respectively. Review comments received have resulted in a revised order of the papers and some strategic revisions of the structure of the papers. The draft of the third concluding paper dealing with effects of micro-scale heterogeneity will be submitted upon acceptance of the two first papers in the series.

3.2.4 True-1 Completion

The True-1 Completion project is a sub-project of the True-1 Continuation project with the experimental focus placed on the True-1 site. True-1 Completion is a complement to already performed and on-going projects. The main activity within True-1 Completion is the injection of epoxy with subsequent over-coring of the fracture and following analyses of pore structure and, if possible, identification of sorption sites. Furthermore, several complementary in situ experiments will be performed prior to the epoxy injection. These tests are aimed at securing important information from Feature A and the True-1 site before the destruction of the site, the latter which is the utter consequence of True-1 Completion.

Objectives

The general objectives of True-1 Completion are:

- To perform epoxy injection and through the succeeding analyses improve the knowledge of the inner structure of Feature A and to improve the description and identification of the immobile zones that are involved in the noted retention.
- To perform complementary tracer tests with relevance to the on-going SKB site investigation programme, for instance in situ K_d and Swiw-test (single well injection withdrawal).
- To improve the knowledge of the immobile zones where the main part of the noted retention occurs. This is performed by mapping and by mineralogical-chemical characterisation of the sorption sites for Cs.
- To update the conceptual micro structural and retention models of Feature A.

The scope of work for identified field and laboratory activities related to the True-1 site includes:

- Re-instrumentation of boreholes KXTT3 and KXTT4 in order to; (a) ensure that the planned activities at the True-1 site do not in anyway interfere with the other projects at Äspö HRL in general and LTDE in particular and (b) successfully perform the complementary tracer tests, the epoxy injection and the subsequent over coring of KXTT3 and KXTT4.
- Complementary tracer tests; Swiw-, CEC- and Reciprocal Cross flow tests.
- Epoxy injection, over coring of KXTT3 and KXTT4 and dismantling of infrastructure at the True-1 site.
- Analysis of core material using picture analysis, microscopy and chemical mineralogy aiming to improve the description of the inner structure of Feature A and possible identification of the immobile zones involved in the noted retention.

Results

The past year has been an eventful year from a True-1 Completion perspective. The project year was initiated with the performance of a second non-radioactive Swiw-test. The aim of this pre-test was to verify if Swiw-tests with radioactive tracers could be performed at the True-1 site without the risk of loosing tracer in the rock. The pre-test was also intended to provide vital information on the tracer distribution around the Swiw borehole. The Swiw-tests indicates a radial distribution of tracer solution from the injection borehole. Passive sampling in the surrounding multi-borehole array intersecting Feature A shows tracer breakthrough in the four sampled boreholes. It has, until now, not been possible to monitor and verify the spreading of tracer solution in the rock mass surrounding the injection borehole. The results of the test form counter evidence that tracer transport during Swiw-tests only takes place in channels with high conductivity. The Swiw-tests resulted in a very low tracer recovery, about 3% and 11%. This recovery stands in sharp contrast to the expected recovery of more than 80%. The low recovery may be the effect of a larger gradient than expected. The immediate consequence of the low recovery being that Swiw-tests with radioactive tracers cannot be performed at the True-1 site.

The site was then used by the Colloid Project (see Section 3.4) to perform a series of dipole tracer tests using fluorescent dye tracers and latex colloids. The colloid tests were followed by a set of multi-hole reciprocal cross flow tests aimed at evaluating the effect of channelling in a single fracture, Feature A. The tests were initiated at the Task Force meeting in Paris in March 2006. The multi-hole reciprocal cross flow tests were performed in KXTT1-5 and KA3005A under ambient (natural) and pumped conditions using a non-sorbing dye-tracer. The field tests included eight hydraulic interference tests with measurements of both flow and pressure responses. The tests also include injection of sorbing, inactive, metal complexes. The injections of metal complexes were made once or twice in each section with the purpose of possible mapping of flow paths to be traced in future excavations of Feature A. Furthermore, the preliminary results from the multi hole reciprocal cross flow tests implicate that the flow in Feature A differ from the homogeneous case, that channelling may be identified in some parts of Feature A and is more developed with higher pumping flows.

The multi-hole reciprocal cross flow tests were followed by a cation exchange capacity (CEC) pre-test which was planned to be followed by the performance of the main CEC-test with radionuclides. However, the planned start of the CEC-test was postponed due to observed changes in Feature A and malfunctioning equipment. During the first CEC pre-test, the recovery was surprisingly low of injected tracer. This may be explained by observed physical changes at the site. The changes gave rise to a thorough investigation of what has happened at the site. The first step was to investigate the groundwater flow under ambient as well as pumped conditions by a series of dilution tests in KXTT4. The dilution tests showed that the observed changes are real and affect the flow to the extent that the prerequisites for the CEC-test have been changed. Hence, an additional pre-test was required before the main CEC-test. This pre-test was successfully performed using the set up, flows and concentrations planned in the upcoming main CEC-test. The equipment and test set up at the True-1 site was also refined and fine-tuned during these tests.

In November and December the main CEC-test with Cs was finally performed. The preliminary results displayed an almost complete recovery of the injected uranine and significant retardation of Cs, see Figure 3-2. The final evaluation of the test will be done during 2007.

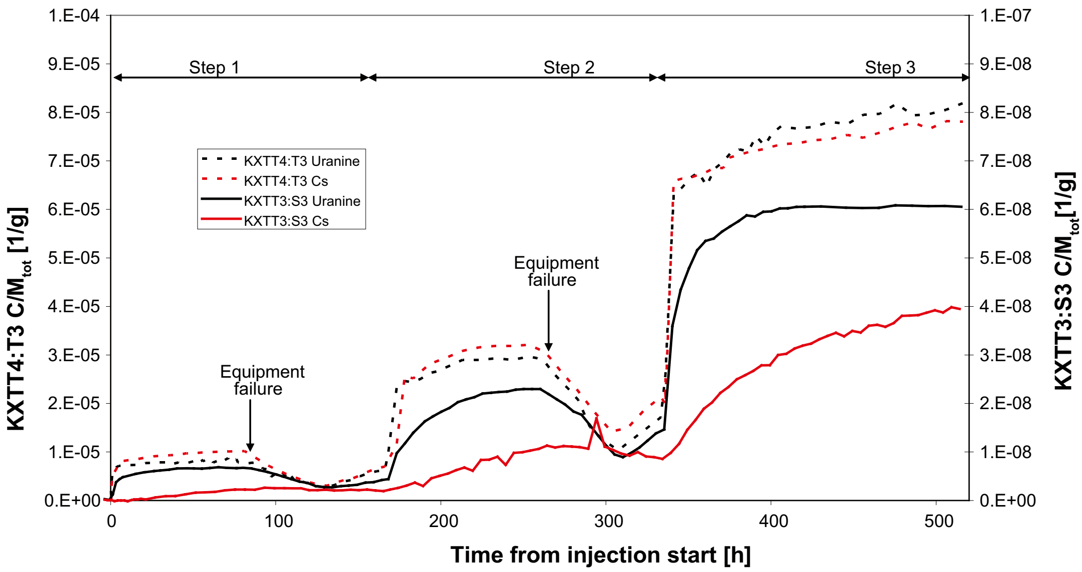


Figure 3-2. *Tracer injection (KXTT4:T3) and breakthrough (KXTT3:S3) curves from the CEC-test.*

3.3 Long Term Sorption Diffusion Experiment

3.3.1 Background

Transport of radionuclides in rock fractures is presently studied within the True experimental programme. To be able to study diffusion and sorption processes over longer time-scales a Long Term Diffusion Experiment (LTDE) has been set up at Äspö HRL. The original experimental plan was laid out by /Byegård et al. 1999/. Since then the experimental concept has been modified to some extent, with complementary addition of a small diameter borehole, enabling study of sorption and diffusion both at a natural fracture surface and onto matrix rock. The priority for the on-going experiments is currently to concentrate the efforts on those experiments which results are needed for safety assessments at SKB. Given the today's priority a decision was taken in late 2005 to emphasise in situ sorption measurements in the LTDE project with shorter time frames than the original project plan. The present project plan considers both the addition of the small diameter borehole to the experimental set-up and the present focus on sorption processes. The changed focus is pointed out by renaming the project LTDE-SD, adding acronyms for Sorption and Diffusion.

3.3.2 Objectives

The LTDE Sorption Diffusion experiment (LTDE-SD) aims at increasing the scientific knowledge of sorption and diffusion under in situ conditions and to provide data for performance and safety assessment calculations. Specific objectives of LTDE-SD are:

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

A core stub with a natural fracture surface is isolated in the bottom of a large diameter telescoped borehole, see Figure 3-3. In addition, a small diameter borehole is drilled through the core stub into the intact undisturbed rock beyond the end of the large diameter borehole, see Figure 3-4 and Figure 3-5. A cocktail of non-sorbing and sorbing tracers are circulated in the test section for a period of 5–7 months after which the core stub and the small diameter extension borehole will be over-cored, and analysed for tracer content and tracer fixation.

The LTDE-SD site is located in a niche at 3,065 m tunnel length at the –410 m level. The experiment is focussed on a typical conductive fracture and intact rock matrix beyond that fracture. The target fracture was identified in pilot borehole KA3065A02 and the experiment is carried out in borehole KA3065A03, a telescoped large diameter borehole (300/197/36 mm) drilled sub-parallel to the pilot borehole in such a way that it intercepts the identified fracture some 10 m from the tunnel wall and with an approximate separation of 0.3 m between the envelope surfaces of the two boreholes.

Figure 3-3. Illustration of the core stub exposing a natural fracture surface in borehole KA3065A03. The fracture surface is covered by diorite, calcite (white) and chlorite (green). Illustration from /Winberg et al. 2003/.

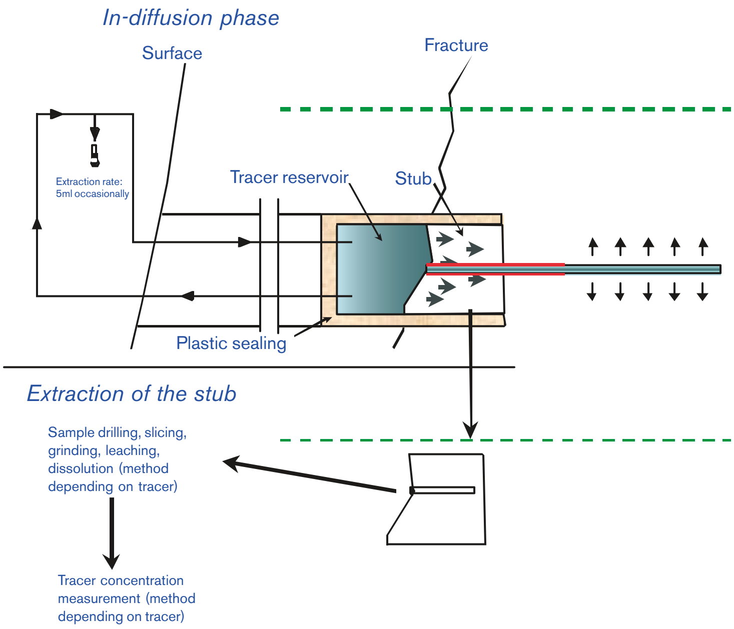


Figure 3-4. *LTDE experimental concept including injection borehole in contact with a fracture surface and matrix rock.*

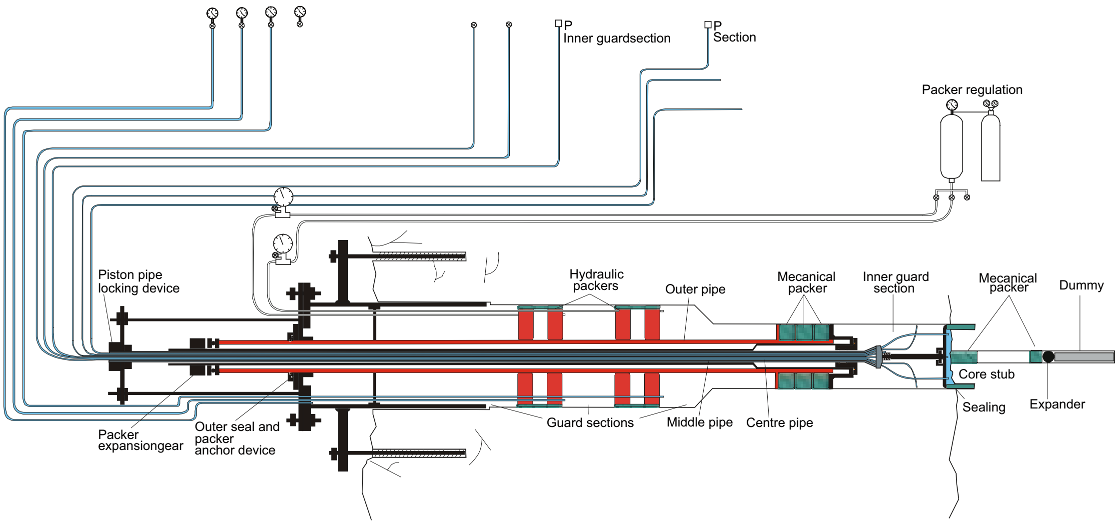


Figure 3-5. *Schematic diagram of the packer system used in the LTDE test hole.*

The small diameter (36 mm) borehole, approximately one metre long, was drilled in the centre of the stub as an extension of KA3065A03 into the intact matrix rock. The small diameter (36 mm) extension is packed off using a double packer system leaving a 300 mm long section that will be exposed for the radionuclides. The natural fracture, as seen on the surface of the stub, is sealed off with a polyurethane cylinder and a PEEK plastic lid, which constitutes a "cup-like" packer. Further, the borehole outside the stub is packed off with a system of one mechanical and two inflatable packers. The system of packers and an advanced pressure regulating system is used to eliminate the hydraulic gradient along the borehole, see Figure 3-5.

During the circulation of tracer, samples of water are collected at various times over the duration of the experiment. Tracer concentration is also being measured using an on-line HPGe (high purity germanium) detector. The red-ox situation in the circulation loop is monitored continuously with a flow through electrochemical cell, which will measure pH, Eh and temperature. A schematic diagram of the experimental system for monitoring and sampling solutions from the test section and the inner guard section is given in Figure 3-6.

After completion of tracer circulation, i.e. 5–7 months of experimental time, the core stub and the rock surrounding the small diameter extension borehole will be extracted by over-core. The sorption on the fracture surface on the core stub (including different fracture minerals) and axial diffusion-sorption through the fracture rim into the intact matrix rock will be studied by performing analyses of the penetration profile of the different tracers used. Sorption on matrix rock surface and radial diffusion-sorption directly into unaltered matrix rock will also be studied by performing analyses of the penetration profile of the different tracers used. This should be done by extracting small diameter cores parallel to the diffusion direction which will be cut in to small slices and analysed for their content of tracers.

The project also involves a variety of mineralogical, geochemical and petrophysical analyses. Laboratory experiments with the core material from KA3065A03 (Ø 270, 177 and 22 mm) and the fracture "replica" material will be performed. Both "batch" sorption and through diffusion experiments are planned with the same radionuclides as used in the in situ experiment. In addition supporting laboratory experiments on core samples from the LTDE borehole KA3065A03 has already been carried out at AECL's Whiteshell Research Laboratories. The experimental programme consisted of porosity measurements, diffusion cell experiments, permeability measurements and radial diffusion experiments. A final report was compiled in December /Vilks et al. 2005/.

The results of the laboratory experiments will be used 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.

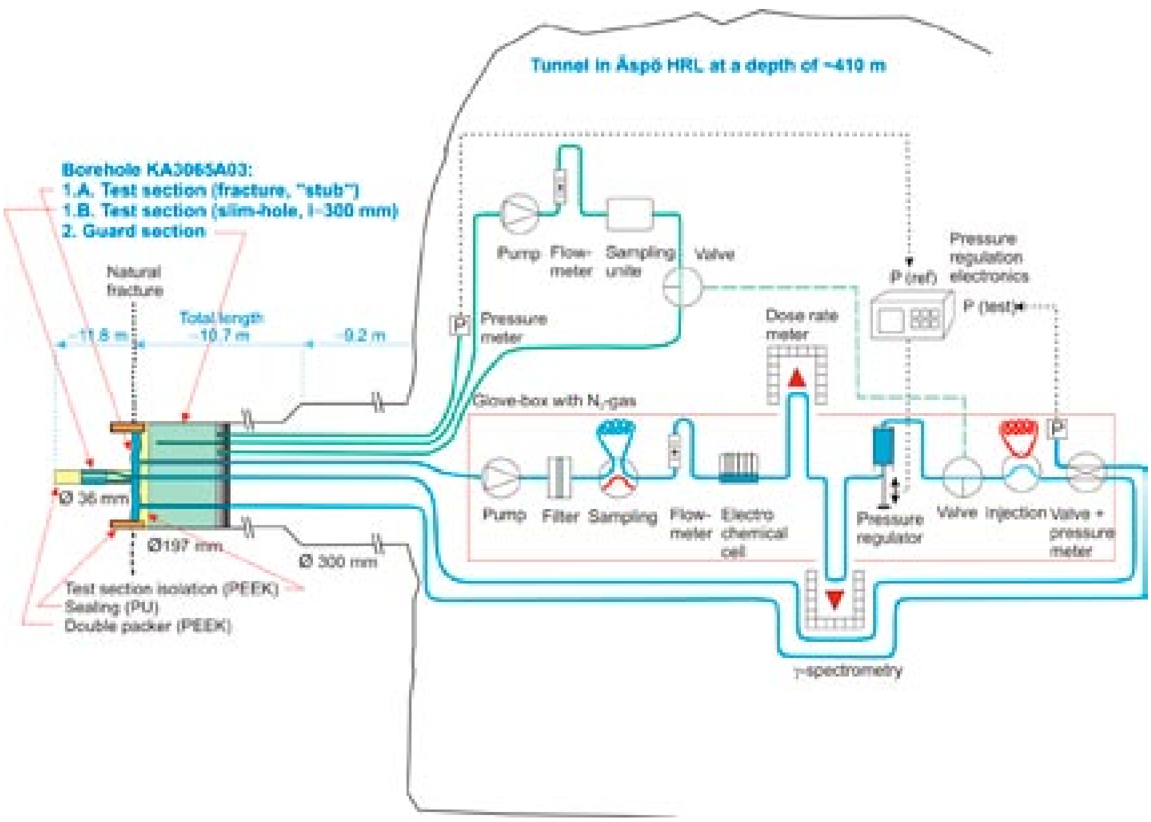


Figure 3-6. *LTDE experimental set-up in the experimental borehole including the water circulation system to the test-section and the hydraulic pressure control system.*

3.3.4 Results

Adjustments and modifications of the test equipment were carried out during the first six months 2006, according to recommendations emanating from the preceding functionality test / Widestrand et al. 2006/ in order to improve the experimental set-up prior to start of the in situ diffusion and sorption test. A new cooling device was installed in the experimental container making it possible to reduce the temperature from 30°C down to 16–20°C. The small leakage in the circulation and pressure regulating equipment in the experimental container was identified and stopped. The automatic alarm functions in the system were updated. The electrochemical flow cell (pH, Eh and temperature measurements) in the glove box was equipped with extra shield and ground connections to reduce disturbances in the data signals. The location in the glove box was also changed in order to facilitate practical work with injection and water sampling.

The in situ sorption diffusion experiment was started on September 27th. A tracer cocktail with 22 radionuclides, which included a range from non-sorbing (^{36}Cl, ^{35}S) to strongly sorbing tracers (^{175}Hf, ^{236}U) according to Table 3-1, was injected. The results from the test running of the experiment, before injection of radionuclides, showed that it is not possible to keep redox potential at negative values in the groundwater in the test section. However, the three redox sensitive radionuclides ^{99}Tc, ^{236}U and ^{237}Np was included in the tracer cocktail since ^{236}U and ^{237}Np are relatively strong sorbing also under oxidising conditions (K_d = 0.01). A redox front is also expected a few centimetres into the rock, making ^{236}U and ^{237}Np to sorb stronger and also ^{99}Tc to sorb at short distance from fracture surface.

On-line measurements of the concentrations of the gamma emitting tracers in the groundwater in the test section have continued since the start of experiment. The test section has also been sampled on a regular basis by extracting small volumes of water to be analysed for the non-gamma emitting tracers by means of scintillation or mass spectrometry, depending on the tracer.

Table 3-1. Tracers injected in main sorption diffusion experiment.

Tracer	Group	Tracer	Group	Tracer	Group
^{22}Na	B1	^{95}Nb	B2	^{137}Cs	B1
^{35}S	A	^{99}Tc	B3	^{153}Gd	B2
^{36}Cl	A	^{102}Pd	B2	^{175}Hf	B2
^{57}Co	B2	^{109}Cd	B2	^{226}Ra	B1
^{63}Ni	B2	^{100}Agm	B2	^{233}Pa	B2
^{75}Se	?	^{113}Sn	B2	^{236}U	B3
^{85}Sr	B1	^{133}Ba	B1	^{237}Np	B3
^{95}Zr	B2				

A non-sorbing, B1 cation exchange, B2 mainly surface complexation, B3 redox sensitive.

Results from on-line HPGe measurements during the first 24 hours after injection are shown in Figure 3-7. The test section was rapidly mixed and the most sorbing tracers rapidly decreased in the water phase while the non to slightly sorbing tracers, e.g. ^{22}Na, levelled out on a constant concentration. Preliminary results for ^{22}Na and ^{137}Cs up to December 10th are shown in Figure 3-8. Two days after injection data are missing for three days due to a detector breakdown, however, the missing data are not of major importance for the experiment. The ^{22}Na considered as more or less non-sorbing in the present environment reacts as expected and levels out on a constant concentration. Also ^{137}Cs reacts as expected with a slowly decreasing concentration caused by diffusion and slow sorption kinetics.

The in situ experiment, with on-line HPGe measurement and sampling is planned to continue until February/March 2007. Thereafter the core stub and the rock surrounding the small diameter extension borehole will be extracted by over core drilling. This activity will be followed by sectioning and analyses of tracer content and fixation in removed core stub and rock core encompassing the small diameter borehole. Laboratory diffusion and sorption measurements on core samples from the small diameter extension borehole, initially planned for 2006, will be performed during 2007 using the same radionuclides as in the in situ experiment.

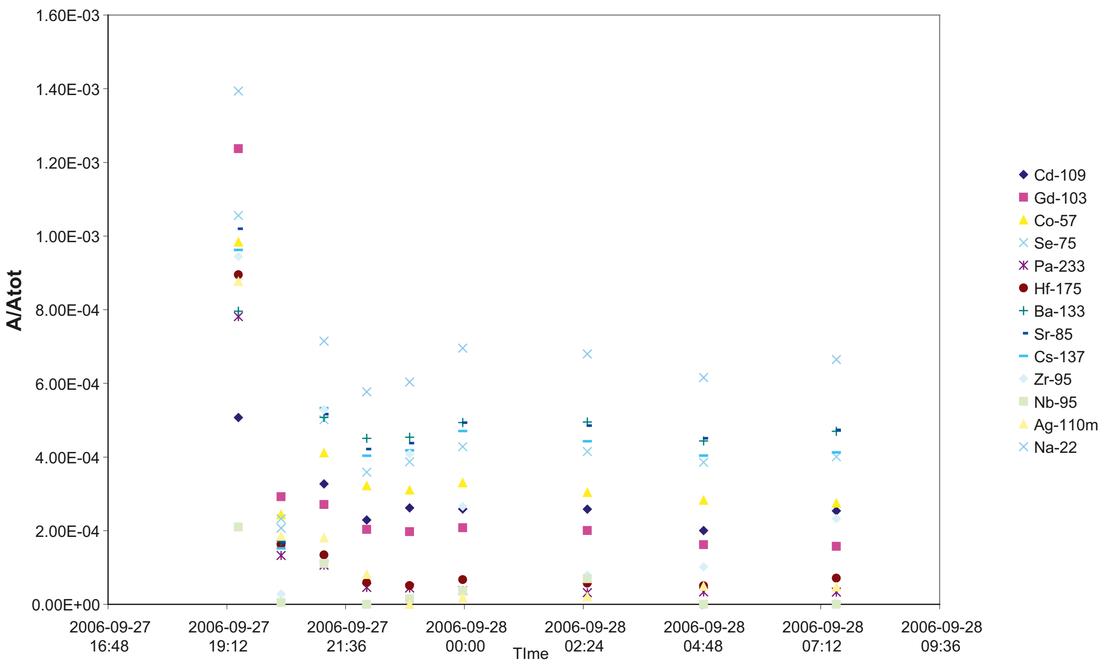


Figure 3-7. Measured radionuclide concentration (normalised) in the test section groundwater the first 24 hours after injection.

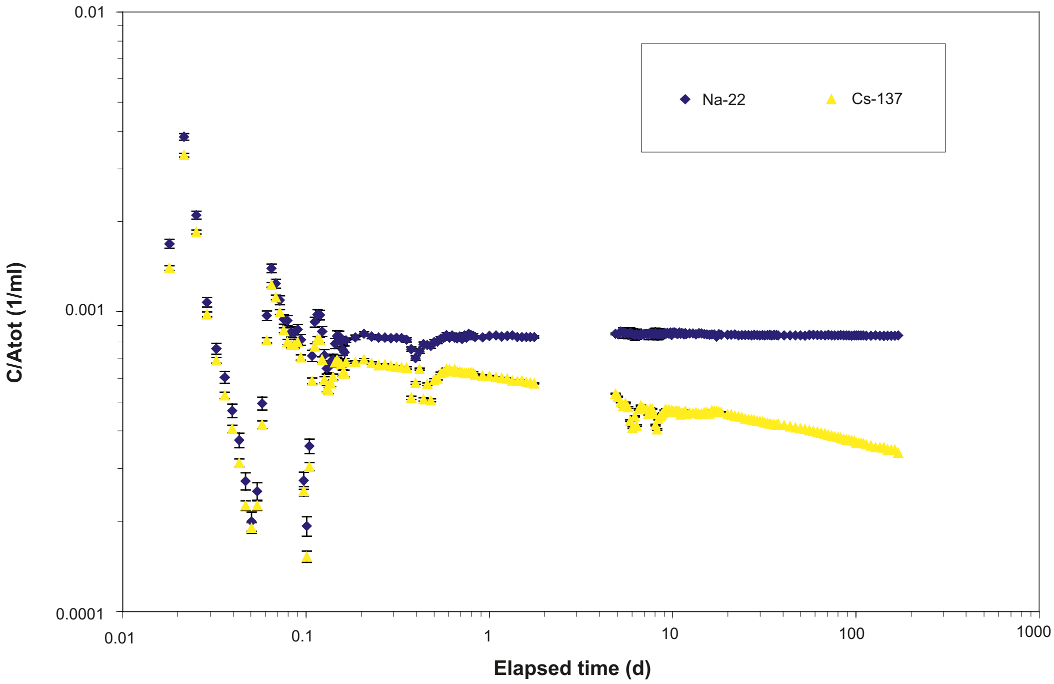


***Figure 3-8.** Preliminary results from on-line HPGe measurements in LTDE-SD in situ experiment. Concentration (decay corrected activity versus total injected activity) of Na^+ and Cs^+ in test section groundwater.*

3.4 Colloid Project

3.4.1 Background

Colloids are small particles in the size range 10^{-6} to 10^{-3} mm (1 to 1,000 nm). The colloidal particles are of interest for the safety of a repository for spent nuclear fuel because of their potential to transport radionuclides from a defect waste canister to the biosphere. SKB has for more than 10 years conducted field measurements of colloids. The outcome of the studies performed nationally and internationally concluded that the colloids in the Swedish granitic bedrock consist mainly of clay, silica and iron hydroxide particles and that the mean concentration is around 20–45 ppb which is considered to be a low value /Laaksoharju et al. 1995/. The low colloid concentration is controlled by the attachment to the rock, which reduces both the stability of the colloids and their mobility in aquifers.

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

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

3.4.2 Objectives

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

- The stability and mobility of colloids.
- The colloid concentration in the groundwater at Äspö.

- Bentonite clay as a source for colloid generation.
- The potential of colloids to enhance radionuclide transport.

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

3.4.3 Experimental concept

The Colloid Project comprises laboratory experiments as well as field experiments – Background measurements, Borehole specific measurements and Dipole colloid experiment. The Dipole colloid experiment is on-going and all the others are finalised and reported:

- The laboratory experiments were performed to investigate in detail the chemical changes, size distribution and the effects from Na versus Ca rich bentonite associated with colloid generation /Wold and Eriksen 2002, Karnland 2002/.
- Background measurements were performed to measure the natural background colloid concentrations in eight different boreholes during 2002, representing groundwater with different ionic strength, along the Äspö tunnel. The colloid content at Äspö was found to be less than 300 ppb and at repository level it is less than 50 ppb /Laaksoharju and Wold 2005/.
- Borehole specific measurements, with the aim to measure the colloid generation properties of bentonite clay in contact with groundwater prevailing at repository depth, were made in four boreholes along the Äspö tunnel and two boreholes at Olkiluoto in Finland. The results indicate that the colloid release from the bentonite clay at prevailing groundwater conditions is small and an increased water flow did not increase the colloid release from the bentonite /Laaksoharju and Wold 2005/.

Dipole colloid experiment

The Dipole Colloid Experiment is a fracture specific experiment performed within the Colloid Project. According to present plans, two nearby boreholes having the same basic geological properties, KXTT3 and KXTT4 intersecting Feature A at the True-site, are selected for the dipole colloid experiment at Äspö HRL. One of the boreholes will be used as an injection borehole and the downstream borehole will be used for monitoring. Since bentonite colloids are not stable in the saline groundwaters at Äspö, fluorescent latex colloids will be used. A cocktail containing three different latex with 50, 100 and 200 nm mean sizes plus a colour tracer will be injected into the injection borehole, see Figure 3-9. The colloidal content will be measured with a flourospectrophotometer and a Single Particle Counter (SPC). The result of major interest is the changes in colloid content prior to and after the transport through the fracture, i.e. to get the filtration factors (α) for colloids. The outcome of the experiment will be used to check performed model calculations and to develop future colloid transport modelling.

In addition, the actinide transport will be studied in the presence of colloids in a water bearing fracture. A core will be placed in a glove box and connected to a borehole in Äspö HRL, which one is not yet decided.

3.4.4 Results

In the laboratory at KTH, Royal Institute of Technology, stability tests of bentonite colloids in different conditions have been performed.

The groundwater composition strongly influences processes as colloid erosion and colloid stability. A kinetic method to predict stability and determine critical coagulation concentration (CCC) values for Na- and Ca-montmorillonite colloids in NaCl and $CaCl_2$ electrolyte has been developed. The results are summarised in a manuscript which will be sent for publication.

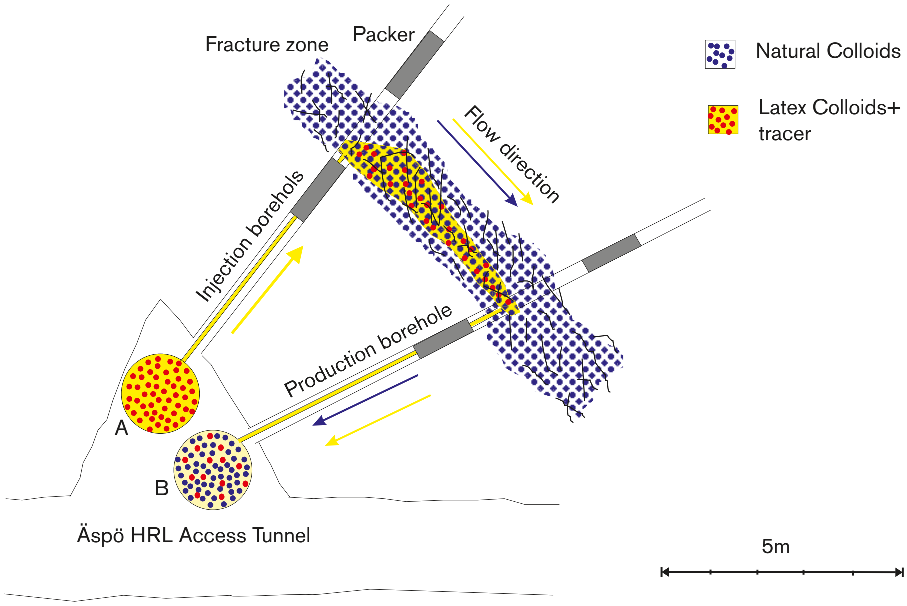


***Figure 3-9.** Dipole colloid experiments – injection of latex colloids and monitoring of the injected and natural colloids in the production borehole.*

The influence of temperature on the stability of bentonite colloids has been studied in 10^{-3} M NaCl solutions. The results have been published in Journal of Colloids and Interface Science in 2006. /Garcia-Garcia et al. 2006/. This study will be extended to wider concentration ranges of NaCl and $CaCl_2$ as well as with other colloids.

The charge of the Al-OH groups in the edges of bentonite particles is pH-dependent due to protonation/deprotonation. The experimental study is finished and after evaluation an article will be sent for publication in a scientific journal.

The interaction between bentonite colloids and mineral surfaces, such as granite, has been studied to identify and quantify the effect of the interaction on the stability of bentonite colloids. The presence of mineral surfaces does not seem to affect bentonite colloid stability. The results will be presented as background information for colloid transport experiments.

Laboratory experiments have also been performed in the Quarried Block (QB) sample, a 1 m × 1 m × 0.7 m block of granite containing a single and complex, but well characterised, through-going, variable aperture fracture. The purpose of this experimental programme was to provide additional information that cannot be obtained on the field-scale at Äspö regarding bentonite versus latex sphere colloid transport, particularly at low flow rates. Dipole tracer tests were performed with a separation distance of 380 mm. Five experiments using MX-80 and 100 nm latex colloids were performed using deionised water at flow rates of 510, 45, and 6.2 mL/h. An additional experiment was performed by injecting a bentonite colloid (suspended in deionised water) into the Quarried Block, after it had been saturated with saline Äspö type water.

The main findings are:

- In dilute water at high flow velocities of 0.4 m/h, typical of field-scale tracer tests, bentonite and latex colloids have similar transport properties, and are mobile with good recoveries.
- At lower flow velocities, closer to those of natural conditions, colloid transport is significantly reduced, particularly for bentonite. Bentonite and 100 nm latex colloids begin to display different transport behaviour, possibly due to differences in size distribution and surface properties. Transported bentonite colloids appear to be mainly in the small size range, 4 to 15 nm, with the larger bentonite colloids remaining in the fracture.
- In saline groundwaters bentonite colloids are flocculated and are not mobile.

- Bentonite colloids can become mobilised to some extent if saline water is replaced by dilute water under conditions of high flow.
- Colloid migration properties appear to influence the transport of co-injected solute tracer.

The results are summarised in an internal AECL-report which will be published in January 2007. This report will after AECL publication be published as an Äspö International Progress Report (IPR).

Laboratory experiments have been performed at FZK-INE aiming at investigating the radionuclide behaviour in colloid-groundwater-fracture infill mineral system. Colloid stability ratios (W) were calculated from coagulation rates of MX-80 colloids measured as a function of the ionic strength varying from 0.001 M up to 1 M in NaCl or $CaCl_2$ media by Photon Correlation Spectroscopy (PCS) in the pH range 4–10. Additional LIBD (laser induced breakdown detection) measurements of the supernatants by decanting solutions after 1 and 4 months were performed. Both analytical methods show clearly the instability of colloids at the high ionic strength of the Äspö groundwater. Coagulation rate of bentonite colloids were determined in presence of fulvic acid (FA), 0.2 M ($CaCl_2$ solution) and pH ~ 7.5. No significant change in the measured stability ratios could be observed as compared to the experiments in absence of organic matter. Additional performed LIBD measurements of supernatants, after 1 and 4 months colloid sedimentation, showed that colloids were still detectable. The first experiments indicate that the conditioning of bentonite with FA prior to increase of the ionic strength increases colloid stability.

Interaction of radionuclides with bentonite colloids have been studied in batch experiments spiked with Sr, Cs, Am, Np, U and Pu at pH 7.5. In a second batch, MX-80 bentonite colloids were added. Evolution of the radionuclide and bentonite colloid concentrations was followed over 2 months by direct analysis of the solution and after ultracentrifugation. Radionuclide concentrations were analysed by LSC (liquid scintillation counting) and ICP-MS (inductively coupled plasma mass spectrometry). Cs(I), Sr(II), and U(VI) spiked to the Äspö groundwater do not show any significant colloidal behaviour in presence or absence of MX-80 bentonite colloids. This result is in agreement with the behaviour of naturally occurring Cs, Sr and U in the investigated groundwater. The bentonite colloids are unstable under these conditions and sediment after 2 days. Am(III) and Pu(IV) exist as colloids when spiked to the Äspö groundwater in presence and absence of MX-80 bentonite colloids. Np(V) is at least partly reduced after 2 months to Np(IV) and appears to show comparable colloidal behaviour as seen for Pu(IV). These colloidal species are unstable and disappear from both solutions (presence and absence of clay colloids) after 2 months.

Colloid dipole experiments have been performed with latex colloids of 50 and 100 nm in size which travelled quite fast with high recoveries. Due to a lot of noise in the data, exact recoveries could not be calculated, but the experiments indicate that almost all of the latex mass is recovered. Filtration coefficients for colloids could not be calculated from these experiments due to the noise in the data. The experiments point out the necessity to continue with similar experiments with refined analysis. Discussion on a new site for these types of experiments is on-going. Evaluation of tracer test data has been carried out and a few key parameters determined. The evaluation results as well as the results of scoping calculations are to be summarised in an interim report with the title: Modelling for the Colloid Dipole Experiment. Scoping calculations and evaluation results will be included/integrated into the project report.

3.5 Microbe Project

3.5.1 Microbial processes

Microorganisms interact with their surroundings and in some cases they greatly modify the characteristics of their environment. Several such interactions may have a significant influence on the function of a future deep repository for spent fuel /Pedersen 2002/. The study of microbial processes in the laboratory gives valuable contributions to our knowledge about microbial processes in repository environments. However, the concepts suggested by laboratory studies must be tested in a repository like environment. The reasons are several. Firstly, at repository depth, the hydrostatic pressure reaches close to 50 bars, a setting that is very difficult to reproduce in the microbiology laboratory. The high pressure will influence chemical equilibrium and the content of dissolved gases. Secondly, the geochemical environment of deep groundwater on which microbial life depends, and influences, is complex. Dissolved salts and trace elements, and particularly the redox chemistry and the carbonate system are characteristics that are very difficult to mimic in a university laboratory. Thirdly, natural ecosystems, such as those in deep groundwater, are composed of a large number of different species in various mixes /Pedersen 2001/. The university laboratory is best suited for pure cultures and therefore the effect from consortia of many participating species in natural ecosystems cannot easily be investigated there. The limitations of university laboratory investigations arrayed above have resulted in the construction and set-up of an underground laboratory in the Äspö HRL tunnel. The site is denoted the Microbe laboratory and is situated at the –450 m level.

There are presently four specific microbial process areas identified that are of importance for proper repository functions and that are best studied at the Microbe laboratory within separate projects. They are: (a) bio-mobilisation of radionuclides (Micomig), (b) bio-immobilisation of radionuclides (Micomig), (c) microbial effects on the chemical stability of deep groundwater environments (Micored) and (d) microbial corrosion of copper (Biocor). The Microbe laboratory, Micomig and Micored are presented here.

3.5.2 The Microbe laboratory

Objectives

The major objectives for the Microbe laboratory are:

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

Experimental concept

The Microbe laboratory is situated at the –450 m level in the F-tunnel (Figure 3-10). A laboratory container has been installed with laboratory benches and a climate control system. Three core drilled boreholes, KJ0050F01, KJ0052F01 and KJ0052F03, intersect water conducting fractures at 12.7, 43.5 and 9.3 m, respectively. They are connected to the Microbe laboratory via 1/8" PEEK tubing. The boreholes are equipped with metal free packer systems that allow controlled circulation of groundwater via respective fracture /Pedersen 2000/. Each borehole has been equipped with a circulation system offering a total of 2,112 cm^2 of test surface in each circulation flow cell set up (four flow cells) for biofilm formation at in situ pressure, temperature and chemistry conditions. The systems operate at pressures around 30 bars. The flow through the flow cells is adjusted to 25–30 ml per minute, which corresponds to a flow rate over the surfaces of about 1 mm per second. Temperature is controlled and kept close to the in situ temperature at around 15–16°C. Remote alarms and a survey system have been installed for high/low pressure, flow rate and temperature. A detailed description of the Microbe laboratory can be found in an International Progress Report /Pedersen 2005/.

Results

The Microbe laboratory is now working very well with respect to installed equipment /Pedersen 2005/. The site selection of the Microbe laboratory in the F-tunnel of Äspö had, until January 2005, assured stable conditions. However, the situation changed dramatically during the time period January to December 2005. The drilling for “In situ Corrosion Testing of Miniature Canisters (Minican)” caused a significant drainage of the formation from which Microbe takes it groundwater.

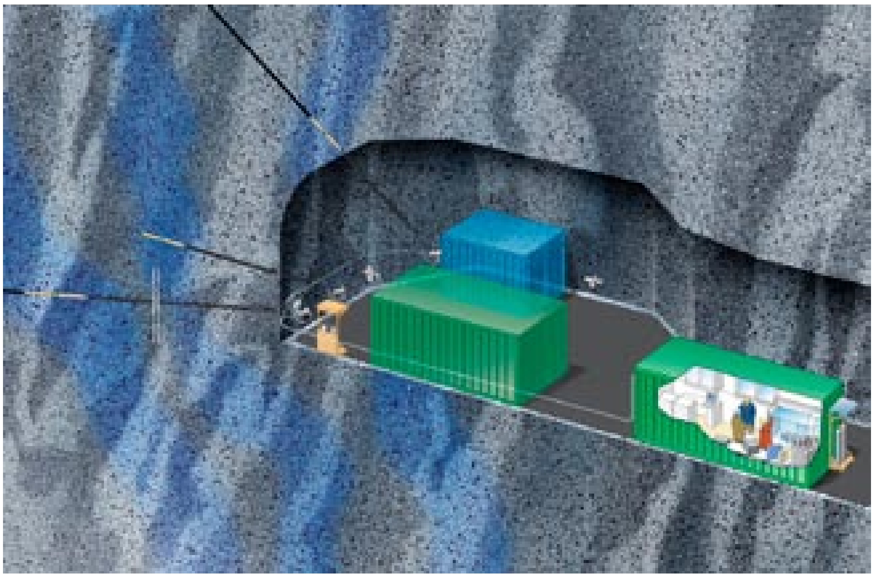


Figure 3-10. The artists view of the Microbe 450 m site and the metal free packer configuration. The laboratory is situated in a steel container and connected to three discrete fractures in the rock matrix. PEEK tubing connects the systems in the laboratory with the groundwater.

A completely new mixing situation developed in the Microbe formation during 2005, with up-coning of deep and high salinity groundwater as the main effect from the Minican installation. Once the drainage was stopped in December 2005, the Microbe site microbiology stabilised during spring 2006 at a new level, generally with higher numbers of microorganisms than what was found before the up-coning was created (Figure 3-11).

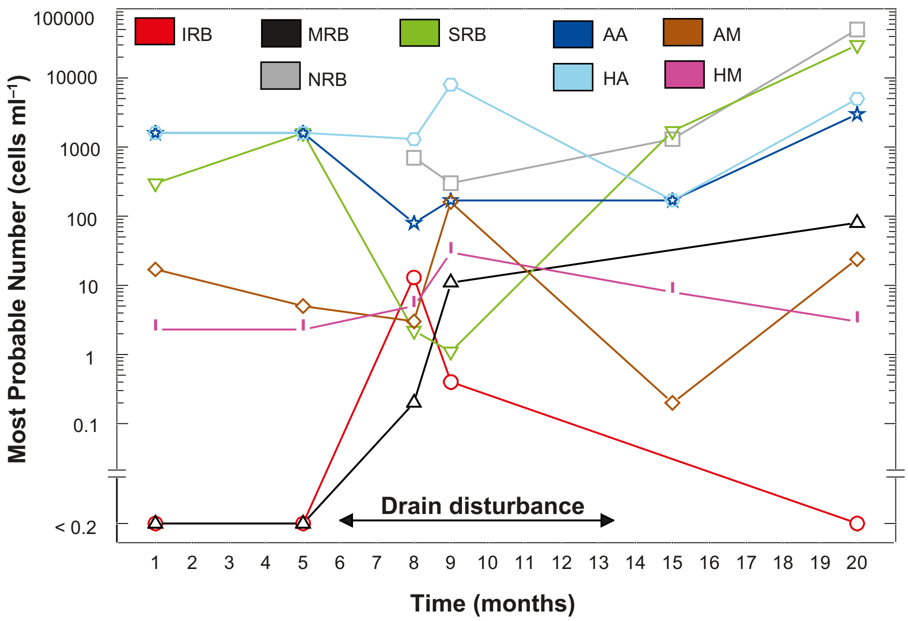


***Figure 3-11.** Most probable number (MPN) of analysed physiological groups in KJ0052F01 at the Microbe site over a period ranging from September 2004 to April 2006. The drain disturbance from the Minican installation is marked with an arrow. Abbreviations: IRB (Iron Reducing Bacteria), MRB (Manganese Reducing bacteria), SRB (Sulphate Reducing Bacteria, AA (Autotrophic Acetogens), AM (Autotrophic Metanogens), NRB (Nitrate reducing bacteria), HA (Heterotrophic Acetogens), HM (Heterotrophic Metanogens).*

3.5.3 Micomig

Background

It is well known that microbes can mobilise trace elements /Pedersen 2002/. Firstly, unattached microbes may act as large colloids, transporting radionuclides on their cell surfaces with the groundwater flow. Secondly, microbes are known to produce ligands that can mobilise soluble trace elements and that can inhibit trace element sorption to solid phases /Johnsson et al. 2006/.

A large group of microbes catalyse the formation of iron oxides from dissolved ferrous iron in groundwater that reaches an oxidising environment /Ferris et al. 1999, 2000/. Such biological iron oxide systems (Bios) will have a retardation effect on many radionuclides. Typically, microbes form stalks and sheaths that increase the volume of the iron oxides from densely packed inorganic oxides to a fluffy, rust-like material with water contents of up to 99%. The microbes contribute to the exposure of a large oxide area to trace elements flowing by with the groundwater and the organic biological material adds a strong retention capacity in addition to iron oxides /Anderson and Pedersen 2003, Anderson et al. 2006c/.

Biofilms in aquifers will influence the retention processes of radionuclides in groundwater. Recent work /Anderson et al. 2006a–b/ indicates that these surfaces adsorb up to 50% of the radionuclides under natural conditions with K_a (m) approaching 10^5 and 10^6 for Co and Pm respectively. The formation of colloids accounted for a further 20% to 40% of aqueous Co and Pm complexation. The anaerobic biofilms and rock surfaces share similar adsorption capacities for Pm but not for Co. The biofilms seemed to isolate the rock surface from the groundwater as diffusion to the rock surface must first proceed through the biofilms. The possible suppression of adsorption by biofilms needs further research. So far this has been observed only with one biofilm type in one Microbe laboratory circulation.

Objectives

- To evaluate the influence from microbial complexing agents on radionuclide migration.
- To explore the influence of microbial biofilms on radionuclide sorption and matrix diffusion.

Experimental concept

In situ formation of complexing agents in the Microbe laboratory circulations are being investigated. The experimental concept from laboratory work /Johnsson et al. 2006/ is adapted to the field. Pressure safe containers will be amended with radionuclide cocktails and groundwater from closed and active circulations will be added under ambient pressure, pH and redox potential. The distribution of the radionuclides between solid and liquid phases will be analysed as previously done in the laboratory.

New experiments with biofilm effects on radionuclide migration will utilise the tested and recently published experimental concept /Anderson et al. 2006a–b/. Different groundwater will be analysed. The types of biofilm microorganisms will be analysed.

Results

The year 2006 have been used to summarise, report and publish accomplishments this far. One thesis (A. Johnsson) and four papers in international peer review journals have been published 2006 /Anderson et al. 2006a–c; Johnsson et al. 2006/ (see list of publications in Section 8.2). One biofilm experiment has been performed during fall 2006 and the analysis will be performed during 2007.

3.5.4 Micored

Background

Microorganisms can have an important influence on the chemical situation in groundwater /Haveman and Pedersen 2002/. Especially, they may execute reactions that stabilise the redox potential in groundwater at a low and, therefore, beneficial level for the repository. It is hypothesised that hydrogen from deep geological processes contributes to the redox stability of deep groundwater via microbial turnover of this gas. Hydrogen, and possibly also carbon mono-oxide and methane energy metabolisms will generate secondary metabolites such as ferrous iron, sulphide, acetate and complex organic carbon compounds. These species buffer towards a low redox potential and will help to reduce possibly introduced oxygen. The circulations in the Microbe laboratory have microbial populations that are reproducible in numbers and species distribution over time under stable hydrological conditions as exemplified in Figure 3-11. All groups execute influence on the redox situation. Anaerobic microbial ecosystems generally force the redox potential towards the range of redox in which they are active. Iron and manganese reducing bacteria are active at higher redox potentials (approximately –100 to –200 mV) than the methanogens and acetogens (approximately –300 to –400 mV). Sulphate reducing bacteria are most active between the optimal redox potentials for those groups (approximately –200 to –300 mV). The stable populations of sulphate reducing bacteria and methanogens and acetogens at the Microbe laboratory makes it very well suited for research on the influence of microorganisms on the evolution and stability of the redox potential in groundwater.

Objectives

- To clarify the contribution from microorganisms to stable and low redox potentials in near- and far-field groundwater.
- To demonstrate and quantify the ability of microorganisms to consume oxygen in the near- and far-field areas.
- To explore the relation between content and distribution of gas and microorganisms in deep groundwater.
- To create clear connections between investigations of microorganisms in the site investigations for a future repository and research on microbial processes at Äspö HRL.

Experimental concept

Pressure resistant electrodes for redox potential, pH and dissolved oxygen will be adapted and installed in the circulations in the Microbe laboratory. The circulations will be run with biofilms under various conditions with additions of the variables hydrogen, acetate, methane and oxygen. There are presently three circulations available, but three more are under construction and will be in operation during spring 2007. The circulations can be coupled in series in groups of two which allows simultaneous testing of two variables with one control at the time.

Results

The Micored work started 2006 with a configuration experiment with additions of acetate and hydrogen plus carbon dioxide as variables. It was found that the numbers of microorganisms, and the sulphide and the acetate concentrations increased most in the circulation with hydrogen addition. This supports the hypothesis that the deep biosphere is hydrogen driven /Pedersen 2001/. The results will be made available during 2007 after evaluation and modelling exercises.

3.6 Matrix Fluid Chemistry Continuation

3.6.1 Background

The first phase of the Matrix Fluid Chemistry Experiment (1998–2003) increased the knowledge of matrix pore space fluids/groundwaters from crystalline rocks of low hydraulic conductivity ($K < 10^{-10}$ m/s), and this complemented the hydrogeochemical studies already conducted at Äspö. The results of this first phase were published in early 2004 /Smellie et al. 2003/.

The continuation phase (2004–2006) focussed on areas of uncertainty which remain to be addressed:

- The nature and extent of the connected pore waters in the Äspö bedrock (chemical, hydraulic and transport properties).
- The nature and extent of the microfracture groundwaters which penetrate the rock matrix (chemical, hydraulic and transport properties) and the influence of these groundwaters (by in- and out-diffusion) on the chemistry of the pore waters.
- The confirmation of rock porosity values previously measured in the earlier studies.

This continuation phase also saw the completion of a feasibility study to assess the effects on the matrix borehole and its surroundings due to the untimely excavation of a new tunnel for the Äspö Pillar Stability Experiment carried out in April/May, 2003. There was concern that repercussions from this excavation may have influenced the hydraulic (and therefore the hydrochemical) character of the matrix borehole and the host rock vicinity.

3.6.2 Objectives

Because of the possibility that the hydraulic and hydrochemical character of the matrix borehole and the host rock vicinity may have been disturbed, the following objectives were identified:

- To establish the impact of tunnel construction on the matrix borehole by evaluating the monitored pressure profiles the hydro monitoring system (HMS) registered on the isolated borehole sections during the period of construction (small-scale).
- To establish the impact of tunnel construction on boreholes located in the near-vicinity of the matrix borehole in “Tunnel F” by similar means (large-scale).
- If the evaluation indicates that the rock hosting the matrix borehole has been unaffected by tunnel construction, the experiment will proceed first to hydrochemically and hydraulically characterise the presently isolated borehole sections containing microfractures and, secondly, to hydrochemically and hydraulically characterise the original fracture-free borehole sections.
- To carry out additional porosity measurements on drillcore samples to confirm or otherwise those values already measured.

3.6.3 Experimental concept

The first phase of the Matrix Fluid Chemistry Experiment was designed to sample matrix pore water from predetermined, isolated borehole sections. The borehole was selected on the basis of: (a) rock type, (b) mineral and geochemical homogeneity, (c) major rock foliation, (d) depth in the tunnel, (e) presence and absence of fractures and (f) existing groundwater data from other completed and on-going experiments at Äspö HRL.

Special downhole equipment, see Figure 3-12, was constructed 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 pore waters (and gases) under pressure and (g) convenient sample holder to facilitate rapid transport to the laboratory for analysis.

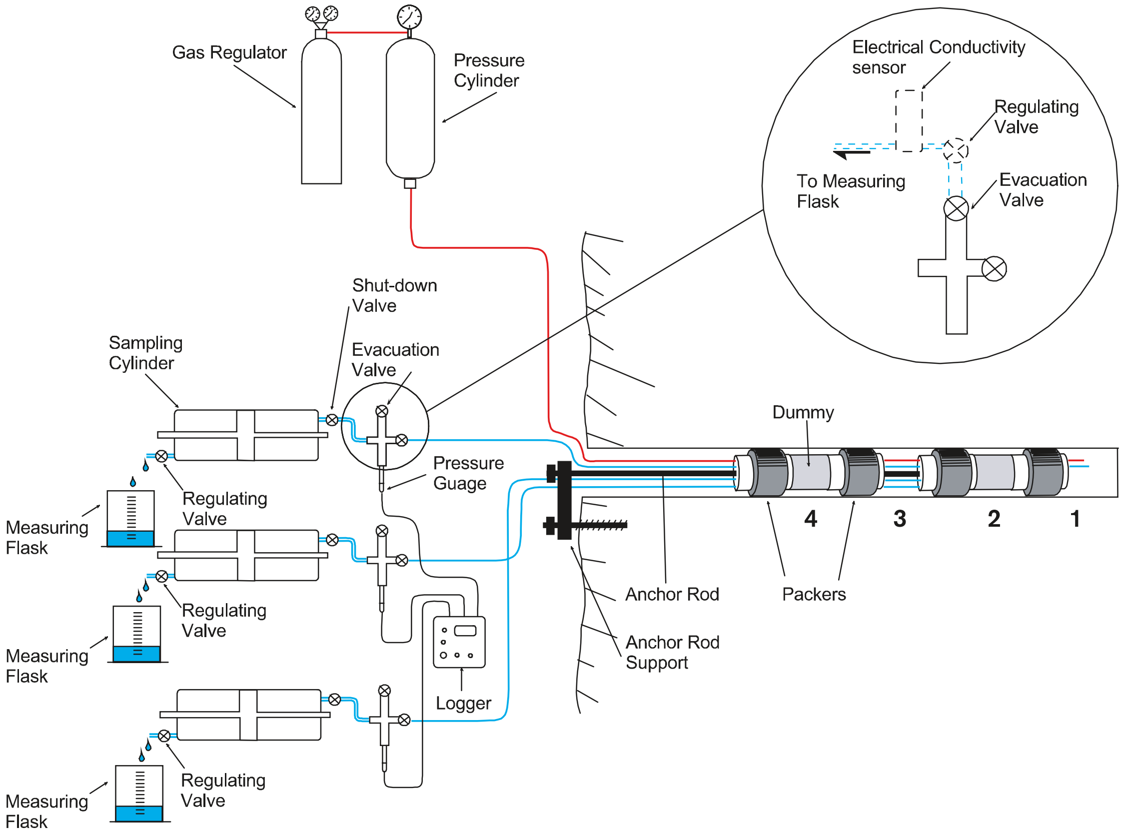


Figure 3-12. *Matrix Fluid Chemistry experimental set-up. Borehole sections 2 and 4 were selected to collect matrix fluid, sections 1–4 were continuously monitored for pressure.*

This experimental equipment, with some modifications, is being used in the continuation phase to sample groundwaters from the microfractures and to measure the hydraulic parameters of the microfractures and the rock matrix.

3.6.4 Results

Hydraulic testing of borehole sections

Figure 3-13 is a sketch of the instrumented matrix borehole KF0051A01 showing the original sealed off, fracture-free borehole sections that were the focus of the Matrix Fluid Chemistry Experiment (1998–2003). During 2005 the equipment was moved 50 cm towards the tunnel wall thus exposing, in particular, microfracture features A and B (< 1 mm wide) in sections 4 and 3 respectively. Subsequently these sections were sampled twice during 2005 for hydrochemical characterisation. On completion, the packer system was removed, modified and then reinstalled at a new position (outwards 90 cm from original), in preparation for the hydraulic testing programme.

The sequence of activities relating to the hydraulic testing of the fracture-free and fracture-containing borehole sections are given in Table 3-2. In addition to microfracture Features A, B and C, previously sampled for hydrochemical characterisation, other identified features were also included in the programme. These comprised Feature C (sealed fracture or mylonite) and Feature H (possible calcite infilled fracture). The results from the hydraulic tests are given in Table 3-3 and Table 3-4.

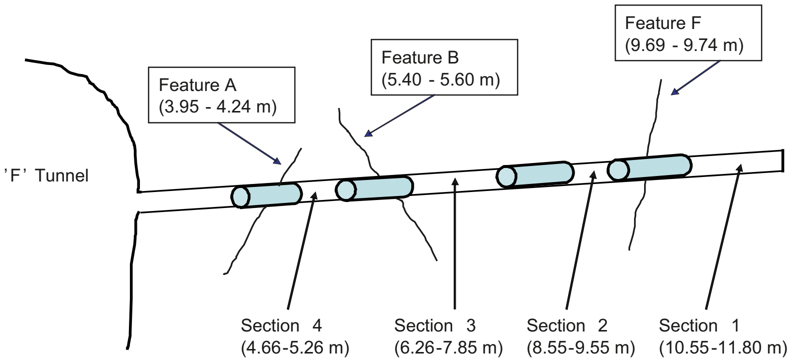


Figure 3-13. *Location of microfractures (Features A, B and F) demarcated for hydrochemical sampling and subsequently for hydraulic testing in the matrix borehole KF0051A.*

Table 3-2. Sequence of activities relating to the hydraulic testing programme (2005–2006).

Time period	Activity
2005-11-28–2005-11-29	Water sampling of microfracture features A and B, followed by removing packer system and modification and reinstallation at outer position (outwards 90 cm from original).
2005-11-29–2006-01-24	Testing of packer installation and injection equipment and procedures.
2006-01-24–2006-03-13	Pressure pulse test. Sections 1, 2, 3 and 4 at outer position (containing micro fractures).
2006-03-13–2006-04-18	Constant pressure injection test. Sections 3 and 4 at outer position (containing micro fractures).
2006-04-18–2006-04-20	Repositioning of packer system to original position.
2006-04-18–2006-05-16	Pressure stabilisation at the new position (i.e. original position).
2006-05-16–2006-06-12	Pressure pulse test. Sections 1, 2, 3 and 4 at original position (containing matrix rock).
2006-06-12–2006-07-06	Constant pressure injection test. Sections 2 and 4 at original position (containing matrix rock).
2006-07-06–2006-08-11	Pressure recovery test. Sections 1, 2, 3 and 4 at original position (containing matrix rock).

Table 3-3. Results from pressure pulse tests in borehole KF0051A01.

Classification	Section	Borehole length (m)	Hydraulic transmissivity (m^2/s)	Hydraulic conductivity (m/s)
Feature H (possibly calcite fracture)	1	10.55–11.80	$4\cdot10^{-14}$	$3.2\cdot10^{-14}$
Feature F (thin microfractures)	1	9.65–11.80	$6.9\cdot10^{-14}$	$3.2\cdot10^{-14}$
Feature E (matrix rock with very thin microfracture)	2	8.85–9.55	$7\cdot10^{-15}$	$1.0\cdot10^{-14}$
Mylonite	2	7.95–8.65	$7.9\cdot10^{-14}$	$1.1\cdot10^{-13}$
Feature C (sealed fracture or mylonite)	3	6.26–7.85	$6\cdot10^{-14}$	$3.8\cdot10^{-14}$
Feature B (thin microfracture)	3	5.36–6.95	$1.2\cdot10^{-13}$	$7.5\cdot10^{-14}$
Matrix rock	4	4.66–5.26	$4\cdot10^{-13}$	$6.7\cdot10^{-13}$
Feature A (thin microfracture)	4	3.76–4.36	$1.9\cdot10^{-13}$	$3.2\cdot10^{-13}$

Table 3-4. Results from constant pressure injection tests in borehole KF0051A01.

Classification	Section	Borehole length (m)	Transmissivity 2D flow* (m^2/s)	Conductivity 2D flow (m/s)	Transmissivity 3D flow** (m^2/s)	Conductivity 3D flow (m/s)
Feature E (matrix rock with very thin microfracture)	2	8.85–9.55	$3.9 \cdot 10^{-14}$	$5.6 \cdot 10^{-14}$	$2.2 \cdot 10^{-14}$	$3.14 \cdot 10^{-14}$
Feature B (thin microfracture)	3	5.36–6.95	$2.9 \cdot 10^{-13}$	$1.8 \cdot 10^{-13}$	$2.1 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$
Matrix rock	4	4.66–5.26	$6.0 \cdot 10^{-14}$	$1.0 \cdot 10^{-13}$	$3.5 \cdot 10^{-14}$	$5.8 \cdot 10^{-14}$
Feature A (thin microfracture)	4	3.76–4.36	$1.2 \cdot 10^{-13}$	$2.0 \cdot 10^{-13}$	$6.7 \cdot 10^{-14}$	$1.1 \cdot 10^{-13}$

* /Todd 1980/, ** /Moye 1967/.

The main conclusions from the hydraulic testing programme are:

- According to inflow rates, the hydraulic transmissivity is in the order of $1 \cdot 10^{-14}$–$1 \cdot 10^{-13}$ m^2/s for both microfracture-free and microfracture-containing borehole sections in the matrix borehole KF0051A01.
- Both hydraulic tests gave nearly similar hydraulic transmissivities in the microfracture-containing sections, i.e. Features A and B.
- These results are in accordance with earlier performed predictions of hydraulic transmissivities determined from inflow rates in the microfracture-free sections /Smellie et al. 2003/.

Analysis of borehole waters

Borehole waters collected during 2005 from the fracture-containing borehole sections are still in the process of being analysed.

3.7 Radionuclide Retention Experiments

Background

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

Laboratory studies of radionuclide retention under natural conditions are extremely difficult to conduct. Even though the experiences from different scientists are uniform it is of great value to be able to demonstrate the results of the laboratory studies in situ, where the natural contents of colloids, organic matter, 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, representative for the properties of groundwater at repository depth, can be obtained.

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 studied.

Objectives

The objectives of the radionuclide retention experiments are to:

- Validate the radionuclide retention data and fuel dissolution data which have been measured in laboratories by data from in situ experiments.
- Demonstrate that the laboratory data are reliable and correct also at the conditions prevailing in the rock.
- Decrease the uncertainty in the retention properties of relevant radionuclides.

Experimental concept – Chemlab

Chemlab 1 and 2 are borehole laboratories built into probes, in which in situ experiments can be carried out under ambient conditions with respect to pressure and temperature, and with the use of natural groundwater from the surrounding rock, see Figure 3-14. Initially one "all purpose" unit, Chemlab 1, was constructed in order to meet any possible experimental requirement. At a later stage, a simplified version, the Chemlab 2 unit, was designed to meet the requirements by experiments where highly sorbing nuclides are involved. In Figure 3-15 the principles of the borehole laboratories are given.

In already completed or almost completed experiments the following have been studied:

- Diffusion of cations (Cs^{+}, Sr^{2+}, and Co^{2+}) and anions (I^{-} and TcO^{4-}) in bentonite.
- The influence of primary and secondary formed water radiolysis products on the migration of the redox-sensitive element technetium /Jansson et al. 2006/.
- Migration of actinides (americium, neptunium, and plutonium) in a rock fracture.

3.7.1 Spent Fuel Leaching

Background and objectives

In the Spent Fuel Leaching experiments, to be performed within the framework of the programme for in situ studies of repository processes, the dissolution of spent fuel in groundwater relevant for repository conditions will be studied.

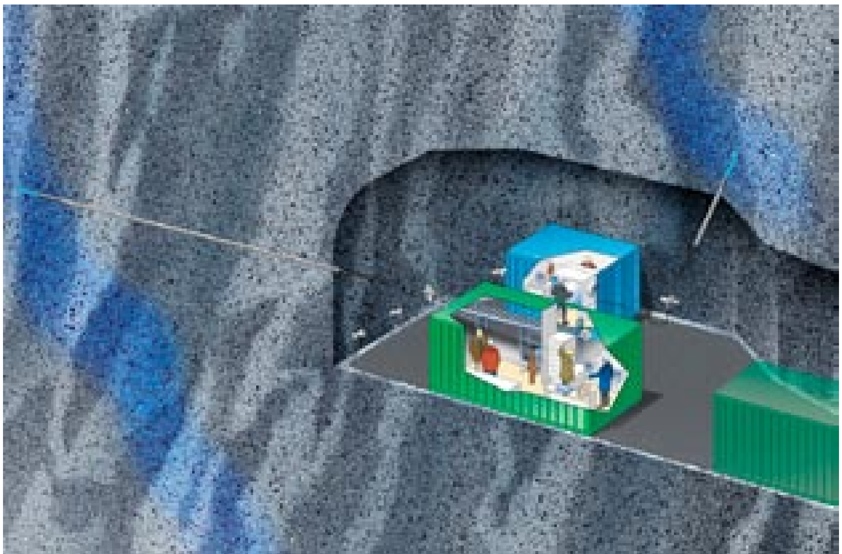


Figure 3-14. *Illustration of the experimental set-up of the Radionuclide Retention Experiments.*

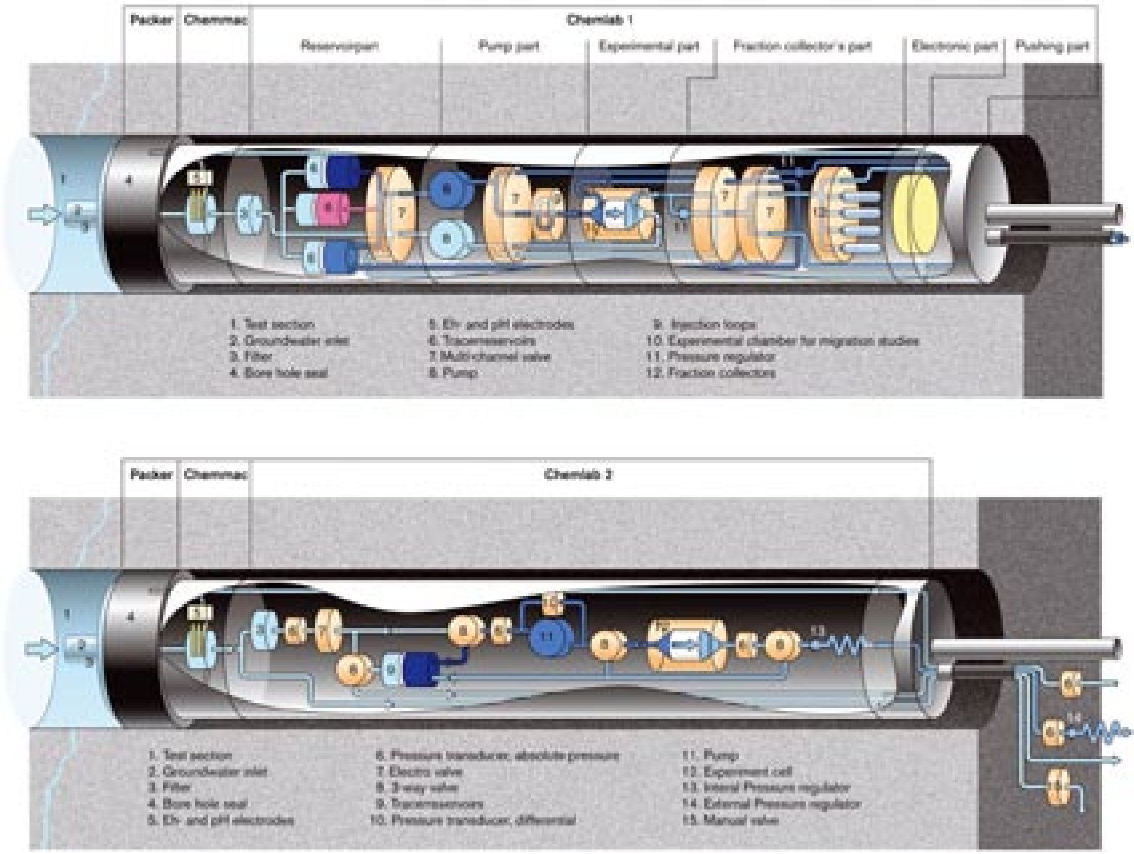


Figure 3-15. *Schematic illustration of Chemlab 1 and 2 borehole laboratories.*

The objectives of the experiments are to:

- Investigate the leaching of spent fuel in laboratory batch experiments and at in situ conditions.
- Validate laboratory data by experimental retardation data from in situ experiments.
- Demonstrate that the laboratory data are reliable and correct for the conditions prevailing in the rock.
- Reduce the uncertainties in the retardation properties of Am, Pu and Np.

Experimental concept

The in situ experiments will be preceded by laboratory experiments where the scope is both to examine parameters that may influence the leaching as well as testing the equipment to be used in the field experiments.

In the field experiments spent fuel leaching will be examined with the presence of H_2 (in a glove box situated in the gallery) as well as without the presence of H_2 (in Chemlab 2).

Results

The design of the experiment is finalised and contact has been taken with Chalmers for the laboratory experiments.

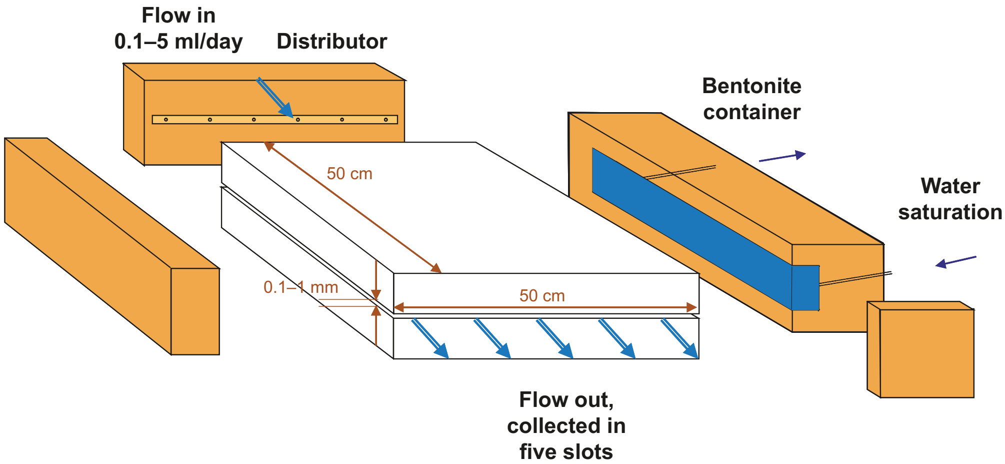


Figure 3-16. Illustration of experimental set-up.

3.7.2 Transport Resistance at the Buffer-Rock Interface

Background and objectives

If a canister fails and radionuclides are released, they will diffuse through the bentonite. If there is a fracture intersecting the canister deposition hole, the water flowing in the fracture will pick up radionuclides from the bentonite.

The transport resistance is concentrated to the interface between the bentonite buffer and the rock fracture. The mass transfer resistance due to the diffusion resistance in the buffer is estimated to only 6% and the diffusion resistance in the small cross section area of the fracture in the rock 94% /Neretnieks 1982/. The aim of the Transport Resistance at Buffer-Rock Interface project is to perform studies to verify the magnitude of this resistance.

Experimental concept

The experiment will be performed in the laboratory, where a fracture is simulated as a 1 mm space between two Plexiglas plates, see Figure 3-16. The equipment includes a water pump for very low flow rates.

Results

The experimental set-up has been used by another SKB-project (Bentonite erosion) and therefore no activities have been made in this project during 2006.

3.8 Padamot

3.8.1 Background

Palaeohydrogeology is a relatively new term used as a common name for information from fracture minerals that is used for interpretations of past hydrogeochemical and hydrogeological systems. The need for such interpretations has become evident in the geological/hydrogeological modelling of sites within the radwaste programmes of several countries. An EC founded 3 year project with the name Equip (Evidences from Quaternary Infills for Palaeohydrogeology) was therefore started in 1997. When the Equip project ended in 2000 /Bath et al. 2000/ there was a need for continued fracture mineral investigations and model testing of the obtained results. A new EC-project called Padamot (Palaeohydrogeological Data Analysis and Model Testing) was therefore initiated in the beginning of 2002 and this was ended and reported to EC in 2005. A continuation of the Swedish part of the project at Äspö has thereafter been agreed to by SKB. This is called Padamot Continuation.

3.8.2 Objectives

The objectives for the Padamot Continuation include:

- Further developments of analytical techniques for uranium series analyses applied on fracture mineral samples.
- Focus on the use of these analyses for determination of the redox conditions during glacial and postglacial time.
- Summarise the experiences of palaeohydrogeological studies carried out at Äspö.

3.8.3 Results

During the project start-up meeting on Äspö in late July the drill core from borehole KAS17 was sampled, see Figure 3-17. This borehole penetrates the large E-W fracture zone called the Mederhult zone and several sections with fractured rocks are intersected by the borehole. Six samples from different depths (ranging from 19 to 200 m core length) have been sieved into different grain sizes and the most fine grained (usually < 0.125 µm) fractions have been split into three (and if possible four) parts. Two for uranium series disequilibrium (USD) analyses at the different laboratories and one for inductively coupled plasma (ICP) analyses (chemical characterisation) which also included determination of the ratio $^{234}U/^{238}U$ with mass spectrometry. The fourth part was used for X-ray diffractometry (XRD) in order to determine the mineralogical composition. The results from the ICP and XRD analyses are already available and show that the sampled material consist of quartz, K-feldspar, albite, chlorite, calcite and clay minerals of mixed layer clay type. The uranium content in the samples varied from 6 to 27 ppm.

Split samples have been distributed to Helsinki University and to SUERC in Glasgow for analyses. The USD analyses will be carried out using different techniques (whole sample analysis and sequential leaching) applied by the two laboratories and the results will be interpreted in common.

Figure 3-17. Photo of sample from a fracture zone at 196.55–196.75 m in borehole KAS17.

3.9 Fe-oxides in Fractures

3.9.1 Background

Uptake of radioactive elements in solid phases can lead to immobilisation, thus minimising the release of these elements to the environment. Uptake extent depends on solution conditions such as concentration, pH, Eh, temperature, pressure and the presence of other species. Transition metals, lanthanides and actinides are often incorporated by identical processes, consequently better understanding of the behaviour of the two first groups mentioned strengthens understanding also of the actinides, which are difficult to study. Moreover, the presence of trace components in minerals can provide information about a mineral's genesis conditions and history.

Fractures lined with Fe-oxides are found in the Äspö bedrock and they are present as minor components nearly everywhere at the earth's surface. Their affinity for multivalent species is high but Fe-oxide uptake of lanthanides and actinides has not been studied to any great extent. Fe(II)-oxihydroxides, known as "green rust", form in Fe-bearing solutions under reducing conditions and are associated with the early stages of corrosion. Their uptake capacity during formation and transition to Fe(III)-oxides is essentially unknown at present. These minerals could be an important sink for radioactive species where Fe is abundant in the natural fractures or in materials brought into the repository. Fe itself can be an indicator of redox state. Fe-isotope fractionation, a very new topic of research, might give clues about redox conditions during Fe-mineral formation or as a result of its inclusion in other secondary fracture minerals.

There are three questions relevant for radioactive waste disposal in fractured granite:

- How extensive is the capacity for Fe(III)-oxides, in fracture linings, to take up and retain radionuclides or other toxicants from solutions, and what happens during transformation of the oxides to more stable phases?
- What capacity do the reduced Fe(II)-oxides have for uptake and retention?
- Does the suite of trace components and isotopes measured in minerals from fracture linings provide information about conditions of the water that passed through them in the past?

These questions can be rephrased more specifically, for direct application to problems for Swedish waste disposal, as:

- Can more detailed information about the uptake of higher valent elements such as Eu^{3+} provide a model for actinide behaviour and Cr^{3+} as a palaeo-redox-indicator?
- Can stable Fe-isotopes from Fe-oxides or from other minerals tell us anything about solution conditions during genesis?
- What is the uptake and retention capacity of green rust under solution conditions relevant for Äspö?
- Is it possible to find evidence to support or dispute the hypothesis that, at the time of glacier retreat, oxidising water might have penetrated to or below the depth of the planned final repository?
- How might secondary Fe-minerals affect the migration of radionuclides released from a repository?

3.9.2 Objectives and experimental concept

The basic idea of the project is to examine Fe-oxide fracture linings, in order to explore suitable palaeo-indicators and their formation conditions. At the same time knowledge about the behaviour of trace component uptake can be obtained from natural material as well as through studies in the laboratory under controlled conditions.

A glove-box set-up, where Atomic Force Microscopy is possible in situ, will be used to investigate green rust under a stable atmosphere at reducing conditions. More possibilities for extracting chemical information from the secondary Fe-oxides will be tested and the merits of stable Fe- and O-isotope fractionation as well as Mössbauer (MS) and energy dispersive X-ray (EDS) spectroscopy will be examined.

3.9.3 Results

Two main activities were carried out in 2006: (a) the reporting of outstanding work carried out from 2004–2005 and (b) the initiation of a project continuation with the title: "To establish the penetration depth of oxidising waters below ground".

Reporting

Reporting during the year has involved preparation of articles (see list in Section 8.2) and reports /Dideriksen and Stipp 2006, Christiansen 2006, Lindbæk Skovbjerg 2005/.

Continuation project

Future plans for a project continuation were finalised at a meeting held in Copenhagen on March 3rd, 2006. This was based on an earlier feasibility study /Dideriksen and Stipp 2006/ which developed a method for differentiating between Fe-oxides precipitated: (a) from hydrothermal solutions, (b) from natural, low temperature waters and (c) as an artefact of drilling activity. The method uses Fe(III)/Fe(II) ratios, Fe-isotope fractionation and rare earth element distribution and has been successful on very small quantities of sample. With this method, it should be possible to define a boundary plane marking the limit of evidence for oxidising water penetration from Fe-oxides gathered from fractures in drill cores. The 'Continuation Project' was entitled "To Establish the Penetration Depth of Oxidising Waters below Ground", and will involve the systematic collection of fracture samples from the site investigation drilling programme at Simpevarp. Sampling was carried out in August 2006 on drillcore material from the Laxemar investigation site programme, and the project is scheduled to be completed by June 2007.

In summary, the main objectives of the activity are:

- To complement data from a recent feasibility study at the Äspö HRL /Dideriksen and Stipp 2006/.
- To integrate samples from site characterisation studies in the Laxemar subarea.
- To sample a well-defined fracture network to demarcate the spatial depth of potentially penetrating oxidising waters.
- To use these data to better interpret the Äspö data already obtained from the Feasibility Study.

3.10 Swiw-test with Synthetic Groundwater

The single well injection withdrawal (Swiw) tests with synthetic groundwater constitute a complement to performed tests and studies on the processes governing retention, e.g. the True-1 and the True Block Scale experiments. This project aims at deepening the understanding for the processes governing retention. Swiw-tests with synthetic groundwater facilitate the study of diffusion in stagnant water zones and in the rock matrix. It also facilitates the possibility to test the concept of measuring fracture aperture with the radon concept.

The location for the tests will be the True Block Scale site and the well characterised Structures #19 and #20. The two structures have been object to a large number of tracer tests, possess different characteristics and are located on different distances from the tunnel. The revisit of the True Block Scale site facilitates the unique possibility to "calibrate" the concept of single well tracer tests, Swiw, to multiple borehole tracer tests. The results from such a calibration can be applied directly to the Swiw-tests performed within the SKB site investigation programme.

3.10.1 Objectives

The general objective of the Swiw-test with Synthetic Groundwater is to increase the understanding of the dominating retention processes and to obtain new information on fracture aperture and diffusion.

3.10.2 Experimental concept

The basic idea is to perform Swiw-tests with radon free synthetic groundwater with a somewhat altered composition, e.g. replacement of chloride with nitrate and the exclusion of potassium and strontium, compared to the natural groundwater at the True Block Scale site. Sorbing as well as non-sorbing tracers are added during the injection phase of the tests. In the withdrawal phase of the tests the contents of the "natural" tracers, radon, chloride, potassium and strontium, as well as the added tracers in the pumping water is monitored. The breakthrough curves contain the desired information on diffusion.

3.10.3 Results

The main activity within the project during 2006 was a feasibility study with the objectives to evaluate the possibility to perform and evaluate a Swiw-test with synthetic groundwater at True-Block Scale and optimise such a test, including pre-tests, by the aspects of test site, test performance and evaluation. The feasibility study comprised:

- Inventory of the hydraulic properties such as conductivities, distances and changes in gradient over time at True-Block Scale.
- Inventory of earlier tests and experiences at True-Block Scale and True-1 as well as from Swiw tests within SKB's site investigation programme.
- Scoping simulations of Swiw-tests with a dominating diffusion from stagnant water as well as from the rock matrix with tracers of different sorption.
- Investigation of the possibility to produce synthetic groundwater with very low concentration of a salt component (e.g. chloride).
- Design calculations in order to find limitations and preferable characteristics of a test site in general (such as time span, hydraulic gradient and conductivity).
- Compile, and report subtasks 2–6 and propose design of pre tests and Swiw-test with synthetic groundwater.

The feasibility study was not finalised during 2006 but will be so during the first half of 2007.

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

3.11.1 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. A Task Force delegate represents each participating organisation and the modelling work is performed by modelling groups. The Task Force meets regularly about once to twice a year.

Different experiments and tests 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 (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, 1st stage (completed).

Task 5: Coupling between hydrochemistry and hydrogeology (completed).

Task 6: Performance assessment modelling using site characterisation data (on-going).

Task 7: Long-term pumping test in Olkiluoto, Finland (on-going).

Occasionally, there is work done in so-called Meta Tasks, which are normally not directly coupled to a specific modelling task, but have an overview perspective. Such a task has been initiated. It is dedicated to updating the Issue Evaluation Table, which is intended to provide a basis for identification and evaluation of key issues in performance assessment of a final geological repository /Ström 1998/.

3.11.2 Objectives

The Task Force shall interact with the principal investigators responsible for carrying out experimental and modelling work for Äspö HRL of particular interest for the members of the Task Force. Much emphasis is put on building of confidence in the approaches and methods in use for modelling of groundwater flow and migration in order to demonstrate their use for performance and safety assessments.

The on-going Task 6 was initiated in 2001. Task 6 does not contain experimental work but it uses experimental results of the former Task 4 and True Block Scale project. Task 4 included a series of tracer tests performed in a single feature over transport distances of about 5 m using simple flow geometry and both conservative and sorbing tracers. In True Block Scale, a series of tracer tests was performed in a fracture network over tens of metres distance. The main objectives of Task 6 are to:

- Assess simplifications used in performance assessment (PA) models.
- Assess the constraining power of tracer experiments for PA models.
- Provide input for site characterisations programme from PA perspective.
- Understand the site-specific flow and transport at different scales using site characterisation models.

These sub-tasks have been defined within Task 6:

6A Model and reproduce selected True-1 tests with a PA model and/or a site characterisation (SC) model to provide a common reference.

6B Model selected PA cases at the True-1 site with new PA relevant (long term/base case) boundary conditions and temporal scales.

6B2 Similar to sub-task 6B, but uses a different boundary condition, a linear source term and the tracers are analysed at a fracture intersecting Feature A.

6C Develop semi-synthetic, fractured granite hydrostructural models. Two scales are supported (200 m block scale and 2,000 m site-scale).

6D This modelling task is similar to sub-task 6A, and is using the semi-synthetic structural model in addition to a 50 to 100 m scale True Block Scale tracer experiment.

6E This modelling task extends the sub-task 6D transport calculations to a reference set of PA time scales and boundary conditions.

6F Sub-task 6F is a sensitivity study, which is proposed to address simple test cases, individual tasks to explore processes, and to test model functionality.

6F2 The purpose of the sub-task 6F2 is to exploit the model setup within sub-task 6E and 6F to perform additional studies evaluating specific topics of concern for the modelling of transport in fractured rock.

Task 7 was presented at the 19th International Task Force meeting in Finland, 2004. Hydraulic responses during construction of a final repository are of great interest because they may provide information for characterisation of hydraulic properties of the bedrock and for estimation of possible hydraulic disturbances caused by the construction. Task 7 will focus on the underground facility Onkalo at the Olkiluoto site in Finland, and is aimed at simulating the hydraulic responses detected during a long-term pumping test carried out in a borehole (OL-KR24).

3.11.3 Results

In the Task Force on groundwater flow and transport of solutes, work has been in progress mainly in Task 6 and 7. Task 6 addresses performance assessment modelling using site characterisation data and Task 7 addresses a long-term pumping test in Olkiluoto, Finland. Work has also been done to update the Issue Evaluation Table.

The 21st International Task Force meeting, hosted by Andra was held March 6–9, 2006 in Paris. Minutes and proceedings of the 21st International Task Force have been published on the Task Force web site at SKB.

The modelling work is completed for Task 6 and most of the modelling reports are finalised. The review report for Task 6D, 6E, 6F and 6F2 is near to be finalised. It has been decided to publish modelling papers and one review paper based on these Task 6 reports.

The work within Task 7 is in progress. The task has been further defined and updated. Preliminary results were presented at the workshop on Task 7, which was held in Rauma, Finland in September 2006.

4 Engineered barriers

4.1 General

To meet stage goal 4, to demonstrate technology for and function of important parts of the repository barrier system, work is performed at Äspö HRL. This implies translation of current scientific knowledge and state-of-the-art technology into engineering practice applicable in a future 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 an appropriate scale. A number of large-scale field experiments and supporting activities are therefore conducted at Äspö HRL. The experiments focus on different aspects of engineering technology and performance testing, and will together form a major experimental programme.

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

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

With respect to repository function, the objectives are to test and demonstrate the function of the engineered barriers as well as the function of the integrated repository system.

The main experiments that are installed in Äspö HRL or under way are:

- Prototype Repository.
- Long Term Test of Buffer Material.
- Backfill and Plug Test.
- Canister Retrieval Test.
- Temperature Buffer Test.
- KBS-3 method with Horizontal Emplacement.
- Large Scale Gas Injection Test.
- In situ Testing of Miniature Canisters
- Cleaning and Sealing of Investigation Boreholes.
- Alternative Buffer Materials.
- Rock Shear Experiment
- Earth Potentials.

4.2 Prototype Repository

4.2.1 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. This technology was developed and is tested and demonstrated in the Prototype Repository.

The execution of the Prototype Repository is a dress rehearsal of the actions needed to construct a final repository from detailed characterisation to resaturation of deposition holes and backfill of tunnels. The Prototype Repository provides a demonstration of the integrated function of the repository and provides 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 installation of the Prototype Repository has been co-funded by the European Commission (EC) with SKB as co-ordinator. The EC-project started in September 2000 and ended in February 2004. The continuing operation of the Prototype Repository is funded by SKB.

4.2.2 Objectives

The main objectives for the Prototype Repository are to:

- Test and demonstrate the integrated function of the final repository components under realistic conditions in full-scale and to compare results with model predictions and assumptions.
- Develop, test and demonstrate appropriate engineering standards and quality assurance methods.
- Simulate appropriate parts of the repository design and construction processes.

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

4.2.3 Experimental concept

The test location chosen is the innermost section of the TBM-tunnel at the –450 m level. 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, separates the test area from the open tunnel system and a second plug separates the two sections. This layout provides two more or less independent test sections. Canisters with dimension and weight according to the current plans for the Swedish final repository and with heaters to simulate the thermal energy output from the spent fuel have been positioned in the holes and surrounded by bentonite buffer. The deposition holes are placed with a centre distance of 6 m. This distance was evaluated considering the thermal diffusivity of the rock mass and the maximum acceptable surface temperature of the canister.

The decision when to stop and decommission the test will be influenced by several factors including performance of monitoring instrumentation, results successively gained, and the overall progress of the deep repository project. It is envisaged that the outer test section will be

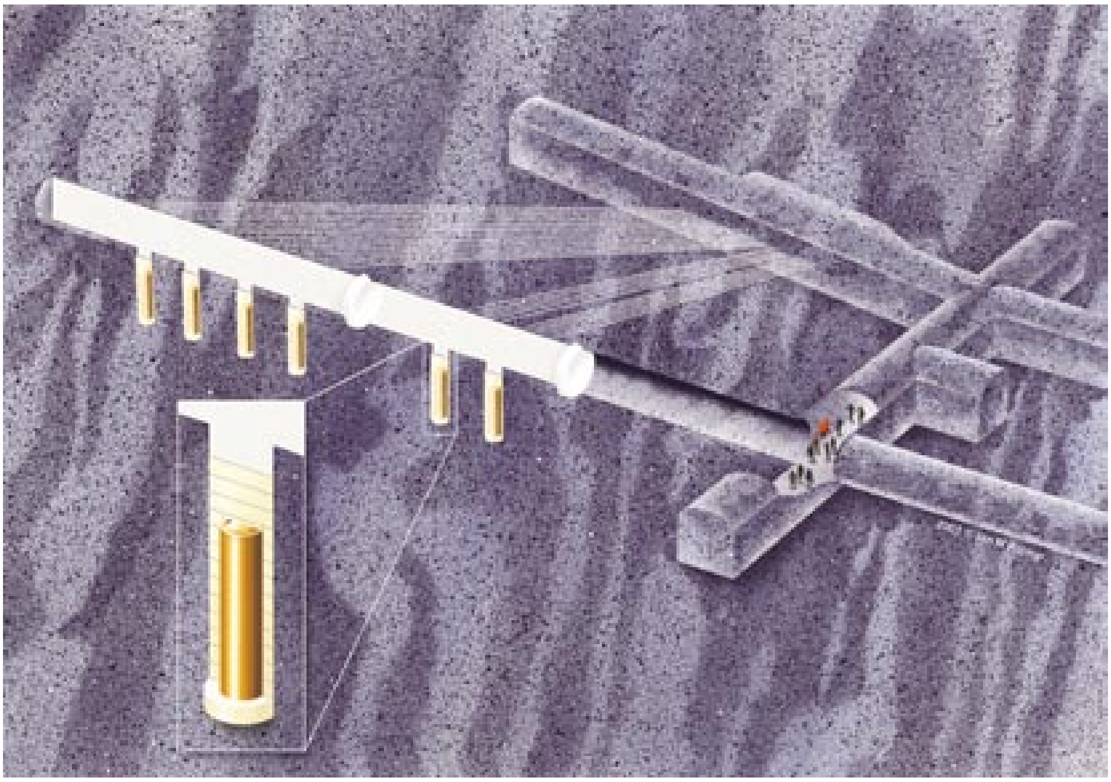


Figure 4-1. Schematic view of the layout of the Prototype Repository (not to scale).

decommissioned after approximately five years to obtain interim data on buffer and backfill performance. Instrumentation is used to monitor processes and evolution of properties in canister, buffer material, backfill and near-field rock. Examples of processes that are studied include:

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

4.2.4 Results

The installation of Section I (inner section) was done during summer and autumn 2001. The heating of the canister in deposition hole 1 started with an applied constant power of 1,800 W at 17th September. This date is also marked as start date. The backfilling started 3rd September and was finished 20th November and the plug was cast at 14th December. In order to simulate the radioactive decay, the power was decreased 40 W one year after start of the first heater. In the beginning of September 2004 the power in deposition holes 1–4 was decreased with about 30 W to 1,710 W. At the beginning of December 2005, a new reduction of the power was made with about 30W to 1,680 W.

The installation of Section II (outer section) was done during spring and summer 2003. The heating of the canister in hole 5 started with an applied constant power of 1,800 W at 8th May. This date is also marked as start date. The backfilling started 29th April and was finished 25th June and the plug was cast at 11th September. In the beginning of September 2004 the power in deposition holes 5–6 was decreased with about 30 W to 1,770 W. The interface between the rock and the outer plug was grouted at the beginning of October 2004. At the beginning of December 2005, a new reduction of the power was made with about 30W to 1,740 W.

At the beginning of November 2004 the drainage of the inner part of Section I and the drainage through the outer plug were closed. This affected the pressure (both total and pore pressure) in the backfill and the buffer in the two sections dramatically. Example of data from the measurements in the backfill of the total pressure is shown in Figure 4-2. The maximum pressures were recorded around 1 January 2004. At that date the heating in canister 2 failed. It was then decided to turn off the power to all of the six canisters. Four days later, damages on canister 6 were also observed. The drainage of the tunnel was then opened again. During the next week further investigations of the canisters were done. The measurements showed that the heaters in canister 2 were so damaged that no power could be applied to this canister. The power to the rest of the canisters was applied again 15th January 2004. The drainage of the tunnel was kept open. At the beginning of August 2005 another failure of canister 6 was observed. The power to this canister was switched off until beginning of October 2005 when the power was switched on again.

Measurements in rock, backfill and buffer

Altogether more than 1,000 transducers were installed in the rock, buffer and backfill /Collin et al. 2002, Börgesson and Sandén 2002, Rhén et al. 2003/. The transducers measure the temperature, the pore pressure and the total pressure in different parts of the test area. The water saturation process is recorded by measuring the relative humidity in the pore system of the backfill and the buffer, which can be converted to total suction.

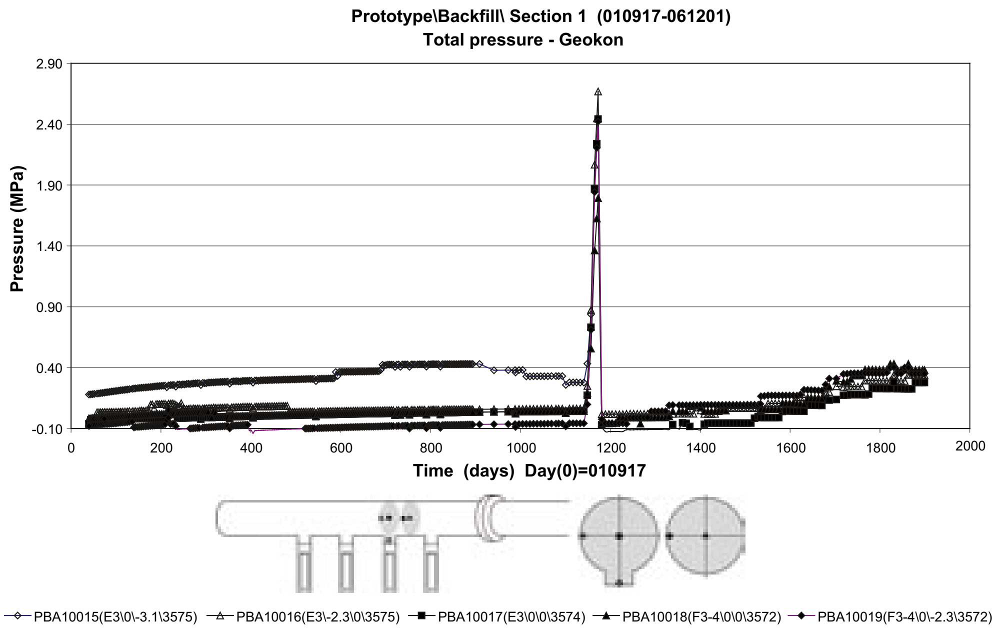


__Figure 4-2.__ Examples of measured total pressure in the backfill around deposition hole 3 (2001-09-17 to 2006-12-01).

Furthermore transducers were installed for recording the displacement of the canisters in deposition holes 3 and 6 /Barcena and Garcai-Sineriz 2001/. In addition resistivity measurements are made both in buffer and backfill /Rothfuchs et al. 2003/. The outcome from these measurements is profiles of the resistivity which can be interpreted to water ratios of the backfill and the buffer. Most transducers are still working and are giving reliable data.

Transducers for measuring the stresses and the strains in the rock around the deposition holes in Section II have also been installed /Bono and Röshoff 2003/. The purpose of these measurements is to monitor the stress and strain caused by the heating of the rock from the canisters.

A large programme for measuring the water pressure in the rock close to the tunnel is on-going /Rhén et al. 2003/. The measurements are made in boreholes which are divided into sections with packers. In connection to this work a new packer was developed that is not dependent of an external pressure to seal off a borehole section. The sealing is made of highly compacted bentonite with rubber coverage. Tests for measuring the hydraulic conductivity of the rock are also made with the use of the drilled holes.

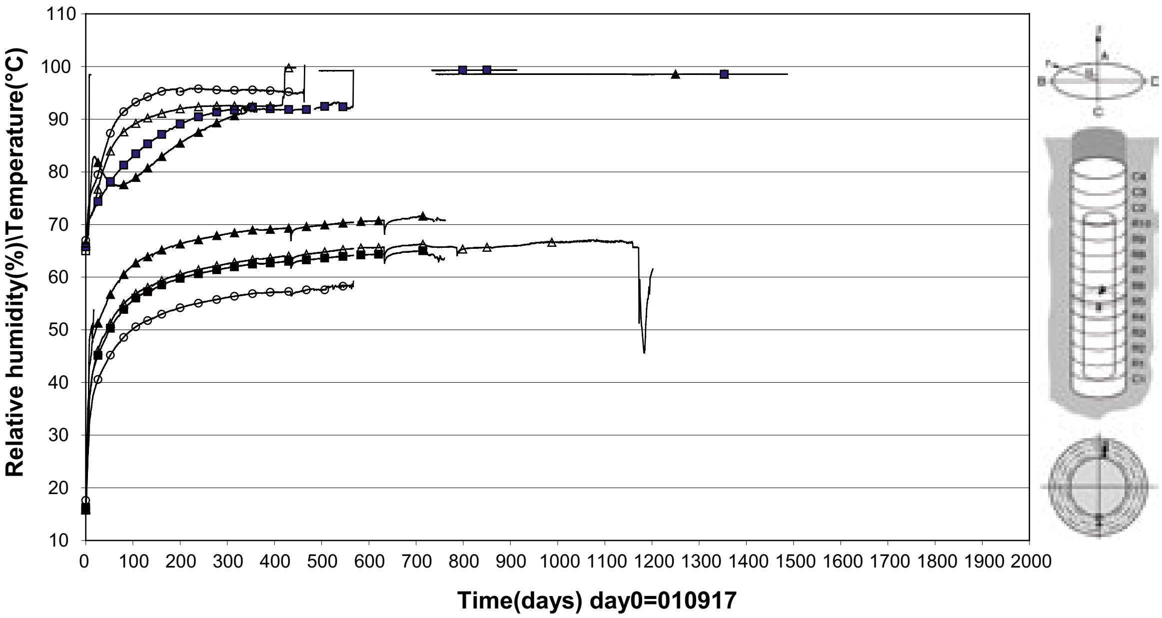
Equipment for taking gas and water samples both in buffer and backfill have been installed. Some sampling and testing have been done /Puigdomenech and Sandén 2001/.

Recording of THM processes

Comparison of the hydration at mid-height canister in “a wet and a dry” hole

The Prototype tunnel has until 1st November 2004 been drained. Most of the water coming into the inner section has been drained. This affects the water uptake both in the buffer and in the backfill. The saturation of the buffer has reached different levels in the six deposition holes due to variation in the access to water.

Deposition hole 1 can be considered a “wet” deposition hole while deposition hole 3 is very “dry”. In Figure 4-3 and Figure 4-4 measurements of relative humidity (RH) and total pressure in the two deposition holes are plotted as a function of days from start. Since the relative humidity sensors also measure the temperature, these values are plotted in the same figures. The transducers are placed in the buffer at mid height of the canisters (Block R5). The measurements in deposition hole 1 indicate a rapid increase both in total pressure and relative humidity. The RH-transducers have stopped yielding reliable values, probably due to high Relative Humidity close to the transducer indicating a high degree of saturation. The total pressure measurements in the buffer also indicate a fast saturation of the buffer. Two transducers are indicating an increase in pressure caused by the closing of the drainage and then a sudden drop in pressure when the heating was interrupted and the drainage was opened. After reopening the drainage and restarting the heaters the pressure increased to almost the same level as before closing of the drainage. Corresponding measurements in deposition hole 3 indicate very small changes in both relative humidity and total pressure with time. One of the RH-transducers indicates a faster hydration after the reopening of the drainage. The measured total pressure in hole 3 is much lower compared to the measurements made in hole 1.



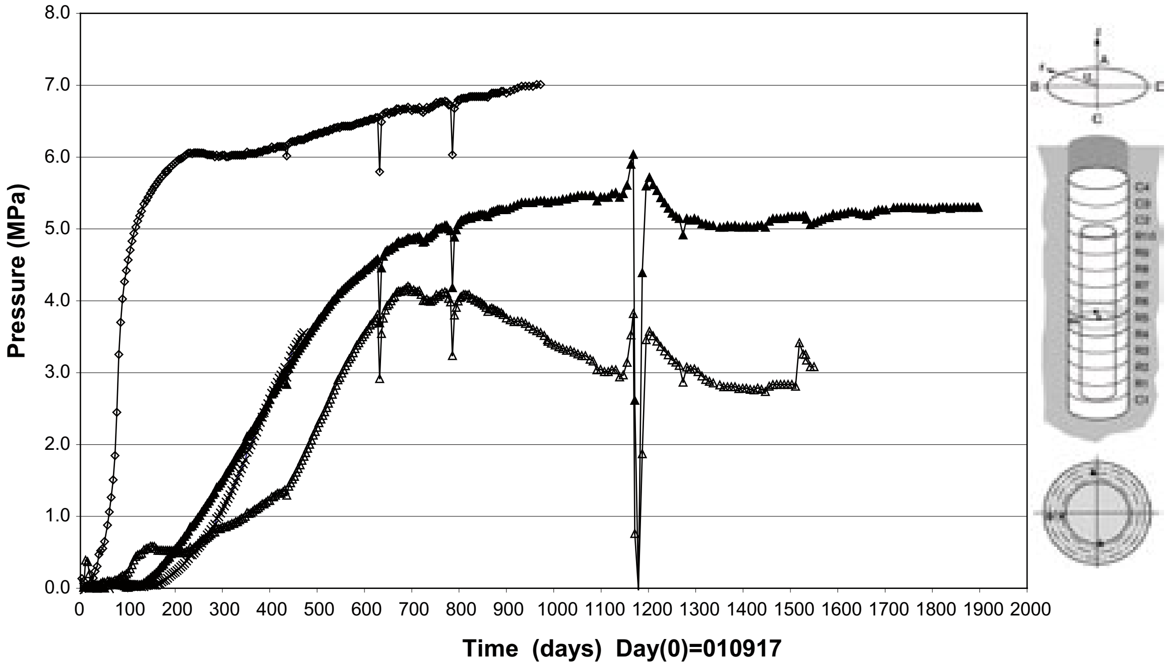
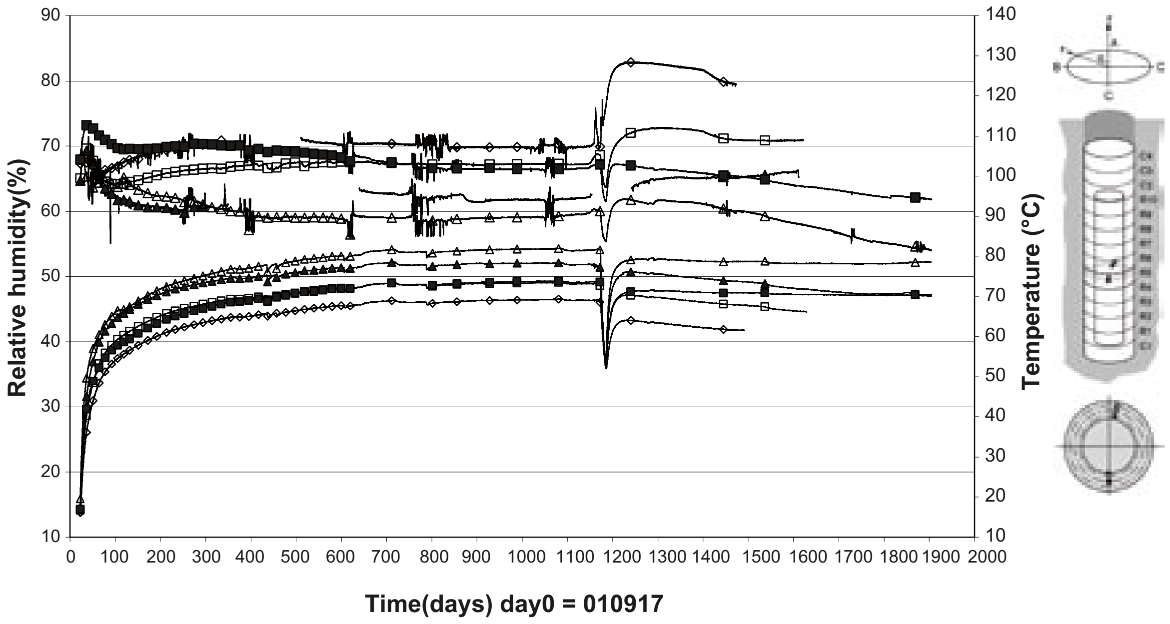


__Figure 4-3.__ Examples of measured relative humidity and temperature measurements made with the RH sensors (upper diagram) and total pressure (lower diagram) in deposition hole 1 (Ring 5, 2001-09-17 to 2006-12-01).



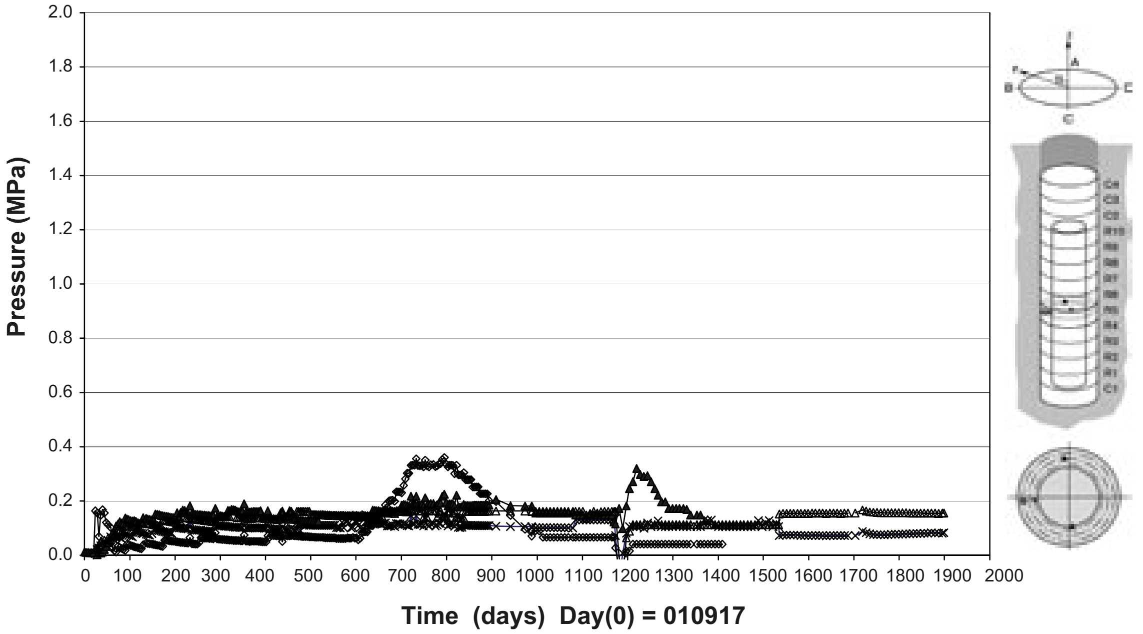


Figure 4-4. *Examples of measured relative humidity and temperature measurements made with the RH sensors (upper diagram) and total pressure (lower diagram) in deposition hole 3 (Ring 5, 2001-09-17 to 2006-12-01).*

Hydration of the backfill

The pore pressure in the backfill in Section I increased fast from a low level when the drainage of the tunnel was closed (see Figure 4-5). This affected the rate in which the backfill was saturated measured both with soil psychrometers and with resistivity measurements made by GRS. After the drainage was reopened the pore pressure stabilised at the same level as before it was closed. Figure 4-4 shows some results from measurements of suction in the backfill of Section I over deposition hole 1. The measurements are made with soil psychrometers. The curves indicate, as expected, a faster saturation of the backfill close to the roof and the walls of the tunnel while very slow changes in suction over time is recorded by transducers placed in the centre of the tunnel. This is valid up to the time when the drainage of the tunnel was closed. The sensors, which still gave reliable values, indicated a faster hydration after this event. However, after the reopening of the drainage most of the sensors, which still gave reliable data, indicated a similar hydration rate as before the closing of the drainage. When a packer placed in a borehole in Section I was broken (at the middle of April 2006) the pressure in the backfill (both total pressure and pore pressure) increased with about 300 kPa (see Figure 4-5). The increase in pressure affected also the measured suction values (measured with soil psychrometers). Six of the sensors measured a decrease in suction of about 500 kPa due to the broken packer.

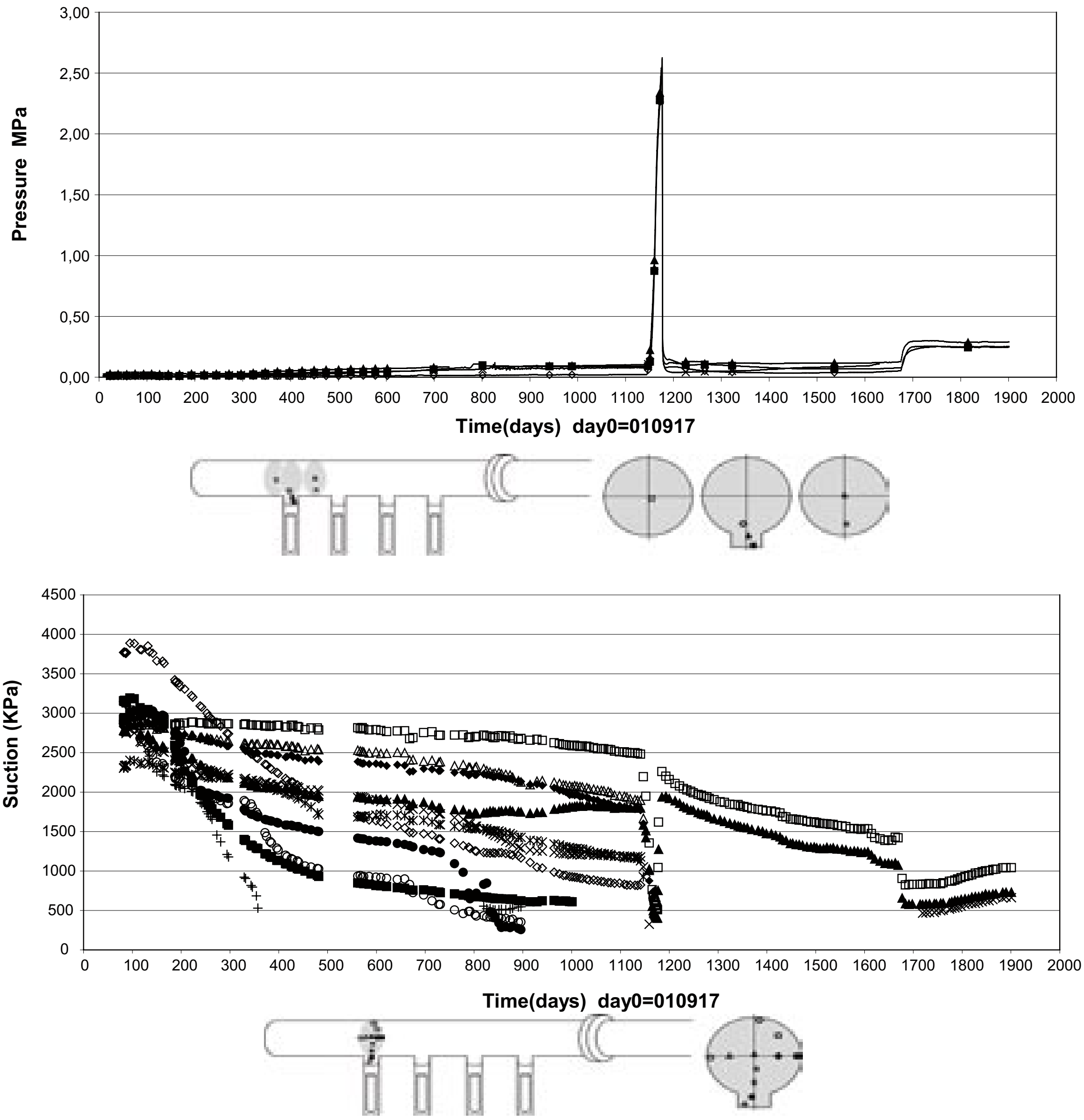


Figure 4-5. Pore pressure (upper diagram) and suction (lower diagram) measured in the backfill in Section I above deposition hole 1 (2001-09-17 to 2006-12-01).

The pore pressure, measured both with total and pore pressure transducers placed in the backfill in Section II, increased also fast from a low level when the drainage of the tunnel was closed (see Figure 4-6) and this affected the rate in which the backfill was saturated measured both with soil psychrometers and with resistivity measurements in the backfill. After the drainage was reopened again the pore pressure stabilised on a higher level than before the drainage was closed. Most of the installed soil psychrometers measured very low suction values after the closing/opening of the drainage which indicates that the backfill was close to fully saturated. The pore pressure in the backfill is continuing to increase although the drainage is kept open.

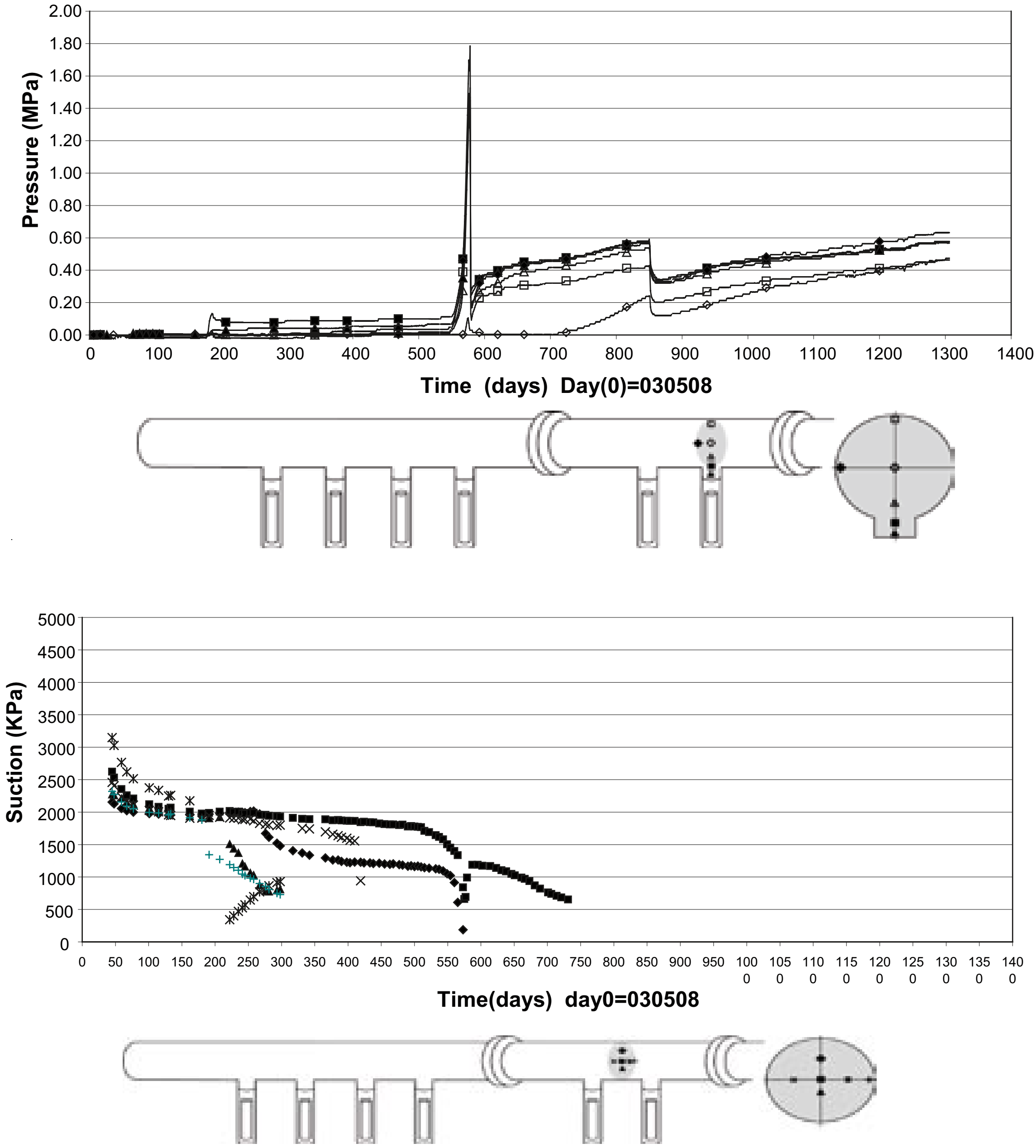


Figure 4-6. Pore pressure (upper diagram) and suction (lower diagram) measured in the backfill in Section I above deposition hole 6 (2003-05-08 to 2006-12-01).

Modelling of THM processes

The model used in predicting and evaluating the various processes in the Prototype Repository buffer and backfill have been described in detail in /Pusch 2001/ and predictive modelling has been reported in /Pusch and Svemar 2003/. The following is a brief summary of the major features of the models used for predicting the THM evolution:

- Thermal evolution in the buffer, backfill and near-field rock.
- Hydration of the buffer and backfill.
- Build-up of swelling pressure in the buffer and backfill.

The on-going THM modelling of the Prototype Repository at Clay Technology has been made with Code_Bright. The work has been carried out in steps, where the first step was to make a 3D thermal model of the Prototype Repository. The 3D thermal analysis has the following main objectives:

- Find relevant time-dependent thermal boundary conditions for local THM models of the individual deposition holes.
- Investigate how well the measured rock temperatures can be reproduced assuming one global and constant value of the rock heat conductivity.
- Check the influence of the backfill thermal properties on the overall thermal development around canister mid-height, i.e. the region where maximum temperatures are expected.
- Explore the effect of the open ventilated tunnel.

An example of results from the analyses is shown in Figure 4-7 where the calculated temperatures in the rock at mid height of the canister near deposition hole 5 are compared with measured temperatures.

The next step in the modelling work was to model the water uptake of the buffer with the use of a 1D model. In this work the focus was aimed at the engineered buffer system between the canister and the hosting rock wall. There are three different sections between the canister and rock wall. The main part is bentonite powder compressed into blocks. There is a slot between the block and the rock wall that is filled with bentonite pellets. There is also a slot between the canister and bentonite block that is open (see Figure 4-8).

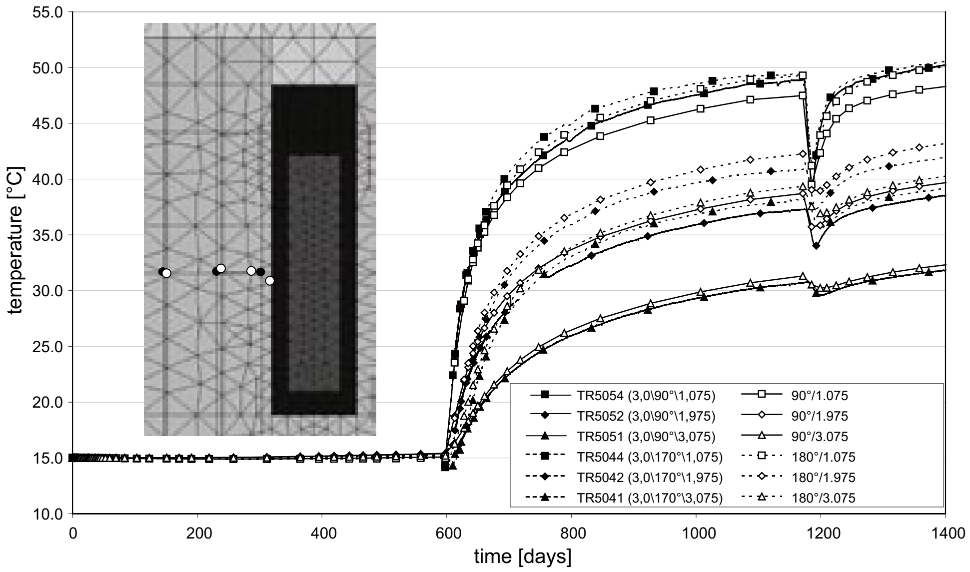


***Figure 4-7.** Calculated (white dots) and measured temperatures (black dots) in the rock close to deposition hole 5.*

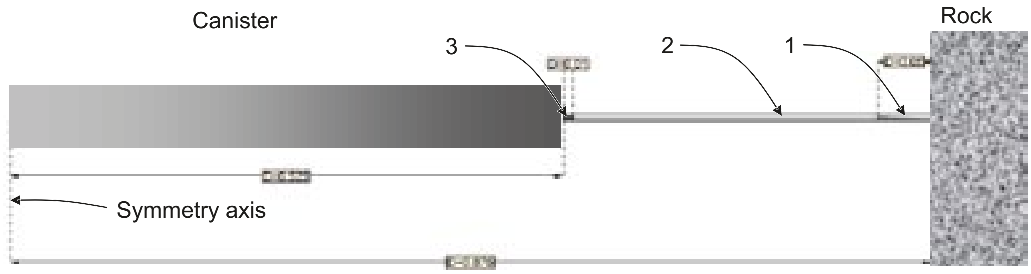


Figure 4-8. 1D model geometry: (1) slot between bentonite blocks and rock (filled with bentonite pellets), (2) bentonite blocks and (3) open slot between canister and bentonite blocks.

The main topics of the investigation were the water saturation process and homogenisation in the buffer. Thermal, hydrologic and mechanical conditions and processes are considered in the numerical study. This study also serves as a general investigation of the usefulness of the numerical tool, Code_Bright, in this field of application.

An example of data from the calculations are shown in Figure 4-9 where the calculated total pressures are compared with the measured pressure as function of time from the start of the test.

The third step in the modelling work was to use a 2D axisymmetric model of a deposition hole. The system considered consists of a canister and three different sections between the canister and rock wall defining the engineered buffer. Here the main focus is aimed at investigating heterogeneous processes in the system. This work is on-going and has not been finalised yet. An example of data from this work is shown in Figure 4-10 where the water saturation in the buffer is calculated with different assumptions on the water inflow at the rock boundary. Centred at mid height of the canister a 1 m section is subjected to full water access. The results are compared to the case where the buffer has access to water from the entire rock boundary.

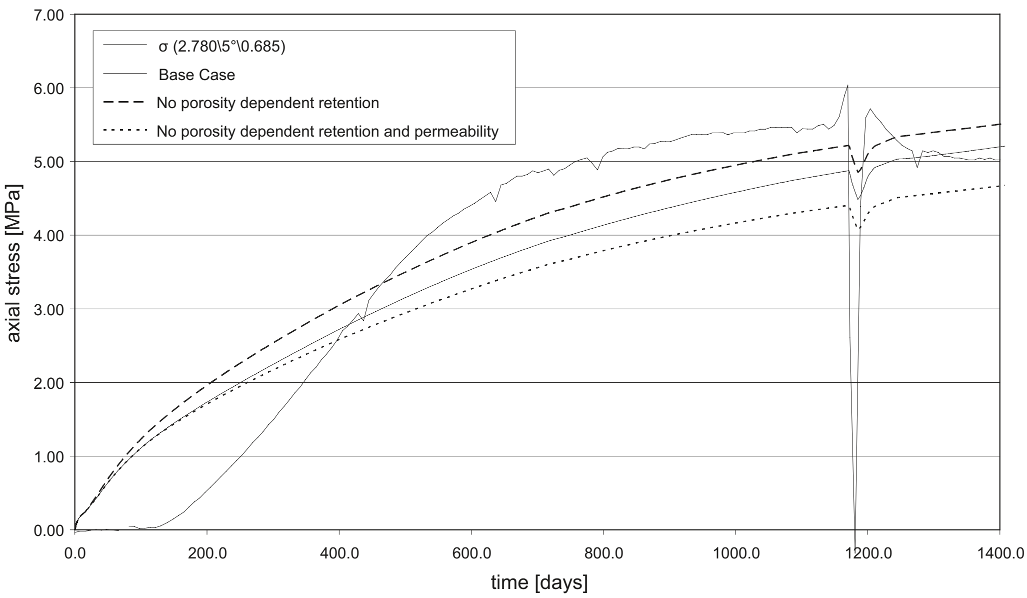


Figure 4-9. Calculated (with the use of a 1D-model) and measured stresses in the buffer (r = 0.685 m) at mid height of the canister in deposition hole 1.

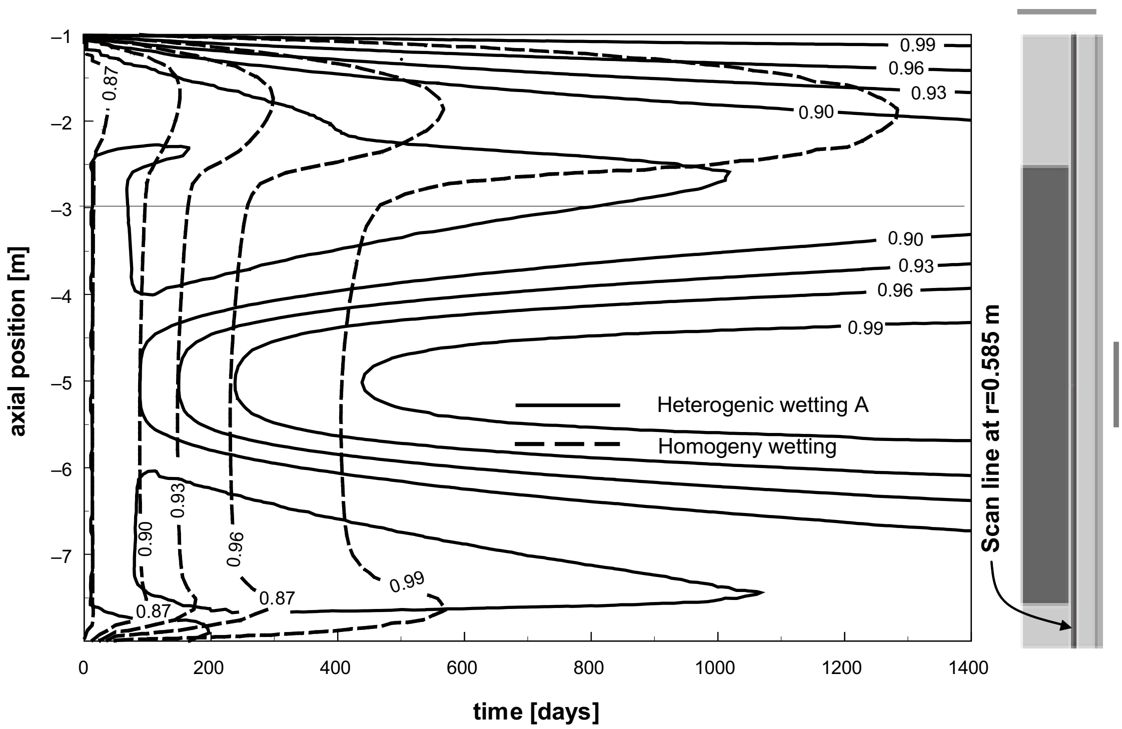


Figure 4-10. Water saturation map at r = 0.585 m for Heterogenic wetting A with Homogeny wetting as a reference.

4.3 Long Term Test of Buffer Material

4.3.1 Background

Bentonite clay has been proposed as buffer material in several concepts for radioactive waste 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 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.

4.3.2 Objectives

The present test series aims at validating models and hypotheses concerning the evolution of bentonite buffer properties. In the tests, related processes regarding microbiology, radionuclide transport, copper corrosion and gas transport under conditions similar to those expected in a KBS-3 repository are studied. 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:

- Collect 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 existing models on buffer-degrading processes, e.g. illitisation and salt enrichment.
- Collect data concerning survival, activity and migration of bacteria in the buffer.
- Check calculation results concerning copper corrosion, and information regarding type of corrosion.
- Check existing models for diffusive transport of cations.
- Collect information, which may facilitate the realisation of the full-scale test series, with respect to clay preparation, instrumentation, data handling and evaluation.

4.3.3 Experimental concept

The testing principle for all tests is to emplace parcels containing heater, central tube, pre-compacted clay buffer, instruments and parameter controlling equipment in vertical boreholes with a diameter of 300 mm and a depth of around 4 m, see Figure 4-11. The test series, given in Table 4-1, concern realistic repository conditions except for the scale and the controlled adverse conditions in three tests.

Adverse conditions in this context refer to high temperatures, high temperature gradients over the buffer, and additional accessory minerals leading to i.e. high pH and high potassium concentration in clay pore water. The central copper tubes are equipped with heaters in order to simulate the decay power from spent nuclear fuel. The heater effect is 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 controlled and temperature, total pressure, water pressure and water content are continuously being measured.

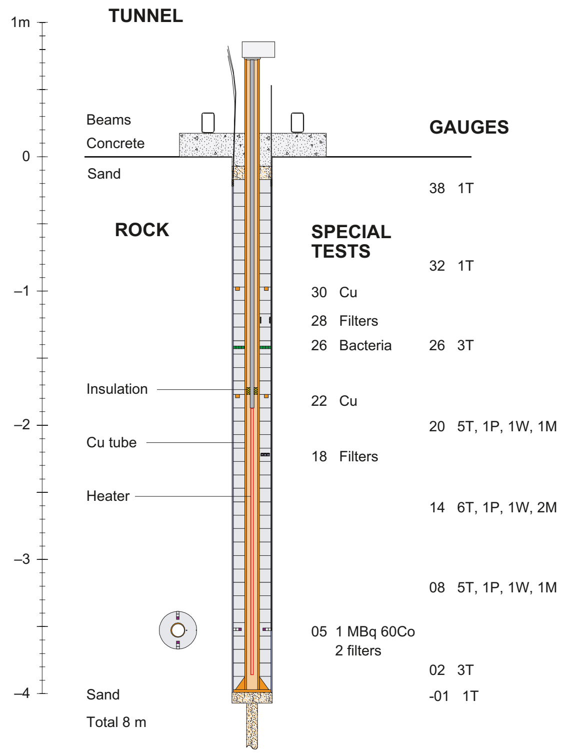


Figure 4-11. *Illustration of the experimental set-up in the Long Term Test of Buffer Material (left) and a cross-section view of one S-type parcel (right).*

Table 4-1. Buffer material test series.

Type	No.	Max T (°C)	Controlled parameter	Time (years)	Remark
A	1	130	T, [K^+], pH, am	1	Reported
A	0	120–150	T, [K^+], pH, am	1	Analysed
A	2	120–150	T, [K^+], pH, am	5	Uplifted, January 2006
A	3	120–150	T	5	On-going
S	1	90	T	1	Reported
S	2	90	T	5	On-going
S	3	90	T	>>5	On-going

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

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 is performed.

4.3.4 Results

Water pressure, total pressure, temperature and moisture in the three remaining parcels have been continuously measured and the data stored every hour. The data are being checked monthly. Minor maintenance and improvement work have been carried out on the running parcels.

Parcel A2 was uplifted in January and bentonite material was sent to the involved laboratories in Finland, France, Germany, Sweden and Switzerland. The physical properties of the exposed bentonite was analysed with respect to water content, buffer density and degree of saturation. Positions representing a radial distribution from the copper tube to the rock were analysed by tri-axial and unconfined compression tests in order to detect potential rheological changes. The same positions were examined with respect to potential changes in swelling pressure and hydraulic conductivity. Mineralogical analyses including mineral composition (powder X-ray), swelling properties (oriented sample X-ray), cation exchange capacity and element distribution were made in five radial positions from the copper tube to the rock both in hot and cold areas.

In general, the bentonite material was fully water saturated and all planned tests and analyses concerning the bentonite mineralogy and physical properties, copper corrosion, tracer element distribution and bacteria activity have been accomplished. The comprehensive set of results from all laboratories will be compiled in a technical report during the first half of 2007.

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 was partly a preparation for the Prototype Repository.

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.

- Test the function of the backfill and its interaction with the surrounding rock in full-scale in a tunnel excavated by blasting.
- Develop technique for building tunnel plugs and to test 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. Figure 4-12 shows a 3D visualisation of the experimental set-up. The test region, which is about 30 m long, is divided into the following three test parts:

- The inner part filled with a mixture of bentonite and crushed rock (six sections).
- The outer part filled with crushed rock and bentonite blocks and pellets at the roof (four sections).
- The 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 is filled with a mixture of bentonite and crushed rock with a bentonite content of 30%. The composition is based on results from laboratory tests and field compaction tests. The outer part is filled with crushed rock with no bentonite additive. Since the crushed rock has no swelling potential, but may instead settle with time, a slot of a few decimetres 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. The remaining irregularities between these blocks and the roof were filled with bentonite pellets.

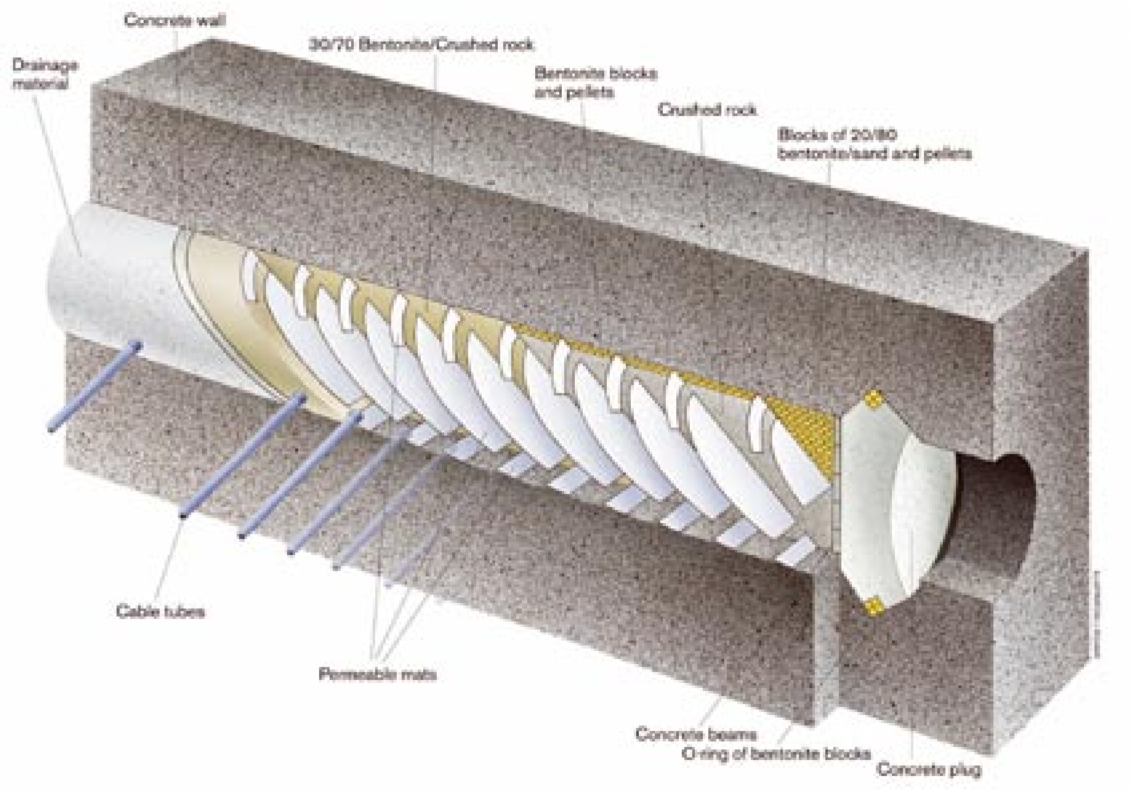


Figure 4-12. Illustration of the experimental set-up of the Backfill and Plug Test.

Each one of the two test parts are divided by drainage layers of permeable mats in order to apply hydraulic gradients between the layers and to study the flow of water in the backfill and near-field rock. The mats are also used for the water saturation of the backfill. The mats were installed in both test parts with the individual distance of 2.2 m. Each mat section was divided into 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 test part ends with a wall made of prefabricated concrete beams for temporary support of the backfill before casting of the plug. Since in situ compaction of the backfill cannot be made in the upper corner, this triangle was instead filled with blocks of bentonite/sand mixture with 20% bentonite content.

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

The backfill and rock are instrumented with piezometers, total pressure cells, thermocouples, moisture gauges, and gauges for measuring the local hydraulic conductivity. The axial conductivity of the backfill and the near-field rock is after water saturation 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 in boreholes drilled between the test tunnel and the neighbouring demonstration tunnel hosting the data collection room.

4.4.4 Results

The installation was completed and the wetting of the backfill from the permeable mat started at the end of 1999. The water pressure in the mats was increased to 500 kPa in steps of 100 kPa between October 2001 and January 2002 and kept at 500 kPa until the backfill was judged to be water saturated in the beginning of 2003. During 2003 the equipment was rebuilt for flow testing and the flow testing started at the end of that year. 2004 and most of 2005 have been devoted to flow testing of the 6 test sections of the 30/70 mixture.

The flow testing was done by decreasing the water pressure in the permeable mat sections (one by one) to 400 kPa and measuring the flow between the mat sections, starting with the filter at the plug. Tests have been done with flow in both directions. Both the inflow into the mats at the high pressure filter and the outflow out from the mats at the low pressure side were measured and the hydraulic conductivity for each section is evaluated as the average of the in- and outflow. Since there were separate mats in the centre of the tunnel, in the floor and in the roof the hydraulic conductivity in the centre could be separated from the hydraulic conductivity close to the floor and roof.

In 2006 measurements of hydraulic conductivity in single points by pressurising filter equipped tubes and measure the water flow into the backfill have been performed in the part filled with 30/70 mixture. Altogether four such measurements were done with probes installed in the central parts of the backfill. The results varied between $K = 10^{-11}$ m/s and $K = 2.3 \cdot 10^{-10}$ m/s with the average value $K = 10^{-10}$ m/s.

Figure 4-13 shows a compilation of all measurements of hydraulic conductivity in the 30/70 backfill. Both results from earlier laboratory results and results from the flow testing between mats as well as the local permeability measurements are included. The high hydraulic conductivity at the roof corresponds well to the expected results at the low densities achieved there.

Late 2006 the tests with the pressure cylinders installed in the roof and in the floor started. In spite of the long time that has elapsed since installation these devices seem to work well.

Logging of measured results from all sensors have continued during 2006 except for the relative humidity sensors, which were disconnected since all those sensors showed full water saturation. Two data reports /Goudarzi et al. 2006a/ and /Goudarzi et al. 2006b/ have been released.

In addition to the field testing, laboratory experiment and modelling with the aim to evaluate the hydraulic conductivity of the backfill materials are in progress but are delayed.

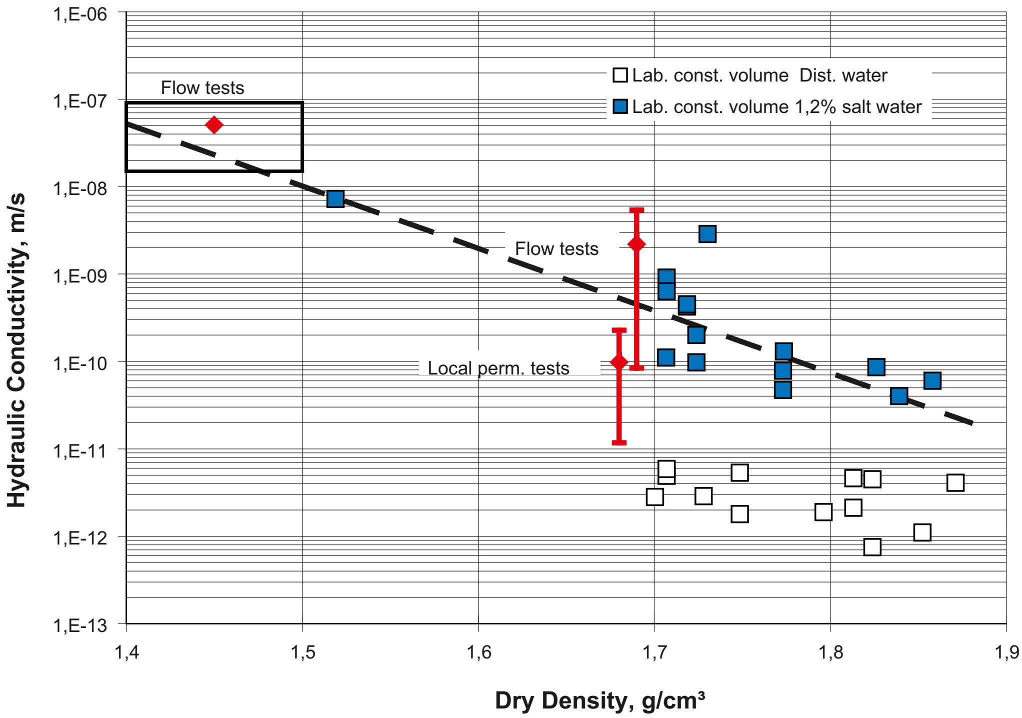


***Figure 4-13.** Compilation of the results of the field measurements of hydraulic conductivity and comparison with laboratory results. The average values and the scatter of the field tests are shown in red.*

4.5 Canister Retrieval Test

4.5.1 Background

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

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.

4.5.2 Objectives

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

- Two vertically bored test holes in full repository scale, which fulfil the quality requirements deemed necessary for the real repository.
- Careful and documented characterisation of the properties of these holes including the boring disturbed zone.
- Emplacement of bentonite blocks, bentonite pellets and canisters with heaters, and artificial addition of water. However, only one of these deposition holes has been used for implementation of the Canister Retrieval Test.
- Saturation and swelling of the buffer are monitored under controlled conditions.
- 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 were made within sub-projects that also concern other tests in the Äspö HRL. In addition to the retrieval test, the results from monitoring of the buffer and the laboratory testing of excavated parts of the buffer will be used to increase the understanding of the THM processes in a deposition hole.

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 period is separated into three stages:

Stage I Boring of deposition holes and installation of instrumented bentonite blocks and canister with heaters in one hole. This hole is covered at the top with a lid of concrete and steel.

Stage II Saturation of the bentonite and evolution of the thermal regime with measurement of thermal, hydraulic and mechanical processes.

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

The buffer was installed in the form of blocks of highly compacted Na-bentonite, with a full diameter of 1.65 m and a nominal height of 0.5 m. Instruments for measuring temperature, relative humidity, total pressure and pore pressure were installed in the bentonite in many of the blocks. When the stack of blocks was 6 m high the canister equipped with electrical heaters was lowered down in the centre. Cables to heaters, thermocouples in the rock and strain gauges in the rock were connected, and additional blocks were emplaced until the hole was filled up to 1 m from the tunnel floor. On top the hole was sealed with a plug made of concrete and a steel plate as cover. The plug was secured against heave caused by the swelling clay with 9 cables anchored to the rock. The tunnel was left open for access and inspections of the plug support. The experimental set-up is shown in Figure 4-14.

Artificial addition of water was provided evenly 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 was 2–3 years in the 350 mm thick buffer along the canister and 5–10 years in the buffer below and above the canister.

4.5.4 Results

Based on the information regarding saturation of the buffer and the problems with the heaters it was decided in 2005 that stage III (Retrieval of the canister) should take place in the beginning of 2006.

Excavation and sampling of the bentonite buffer started in January. The measurements with the remaining transducers continued during the excavation and retrieval until all transducers were recaptured in order to yield as much information as possible about the effect of the pressure decrease during excavation. A final data report covering the period up to the end of May has been delivered /Goudarzi et al. 2006c/.

The canister was successfully retrieved and the main field activities during the retrieval are described below.

Removal of lid

The removal of the lid in the deposition hole showed to be a straight forward task. Once the tension of the restraining wires was loosened the steel plate was easy to lift. There were no issues with deformations or corrosions etc. The same applies to the underlying concrete plug.

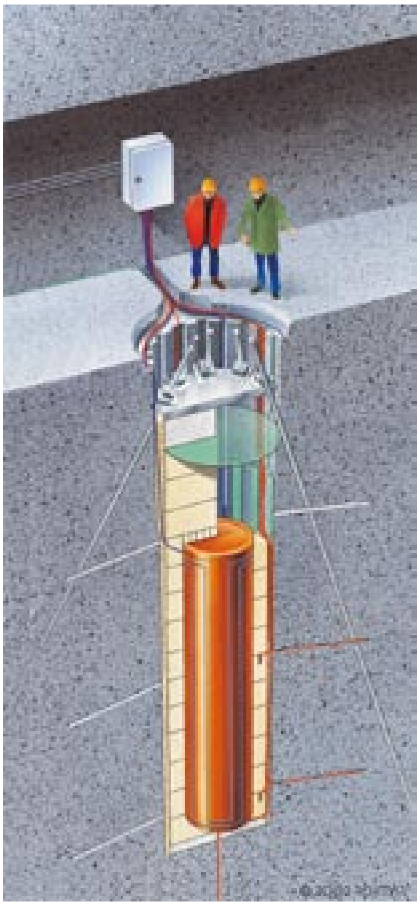


Figure 4-14. *Illustration of the experimental set-up of the Canister Retrieval Test.*

Buffer sampling

The buffer sampling was executed with core drilling technique. About 60 cores were drilled from each buffer block above the canister and approximately 45 from each of the buffer rings along the upper half of the canister. The bentonite was sampled down to half the canister height. The cores was then sawed in smaller parts and analysed. Initial analysis was conducted during 2006 to look at the water content and density. Further studies will also be performed in 2007, focusing on hydraulic conductivity, compressibility, chemical/biological composition etc.

Buffer disintegration

Earlier the disintegration method has been tested in small scale at Äspö HRL. The canister retrieval test is the first time the method is tested in full scale with saturated bentonite and a full scale canister. The method proved to be an efficient way of removing the buffer from the deposition hole. Some unforeseen events interrupted the process which was initially planned to run continuously. However the total running time of the system was close to the calculated running time for the process. The results from the test give vital input for further development of the equipment used for buffer disintegration.

Canister retrieval

Retrieval of the canister was performed in May 2006. The same machine was used as during the deposition of the canister. The canister was lifted from the deposition hole and put on its side in the machine. The canister remained in the tunnel at the experimental site for two weeks before being transported out of the tunnel to a storage building near the tunnel entrance. At the end of August the canister was transported to SKB's Canister Laboratory in Oskarshamn for analyses.

Investigation of heater power cables

Power failure to the heaters was a worrisome problem in the project operational phase. During buffer excavation and sampling the heater power cables were removed and examined. Cable damage is clearly visible, both in sections that have been inside and outside the canister. Outside the canister the cables are compressed and twisted by the buffer pressure, analyses show that these damages are not significant and that these damages are not the reason for power failure.

The critical damages of the cables are present in the sections between the canister lids (the retrieval canister has one extra copper lid to protect the cables and sensor connectors). The cable outer shields are at sections entirely broken. The failure of the shield has allowed water to enter the cable, thus causing power failure. For some reason the cable has not been able to withstand the hot and moist conditions.

Further testing of the heaters inside the canister will show if there are any problems with the heaters or power connectors inside the canister.

4.6 Temperature Buffer Test

4.6.1 Background

The aim of the Temperature Buffer Test (TBT) is to evaluate the benefits of extending the current understanding of the behaviour of bentonite buffer to include high temperatures (above 100°C). The French organisation Andra is running the test in Äspö HRL in co-operation with SKB. In support of the field Temperature Buffer Test, a mock-up test has been implemented. This test, performed by CEA, is further presented in Section 7.2.1.

The scientific background to the project relies on results from large-scale field tests on engineered barrier systems carried out in underground laboratories: the Buffer Mass Test (Stripa), the Buffer/Container Experiment (URL in Canada), Febex (Grimsel Test Site), Canister Retrieval Test and Prototype Repository (Äspö HRL).

4.6.2 Objectives

The Temperature Buffer Test aims at improving the current understanding of the thermo-hydro-mechanical behaviour of clay buffers at temperatures around and above 100°C during the water saturation transient, in order to be able to model this behaviour.

4.6.3 Experimental concept

TBT is located in the same test area as the Canister Retrieval Test (CRT) at the –420 m level. Two identical heater probes, each 3 m long and 0.6 m in diameter, are stacked in a vertical 1.8 m diameter deposition hole. The principle design of the test and the experimental set-up are shown in Figure 4-15.

Two buffer arrangements are being investigated:

- One probe is surrounded by bentonite in the usual way, allowing the temperature of the bentonite to exceed 100°C locally.
- The other probe has a ring of sand between the probe and the bentonite, as thermal protection for the bentonite, the temperature of which is kept below 100°C.

The principle of the TBT test is to observe, understand and model the behaviour of the deposition hole components, starting from an initial unsaturated state under thermal transient and ending with a final saturated state with a stable heat gradient.

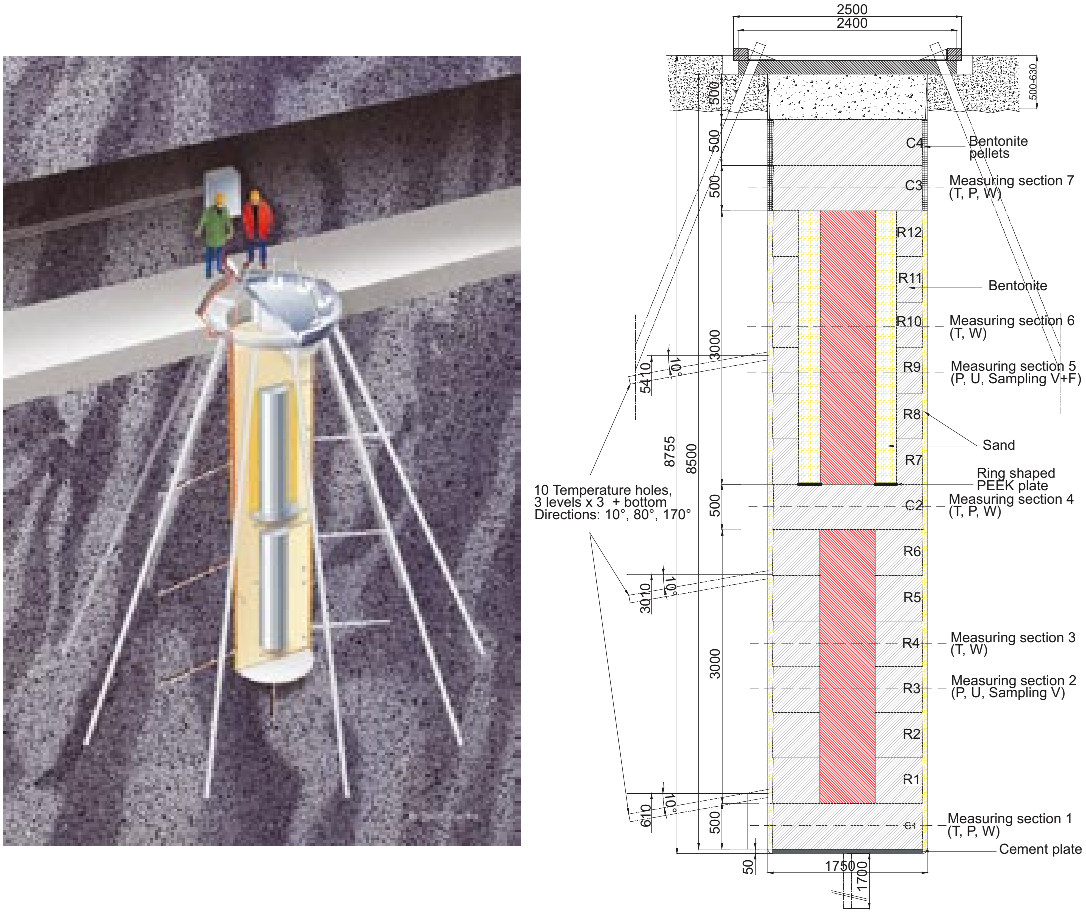


Figure 4-15. *Principle design and experimental set-up of the Temperature Buffer Test.*

Heat transfer comes into play from the start of the test, possibly redistributing water being present in the buffers, with partial desaturation of very hot zones (> 100°C). Inflow of water then causes saturation and consequent swelling of the bentonite.

The effects of a bentonite desaturation/resaturation cycle on the confinement properties are not well known. An open question which TBT is designed to answer is whether the mechanical effects of desaturation (cracking of the material) are reversible.

The similar geometries of CRT and TBT, the similar artificial water saturation systems, and the use of MX-80 bentonite buffer will facilitate interpretation of data and comparisons of results.

4.6.4 Results

Experimental results

The experiment has generated data since the start in March 2003. The results include measurements of temperature, relative humidity, total pressure, pore pressure and cable forces in the anchoring system. The inflow into the sand filter surrounding the experiment is also recorded. The data are reported in sensor data reports /Goudarzi et al. 2006d/.

The thermal conditions in the experiments at mid 2006 are illustrated in Figure 4-16. The dense arrays of thermo-couples enable a continuous evaluation of thermal conductivity distribution, which in turn give an indication of the saturation process. The CRT experiment is located 6 m from the TBT experiment and has therefore contributed with a certain heat flux. The heaters in the CRT was turned off in October 2005. In order to compensate for this loss, the power output from the TBT heaters was increased from 1,500 to 1,600 W on June 9, 2006.

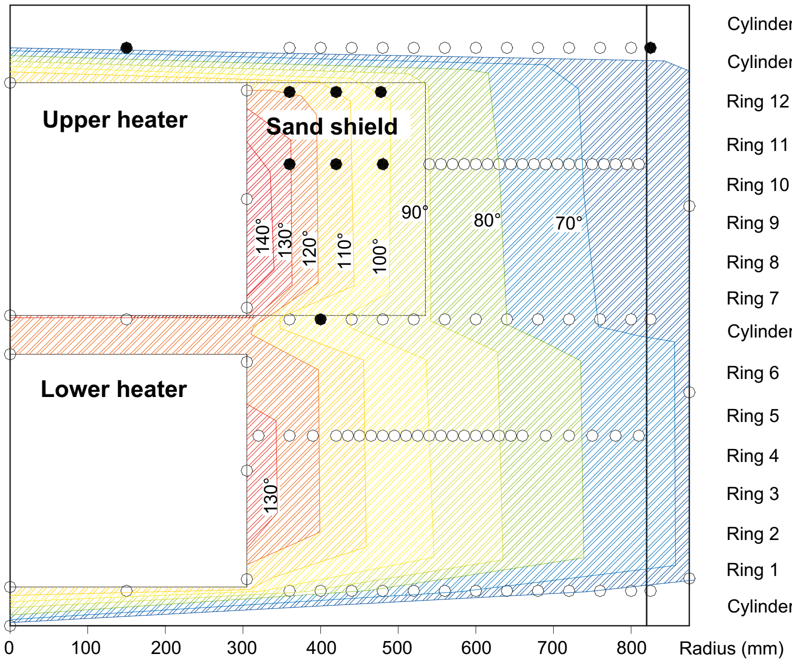


***Figure 4-16.** Temperature distribution 1st July 2006. Rings indicate sensor positions. Filled rings indicate sensors out of order.*

The hydration of the buffer, as recorded by the relative humidity (RH) sensors, is illustrated in Figure 4-17. Occasions when capacitive sensor signals showing RH ≈ 100% (Vaisala and Rotronic), and all active signals from psychrometers, corresponding to RH > 95% (Wescor), are compiled. These occasions have earlier been taken as indication of saturation. Recent results from the pore pressure sensors have, however, led to a reassessment of this interpretation. The current understanding is that the process of reaching full saturation is slow, and that only the bentonite at the mid-section around the upper heater has yet reached this condition.

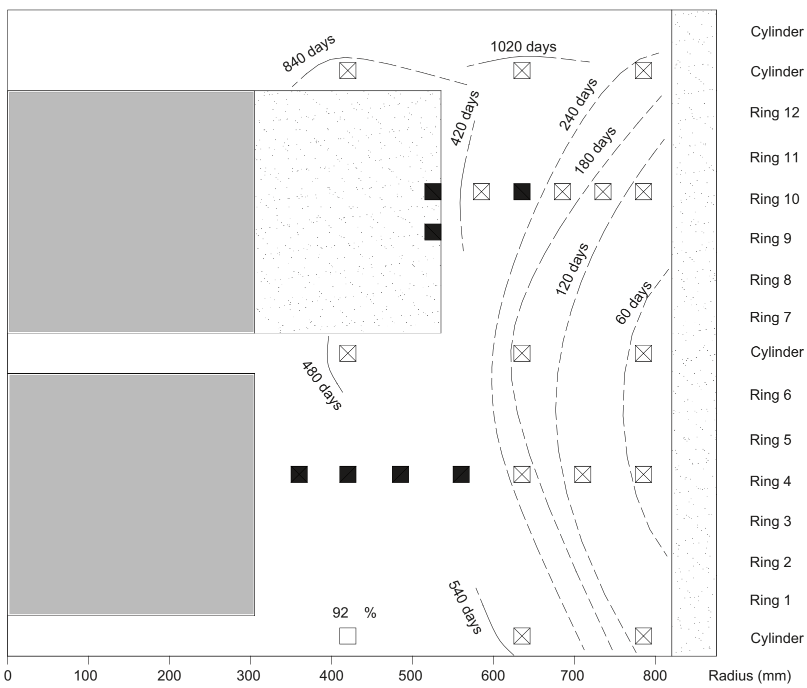


***Figure 4-17.** Occurrences of saturation up till 1st July 1 2006. Boxes are sensor positions. Ticked boxes indicate saturation. Filled boxes indicate sensors out of order. Percentages are current RH values.*

Pore pressure sensors should ideally give a zero signal as long as the condition is not totally saturated. At present, four sensors, the outermost in Ring 3 and all sensors in Ring 9 located in the bentonite, clearly show positive values, which indicates that these parts are saturated. The development of the relative humidity in Ring 10 and the pore pressure in Ring 9 are shown in Figure 4-18 and Figure 4-19 respectively. The response of the pore pressure was apparently much slower than the relative humidity.

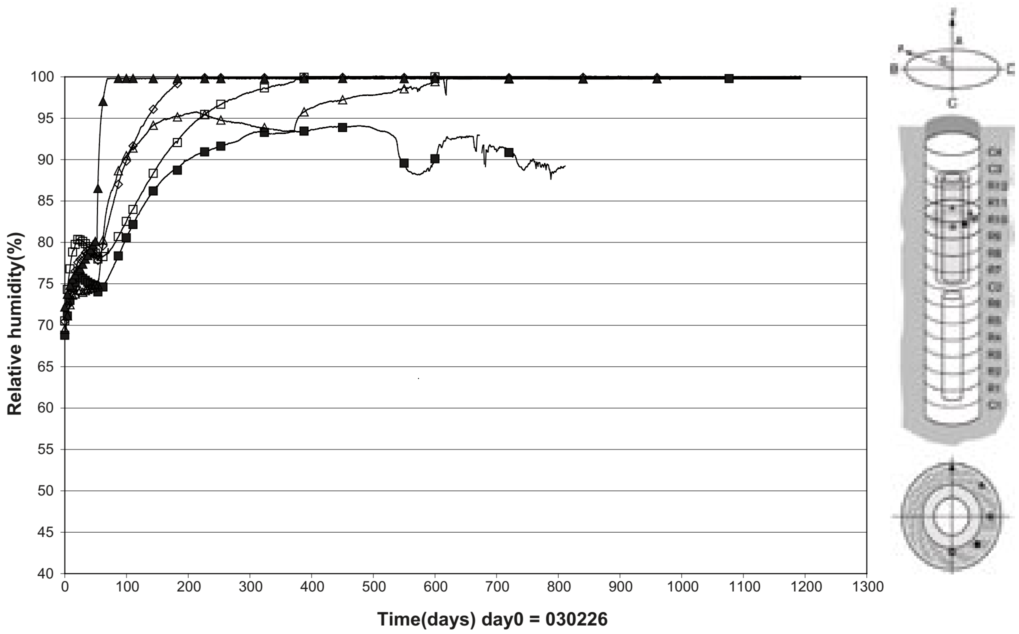


Figure 4-18. *Measured relative humidity in Ring 10 (2003-03-26 to 2006-07-01).*

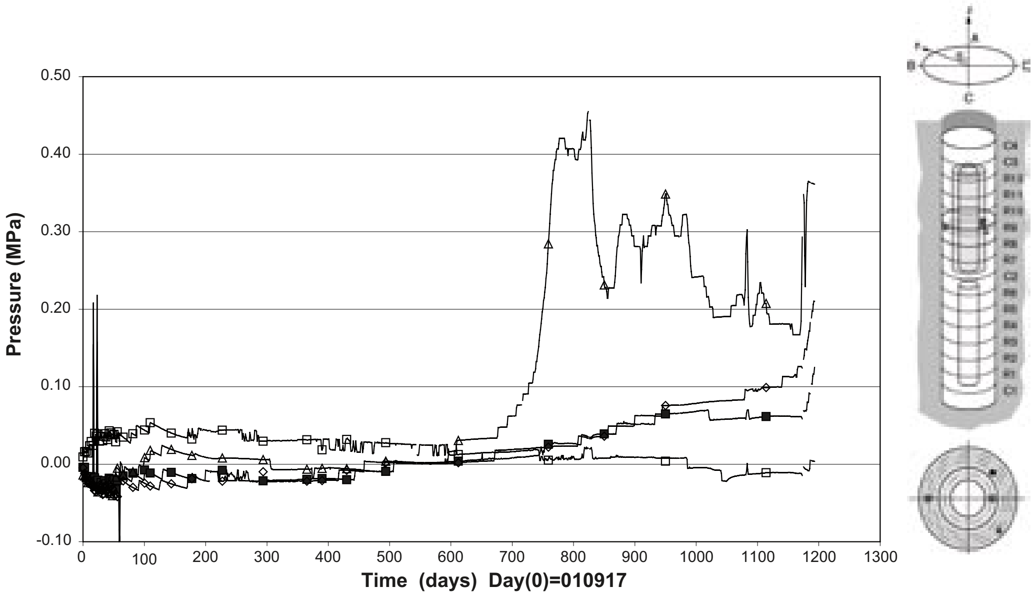


Figure 4-19. *Measured pore pressure in Ring 9 (2003-03-26 to 2006-07-01).*

A compilation of recent total pressures is shown in Figure 4-20. From this a number of observations can be made. Higher pressure levels occur in the outer parts throughout the experiment. An exception is upper Cylinders 3 and 4, which display the lowest pressure levels as they are not yet saturated. The conditions in lower Cylinder 1 and in Cylinder 2 at mid height are quite isostatic, while Rings 3 and 9 around the heaters are characterised by deviatoric stresses, with relatively lower radial stresses.

The water inflow has been found to be correlated with the filter pressure since July 2005 (Figure 4-21). This condition suggests that a major part of the injected water since that date has been lost as a leakage, while the actual uptake in the buffer has been small. An evaluation of these relations are reported in /Goudarzi et al. 2006d/.

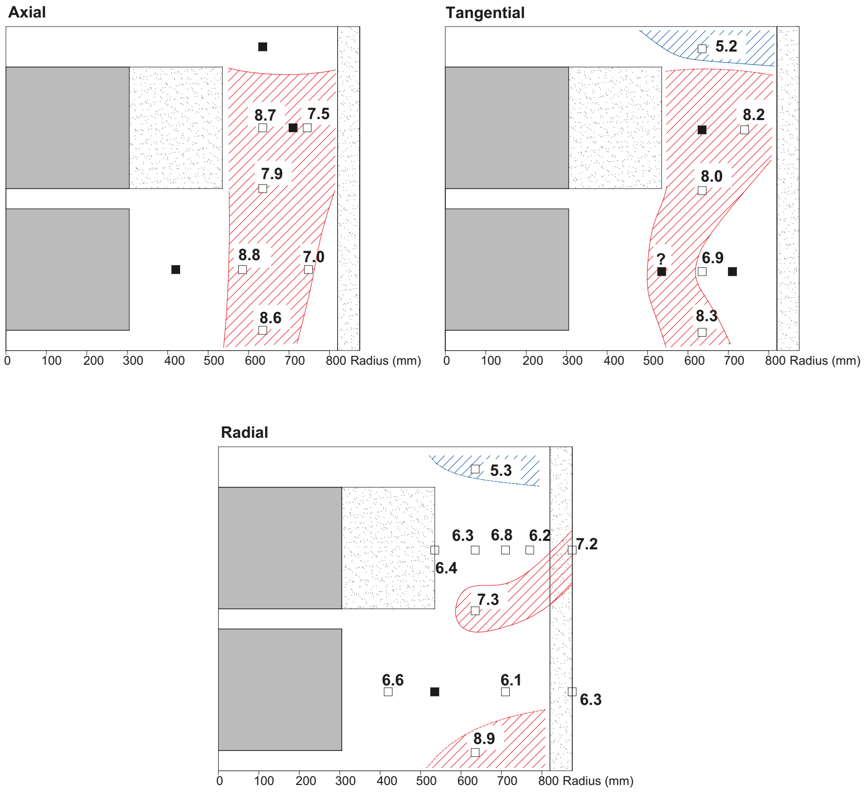


Figure 4-20. *Total pressure distribution 1st July 2006. Values in MPa. Boxes are sensor positions. Filled boxes indicate sensors out of order. Levels above 7 MPa marked red; below 6 MPa marked blue.*

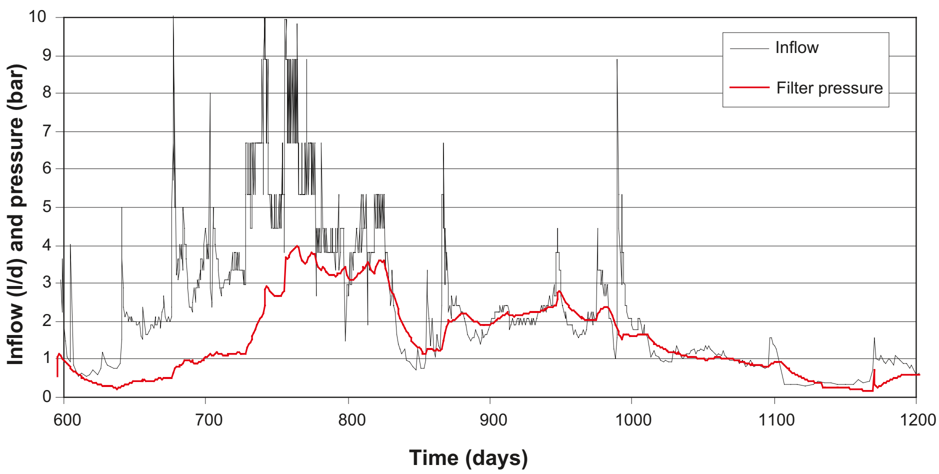


Figure 4-21. *Evolution of water pressure in sand filter and inflow since November 2004.*

Modelling results

Two modelling tasks were initiated during 2006:

- *Predictive modelling of mock-up test (TBT_3).* This task was similar to the previous task (TBT_2), with simultaneous blind predictive modelling and experimental work. TBT_3 followed a simpler and more efficient thermal protocol and the experimental setup was also improved. Due to the novelty of the experimental results, the task was extended to include an evaluation modelling phase, in which the models were modified. This task was completed in November 2006.
- *Field-test modelling task.* This task focuses on replication of obtained high-confidence experimental results from the field test: stresses, cable forces and lid displacements. Preliminary results were presented at the modelling meeting held in November 2006. The task is currently regarded as second priority, temporarily interrupted by preparatory activities necessitated by the decision to launch a gas injection test in 2008. The task will be readdressed when these activities are completed.

Both tasks have been carried out by groups from CIMNE-UPC (supported by Enresa, Spain) and Clay Technology (Sweden). Both groups use the Code_Bright FEM code.

The TBT_3 mock-up test was conducted by CEA (France) and designed to mimic the conditions at the interior of the buffer around the lower heater in TBT. Predictions were based on information of geometry, initial density and water ratio, and a prescribed thermal protocol. The experiment is presented in more detail in Section 7.2.1.

In the course of the evaluation modelling phase, it was found that deviations from the conventional concepts of THM modelling had to be made in order to mimic the experimental results from TBT_3. This concerned the applied mechanical constitutive laws, the retention properties and the liquid relative permeability. These findings may very well be relevant for the understanding of the field test.

Although only preliminary results have been presented from the field test modelling task, some general observations can be made:

- The thermal problem is highly influenced by the thermal properties of the host rock. In order to solve the thermal problem it is necessary to explicitly model a significant volume of rock. This leads on the other hand to a geometry significantly larger than the actual experiment, which in turn implies very time consuming calculations. Both modelling groups made different attempts to minimise this superfluous volume.
- More work is needed to ensure that fully coupled THM-models can be executed with satisfactory numerical stability.
- Other mechanical models, e.g. the Barcelona Expansive Model, appear to be more adequate for representing the bentonite mechanical behaviour in this type of problem.

4.7 KBS-3 Method with Horizontal Emplacement

4.7.1 Background

The KBS-3 method based on the multi-barrier principle is accepted by the Swedish authorities and the government as base for the planning of the final disposal of the spent nuclear fuel. The possibility to modify the reference method and make serial deposition of canisters in long horizontal holes (KBS-3H) instead of vertical emplacement of single canisters in the deposition hole (KBS-3V), see Figure 4-22, has been considered since early nineties.

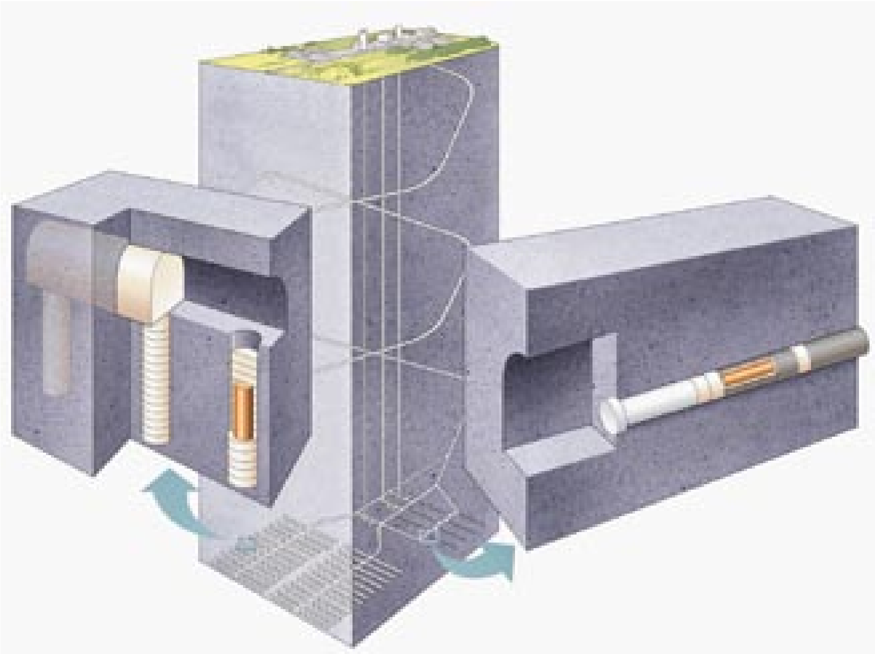


Figure 4-22. Principal for the multi barrier KBS-3 concept showing both the vertical deposition (KBS-3V) and the horizontal deposition (KBS-3H).

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

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

Late 2001 SKB published an R&D programme for the KBS-3 method with horizontal emplacement. The RD&D programme /SKB 2001/ is divided into four parts: Feasibility study, Basic design, Demonstration of the concept at Äspö HRL and Evaluation. The RD&D programme is carried through by SKB in co-operation with Posiva.

4.7.2 Objectives

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

The second step, the Basic design study /Thorsager and Lindgren 2004/, focuses on technology for excavation of holes, emplacement and design of the Supercontainer. The deposition process requires that each copper canister and its buffer material are assembled into a prefabricated so-called Supercontainer. In addition, an evaluation of the long term safety of the concept is carried out.

4.7.3 Demonstration site

A need for a demonstration of the KBS-3H concept was foreseen in the KBS-3H feasibility study and it was decided to investigate a suitable location and prepare a site at Äspö HRL. The demonstration site is located at the –220 m level in a niche, 15 times 25 metres. The niche is designed to accommodate vehicles, machinery and auxiliary equipment for drilling of the holes. Two horizontal holes with a diameter of 1.85 m have been excavated, one hole is 15 m long and the other is 95 m. The short hole will be used for construction and testing e.g. of a low-pH shotcrete plug and other design components, and the long hole will primarily be used for demonstration of the deposition equipment but also for evaluation of the chosen excavation method.

4.7.4 Results

Preparation work at the niche at –220 m level at Äspö HRL was finalised in the beginning of 2006. The deposition equipment for emplacement of Supercontainers into the drift was delivered 10th of March and the transportation to –220 m level was performed 17th of March, see Figure 4-23. During the manufacturers (CNIM) preparation work before the Site Acceptance Test (SAT) problems with the balancing/rotation of the deposition machine arose. The rest of the year, modifications were done to solve the problems and the Site Acceptance Test was postponed to be performed in February 2007.

Test of low pH shotcrete plug

The low pH shotcrete plug was installed in November 2005 by Aitemin. The pressure test was planned to be carried out in early February. During the preparation test, a leakage was found and the pumps had to be changed. The test was performed in the beginning of March and showed 12 mm displacement of the plug at the pressure of 2.76 MPa. The dismantling was performed during May and June. The test was evaluated and reported inside the Esdred-project by Enresa/Aitemin.

Figure 4-23. *The KBS-3H deposition equipment in the niche at –220 m level at Äspö HRL.*

Test of low pH shotcrete for rock support

The shotcrete test was accomplished late May, in nische Nasa 1504A at –200 m level. A sample test and an adhesion test were performed in June. The tests have been evaluated and reported inside the Esdred-project. The conclusions are that the mixing of concrete is a very important factor to get a feasible concrete and also that the accelerator has to be distributed better at the nozzle to have the right effect when the shotcrete is applied.

Test of steel plug

To isolate sections in the KBS-3H drift with too high water inflow steel plugs are planned to be used to seal off those parts. The steel plug has been designed and will, during 2007, be tested in the 15 m long drift at –220 m level at Äspö HRL.

Other activities

Design work

In the design work important components as the steel plug and the Mega Packer (grouting device to be used in the drift) have been designed. The buffer design has continued during year 2006 with a number of experiments in different scales. The objective has been to further verify the limitations of the system with respect to water inflow and pressure increase rate, but also to give input to the design of the so called fixing ring which is a necessary part of the tight distance block design. In order to evaluate the feasibility of the KBS-3H concept, an Olkiluoto specific layout adaptation has been carried out to assess the site utilisation degree of the concept and to provide basis for a safety assessment. A feasibility study of the retrievability of the KBS-3H concept will be performed.

Safety case

A planning report for the KBS-3H safety case has been finalised. Work has continued with the completion of a Process and Evolution report. Work to resolve the critical issues highlighted in the review of the preliminary safety assessment has continued. The report on the experimental study on the interaction between corroding iron under anaerobic conditions and bentonite has been finalised. It is necessary to perform further work regarding the iron-bentonite interaction.

4.8 Large Scale Gas Injection Test

4.8.1 Background

The bentonite buffer is an important barrier in the KBS-3 system. A key purpose of the buffer is to serve as a diffusion barrier between the canister and the groundwater in the rock. An important performance requirement of the buffer material is not to cause any harm to the other barrier systems. Gas build up from, for example, corrosion of the iron insert could potentially affect the buffer performance in three ways:

- Permanent pathways in the buffer could form at gas breakthrough. This could potentially lead to a loss of the diffusion barrier.
- If the buffer does not let the gas through, the pressure could lead to mechanical damage of the other barriers.
- The gas could dehydrate the buffer.

Current knowledge pertaining to the movement of gas in initially water saturated buffer bentonite is based on small-scale laboratory studies. While significant improvements in our understanding of the gas-buffer system have taken place, recent laboratory work has highlighted a number of uncertainties, notably the sensitivity of the gas migration process to experimental boundary conditions and possible scale-dependency of the measured responses. These issues are best addressed by undertaking large scale gas injection tests.

4.8.2 Objectives

The aim of the Large Scale Gas Injection Test (Lasgit) is to perform a gas injection test in a full-scale KBS-3 deposition hole. The objective of this experimental programme is to provide data to improve process understanding and test/validate modelling approaches which might be used in future performance assessment activities. Specific objectives are:

- Perform and interpret a large scale gas injection test based on the KBS-3 repository design concept.
- Examine issues relating to up-scaling and its effect on gas movement and buffer performance.
- Provide additional information on the process of gas migration.
- Provide high-quality test data to test/validate modelling approaches.

The Lasgit project will end after two years of gas testing. At that stage a decision will be taken whether to dismantle the experiment or to continue with testing in a new project.

4.8.3 Experimental concept

Lasgit is a full-scale demonstration project conducted in the assembly hall area in Äspö HRL at a depth of –420 m. A deposition hole, 8.5 m deep and 1.8 m in diameter, has been drilled into the gallery floor. A full-scale KBS-3 canister (without heater) has been emplaced in the hole. Thirteen circular filters of varying dimensions are located on the surface of the canister to provide point sources for the injection of gas to mimic canister defects. Pre-compacted bentonite blocks with a high initial water saturation have been installed in the deposition hole. The hole has been capped by a conical concrete plug retained by a reinforced steel lid capable of withstanding over 5,000 tonnes of force (Figure 4-24).

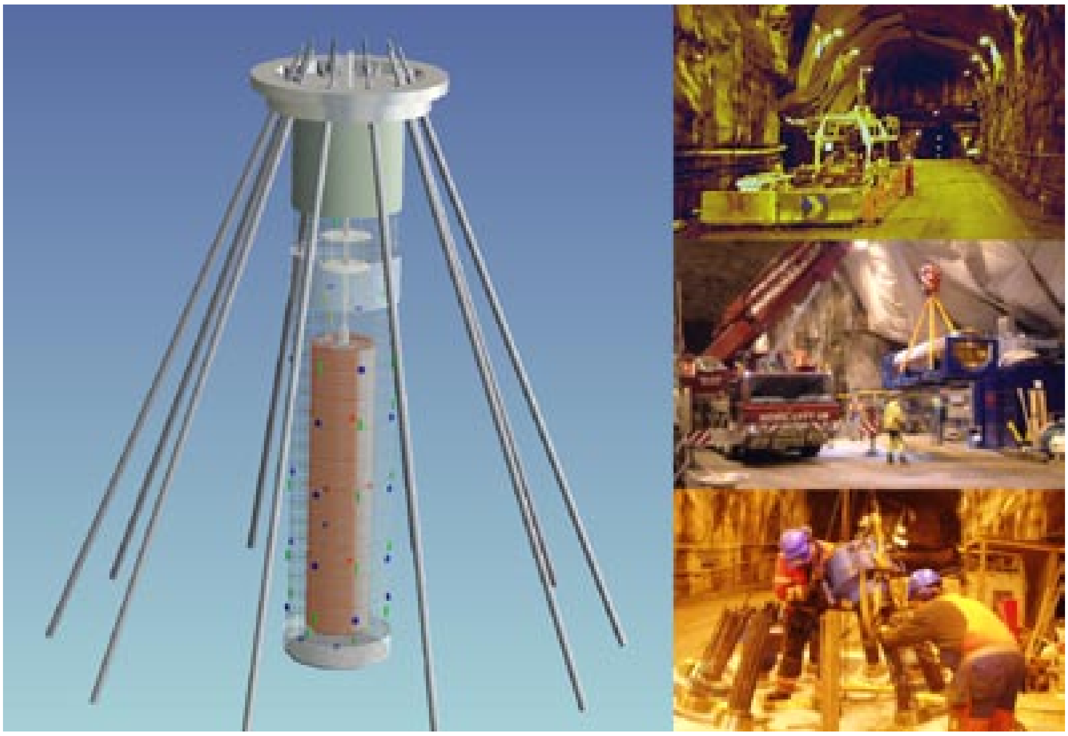


Figure 4-24. *Layout of the Lasgit experiment showing the copper canister, the bentonite buffer, the location of some of the instrumentation, the plug and rock anchors. From top to bottom the photographs on the right-hand side show the assembly hall area, the movement of the copper canister prior to installation and the pre-tensioning of the steel lid.*

In the field laboratory instruments continually monitor variations in the relative humidity of the buffer, the total stress and porewater pressure at the borehole wall, the temperature, any upward displacement of the lid and the restraining forces on the rock anchors. The experiment is a "mock-up test" which does not use any radioactive materials.

The Lasgit experiment consists of three operational phases; the installation phase, the hydration phase and the gas injection phase. The installation phase was undertaken from 2003 to early 2005 and consisted of the design, construction and emplacement of the infrastructure necessary to perform the Lasgit experiment. This included:

- Characterisation of the deposition hole, hydraulic measurements and instrumentation of the rock wall.
- Development of a technique for the manufacturing of buffer blocks with exceptionally high water content. Manufacturing of a set of blocks. Preliminary modelling of the hydration of the buffer.
- Preparation of a full-scale canister with gas injection equipment. Design and construction of a lid to seal the deposition hole and simulate the tunnel backfill.
- Design and construction of a gas injection and measurement field laboratory. Installation and testing of the equipment before deposition of the canister.
- Installation of canister, buffer, lid, and sealing of the deposition hole.

The hydration phase began on the 1st February 2005 with the closure of the deposition hole. The aim of this phase of the experiment is to fully saturate and equilibrate the buffer. This will be done by:

- Water uptake from natural groundwater in the deposition hole.
- Artificial saturation by water injection through the gas injection ports mounted on the surface of the canister.
- Artificial saturation by water injection through mats located at a number of positions within the buffer and around the walls of the emplacement borehole.

The saturation will be monitored by measuring pore pressure, total pressure and suction at both the buffer/rock interface and key locations within individual clay blocks.

The hydration phase will provide an additional set of data for (T)HM modelling of water uptake in a bentonite buffer. However, no such modelling is planned within the project at this stage.

The gas injection phase will start when the buffer is considered to be fully saturated. A series of detailed gas injection histories will be performed examining the processes and mechanisms governing gas flow in bentonite.

4.8.4 Results

The Lasgit deposition hole was closed on the 1st February 2005 signifying the start of the hydration phase. Groundwater inflow through a number of conductive discrete fractures resulted in elevated porewater pressures. This problem was addressed by drilling two pressure-relief holes in the surrounding rock mass. Artificial hydration began on the 18th May 2005 after 106 days of testing. Initial attempts to raise porewater pressure in the artificial hydration arrays often resulted in the formation of preferential pathways. These pressure dependent features were not focused in one location but occurred at multiple sites at different times in the test history. These pathways appear to be relatively short lived, closing when water pressure is reduced.

At present monitored porewater pressures within the clay remain rather low ranging from 85 kPa to 380 kPa. This is in contrast to the water pressure measured at the face of the deposition hole which ranges from 1,240 kPa to 2,605 kPa and is non-uniformly distributed across the rock face, Figure 4-25(a). Monitored radial stress around the canister continues to increase steadily ranging in value from 1,450 kPa to 4,970 kPa, with an average value of 3,785 kPa. Analysis of the distribution in radial stress shows a narrow expanding zone of elevated stress propagating vertically upwards from the base of the hole, Figure 4-25(b). Stress measurements on the canister surface indicate radial stresses in the range 4,350 kPa to 4,550 kPa, which are comparable with the values of radial stress monitored on the rock face. Axial stress is significantly lower at 2,920 kPa. Axial stress within the clay ranges from 3,260 kPa to 5,660 kPa and is non-uniformly distributed across the major axis of the emplacement hole. The average axial total stress within the bentonite is now greater than the initial pre-stress applied by the lid. Movement and distortion of the steel retaining lid has occurred following the installation and initial closure of packered intervals within the pressure relief holes. Estimates of effective stress (swelling pressure) at the rock face suggest values in the range of 70 to 3,050 kPa with an average of around 1,910 kPa. Suction data from devices located within the buffer above and beneath the canister indicate that a significant amount of the clay remains in suction.

Analysis of the flow data from the artificial hydration system suggests a disproportionably large flux from the canister filters compared to the hydration mats. This can be explained by a number of factors including compression of the filter mats (i.e. a reduction in permeability) or a zone of elevated permeability around the canister.

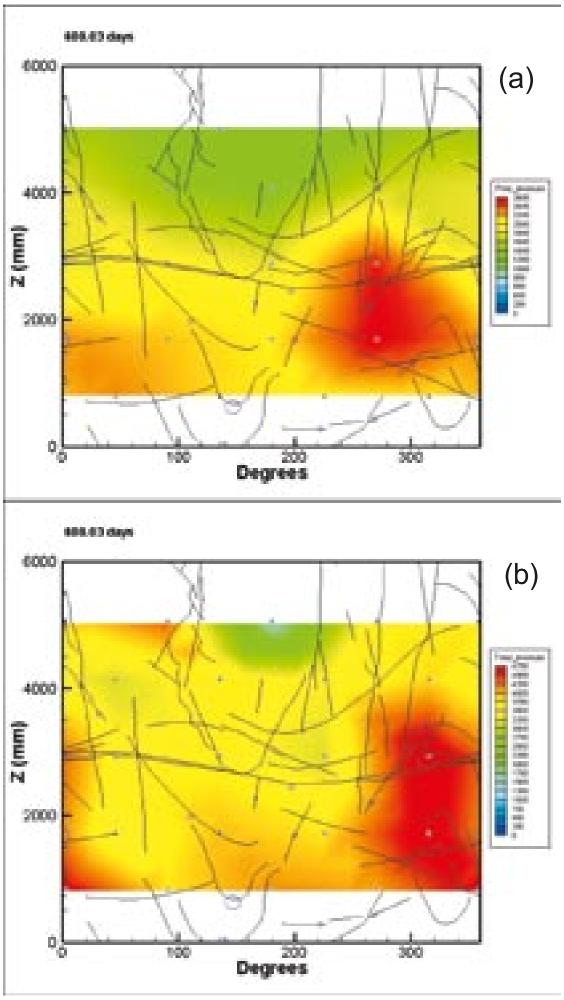


__Figure 4-25.__ The distribution of porewater pressure (a) and radial stress (b) respectively measured at the rock face of the deposition hole at an elapse time of 680 days. A narrow zone of elevated radial stress can be clearly seen in Figure (b) extending vertically upwards from the base of the deposition hole.

The test has been in successful operation for in excess of 680 days. Since closure of the deposition hole there have been no instrumentation failures. The Lasgit experiment continues to yield high quality data amenable to the development and validation of process models aimed at repository performance assessment.

During 2007 preliminary hydraulic and gas injection histories will be performed with a view to verifying the operation and data reduction methodologies for the experiment, providing qualitative data on hydraulic and gas transport parameters. The test will be designed in such a ways as to minimise the effect of reintroducing gas and will be performed in one of the lower filter arrays where the bentonite is locally saturated. The remaining filters on that level will be isolated from the artificial hydration system and their pressure allowed to evolve to provide temporal data on local porewater pressures within the buffer clay. Simultaneously artificial hydration will continue through all remaining canister filters and hydration mats.

4.9 In Situ Corrosion Testing of Miniature Canisters

4.9.1 Background

The evolution of the environment inside a copper canister with a cast iron insert following failure is of great importance to the release of radionuclides from the canister. After failure of the outer copper shell, the course of the subsequent corrosion in the gap between the copper shell and the cast iron insert will determine the possible scenarios for radionuclide release from the canister. This process has been studied experimentally and been modelled. The corrosion will take place under reducing, oxygen free conditions and such conditions are very difficult to create and maintain for longer periods of time in the laboratory. In situ experiments at Äspö HRL will be invaluable for understanding the development of the conditions inside the canister after initial penetration of the outer copper shell.

4.9.2 Objectives

The objective of the project is to obtain a better understanding of the corrosion processes inside a failed canister. The results of the experiment will be used to support process descriptions and safety analyses.

4.9.3 Experimental concept

Five miniature copper canisters, with a diameter of 150 mm, will be emplaced in boreholes, with a diameter of 300 mm. The canisters will be mounted in support cages which can contain bentonite clay. Three of the canisters will be surrounded by low permeability bentonite, one will be surrounded by fully compacted bentonite and one will be emplaced without any bentonite buffer. The canisters will be exposed to natural reducing groundwater for several years during which the experiment will be monitored.

Two of the canisters will be monitored using strain gauges. All the canisters have one or more defects in the outer copper shell (1 mm diameter defects), in a range of different orientations. Cast iron and copper corrosion coupons are mounted in each experiment and the corrosion behaviour is being monitored electrochemically. In addition, cast iron and copper weight loss specimens are present. Each experiment contains a "sandwich type" copper-cast iron specimen to investigate oxide jacking effects and galvanic corrosion. U-bend and wedge open loading stress corrosion specimens will be mounted in one of the boreholes in direct contact with the groundwater, to assess the possible risk of stress corrosion cracking of copper. Eh is being monitored using a combination of metal oxide, platinum and gold electrodes.

4.9.4 Results

Grouting of the rock wall near the five boreholes for the Miniature Canister corrosion experiments was completed in 2006. Manufacture and procurement of all the test specimens and equipment were completed and the first experiment, which did not contain any bentonite, was set up in September 2006. At the end of December three canisters were installed and the remaining two will be installed early in 2007. Electrochemical data collection was in progress on the installed canisters.

4.10 Cleaning and Sealing of Investigation Boreholes

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

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

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

4.10.1 Objectives

The main objective of this project is to identify and to demonstrate the best available techniques for cleaning and sealing of investigation boreholes. The project comprises three phases. Phase 1, mainly an inventory of available techniques, was finalised in 2003. Phase 2, which aimed to develop a complete "Basic Concept" for cleaning and sealing of boreholes, is finalised. In Phase 3, the techniques and handling will be tested and demonstrated in full scale. The work in Phase 3 is divided in the four sub-projects as described below.

Sub-project 1

This sub-project comprises the engineering of design solutions for borehole plugs of clay and cement, respectively. The development of design for the "Basic Concept" for sealing, with highly compacted clay in perforated tubes primarily intended for use in boreholes longer than 100 m, comprises the following steps:

- Theoretical modelling of the hydration and maturation of clay components in perforated tubes, taking perforation geometry and clay density as main variables.
- Definition of most suitable density and water content of clay components according to the modelling.
- Laboratory and small-scale field testing of erodability of clay components in perforated tubes (Figure 4-26).

Figure 4-26. Laboratory and small-scale field testing of erodability of clay components in perforated tubes.

- Laboratory testing of the maturation rate for assessment of the theoretical model using different water salinities and perforation geometries.
- Manufacturing of clay components for plugging of short and long holes.
- Investigation and pre-testing of alternative methods for plugging short holes by use of clay.

Sub-project 2

This sub-project comprises plugging and testing of eight 5 m deep, 76–80 mm diameter boreholes at Äspö HRL. While the clay plug in the "Basic Concept" for sealing boreholes longer than about 100 m implies use of perforated copper tubes with tightly fitting cylindrical blocks of highly compacted smectite-rich clay, simpler techniques are estimated to be applicable in shorter boreholes, especially in holes drilled from repository rooms within the near-field. Some of these techniques will be tested, taking the following issues into consideration:

- Practicality – This includes assessment of how doable the plugs are, estimation of the need for rigs and tools for placement and possible retrieval, and required forces for bringing the plugs into and out from the holes. Also, the techniques and costs of manufacturing, transporting and storing of the plug components must be estimated.
- Possibility to plug graded horizontal and upward-directed holes.
- Risk of failure in placement and retrieval of plugs by breakage and loss of clay and other components or problems related to too quick maturation of the clay.

Sub-project 3

This sub-project comprises preparation, stabilisation and installation of plugs in the 76 mm wide cored borehole OL-KR24 at Olkiluoto. The major issues are:

- Demonstration of the feasibility of the "Basic Concept" plugging method, i.e. placement of segments of jointed units of perforated copper tubes filled with highly compacted Na-bentonite columns.
- Demonstration of the feasibility of filling parts of the borehole that intersect fracture zones with chemically stable quartz-based fill.

- Demonstration and evaluation of a technique to bring down a dummy for checking the clearance of a real plug segment before installing it.
- Demonstration of the accuracy of replacing natural water in the hole by tap water.

Sub-project 4

The aim of this sub-project is to test the feasibility of three candidate techniques intended for mechanical securing of the tight seals emplaced lower in deep boreholes as outlined in the main Borehole Plugging Report.

This sub-project comprises plugging and testing of four 1.5 m long, 200 mm diameter boreholes at Äspö. The boreholes are located within the same area as the 5 m long holes at Äspö. The 200 mm holes are planned to be used for simulating sealing of the upper ends of deep boreholes.

4.10.2 Results

In the "Basic Concept" a clay plug for plugging holes of almost any length and orientation has been defined (see Figure 4-27). Plugs have been applied in the about 500 m deep vertical borehole OL-KR24 at Olkiluoto and in shorter 76–80 mm diameter holes at the –450 m level in Äspö HRL. The maturation rate and physical properties have been predicted and successfully tested in simulated 5 m long holes in the laboratory and in the boreholes in Äspö HRL.

Alternative clay plug concepts, termed "Container", "Couronne" and "Pellet", see Figure 4-27 have been worked out and their maturation rate and physical properties predicted and found to be in agreement with prototypes tested in simulated 5 m long holes in the laboratory and in the boreholes at the –450 m level in the Äspö HRL. The "Basic Concept" has a potential of serving well in holes with nearly any length and orientation while the others can be used in shorter holes with defined orientation.

A special concrete recipe has been worked out for plugging the parts of boreholes that intersect fracture zones. Between these zones the boreholes are being sealed with clay plugs, according to the proposed plugging scheme. Concrete plugs have been cast in the OL-KR24 hole at Olkiluoto.

Plug concepts for large-diameter holes have been worked out. One is based on the use of special concrete reinforced by coarse quartzite fragments and anchored in shallow recesses, and another consists of a metal expander of copper. Both have been constructed and tested in 200 mm wide holes in the Äspö HRL. They can be given larger diameter for serving as long-term seals in the uppermost part of deep boreholes extending from the ground surface.

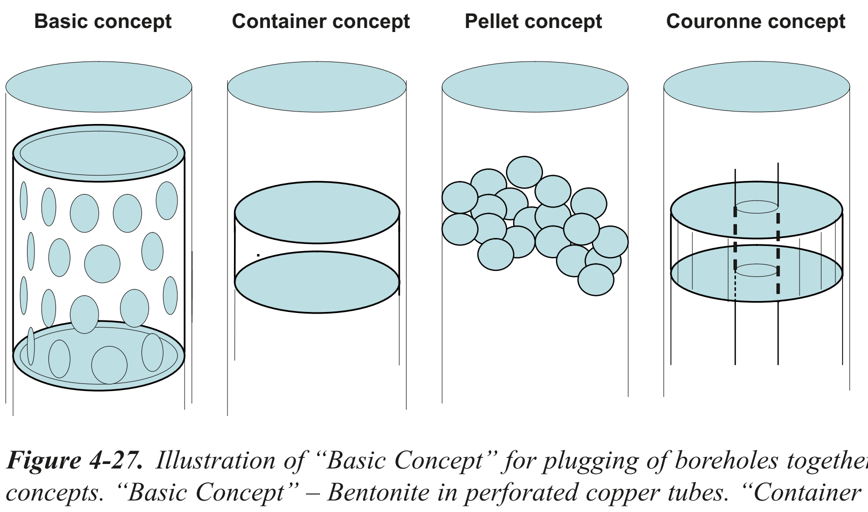


Figure 4-27. Illustration of "Basic Concept" for plugging of boreholes together with three alternative concepts. "Basic Concept" – Bentonite in perforated copper tubes. "Container Concept" – bentonite blocks in a container. "Pellet Concept" – Bentonite pellets. "Couronne Concept" – Bentonite blocks with a hole in the centre placed on a copper rod.

6 m long vertical holes have been bored from a drift at the –220 m level at Äspö HRL for investigating chemical interaction of a 3 m long clay plug of "Basic Concept" type and two adjacent concrete plugs. The interaction of concrete and clay, which takes place under low water-pressure conditions in contrast to OL-KR24, will be investigated with respect to chemical and mineralogical changes.

4.11 Alternative Buffer Materials

4.11.1 Background

Bentonite clay has been proposed as buffer material in several concepts for radioactive waste 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 MX-80 bentonite from American Colloid Co (Wyoming) has so far been used by SKB as a reference material. A large scale programme to study the use of a possible alternative buffer material has been initiated, mainly to correlate the physical and chemical properties to fundamental mineralogical properties.

A number of commercial bentonites from large producers have been investigated with respect to mineralogy and swelling properties. So far the investigations have been done on the reference material MX-80, four samples from India (Ashapura) and one sample from Greece (Silver and Baryte). This project aims at studying the long term stability of bentonites and the influence by the accessory minerals in the materials.

4.11.2 Objectives

The project will be carried out using materials that according to laboratory studies are conceivable buffer materials. The experiment will be carried out in the same way and scale as the Long Term Test of Buffer Material (Lot) experiment at Äspö HRL. The project objectives are to:

- Verify results from laboratory studies during more realistic conditions with respect to temperature, scale and geochemical circumstances.
- Discover possible problems with manufacturing and storage of bentonite blocks.
- Give further data for verification of THMC models.

4.11.3 Experimental concept

The testing principle is comparable with the Long Term Test of Buffer Material, see Section 4.3. Packages containing heater, central tube, pre-compacted clay buffer, instruments and parameter controlling equipment will be emplaced in vertical boreholes with a diameter of 300 mm and a depth of around 3 m.

The goal temperature of the packages is 130°C. To safely reach this temperature with minimal risk of piping etc the heater power will be stepwise increased. After heater start the packages temperature will initially be held at 50 degrees for a period of time. When it is concluded that there is no piping and the system has been running at steady state the heater power will be adjusted. Increments of 10–15°C will be used to reach the goal temperature.

The experiment will be running for about one year before the first package is retrieved. The second and third package will be in operation for another 2–5 years before retrieval.

In addition to the deposited bentonite blocks in the packages, identical bentonite blocks will be stored to monitor the effects of storage.

4.11.4 Results

During the year 2006 all of the field activities regarding the installation of the experiment have been executed in accordance with the planning for 2006.

A new niche was excavated in the TASQ-tunnel at the –450 meter level in the beginning of the year. Drilling of the deposition holes as well as rock characterisation were conducted in the spring.

Clay Technology manufactured buffer blocks from the different materials that were to be tested. A total of 104 blocks were manufactured from 11 different materials. The materials that were used are:

- Ikosorb.
- Deponit CA-N.
- Ibeco Seal M-90.
- Friedland.
- Asha 505.
- Calcigel.
- Febex.
- Kunigel V1.
- Callovo Oxfordian (milled).
- Rokle.
- MX-80.

In addition to these blocks discs of Callovo-Oxfordian material and MX-80 pellets, both with and without quartz, are included in the test.

In September the package assembly and installation was initiated. All three packages were installed in the deposition holes within three weeks. After each package was installed the deposition hole was sealed and a concrete block installed as backfill simulation. The heaters and saturation system were started in December.

4.12 Rock Shear Experiment

4.12.1 Background

Rock displacement is one out of a few processes, which can seriously damage a canister, and constitutes thereby a threat against the integrity of a final repository. The effect of the process is thus of importance to analyse and describe in an accurate way.

Fractures and fracture systems are natural components in granitic rock, and can not be avoided totally in the repository areas. Deposition holes will be bored through such features and the issue for the final decision on accepting or rejecting a bored deposition hole will among other things be based on the properties of the fractures the deposition hole is crossing. One of these properties is the possible displacement along the fracture caused by seismic events. The buffer in KBS-3 is assumed to protect the canister from loosing its integrity for instant displacements up to 100 mm. The forces on the canister at such a major displacement have been modelled as well as analysed based on experiments in laboratory scale (up to 1:10 scale). The results are, however, proposed to be verified in larger scale than 1:10, if a significantly more accurate criterion shall be feasible to apply in the accepting/rejecting process.

4.12.2 Objectives

The project aims at observing the forces that act on a KBS-3 canister if a displacement of 100 mm would take place in a horizontal fracture that crosses a deposition hole at canister height. Such a displacement is considered to be caused by an earthquake, and the test set-up needs to provide a shearing motion along the fracture that is equal to an expected shearing motion.

4.12.3 Experimental concept

An in situ test set-up is feasible at the site of the Äspö Pillar Stability Experiment since the rock mechanics test there has been completed. Two full scale deposition holes exist with a rock pillar of one metre in between. Figure 4-28 illustrates the present, schematic idea for a test set-up. The left deposition hole could be used for the buffer and canister, while the right deposition hole would be used for the shearing equipment. Half of the rock between the holes is removed (partly fractured after the pillar experiment) and replaced by a steel structure that has a plane for movements. Half of the upper part of the left hand hole is enlarged by sawing away about 200 mm in order to make room for the shear displacement. This upper part, which shall be sheared, is surrounded by a steel pipe, which is attached to the steel structure and is mobile in the direction of the shearing. The hole is plugged by a combined steel and concrete structure, which is anchored to the rock by a steel beam or by cable bolts as in Canister Retrieval Test and Temperature Buffer Test.

The shearing may not be done before the buffer has saturated. This time can, however, be reached after about two years by using highly saturated bentonite blocks, 95–98% saturation, and lining the hole with permeable mats for artificial water supply. Planned shearing speed is 0.1 m/s. For this shearing speed pistons may be used as shown in Figure 4-28.

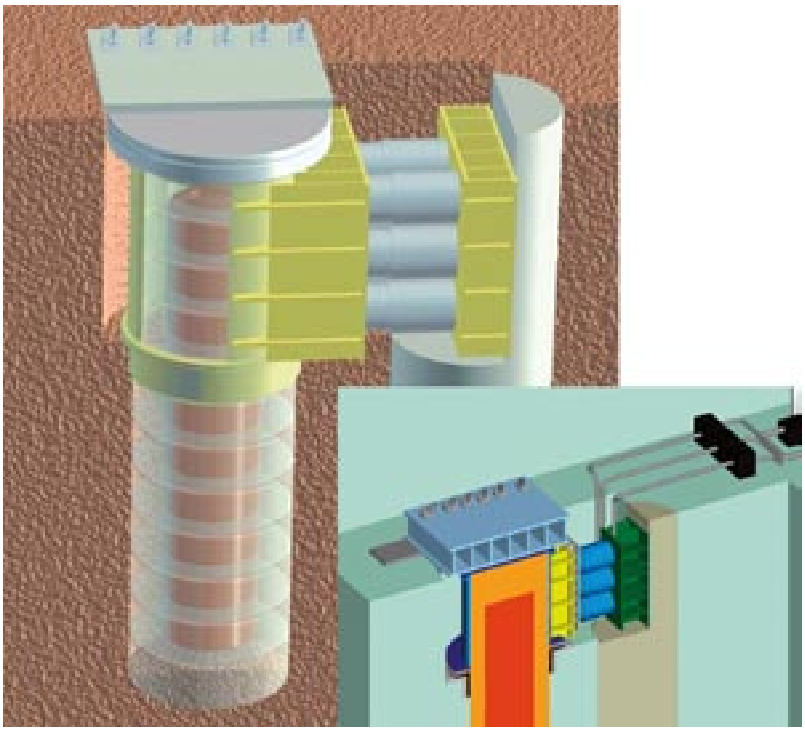


Figure 4-28. Schematic view of a possible test set-up for verification of the stress and strain a canister may exhibit during an instant shearing of 100–200 mm.

4.12.4 Results

The first phase, a pre-study of design and feasibility is completed /Börjesson et al. 2006/. Scoping calculations indicating the forces and shearing speed needed have provided the basis for the design of the test set-up. The conclusion from the study is that the test is feasible. A meeting for discussion and decision on how to continue was held 13th May 2005. The plans include possible international co-operation. At the meeting it was decided to continue with planning and preparations for the test. Supporting laboratory tests could be started in 2007, with the aim of performing the actual shear simulations around 2010.

4.13 Earth Potentials

4.13.1 Background

A stray current is a current flowing via a path other than the intended circuit. Due to the resistance variations in the path, a potential difference can be measured between different locations. If this current intersects a conducting (metallic) object, the point on the structure at which the current enters will be cathodically protected and the point at which the current leaves the structure and re-enters the ground path will be anodically polarised. Based on the source of the current, stray currents can be classified as either man-made or geomagnetically induced currents (GIC).

Man-made currents result from interference from either DC- or AC-power cables. DC-current could also occur in AC-installations if the system is not grounded properly. Corrosion is most severe for DC currents. AC stray currents are less of a problem.

Geomagnetically induced currents arise from two sources, interaction of the earth's magnetic field with solar particles emitted from the sun and voltage gradients induced at the earth/sea interface by tidal movement. The magnitudes of GIC due to solar particles (often referred to as telluric currents) are largest in polar and sub-polar regions.

4.13.2 Objectives

The main objectives for the project are to identify the magnitude of potential fluctuations and stray currents for GIC and man-made stray current sources at repository depth, and by that estimate the potential problems that could occur.

4.13.3 Results

External electrical fields

Possible effects of external electrical fields on the corrosion of copper in bentonite have been studied. External potentials that develop across a repository may interact with the copper canister. A study was undertaken to investigate the potential corrosion effects of voltage differences in a repository.

A set of experiments was performed to study the tendency of copper in bentonite to corrode under influence of an externally applied electrical field. A model study was made to estimate possible corrosion effects of an external electrical field on a full-scale canister in the KBS-3 concept.

MX-80 bentonite exposed to $CuCl_2$

The expansion and ion exchange properties of MX-80 bentonite exposed to $CuCl_2$ solution at room temperature and after heating to 250° has been studied. The preliminary results from this study may be summarised in the following items:

- Ion exchange to a copper (II) dominated MX-80 bentonite leads to a change in swelling pressure and hydraulic conductivity which previously has been found for calcium exchanged MX-80 bentonite.
- Cu is incorporated in excess of the cation exchange capacity (CEC) of the untreated bentonite.
- A fraction of the sites occupied by Cu are not readily accessible for exchange, neither with Mg nor with Ba, which results in 10–20% loss in CEC of the Cu-bentonite. This apparent fixation of Cu increases on thermal treatment (250°C overnight), giving a dramatic reduction of the CEC of heated Cu-montmorillonite derived from MX-80. Although still significant, the loss in CEC is less dramatic for Cu-smectite derived from Rokle bentonite.
- Interlayering of Cu (in some form) in montmorillonite is paralleled by a partial loss of the expandability. The loss seems to increase on thermal treatment (250°C) although the Cu-montmorillonite still expands when treated with glycerol. However, equilibration of the heated and collapsed Cu-montmorillonite at a relative humidity of 35% during three weeks failed to re-hydrate the clay.

The high incorporation of copper in the bentonite samples indicates that hydrolysis has occurred, and probably also some precipitation.

Measurements of earth potentials at Forsmark

During two weeks in July 2006 measurements of the electric voltage differences between the boreholes KMF07A, KMF08A and KFM08C, located about 0.5 kilometres from the nuclear power station at Forsmark were carried out. At the same time the magnetic field was registered by means of three-component magnetometers placed on the surface next to the boreholes KMF08A/C.

The high voltage direct current (HVDC) cable between Finland and Sweden carries currents between 0 and 1,200 A. By correlating time series of current variations and electromagnetic field variations a nearly perfect correlation can be found between the current and the electric field in the boreholes. By comparing with registrations at the geomagnetic observatory at Fiby (run by the Geological Survey of Sweden) it became clear that the horizontal magnetic field at Forsmark is nearly free of disturbances caused by man, whereas the vertical magnetic field showed clear disturbances that could be correlated with the disturbances observed on the electric components between the boreholes.

All the experiments and tests were finished during the year. The information from the laboratory study together with the field work will be summarised in a technical report that will be finished during spring 2007.

4.14 Task Force on Engineered Barrier Systems

4.14.1 Background

The Task Force on Engineered Barrier Systems (EBS) is a continuation of the modelling work in the Prototype Repository project, where also modelling work on other experiments, both field and laboratory tests, are conducted. The Äspö HRL International Joint Committee (IJC) has decided that in the first phase of this Task Force (period 2004–2008), work should concentrate on modelling of:

Task 1 THM processes during water transfer in buffer, backfill and near-field rock. Only crystalline rock is considered initially, although other rock types could be incorporated later.

Task 2 Gas transport in saturated buffer.

The objectives of the Tasks are to: (a) verify the capability to model THM and gas migration processes in unsaturated as well as saturated bentonite buffer, (b) refine codes that provide more accurate predictions in relation to the experimental data and (c) develop the codes to 3D standard (long-term objective).

The following tasks are modelled in this first phase of the Task Force:

- Benchmark 1 – Laboratory tests
  - Task 1 – THM tests
    - 1.1.1 Two constant volume tests on MX-80 (CEA)
    - 1.1.2 Two constant volume tests on Febex bentonite – one with thermal gradient and one isothermal (Ciemat)
    - 1.1.3 Constant external total pressure test with temperature gradient on Febex bentonite (UPC)
  - Task 2 – Gas migration tests
    - 1.2.1 Constant external total pressure (BGS)
    - 1.2.2 Constant volume (BGS)
- Benchmark 2 – Large scale field tests
  - Task 1 – THM tests
    - 2.1 URL tests Buffer/Container Experiment and Isothermal Test (AECL)
    - 2.2 Canister Retrieval Test in Äspö HRL (SKB)

Participating organisations besides SKB are at present: Andra (France), BMWi (Germany), CRIEPI (Japan), Nagra (Switzerland), Posiva (Finland), OPG (Canada) and RAWRA (Czech Republic). All together 12–14 modelling teams are participating in the work.

Since the Task Force does not include geochemistry a decision has been taken by IJC to start a parallel Task Force that deals with geochemical processes in engineered barriers. The specific tasks have not yet been selected. The two Task Forces will have a common secretariat but separate chairmen.

4.14.2 Results

A Task Force meeting was held at Äspö HRL in April 2006.

For Benchmark 1 (laboratory tests) the modelling results for Task 1 (THM) were reviewed and a third test presented (1.1.3). It consists of two samples of Febex bentonite enclosed in a membrane without external pressure. The samples were exposed to a temperature gradient without any additional water available. The redistribution of moisture and density was measured. For Task 2 (gas) the preliminary results of the modelling of the two benchmark tests (1.2.1, 1.2.2) were presented at the meeting.

For Benchmark 2 (large scale tests) it was decided to use the Canister Retrieval Test (CRT) (see Section 4.5) and two URL tests, carried out by AECL. The URL tests comprise a Buffer/Container Experiment (BCE) and an Isothermal Test (ITT). The modelling of these tests will start at the beginning of 2007.

A Task Force meeting was also held in November in Barcelona.

For Benchmark 1 Task 1 (THM) the modelling results of the third test (1.1.3) were presented as well as additional results from the other test configurations. Decent agreements between modelled and measured results have been reached. Written reports were requested at the end of the year.

For Benchmark 1 Task 2 (gas) two test configurations have been presented and attempts made to model these tests. Both tasks concern gas break through in highly compacted water saturated bentonite (MX-80). The modelling groups have had considerable problems in the modelling and so far the models used do not seem to be appropriate. Written reports were requested at the end of the year.

5 Äspö facility

5.1 General

Important parts of the Äspö facility are the administration, operation, and maintenance of instruments as well as development of investigation methods. The Public Relations and Visitor Services group is responsible for presenting information about SKB and its facilities e.g. the Äspö HRL. They arrange visits to the facilities all year around as well as special events.

5.2 Äspö HRL

Background

The main goal for the operation of the rock laboratory is to provide a facility which is safe for everybody working in it, or visiting, and for the environment. This includes preventative and remedial maintenance in order to ensure that all systems such as drainage, electrical power, ventilation, alarm and communications are available in the underground laboratory at all times.

Results

No shutdowns or unplanned service interruptions have occurred during the year. The facility is well maintained and the goal, to have a degree of operational time of 98% during 2006, has been exceeded. The long term rock control and reinforcement programme has been continued to ensure safe and reliable rock conditions.

The work with the operational and monitoring system has been successful. According to present plans the inspection of the system will be done early 2007. The system has information on where personnel and visitors are at present. This is useful information if an accident occurs. The operational and monitoring system will be included in the maintenance system. This will facilitate the adjustment of the ventilation in the tunnel. The air quality in the below-ground facility was measured and the radon concentration in the air has decreased by 20% after an adjustment of the ventilation.

5.3 Bentonite Laboratory

Background

A number of experiments which are being carried out at the Äspö HRL (Canister Retrieval Test, Prototype Repository and Large Scale Gas Injection Test) have confirmed that, at full scale, it is possible to place pre-pressed blocks and rings of bentonite around a canister under both ideal and more demanding conditions. Conditions regarded as more demanding usually involve the inflow of groundwater in the deposition hole. Piping – usually flow channels between the rock wall and the buffer – arises when the inflow of groundwater in combination with the groundwater pressure are so great that the buffer is not able to swell quickly enough to counteract the pressure arising. When setting up the current experiments different solutions were applied to prevent flow channels forming or at least to stop the development of them. Before building a final repository, where the operating conditions include the deposition of one canister per day, further studies of the behaviour of the buffer under different installation conditions are required. SKB has therefore decided to build a Bentonite Laboratory in the Äspö Research Village. This new laboratory is designed for studies of buffer and backfilling materials.

The Bentonite Laboratory includes two stations where the emplacement of buffer material at full scale can be tested under different conditions. The laboratory will also be used for continued testing of different types of backfill material and the further development of techniques for the backfilling of deposition tunnels.

Results

The construction activities on site were initiated in May 2006 when the excavation of rock started. The complete building structure was delivered to Äspö at the end of 2006 and construction work is scheduled to be finished in March 2007, see Figure 5-1.

Figure 5-1. *Bentonite Laboratory under construction.*

5.4 Public Relations and Visitor Services

General

SKB operates three facilities in the Oskarshamn municipality: Äspö HRL, Central interim storage facility for spent nuclear fuel (Clab) and Canister Laboratory. In 2002 SKB started site investigations including drilling of deep investigation boreholes at Simpevarp and Laxemar.

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

During the year 2006, the Äspö HRL and the "Äspö path" were visited by 11,144 visitors. The visitors represented the general public, municipalities where SKB perform site investigations, teachers, students, politicians, journalists and visitors from other countries.

The total number of visitors during year 2006 to all SKB facilities, Äspö HRL, Clab, Canister Laboratory and SFR, was 28,217 persons (25,859 year 2005), see Figure 5-2. The information group has a special booking team at Äspö HRL, which books and administrates all visitors.

Special events

During the year 2006 the guided summer tours for the general public, called "U-500", started in June and ended the 20th of August. The project set a new record, with 2,886 visitors which is 400 more visitors than last year. The goal was to reach 2,500 visitors.

The annual event "The Äspö Day" took place in May. It is an open house where the visitors can see the underground laboratory and also participate in tours on the ground. These tours provide information about e.g. geology, history and nature. About 170 persons from the local district came this year, 30 persons less than last year

The official inauguration of "The Geology Day" took place at Äspö 15th September. The county governor conducted the inauguration and the event was visited by 120 persons during the day. The event was celebrated for the sixth time in Sweden.

"Light in the URL" a new project for this year with guided tours, which ended with a fire-eater show at –450 m level. The tours were open for the general public one day in November and one day in December. The arrangements were a contribution to a bigger event, "Oskarshamn in Light", arranged by the municipality of Oskarshamn. The tours were fully booked and extra tours were therefore arranged.

The Äspö running competition was held in the Äspö-tunnel in December. Fifty participants ran all the way up from the –450 m level. The length of the race is 3.5 km and the inclination is 14%. This has been an annual event for the last eight years.

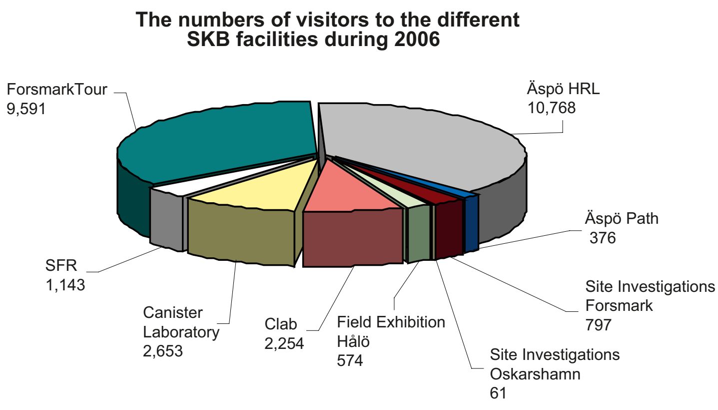


Figure 5-2. The number of visitors to the different SKB facilities during 2006.

6 Environmental research

6.1 General

Äspö Environmental Research Foundation was founded 1996 on the initiative of local and regional interested parties. The aim was to make the underground laboratory at Äspö and its resources available for national and international environmental research. SKB's economic engagement in the foundation was concluded in 2003 and the activities are now concentrated to the Äspö Research School.

6.2 Environmental and exogene geochemistry – studies within the Äspö Research School

The research carried out within the Äspö Research School focuses on environmental and exogene hydrogeochemistry. The sites of research include the Äspö HRL, Laxemar, Forsmark, other sites in the region such as Degerhamn on Öland and selected sites abroad. Within the first few years of activities there has been an effort to analyse existing hydrogeochemical data from Äspö and the site investigations, as such data both contains a wealth of interesting and relevant scientific information and form a suitable background for further more detailed and specific hydrogeochemical studies. Current studies focuses on the behaviour of selected chemical elements (e.g. niobium and uranium) in surface and ground water, on spatial and temporal hydrochemical patterns in streams and lakes in Forsmark and Laxemar, and on the behaviour of major and trace elements during litter decomposition, see Figure 6-1. In addition, experiments are currently carried out at carefully selected sites elsewhere, in order to widen the understanding of hydrogeochemical processes and trace-element mobility and transport in various natural environments. Below follows a short description of the various projects carried out by the PhD-students with the Äspö Reseach School.

Figure 6-1. *From left PhD student Pernilla Rönnback, PhD student Anna Augustsson, PhD student Christian Brun and professor Mats Åström looking at litter decomposition in Laxemar.*

Cross-utilisation of geochemical data (Pasi Peltola)

Background and objectives

Environmental geochemical data, such as concentrations of various elements in soil, water and biota, is today produced in a multitude by many organisations and researchers. For instance environmental monitoring programmes produce much data. Many times the aim of various projects and data is focused on single or only a few research questions. This was of course appropriate earlier when data production (chemical analysis) was more time-consuming and, for example, only single elements of special interest were determined. During recent decades the use of multi-element techniques together with multi parameter approaches has become common, while at the same time quality has increased and the cost for many analyses have decreased. This is also partly the basis of the SKB's site investigations where a multitude of parameters are determined, many with an instant use in site descriptions and safety assessment, but also several parameters are "only" presented in a basic way and stored in the data base. This type of data (and stored samples) can be of greater scientific interest. One way of "dusting off" data and stored samples is to compare these data against new data when investigating the behaviour of specific elements. In the most simplified form this type of investigation could be a form of review but when using the original datasets much more extensive comparisons can be made.

The main goal is to expand the knowledge about the behaviour of chemical elements in the environment using geochemical results from various biogeochemical compartments. Elements of special interest are those which have radioactive isotopes.

Results

Several projects are currently in progress. Niobium has been studied in a multitude of environmental compartments such as sediments, stream water and groundwater /Åström et al. 2007/. The most pronounced feature of Nb is found in Baltic Sea sediments where a distinct enrichment of Nb occurs when moving from lacustrine (Ancylus) to brackish (Litorina) water sediments, see Figure 6-2. While other data in the study showed that non-detrital Nb is bound to organic ligands the sedimentary results show that Nb is far more enriched than the present organic matter in the sediment. These findings have implications for the behaviour of radioniobium in the environment.

Submitted is also a manuscript dealing with the aqueous behaviour of uranium in the boreal zone, with special attention to waters at Simpevarp and Forsmark. In this study both well-water, regional geochemical stream-water and groundwater data is used. In Figure 6-3 uranium and chloride concentrations in and around the Baltic Sea are plotted and it is evident that coastal waters at Forsmark receive a natural input from stream-water and possibly also from groundwater.

Future studies with the same approach will e.g. include data from a peat core and data from plant-litter decay experiments. Elements of interest are especially micronutrients and elements mimicking these, such as rubidium, cesium and thallium.

Hydrochemical characteristics of surface- and groundwater in two boreal granitoidic settings, Forsmark and Simpevarp/Laxemar (Pernilla Rönnback)

Background and objectives

The Baltic Sea and its terrestrial surroundings consist of a unique environment due to the brackish water and still active land uplift (up to 8–9 mm/year). These two features plus the northern location result in a combination of characters of small near-coastal catchments including melt-water discharge in spring, huge increase in biological activity during the short but bright summer months, strongly developed seasonality, sporadic intrusions of brackish waters, and young relatively unweathered soils. This region thus consists of an area of significant scientific interest in terms of providing knowledge of causal relationships among contrasting parameters affecting surface- and groundwater chemistry.

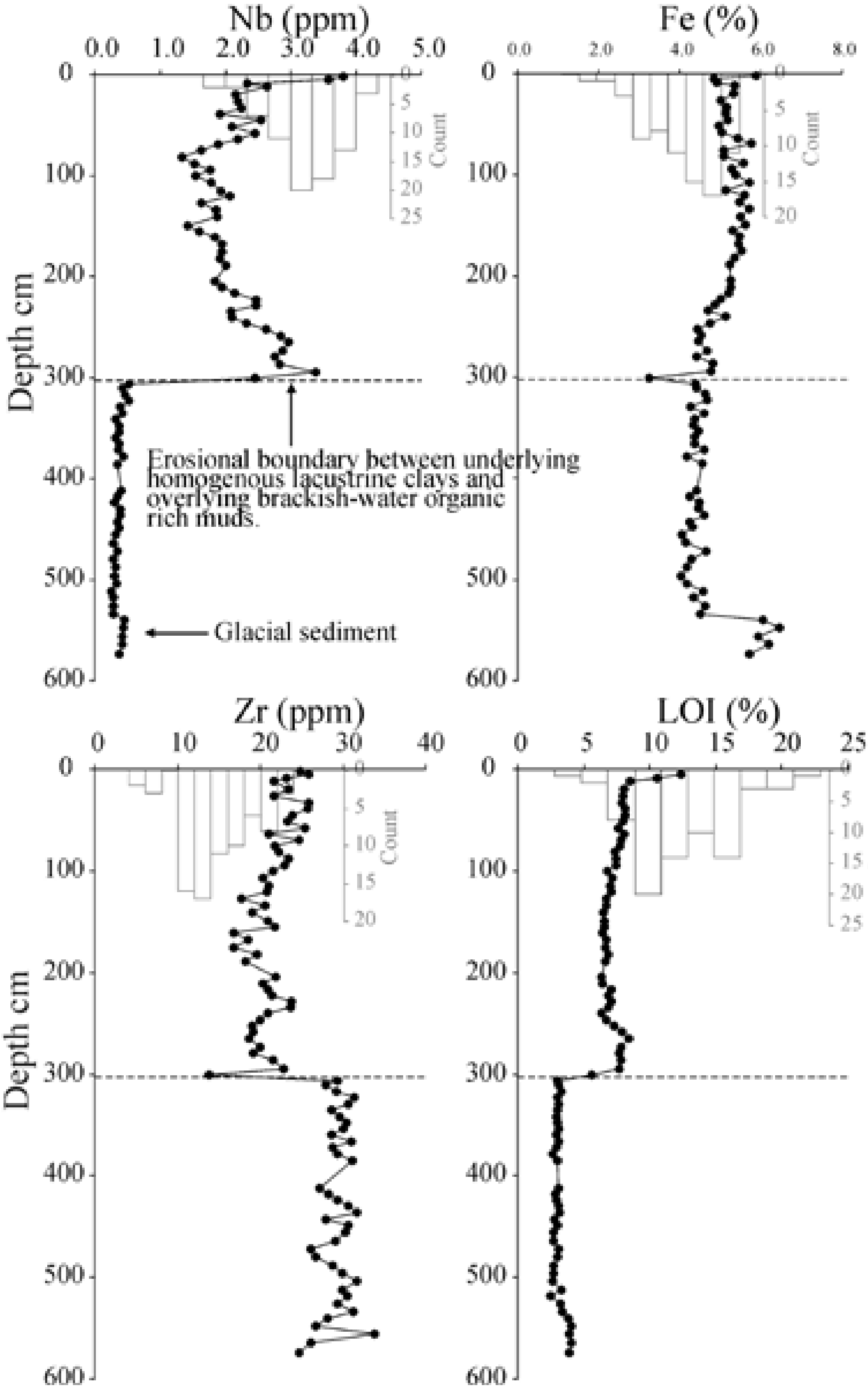


Figure 6-2. *Distribution of aqua regia extractable concentrations of metals (Nb, Fe, Zr) and loss on ignition (LOI) in a sediment core (filled circles) and in recent sediments at 75 sites (frequency distribution) in the Archipelago Sea.*

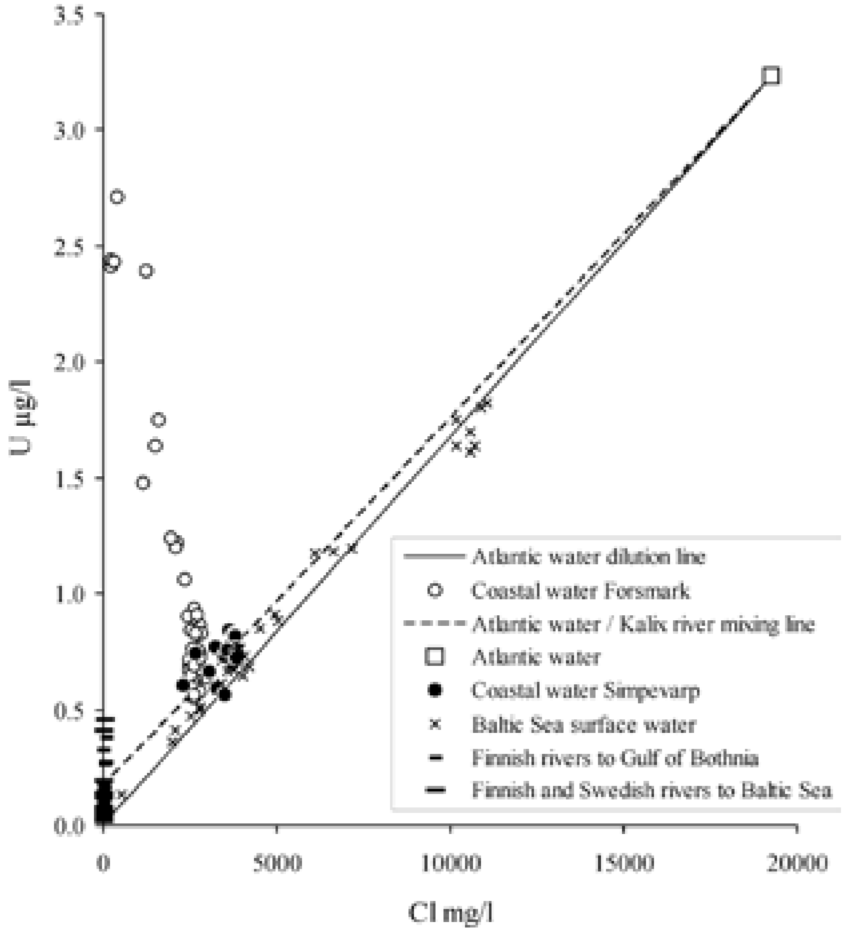


Figure 6-3. *Uranium versus Cl concentrations for terrestrial and Baltic Sea surface waters. Data sources and description: Atlantic water /Chen et al. 1986/; Atlantic water/Kalix river mixing line based on data in /Andersson et al. 1995/; Baltic Sea surface water includes 30 water samples (0–5 m) from various sampling stations /Löfvendahl 1987/; Finnish rivers to Gulf of Bothnia consist of median of time series of 21 rivers including the Munsala stream /Roos and Åström 2005/; Finnish and Swedish rivers to Baltic Sea consist of 13 rivers measured once /Edén and Björklund 1994/. Note: Cl concentrations, when not available, were calculated from salinity and/or the Na-concentration, and for the first three references the data is given in µg/kg and for the others in µg/l.*

The overall aim of the project is to increase the understanding of the chemical dynamics that control water chemistry in small natural catchments in this region, with focus on spatial and temporal trends. The work is done within the Swedish nuclear waste programme and both Forsmark, which has a carbonate-rich till, and Laxemar, with a carbonate-poor till, are studied (Figure 6-4). The project will also assess the catchment properties and hydrochemical features in relation to the potential release from a future final repository for spent fuel.

Experimental concept

Surface water (lake and stream water) and groundwater (overburden and bedrock water) were collected and analysed for major elements, nutrients and trace elements, U and rare earth elements (REEs). The data are owned by SKB and stored in Sicada. For surface water, the samples were collected continuously during nearly four years while the groundwater samples were collected sporadically during the same period. Continuous flow measurement was carried out in some of the catchments over the last two years.

Figure 6-4. *Sampling point PSM002087 at Laxemar catchments area.*

Results

Repetitive seasonal cycles in surface water chemistry have been observed each year along with seasonal cycles in stream discharge. The major findings in surface water chemistry were: (1) the concentrations of elements derived from rock weathering increased in stream water during low flow, (2) sporadic intrusions of brackish water from the Baltic Sea, particularly seen in Forsmark, resulted in strong increase in salinity (Na, Cl^-, Br^-, SO_4^{2-}), (3) a huge increase in biological activity during summer months resulted in decreased concentrations of NH_4^+, NO_3^- and Si and increased pH and concentrations of chlorophyll a, O_2, DON, POC, PON and POP and (4) the U-concentrations were high at both areas in comparison with surface waters in the Barents region and a possible source is reduced U-minerals in the overburden due to the young and unweathered soil.

The concentrations and fraction patterns of REEs were examined in both surface- and groundwater. Large variations existed in REE abundance, REE-fractionation patterns and in the behaviour of Ce and Eu among different water types, but also between similar water types in the two areas. The highest concentrations were found in overburden groundwater, which were characterised by REE-enrichment and negative Ce and Eu anomalies, see Figure 6-5. The Visual MINTEQ speciation calculations predicted that all REEs in all waters were closely associated with dissolved organic matter. There was, however, strong indication (in overburden groundwater in particular) of association with inorganic colloids, which were not included in the speciation model. The REEs are of particular interest because of the systematic change in behaviour across the lanthanide series and as they consist of analogues for several radionuclides.

Patterns in major and trace element contents in boreal forest ecosystems, with particular focus on the litter layer (Christian Brun)

Background and objectives

The main concept is to examine the content of a large number of major and trace elements in different parts of the boreal forest ecosystem. The sample material is partly from long-term studies in the 1980's and partly from SKB's site investigations at Forsmark and Simpevarp.

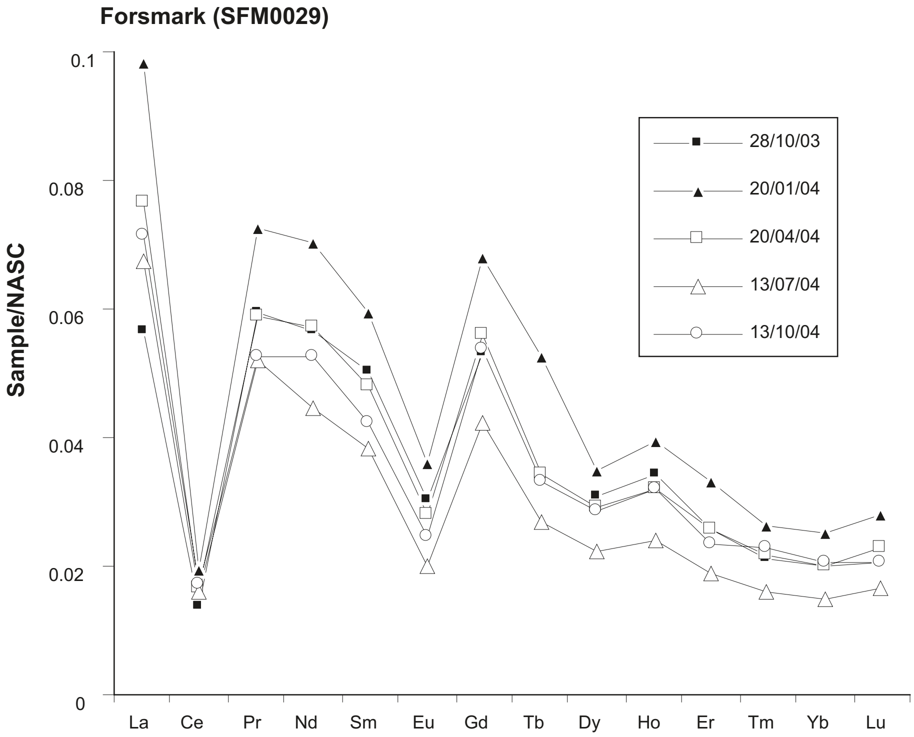


Figure 6-5. *A characteristic NASC-normalised REE fractionation pattern in overburden groundwater (sample SFM0029 from Forsmark). The symbols correspond to day/month/year.*

The process of litter decomposition is an important part of many biogeochemical element cycles. Nutrients are being recycled, while other elements are rather firmly bound to the recalcitrant litter fractions and others yet are being leached downward into the soil profile. The knowledge of different elements' behaviour during decomposition of litter is limited to a rather small number of elements that are either essential to plants (i.e. nutrients) or potentially toxic (i.e. "heavy metals").

The objectives of this study is to determine differences in the behaviour of a large number of major and trace elements, for which very little is known. Long-term multielement studies of the litter decomposition process are quite rare, and studies of an entire ecosystem are even more so.

Experimental concepts

The main part of this project consists of studies of the multielement dynamics during litter decomposition, while additional samples from different vegetation and soil compartments are used in the studies from SKB's site investigations. The litter decay process was examined using the litterbag method, where fresh local litter was contained in nylone net bags and incubated for up to eight years in the humus layer. The samples were then analysed for a large number of major and trace elements using ICP-MS and ICP-AES at accredited laboratories. Statistical analysis was carried out using both multivariate (Principal Component Analysis) and univariate statistical methods.

Results

Through examination of PCA and scatter plots, three principal patterns were found in the data, although there was a slight variation in these groups depending on the species studied. One group, mostly containing nutrients, showed a trend where the amounts decreased during decomposition. These elements are thus loosely bound to the litter and/or easily released, so that there is a net leaching from the litterbags (Ca shown in Figure 6-6a). A second, rather large group of elements, mostly consisting of unessential elements and metals, showed a trend with

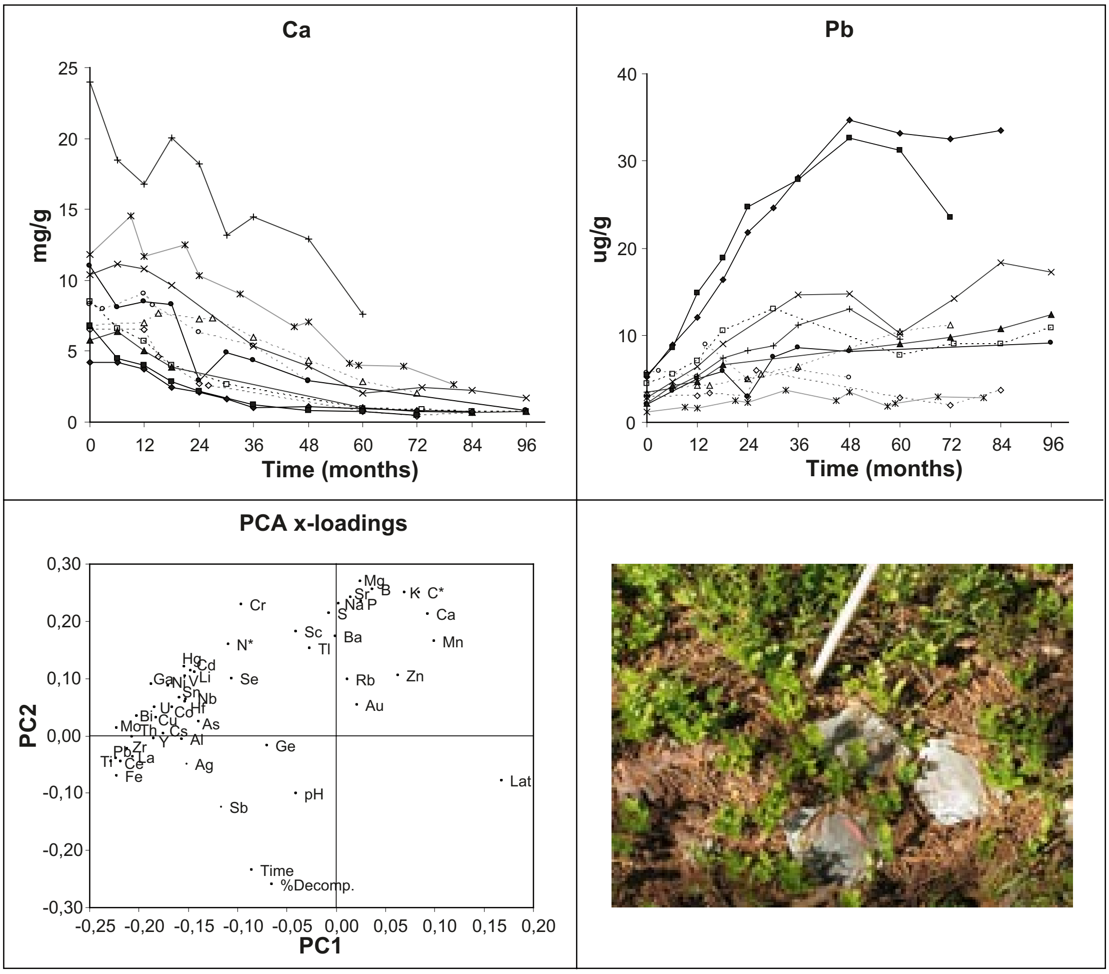


Figure 6-6. Total amounts of (a) Ca and (b) Pb with time and (c) PCA loadings from (d) the Norway spruce/Scots pine litter decomposition study.

increasing amounts during decomposition (Pb shown in Figure 6-6b). This means that there was a net addition of the elements into the litterbags over the study period. All these elements were also according to the PCA-scores plot more or less negatively correlated to the latitude of the locations (Figure 6-6c). Some elements, e.g. Cd, Hf, Hg and Zr increased during the first years after which there was a decrease to an amount that was similar to the initial value. These elements thus accumulate in the litter initially, but are later leached, possibly into lower horizons and potentially more sensitive ecosystems. A third group, not distinctly different from the group dominated by nutrients contains e.g. Cr, Zn and Au, that seem to be somewhere between a slow decrease and a steady state throughout the decomposition process. Zn and Cr are not tightly bound to organic material and are thus more susceptible to leaching than most other heavy cations.

Behaviour of sulphur and metals in an alum-shale environment (Ulf Lavergren)

Background and objectives

Alum shale, internationally usually called black shale, is a sedimentary rock with Swedish as well as worldwide occurrences. It was formed from sediments deposited in stagnant aquatic environments with high organic productivity and oxygen deficiency at the bottom, creating sediments rich in organic matter and sulphides. Alum shale is also known to contain high concentrations of many potentially toxic elements such as As, Cd and U. The shale is readily weathered when exposed to air and water and can produce acidic drainage water rich in various metals, thus constituting a potential contamination source for soils and waters. Such effects have also been observed in some international studies.

In Sweden alum shale has historically been mined for production of alum and quicklime, leaving behind exposed surfaces of the bedrock together with deposits of burnt shale, see Figure 6-7. In 1999 high Cd concentrations were found in sewage sludge in a local wastewater treatment plant in Degerhamn, Öland, an area where alum shale previously have been mined and burnt on site. It was soon realised that the former mining area was the source of the metal pollution, motivating further studies to assess the extent of metal leakage in the area.

The overall aim of this project is to characterize the mobilisation of trace elements, e.g. As, Co, Cr, Cu, Mo, Ni, U, V and Zn, when exposed alum shale undergoes chemical weathering. The knowledge obtained from this study can be used in risk assessments for areas where this type of material is abundant, in Sweden and globally.

Experimental concepts

The Degerhamn area functions as study area and two main approaches are used in the study, in which both the natural bedrock shale and the burnt shale originating from the historical industrial activities are being investigated. First, the abundances and mobility of trace elements in the material are analysed through a series of different leaching test (batch test, availability test, oxidised availability test and humidity cell test) together with sequential chemical extractions. These tests provide not only information on the metal mobility in the material but also on which type of extractions that preferably should be used in environmental studies regarding this type of material. Secondly, the geochemistry in the area is monitored in situ. This includes monthly sampling of groundwater, for a period of eight months, in 16 groundwater tubes installed in the area. Surface water samples are also taken in five small watercourses, when available. This provides information of the actual magnitude of metal dispersion under field conditions.

Results

The laboratory tests show that the alum shale is very rich in As, Cd, Mo, U and V, and that Cd and Mo in the natural shale bedrock potentially has a very high mobility. U and V are in both types of material found mainly in weathering resistant mineral phases and shows a comparatively low mobility, while arsenic upon oxidation is transferred to stable solid phases and thus not mobilised. The material is also relatively rich in Cu, Ni and Zn, of which the latter two are easily mobilised while Cu is less mobile. The tests thus show that this type of material has a high potential for releasing several metals to the environment during weathering, and further that an oxidized availability test (utilizing pH-controlled leaching media and hydrogen peroxide) is a suitable procedure for assessing this potential release, see Figure 6-8.

The in situ study shows that the area displays large spatial variations in groundwater chemistry between nearby sampling points. At some locations the groundwater is highly acidic from oxidizing sulphides, while at others it is circumneutral. In general, however, the groundwater

Figure 6-7. *Alum shale outcrop in Degerhamn, Öland, Sweden.*

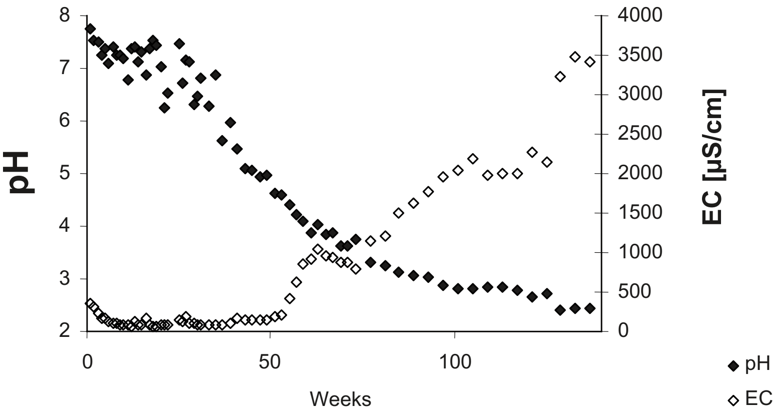


Figure 6-8. Changes in pH and electrical conductance (EC) of leaching water during long term humidity cell test of alum shale.

is clearly affected by the shale material, as shown by elevated metal concentrations. The acidic groundwater is found in an area covered by extensive deposits of burnt shale where the conditions for sulphide oxidation are especially favourable, and the water there is strongly elevated in several metals including Cd, Co, Cu, Ni, U and Zn. U and Cd are, however, also abundant in the circumnetral groundwater only affected by the natural bedrock, together with Mo. Altogether, this shows that the mobilisation of metals clearly is enhanced by the historical mining activities, but also that weathering of the natural alum shale bedrock in itself can be a considerable source for metal contamination of the groundwater.

Behaviour of major and trace elements in water, soils and sediments in the SubAndean Amazonia (Lina Lindell)

Background and objectives

In the great Amazon basin there are still continuous and vast areas of primary forest that holds a unique biodiversity and an ecological and biogeochemical complexity largely unknown to man. The pressure from anthropogenic activities, however, result in an ever increasing extent of deforested areas. One of the regions experiencing the most severe deforestation is the Andean Amazon. The main reason for deforestation in this region is small scale sustenance agriculture which continuously increases due to population growth caused by migration from other regions. The Andean Amazon is, for several reasons, a very important part of the Amazon basin. According to Conservation International the Tropical Andes is the richest and most diverse region on Earth. Further, the Andean Amazon is the main source of river-transported chemical and physical components in the downstream Amazon plain. Deforestation in the Andean Amazon has thus the potential to strongly affect the hydrochemical and hydrophysical characteristics of the Amazon River, its adjacent floodplain, and estuary.

The objective of this study is to enhance the current understanding on how deforestation and the subsequent change in land-use effects the natural environment (water and soil) and the people living in the SubAndean Amazon. The environmental data (including results on behavior of potentially toxic metals, soil-nutrient losses and water-quality degradation) together with the sociological data (perceptions on resource degradation) will be an important asset for the planning of environmental sustainability and socioeconomic growth in this and similar regions.

Experimental concept

Two catchments located in the SubAndean Amazon were selected as study areas. During the first round of field work water samples were collected at 50 tributaries to the main rivers in these two basins. The chemical compounds and elements were evaluated in respect to each other and to discharge, sub-basin characteristics, lithology and land cover. The latter was produced by analysing optical remote sensing data.

Historical water chemistry and geochemistry data are virtually non-existing in this region, thus, to study historical changes in geochemistry five vertical profiles of floodplain sediments were collected and analysed. The geochemistry of this sediment type has often been used for tracking natural and anthropogenic processes in catchments.

In the current land practices (slash and burn agriculture) the soils capacity to carry crops rapidly decreases after deforestation. As a result 80% of the deforested area in this region is composed of abandoned land. A more effective way to cultivate the soils could assist in reducing the extent of deforestation. To investigate changes in soil quality, samples were collected from pristine forest and varying kinds of land use. The material is currently being analysed.

The upcoming field study consists of an interview study focusing on attitudes and perceptions towards natural resources and environmental change. Differences between replies from locals, colonists from the high Andes, non-governmental organizations and mayors will be analysed.

Results

The water chemistry is dominated by dissolution of carbonate rock with massive evaporitic deposits. Variations in lithology and topography dominate the water chemistry.

However, effects from deforestation cannot be ruled out (especially for K, dissolved oxygen and water temperature) as they may be masked by the strong signal from lithology. We detected significant deviations from background concentrations in the floodplain sediments, especially for the following metal cations: Hg, Pb, Cd, Mn, Co, Ni, As and Cu (Figure 6-9). The origin of the peaks may be deforestation followed by increased surface erosion, causing a deposition of sediments enriched in organic material complexing atmospherically deposited elements. However, in situ processes may also, partly or entirely, have caused the accumulation of metals.

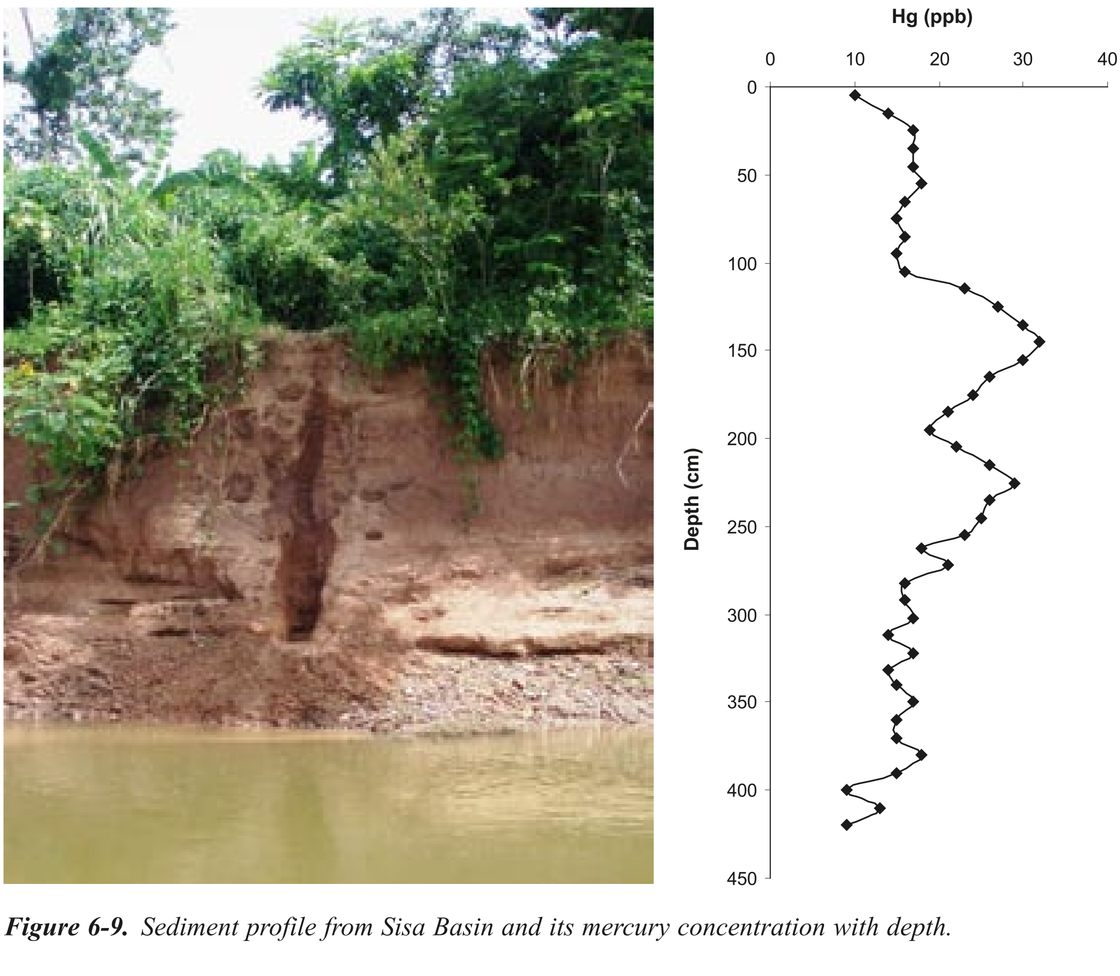


Figure 6-9. *Sediment profile from Sisa Basin and its mercury concentration with depth.*

7 International co-operation

7.1 General

During 2006 nine organisations from eight countries participated in the co-operation at Äspö HRL in addition to SKB. Six of them; Andra, BMWi, CRIEPI, JAEA, OPG and Posiva together with SKB form the Äspö International Joint Committee (IJC), which is responsible for the co-ordination of the experimental 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 participating 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. Presentations of the organisations represented in the IJC are given below.

Most of the organisations participating in the Äspö HRL co-operation are interested in groundwater flow, radionuclide transport, rock characterisation and THMC modelling. Several of the organisations are participating in the two Äspö Task Forces on (a) Modelling of Groundwater Flow and Transport of Solutes and (b) THMC modelling of Engineered Barrier Systems. These specific technical groups, so called Task Forces, are another form of organising the international work The Task Force on Modelling of Groundwater Flow and Transport of Solutes, which is a forum for co-operation in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock, has been working since 1992. The Task Force on Engineered Barrier Systems, a forum for code development on THM processes taking place in a bentonite buffer and gas migration through a buffer, was activated during 2004 and will be a prioritised area of work in coming years.

SKB also takes part in several international EC-projects and participates in work within the IAEA framework. During 2006 an IAEA training course on modelling took place at Äspö HRL and three IAEA-fellows were hosted at Äspö HRL for three to four months during autumn.

The international organisations are taking part in the projects, experiments and Task Forces described in Chapters 2, 3 and 4 (Geo-science, Natural barriers and Engineered barriers). The co-operation is based on separate agreements between SKB and the organisations in question. The participation by JAEA and CRIEPI is regulated by one agreement. The participation of each organisation is given in Table 7-1.

Table 7-1. International participation in the Äspö HRL projects during 2006.

Projects in the Äspö HRL during 2006	Andra	BMWi	CRIEPI	JAEA	OPG	Posiva	Enresa	Nagra	RAWRA
Geo-science									
Äspö pillar stability experiment					X	X			
Natural barriers									
Tracer retention understanding experiments	X			X		X			
Long term diffusion experiment					X				
Colloid project		X				X			
Microbe project		X							
Radionuclide retention project		X							
Task force on modelling of groundwater flow and transport of solutes	X		X	X	X	X			
Engineered barriers									
Prototype repository	X	X		X		X			
Alternative buffer materials	X	X		X		X		X	X
Long term test of buffer materials						X			
Temperature buffer test	X	X					X		
KBS-3 method with horizontal emplacement						X			
Large scale gas injection test	X	X			X	X			
Task force on engineered barrier systems	X	X	X		X	X		X	X

7.2 Andra

The Agence nationale pour la gestion des déchets radioactifs, Andra, is co-operating in various projects, most of them being devoted to the understanding of engineered barrier systems behaviour. The work carried out in 2006 with the support of the French agency has been integrated in the projects and is described in the respective project sections.

However, in support of the field Temperature Buffer Test, a new mock-up test has been implemented. This test and the related modelling work are further presented below.

7.2.1 Temperature Buffer Test

Experimental work TBT_3 mock-up test

In 2004, a mock-up test called TBT_1 was designed to mimic the (T)HM sand-bentonite buffer behaviour observed in the field test when a water shortage occurred. The test was carried out in a laboratory of the French Commissariat à l'Energie Atomique, CEA /SKB 2005/.

In 2005, a second mock-up test, TBT_2, was fulfilled to further investigate the TH(M) phenomena of water redistribution occurring in the MX-80 bentonite as a consequence of the initial thermal load. It aimed at studying the role of temperature gradients and temperature levels, with a view to provide the modellers with data complementary to those collected during the field test /SKB 2005/.

Difficulties encountered in controlling TBT_2's thermal boundary conditions resulted in uncertainties in the interpretation of the test results. This led to modifications to the mock-up cell which is a large oedometer for testing of a cylindrical bentonite specimen of 20 cm in height and 20 cm in diameter.

During 2006 the test has been repeated as TBT_3. The results of which are reported by CEA in "TBT_3 mock-up test, final report" /Gatabin et al. 2006/. The test TBT_3 followed the protocol established together with the Swedish (Clay Technology) and Spanish (Universitat Politècnica de Catalunya, UPC) modelling teams.

During a first phase lasting 15 days, the unsaturated bentonite specimen was uniformly heated from room temperature to 84°C, avoiding thermal gradient across the specimen. Then a mean thermal gradient of 1.8°C/cm was installed over 15 days with the "cold" face maintained at 84°C while the "hot" one was raised to 120°C. These thermal conditions were then maintained over 70 days in order to reach water equilibration.

Improvements made in the design of the mock-up cell heating device between TBT_2 and TBT_3 proved effective in controlling the specimen thermal boundary conditions.

Maximum desaturation of the bentonite reached 40% relative humidity in the hottest part, while full saturation was achieved in the coldest part (one fourth of the specimen height). Observation of TBT_3 shows that water redistribution in the bentonite specimen occurs as soon as a temperature gradient is applied, without any threshold effect. This result is in line with Clay Technology and UPC modelling predictions.

TBT_3 provided a new and reliable set of data to the modellers. Significant experimental results are presented below together with simulations carried out by UPC supported by Enresa and by Clay Technology supported by Andra.

Experimental support work (CIEMAT)

Centro de Investigationes Energéticas, Medioambientales y Technològicas, CIEMAT, performed laboratory work complementing the activity developed by the Spanish group involved in numerical analyses. This work is reported in "Behaviour of MX-80 Bentonite at Unsaturated Conditions and under Thermo-Hydraulic Gradient", /Villar et al. 2006/, and some conclusions are reproduced here for consistency.

Bentonite retention properties at high temperature

To determine the retention curves of the bentonite at high temperature, a method was set up consisting in measurement of the relative humidity of blocks of compacted bentonite with different water contents, while they are kept in a hermetic cell that can be heated. Results agree with those obtained previously using other methods. They show (Figure 7-1) the decrease of the retention capacity with temperature and the hysteresis between heating and cooling. In addition, the differences observed between the two densities tested (1.60 and 1.75 g/cm^3) become more important for the low suctions.

Infiltration tests under high thermal gradient

Infiltration tests were performed by CIEMAT in compacted MX-80 bentonite under high thermal gradient. These tests presented major difficulties like air tightness, water intake measurement and capacitive sensors long lasting behaviour. The vapour phase moves quickly even in highly saturated material. With 140°C heater temperature, high thermal gradient is soon established and remains constant (> 5°C/cm). The bentonite water intake is very low. Water and density distributions along the bentonite follow a linear pattern, dry density decreasing as the water content increases.

Modelling TBT_3 (CIMNE-UPC, DM Iberia and CIEMAT)

Enresa coordinated the Spanish participation in the TBT including groups from CIMNE-UPC, DM Iberia and CIEMAT.

A first blind modelling work has been performed and reported in "TBT_3 Predictive modelling programme" /Ledesma et al. 2006ab/ considering guidelines defined by Clay Technology. Then an updated simulation has been reported in "TBT_3 Predictive modelling programme – Step 2" (November 2006) using information from the CEA TBT_3 Final report.

The Code_Bright, a finite element method code for the analysis of coupled THM processes developed by CIMNE-UPC, has been used in all cases. In the "Step 2" simulation, two objectives have been pursued. At first, a simulation was carried out using the same model as in the previous April 2006 report and considering the updated timetable of the test. As a second exercise, a new mechanical model was considered in order to improve the prediction of stresses.

"T-H" variables are in general reasonably predicted in the simulations. This can be seen in the following figures comparing measured and computed values using the standard mechanical model "Barcelona Basic Model". Figure 7-2 shows the evolution of some temperatures with time, Figure 7-3 the evolution of relative humidity with time. And Figure 7-4 shows the final water content distribution in the bentonite specimen.

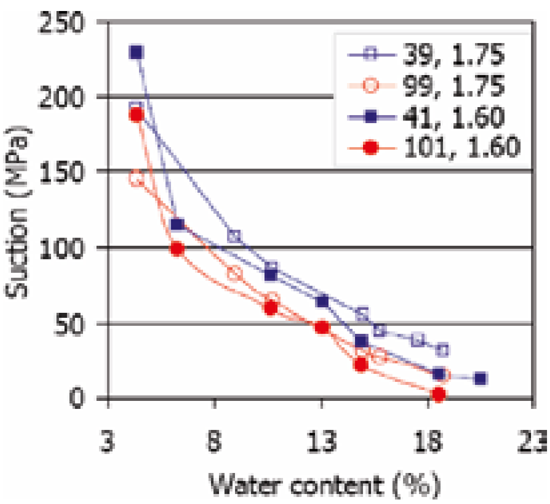


Figure 7-1. *Water retention curve of MX-80 for various temperatures and dry densities (1st number indicates temperature in °C, 2nd number refers to dry density in g/cm*^{3}*)*

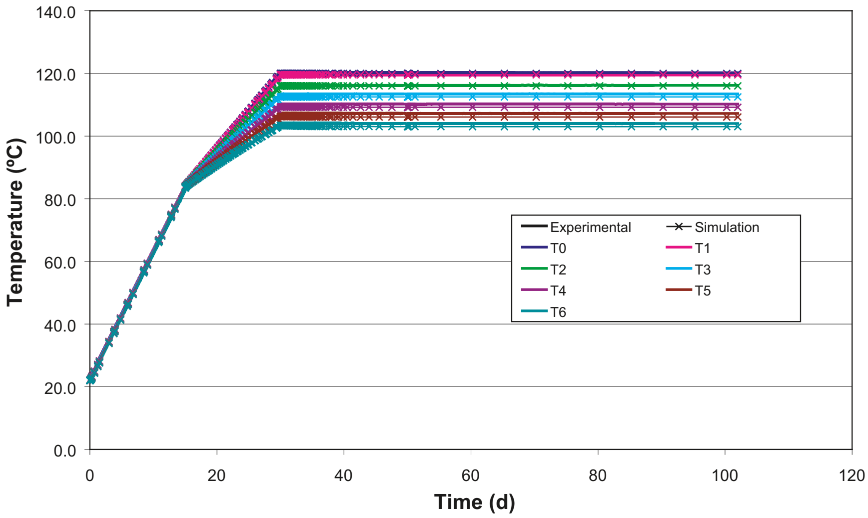


Figure 7-2. *Temperature evolution. TBT_3 – Barcelona Basic Model.*

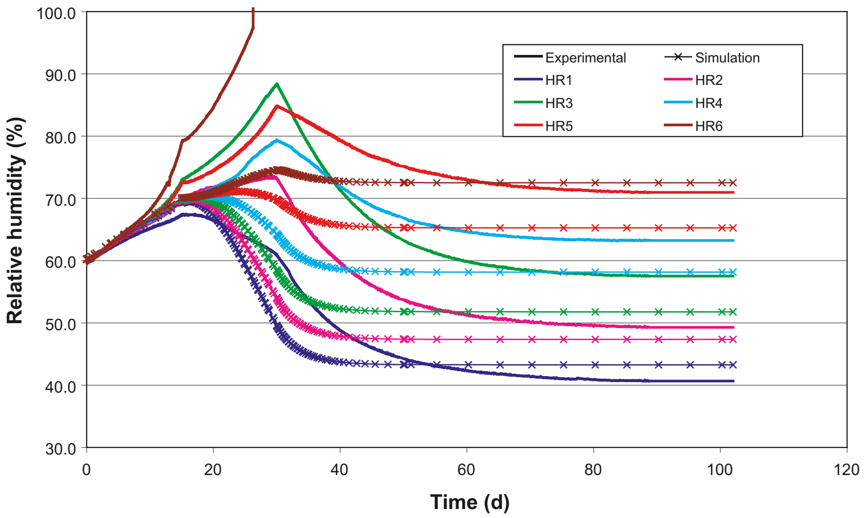


Figure 7-3. *Relative humidity evolution. TBT_3 – Barcelona Basic Model.*

The CEA mock-up tests have been useful to check the ability of the "conventional" models implemented in Code Bright to reproduce the fundamental features of the systems at high temperatures.

"M" variables have been more difficult to simulate. In general, the constitutive model usually considered in the simulations (Barcelona Basic Model), under-predicts the stress level in the bentonite, if typical parameter values are considered. In the mock-up tests, for instance, the same bentonite specimen is subjected to an extensive swelling on the cold side and shrinkage on the hot side, and that different behaviour is very difficult to reproduce with a single set of parameters.

It became necessary to evolve another constitutive model taking in account the macro and micro structural changes of the bentonite. This model assumes that in the material fabric it is possible to define two structural levels: the macro structural level which is responsible for major structural rearrangement and the micro structural level where swelling of active minerals takes place. The analysis performed using the new "Barcelona Expansive Model" implemented in a version of Code_Bright is encouraging. Figure 7-5 and Figure 7-6 are showing the evolution of axial and radial stresses with time comparing measured values for the TBT_3 mock-up test and computed values. The agreement between these values is quite good, considering the difficulties of reproducing the mechanical behaviour of bentonite when shrinking and swelling occur in the same experiment.

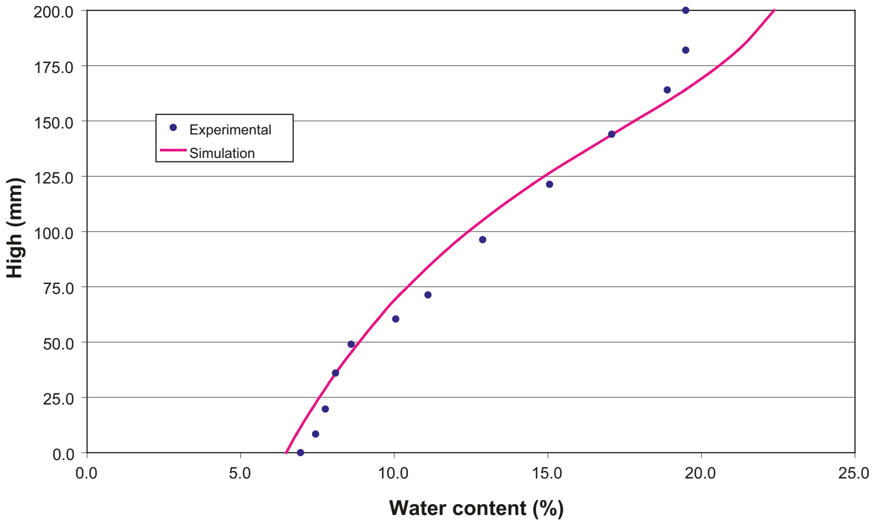


Figure 7-4. *Water content along the specimen. TBT_3 – Barcelona Basic Model.*

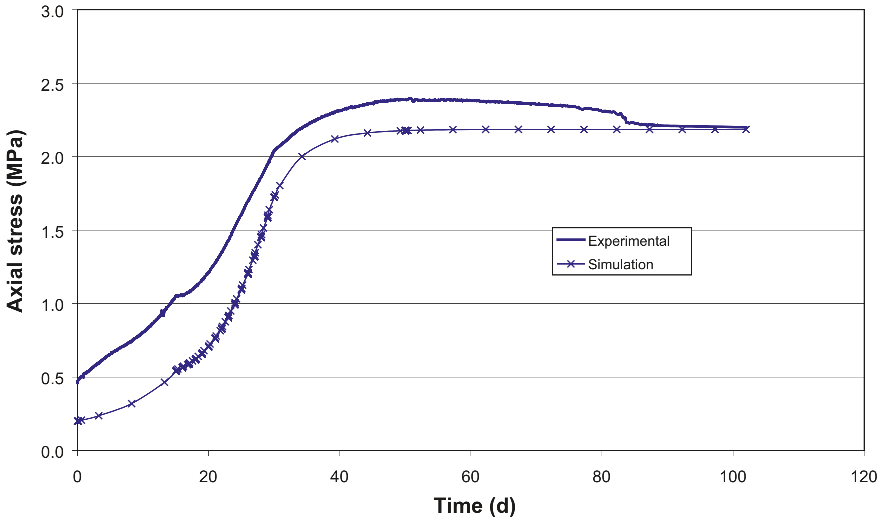


Figure 7-5. *Axial stress evolution. TBT_3 – Barcelona Expansive Model.*

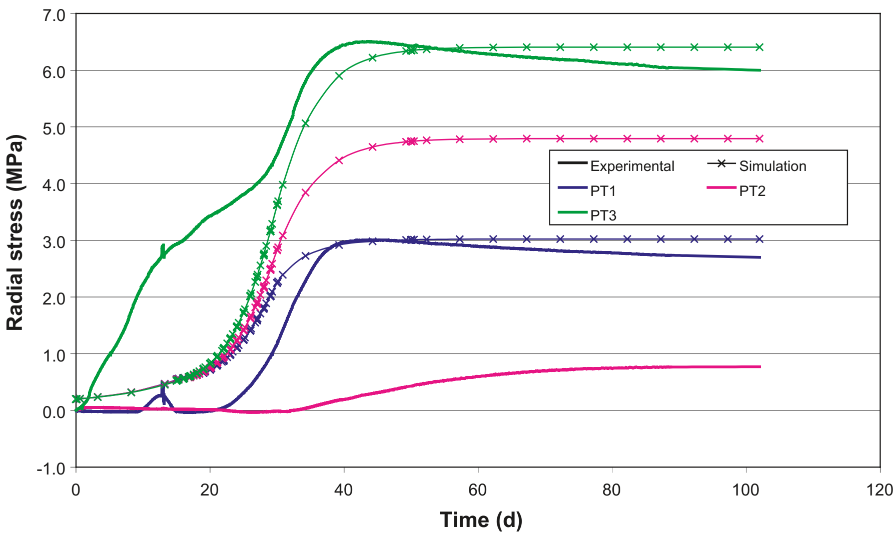


Figure 7-6. *Radial stress evolution. TBT_3 – Barcelona Expansive Model (experimental PT2 data are considered erroneous).*

It should be stressed that both models gave in practice similar results in terms of TH variables. However, a substantial difference was found in the evolution of the stresses.

Application of the Barcelona Expansive Model to TBT field test in the future is under consideration. The challenge associated to that is the computing effort which increases dramatically due to the complexity of this expansive constitutive law. Future work should be devoted to simplification of the actual problem, identifying the mechanisms that are more relevant regarding THM issues.

Modelling TBT_3 (clay technology)

TBT_3 mock-up test results indicate that some conventional concepts of the THM processes show limitations concerning hydrodynamic transport processes and retention properties. Experimental values of vapour pressure and suction were directly derived from measured relative humidity and temperatures. Steady-state profiles of these quantities showed that the vapour pressure gradient was negligible, whereas the suction gradient was significant. This indicates that the suction-driven advective liquid flow was negligible. After the dismantling the bentonite was sampled and analysed. A retention curve can be evaluated from these results together with the steady-state suction values. This relation implies that vapour can be saturated although the bentonite is unsaturated.

An axis-symmetric 2D TH Code_Bright model was elaborated with the intention to check the above mentioned observations. In general, the work followed the conventional approach for this kind of problem. Main exceptions were the use of a retention curve with a maximum saturation limit and the absence of advective liquid flow. Simulated relative humidity is shown together with experimental results in Figure 7-7.

Separation of the RH-levels and their time scale evolution is reasonably well captured by the model, notably during the final equilibration phase. Prior to this however, when the thermal gradient was applied, agreement was less good. There is no obvious explanation for this, but it should be noted that experimental RH-results began separating slightly before the time when thermal gradient were applied.

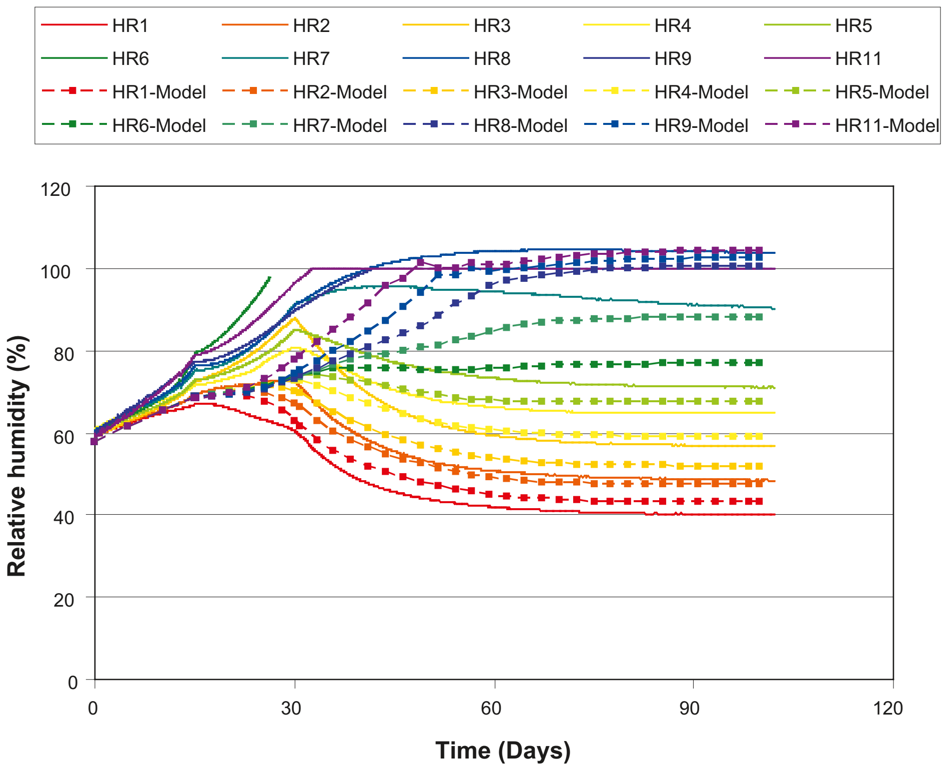


***Figure 7-7.** Relative humidity evolution: simulation (dots) and experimental (lines).*

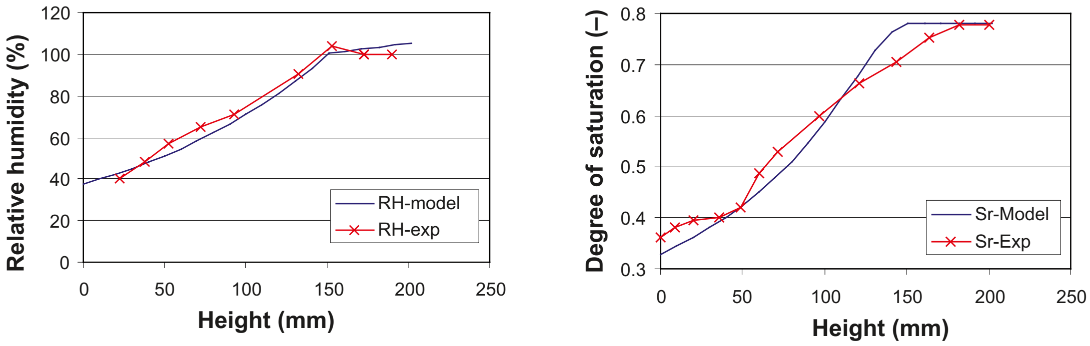


Figure 7-8. Steady-state distribution of relative humidity (left) and degree of saturation (right): simulation (blue) and experimental (red).

Steady-state distributions of relative humidity and degree of saturation are shown in Figure 7-8. Simulated and experimental distributions are quite in good agreement, although minor differences can be noticed.

7.2.2 Large Scale Gas Injection Test

Andra supports Colenco modelling work on gas transport processes through bentonite. Following simulations of the Gas Migration Test carried out at Grimsel Test Site and considering Lasgit, Colenco modelled in 2006 the bentonite buffer saturation process.

Making use of the finite element code Mherlin, a first set of axis-symmetric 2D HM simulations was performed considering different swelling properties coupled with hydraulic conductivity, and various boundary conditions (Figure 7-9).

A second set of 3D simulations was done to take in account the actual location of the injection filters (Figure 7-10) when evaluating the time needed to reach a complete water saturation of the bentonite.

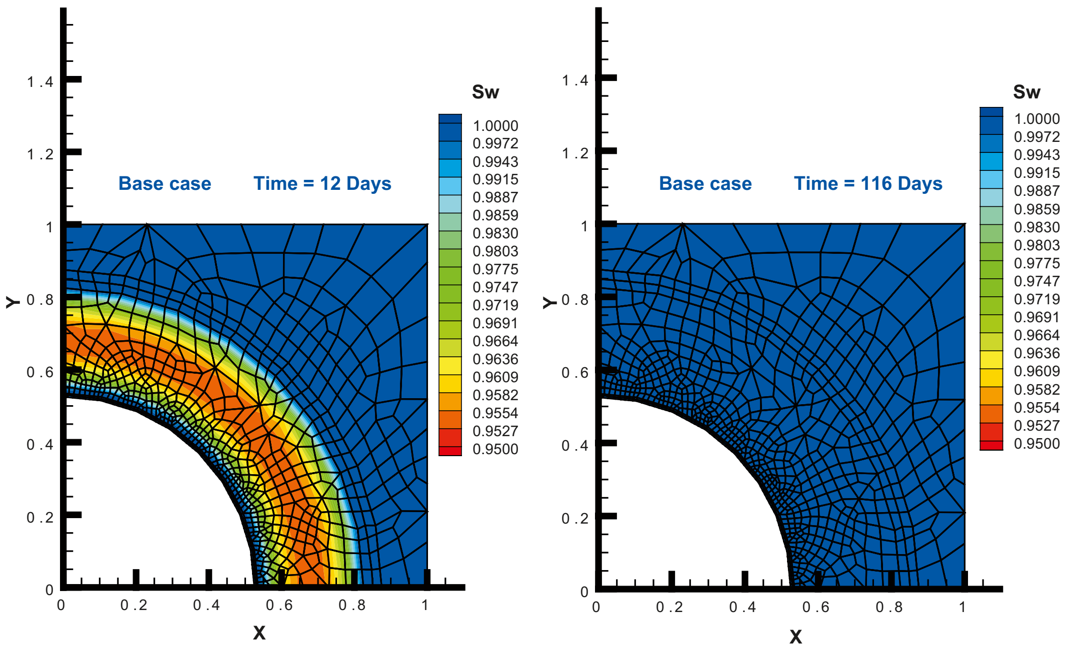


Figure 7-9. Distribution of water saturation in 2D geometry.

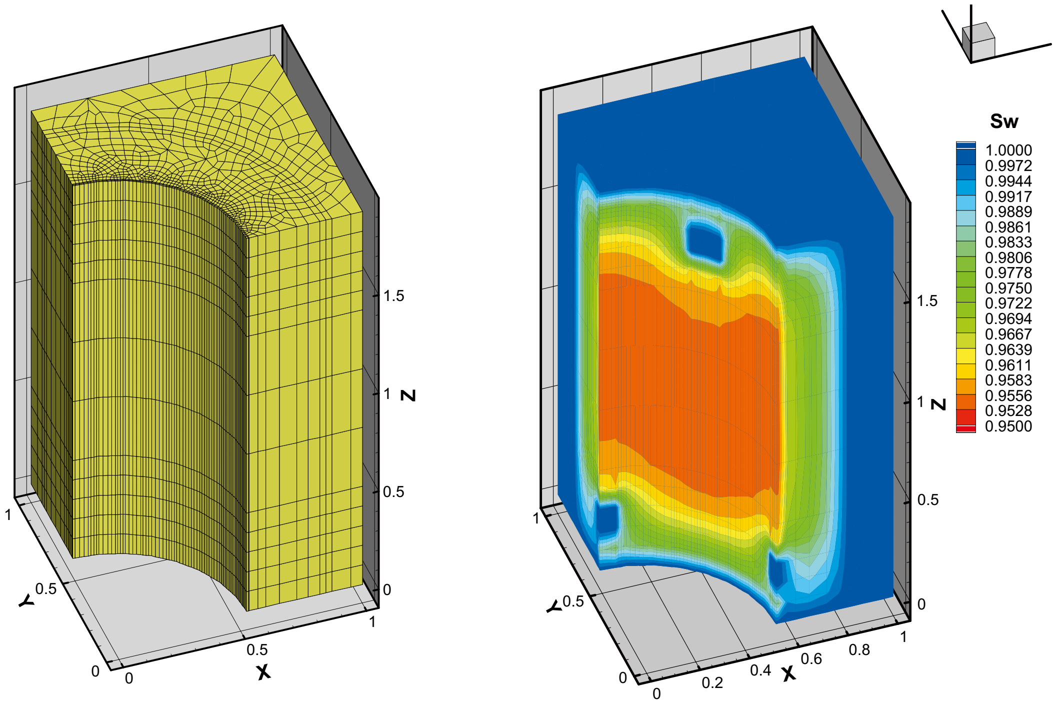


Figure 7-10. *Water saturation at 0.5 year in 3D geometry.*

7.2.3 Long Term Test of Buffer Material and Alternative Buffer Materials

In continuity of the Long Term Test of Buffer Material (Lot) and in the frame of the new Alternative Buffer Materials project, complementary actions began in 2006.

Analyses of clay material from the Lot test parcel A2 retrieved early 2006 have been carried out by /Rousset et al. 2006/, from French CREGU and LEM laboratories, to understand the evolution of MX-80 bentonite heated and hydrated over 5 years.

The block being sawed in 5 slices from the Cu/MX-80 contact to the granite/MX-80 one, each slice was devoted to specific characterisation. Slice #1 in contact with Cu was used for bulk chemistry analysis, electron microscopy and X-ray diffraction, slice #2 for microstructural study, Fourier transform infrared (FTIR) spectrophotometry and cation exchange capacity (CEC) determination, slices #3 to #5 to thin section processed following ^{14}C-MMA autoradiograph method.

Results show that heating did not modify the main properties of the bulk material. Very slight modifications have been recorded in relation with temperature and hydration degree: decrease in micro porosity and decarbonisation. The destabilisation of primary minerals (pyrite and carbonates) has led to formation of secondary phases such as Ca sulphates, Cu sulphides and Fe oxides. Occurrence of Cu-Fe-S mixture is shown in slice #1, but formation processes of these phases remain unclear.

Samples of Callovo-Oxfordian argillite (COX) from the clay layer where Andra is developing an underground research laboratory in the Meuse/Haute-Marne site, have been sent to Clay Technology and then installed in September 2006 in the Alternative Buffer Materials boreholes in Äspö. The COX argillite is used in two forms, rock blocks and remoulded material, and its behaviour will be compared with other swelling clays.

To complement the THMC characterisation of the COX argillite during water saturation under high temperature, a mock-up test started early 2007. It makes use of the CEA mock-up cell previously used for TBT with a clay specimen made of remoulded COX.

7.2.4 Task Force on Engineered Barrier Systems

CEA tests results constituted the experimental data set of Benchmark 1.1.1 of the EBS Task Force. These tests which dealt with THM processes during water transfer in a MX-80 bentonite under high temperature (maximum 150°C) had been implemented in the frame of a scientific cooperation between Electricité de France, the CEA and Andra.

Andra supported in 2006 the Centre Internacional de Mètodes Numèrics en Enginyeria, CIMNE-UPC, as modelling team in the EBS Task Force. The Spanish group performed simulations on Benchmark 1.1.1 using MX-80 thermal conductivities measured by Clay Technology /Börgesson and Hernelind 1999/ and retention curves under high temperature obtained by CIEMAT /Villar et al. 2006/. Investigations were notably conducted on the sensitivity of tortuosity and of retention parameters on the THM and gas analysis. The importance of the gas balance equation for the test simulation was also addressed.

CIMNE-UPC also contributed to Benchmark 1.1.2 dealing with CIEMAT infiltration tests and Benchmark 1.1.3 considering a heating test carried out by UPC. From these two tests on Febex bentonite, it is observed that the gas balance equation in the coupled THM and gas analysis is not important for test simulation when the maximum temperature in the specimen is less than 80°C. These simulations are reported in "Modelling experiments regarding THM behaviour of bentonite within the framework of the EBS Task Force".

7.2.5 Task Force on Modelling of Groundwater Flow and Transport

During the 21st international meeting of the Task Force held in Paris in March 2006, the last Task 6 results were presented and the overall evaluation discussed. Andra supported Golder and CEA modelling teams and a PhD student contributing to the Task 6 dedicated to bridge site characterisation and performance assessment modelling. Main conclusions and recommendations drawn from the modelling teams are:

- Tracer tests seem to constrain only weekly site characterisation conditions and not at all performance assessment conditions.
- Performance measured do not well discriminate between various modelling approaches, as differences in modelling results seem difficult to explain.
- Task6 results improved understanding of transport and retention in fractured media. However, uncertainty of the flow wetted surface is still unconstrained. Influence of flow distribution and channelling on transport needs investigation.
- An objective for site investigation is to establish a relationship between fracture networks connectivity, flow distribution and transport and retention area.
- A site investigation strategy should be developed in order to optimise the acquisition of characterisation data for performance assessment calculations.

Andra took advantage of methods developed within the Task Force to investigate the interest of various generic granite sites. Thus, results of Task 6 provided an input for preliminary safety analysis on suitability of granite rock for geological disposal in France. This work is reported in Andra "Dossier 2005 Granite".

Andra is also participating to Task 7 on "Reduction of performance assessment uncertainty through site scale modelling of a long-term pumping test at Olkiluoto".

7.3 BMWi

In 1995 SKB and the then BMBF (Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie) signed the co-operation agreement being the frame for participating in the activities in the Äspö HRL. In 2003 the agreement was extended for a period of six years. On behalf of and/or funded by the BMWi (Bundesministerium für Wirtschaft und Technologie) six research institutions are currently participating in experiments and activities connected to R&D in the Äspö HRL: Bauhaus Universität Weimar, BGR, DBE Technology, Forschungszentrum Dresden-Rossendorf (FZ D), Forschungszentrum Karlsruhe (FZ KA), and GRS.

The general purpose of the co-operation is to complement the state of knowledge concerning potential host rocks for high-level waste repositories in Germany and to extend the knowledge of the behaviour of the EBS (engineered barrier systems). Topics of special interest are:

- Studying the buffer material behaviour and the related basic processes by experiments and modelling.
- Investigations of the migration behaviour of radionuclides, especially actinides, under near-field and far-field conditions.
- Geochemical modelling of individual processes controlling migration.
- Investigation of the microbial activity with regard to the interaction with radionuclides.
- Thermodynamic databases for radionuclides relevant for long-term safety.

The work carried out in 2006 is described below.

7.3.1 Colloid Project

The FZK-INE studies aim investigating the behaviour of radionuclides in a colloid-groundwater-fracture infill mineral system. Background of the experiments is the scenario of a potential release of clay colloids from the bentonite barrier in a repository and their subsequent transport with the groundwater flow in a water conducting fracture. Those colloids may sorb radionuclides and thus can act as carriers for the colloid-mediated radionuclide migration.

The stability of clay colloids prepared from MX-80 bentonite in solutions of varying ionic strength and pH and in a groundwater sampled at the Äspö HRL (True site, borehole KXTT) has been studied within the reported period. The impact of colloids on the speciation of various radionuclides including the actinides was observed in Äspö groundwater over a period of months. In preparation of batch sorption studies, fracture filling minerals from Äspö were equilibrated with groundwater from the site.

Characterisation of Äspö groundwater

The groundwater was stored under anaerobic conditions (Ar/1%CO_2). LIBD (laser induced breakdown detection) analysis reveals the presence of colloidal species in the natural groundwater. Additional analysis after ultracentrifugation shows that colloids are composed of iron and contain as well lanthanides while naturally present Cs^+, Sr^{2+} and U do not indicate colloidal behaviour.

In order to study the influence of oxygen contact on groundwater chemistry, ~ 130 ml of the groundwater have been sampled, placed in a PE-container with a magnetic stirrer and left in contact with air. After 3–4 days, the magnetic stirrer became coloured and brown entities were appearing, sticking on the container walls. Scanning electron microscope (SEM) analysis of these entities reveals iron associated calcite precipitates. Additional Inductively Coupled Plasma Mass Spectrometry (ICP-MS) analysis performed before and after filtration (filter pore size: 100 nm) leads to the conclusion that iron pseudocolloids > 100 nm are formed. It can be concluded: Oxygen contact (formation of Fe(III) oxy/hydroxide colloids) and pressure release (precipitation of calcite) can significantly influence the colloid composition in Äspö groundwater, see Table 7-2.

Table 7-2. Physico-chemical parameters determined for a water sample (borehole KXTT from True-1 site) stored in an Al-barrel under anoxic conditions.

Parameter	
pH	7.5 ± 0.1
$E_{h(SHE)}$	~ 100 mV
Groundwater composition	
Ionic strength	0.2 M
$[Mg^{2+}]$	70.9 mg/L
$[Ca^{2+}]$	1.06 g/L
$[Na^{+}]$	1.2 g/L
$[Sr^{2+}]$	15.9 mg/L
$[Cl^{-}]$	3.9 g/L
$[SO_4^{2-}]$	270 mg/L
$[Fe^{2+,3+}]$	0.76 mg/L
$[La^{3+}]$	0.2 µg/L
$[Cs^{+}]$	15.7 µg/L
[U]	0.28 µg/L

MX-80 bentonite colloid stability

Colloid preparation

Delamination of the clay was achieved by washing the < 64 µm fraction obtained after sieving the raw MX-80 bentonite with 1 M NaCl solution during 1 week. Smaller-sized colloids were collected after 4 centrifugation-collection-resuspension cycles in ultra-pure water. The final colloidal stock solution was at pH 8.5 and contained ~ 0.56 g/L colloids. X-ray diffraction (XRD) characterisation showed pure montmorillonite, (80% Ca-form + 20% Na-form). The presence of predominantly Ca-montmorillonite in the clay colloids will be verified by further characterisation. Atomic Force Microscope (AFM) imaging showed the presence of a bimodal size distribution with larger platelet-like particles ~ 180 nm and smaller colloids in the size range around ~ 30 nm.

Colloid stability

Colloid stability ratios (W) were calculated from the coagulation rates of the bentonite MX-80 colloids measured as a function of the ionic strength varying from 0.001 M up to 1 M in NaCl or $CaCl_2$ media by Photon Correlation Spectroscopy (PCS) in the pH range 4–10. Additional LIBD (laser induced breakdown detection) measurements of the supernatants by decanting solutions after 1 and 4 months were performed. Both analytical methods show clearly the instability of colloids at the high ionic strength of the Äspö groundwater. Instantaneous agglomeration with subsequent sedimentation is observed indicating that the current Äspö groundwater chemistry represents a regime of solely diffusion controlled agglomeration. In future work we will characterise the colloidal precipitates by SEM analysis in order to specify whether groundwater components (e.g. FeOOH or calcite-colloids play a role for the agglomeration reaction).

In a first set of experiments, the coagulation rate of bentonite colloids (1.2 mg/L and 0.12 mg/L) was determined in presence of fulvic acid (FA) varying from 0.8 up to 770 mg/L) at an ionic strength of 0.2 M ($CaCl_2$ solution) and pH ~ 7.5. This natural organic matter (FA) addition simulates the DOC (dissolved organic carbon) concentrations found in various Äspö groundwaters. No significant change in the measured stability ratios could be observed as compared to the experiments in absence of organic matter. Additional performed LIBD measurements of supernatants, after 1 and 4 months colloid sedimentation, showed that colloids were still detectable. First experiments indicate that the conditioning of bentonite with FA prior to increase of the ionic strength increases colloid stability.

Those experiments are continued to assess the long-term stability of colloids in presence of organic matter at varying colloid-organic matter ratios, ionic strength, pH and with different types of fulvic or humic acid. It is also foreseen to characterise the colloidal species stabilised in presence of organic matter.

Interaction of radionuclides with bentonite colloids

For this study, two batch experiments have been conducted. In the first one, Äspö groundwater has been spiked with radionuclides: Sr^{90}($2.2\cdot10^{-9}$ M), Cs^{137}($2.3\cdot10^{-9}$ M), Am^{241}($1\cdot10^{-10}$ M), Np^{237}($1.06\cdot10^{-8}$ M), U^{233}($2.3\cdot10^{-8}$ M) and Pu^{244}($1.07\cdot10^{-9}$ M) at pH 7.5 ± 0.2. In a second batch, MX-80 bentonite colloids (2.4 mg/L) have been added. Evolution of the radionuclide and bentonite colloid concentrations has been followed over two months by direct analysis of the solution and after ultracentrifugation. Radionuclide concentrations were analysed by LSC and ICP-MS.

Cs(I), Sr(II), and U(VI) spiked to the Äspö groundwater do not show any significant colloidal behaviour in presence or absence of MX-80 bentonite colloids. This result is in agreement with the behaviour of naturally occurring Cs, Sr and U in the investigated groundwater. In agreement with the results of the colloid stability study, the MX-80 bentonite colloids are unstable under these conditions and sediment after two days. Am(III) and Pu(IV) exist as colloids when spiked to the Äspö groundwater in presence and absence of MX-80 bentonite colloids. Np(V) is at least partly reduced after 2 months to Np(IV) and appears to show comparable colloidal behaviour as seen for Pu(IV). These colloidal species are unstable and disappear from both solutions (presence and absence of clay colloids) after 2 months.

7.3.2 Microbe Project

Introduction

The FZD/IRC contributions within the microbe project are concentrated in a project addressing the indirect interaction mechanism of a mobilisation of actinides by released bioligands in the aquifer system from relevant Äspö bacteria. The on-going study is focused on: (a) isolation and characterisation of microbial ligands produced from a subsurface strain of *Pseudomonas fluorescence* isolated at Äspö, (b) interaction of U(VI), Np(V), and Cm(III) with the microbial ligands including compounds simulating the functionality of the microbial ligands and the surface of the bacteria and (c) spectroscopic characterisation of the formed actinide complexes/compounds. The formation constants determined will be used directly in speciation and transport models. This project should help to identify the dominating process of the interaction between actinides and microbes (direct or indirect ones). The research performed in our project improves the understanding of the behaviour of colloids and microbes and their respective interaction with radionuclides. The activities in 2006 were concentrated on (a) the isolation and characterisation of bioligands secreted by a subsurface strain of *P. fluorescence* found at Äspö HRL and (b) complexation studies of actinides with relevant model compounds to explain the interactions of actinides in biologically systems on a molecular level. Main results of these subjects will be reported here.

Isolation and characterisation of the bioligands secreted by P. fluorescens (CCUG 32456 A)

The isolation of the bioligands was performed by our Swedish colleagues at Göteborg as part of the cooperation between the FZD/IRC and the group of Prof. K. Pedersen from the Göteborg University (Department of Cell and Molecular Biology). In order to characterise the produced bioligands by mass spectrometry cooperation between the FZD/IRC and Prof. H. Budzikiewicz and Dr. M. Schäfer from the Universität zu Köln (Institut für Organische Chemie) was established.

Microorganisms synthesise bioligands in order to mobilise essential elements like iron, to use these metals in their metabolism or in enzymes. The mobilisation of other metals, like actinides, by these bioligands, for instance in the Äspö-aquifer system, is not yet understood. Pyoverdins are special bacterial siderophores produced by fluorescent *Pseudomonas* species. This unique class of bioligands possess a high potential to bind and therefore to transport actinides in the environment. Pyoverdins are yellow-green, water-soluble and, due to the presence of a chromophore, fluorescent pigments which are very effective in complexing and transporting iron(III) /Budzikiewicz 2004/. The structure of pyoverdins can be divided into three parts a) a chromophore, b) a peptide chain, composed of 6 to 12 mainly hydrophilic amino acids, bound via its N-terminus to the carboxyl group of the chromophore, and c) an acyl chain, attached to the NH_2 group of the chromophore, consisting of dicarboxylic acid residues (e.g. succinate or its amide form), the type of which depends on the growth conditions /Budzikiewicz 2004/.

Bioligands secreted under aerobic conditions by *P. fluorescens* (CCUG 32456 A) were isolated and characterised by mass spectrometry. In order to understand the mobilising potential of pyoverdins towards actinides it is essential to explore their speciation in aqueous solution in the absence of actinides. We studied the protonation equilibria of *P. fluorescens* (CCUG 32456 A) pyoverdins within a pH range of 3 to 10 by UV-vis spectroscopy. The fluorescence properties of the bioligand mixtures were investigated by applying fs-TRLFS.

Experimental

P. fluorescens (CCUG 32456 A) was grown in batch cultures under aerobic conditions in the standard succinate medium at room temperature. After one week the cultures were pooled and the pooled material was centrifuged at 8,000 G for 10 minutes. The supernatants were then suction-filtered (0.2 µm). The pH of the filtered supernatant was lowered to 6 and the solution was frozen pending purification. Purification was done using uncomplexed pyoverdin, as outlined in /Meyer et al. 1978/. Columns packed with XAD-4 Amberlite resin were loaded with pyoverdin solution, rinsed with Milli-Q water (MQ) and eluted with 50% methanol (MetOH). The resulting pulverised pyoverdin mixtures were used for the mass spectrometry studies.

Mass spectra were obtained with a MAT 900 ST instrument with an EB-QIT (quadrupol ion trap) geometry and equipped with an ESI II ion source (Finnigan MAT, Bremen, Germany); spray voltage 3.4–3.6 kV, capillary temperature 230°C. Collision activation (CA) in the octapole unit in front of the QIT with He diffusing from the QIT as collision gas was followed by product ion analysis in the QIT.

In the UV-vis investigations the pyoverdin concentration $[LH_4]$ was fixed to $5.8 \cdot 10^{-5}$ M and the pH was varied between 3 and 10. All experiments were made at an ionic strength of 0.1 M ($NaClO_4$). The absorption spectroscopy experiments were performed using a CARY5G UV-vis-NIR spectrometer (Varian Co.) at 22±1°C. The spectra were evaluated using the factor analysis program SPECFIT. Experimental details of the fs-TRLFS setup are given in /Geipel et al. 2004/.

Results

Figure 7-11 shows the molecular ion region ($[M+2H]^{2+}$) of a pyoverdin sample from *P. fluorescens*. Comparison of the fragmentation patterns of the various species obtained by collision activation with archives' material /Baysse et al. 2002/ demonstrated the presence of siderophores corresponding to those produced by *P. fluorescens* ATCC 17400 /Demange et al. 1990/. Specifically, the following species were observed: *m/z* 650.24 pyoverdin with succinamide side chain (Figure 7-12), *m/z* 650.74 pyoverdin with succinic acid side chain, *m/z* 644.25 ferribactin with succinamide side chain (cf. /Budzikiewicz et al. 2007/), *m/z* 659.27 ferribactin with glutamic acid side chain, *m/z* 653.27 and 668.27 are probably the open chain analogs of *m/z* 644.25 and 659.27 (Gln-Dab, glutamine and 2,4-diaminobutanoic acid instead of their tetrahydropyrimidine condensation product) (cf. /Boukhalfa et al. 2006/). This is evidenced because the ions B_7^{++} (cleavage after Dab) at *m/z* 509 (side chain succinic acid amide (Suca)) and *m/z* 524 (glutamic acid (Glu) side chain), respectively, are of high abundance especially in the MS^n-QIT product ion mass spectra while analogous ions of the analogues with the tetrahydropyrimidine condensation product are missing in the spectra. The free Dab stabilises the second ionising proton.

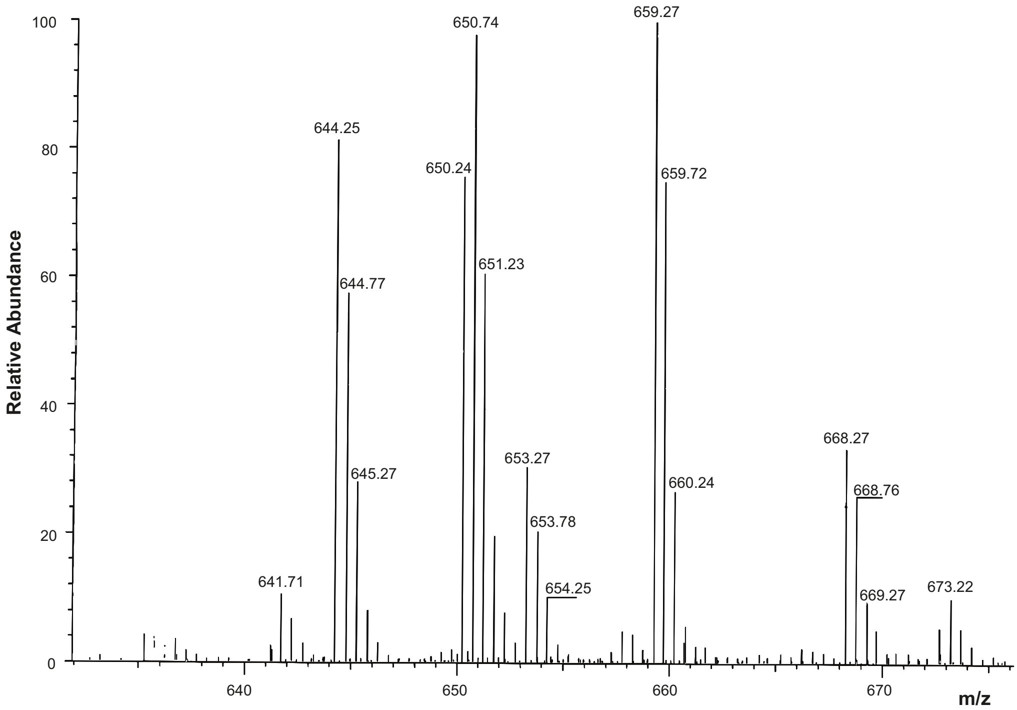


Figure 7-11. *Molecular ion region ($[M+2H]^{2+}$) of a sample of a pyoverdin preparation from P. fluorescens (CCUG 32456 A).*

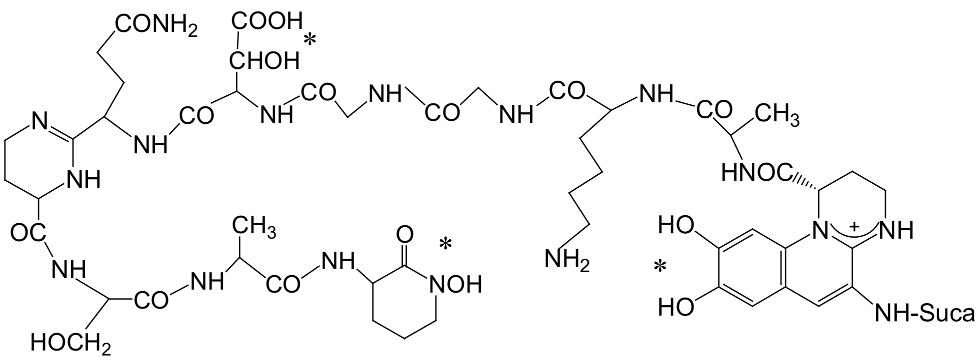


Figure 7-12. *Structure of the pyoverdin from P. fluorescens (CCUG 32456) with a succinamide (Suca) side chain (Suca-Chr-Ala-Lys-Gly-Gly-OHAsp-(Gln-Dab)-Ser-Ala-cOHOrn). Asterics indicate the complexation sites. The amino acids Ala, Lys, and Gln (underlined) are D-configured.*

These open forms are probably not artifacts since the tetrahydropyrimidine ring can be hydrolysed only under drastic conditions as described in /Gipp et al. 1991/. As frequently observed for a succinate culture the production of ferribactin (biogenetic precursors of the pyoverdin /Budzikiewicz 2004/) prevails over that of pyoverdin /Budzikiewicz et al. 2006/, here in a ratio of 2:1.

The observed pH sensitivity of the absorption spectra of the pyoverdin sum fraction in aqueous solution is depicted in Figure 7-13(a). At pH values below 5 the absorption spectra are characterised by a double peak at 365 and 379 nm. Whereas the maximum at 365 nm decreases with increasing pH, the maximum at 379 nm remains nearly unchanged up to pH 6. In the pH region above 7 one single absorption band at 403 nm dominates the interesting wavelength region. The visible absorption bands shown in Figure 7-13(a) are dominated by the pyoverdin chromophore even if the pyoverdin mixture contains 1/3 pyoverdins and 2/3 ferribactins as described above.

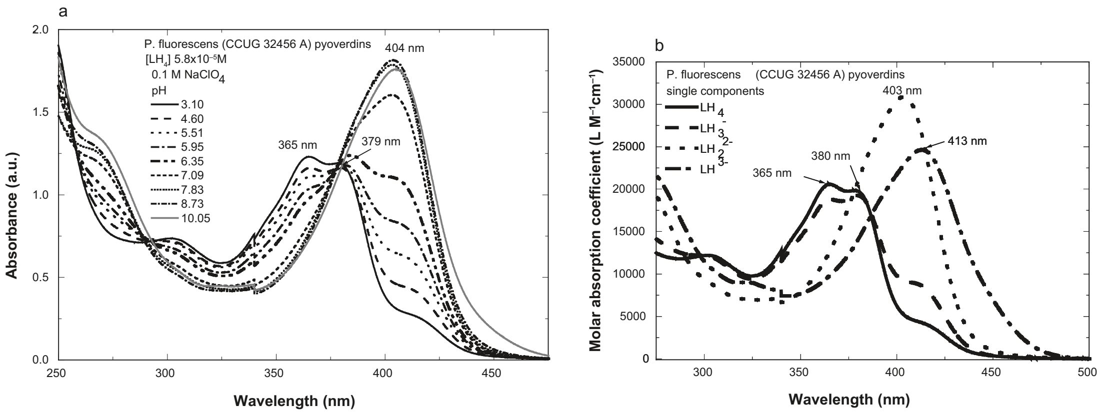


Figure 7-13. *(a) Absorption spectra of the P. fluorescens (CCUG 32456 A) pyoverdin sum fraction as a function of pH at an ionic strength of 0.1 M (NaClO4).* ***(b)*** *Absorption spectra of the single components in the aqueous P. fluorescens pyoverdin system as derived by peak deconvolution using SPECFIT.*

The pyoverdin molecule will be denoted as LH_4 according to the general approach that pyoverdin molecules can liberate four labile protons from the complexing sites most likely responsible for metal binding /Teintze et al. 1981, Bouby et al. 1999/. Three pK values could be determined using SPECFIT. The calculated spectra of the different aqueous pyoverdin species are shown in Figure 7-13b. The absorption spectrum of the deprotonated catechol-type moiety, L^{4-}, could not be characterised with sufficient accuracy due to indications of a sample decomposing at pH > 10. The following formation constants were calculated: log $ß_{012} = 22.67 \pm 0.15$ ($pK_1 = 4.40$), log $ß_{013} = 29.15 \pm 0.05$ ($pK_2 = 6.48$) and log $ß_{014} = 33.55 \pm 0.05$ ($pK_3 = 10.47$), respectively.

The excellent fluorescence properties of the pyoverdin sum fraction after excitation with a monochromatic laser-beam at 266 nm is shown in Figure 7-14. The broad emission spectrum with a maximum at 465 nm could by fitted by applying two species at 456 and 487 nm. The evaluation of the fluorescence decay showed again two main components having different fluorescence lifetimes of 690±85 and 4,850±30 ps. This can be explained by the identification of two major constituents, ferribactins (biogenetic precursors of the pyoverdin) and pyoverdins, of the pyoverdin sum fraction by mass spectrometry. To our knowledge this is the first detailed characterisation of aqueous pyoverdin species by fs-TRLFS.

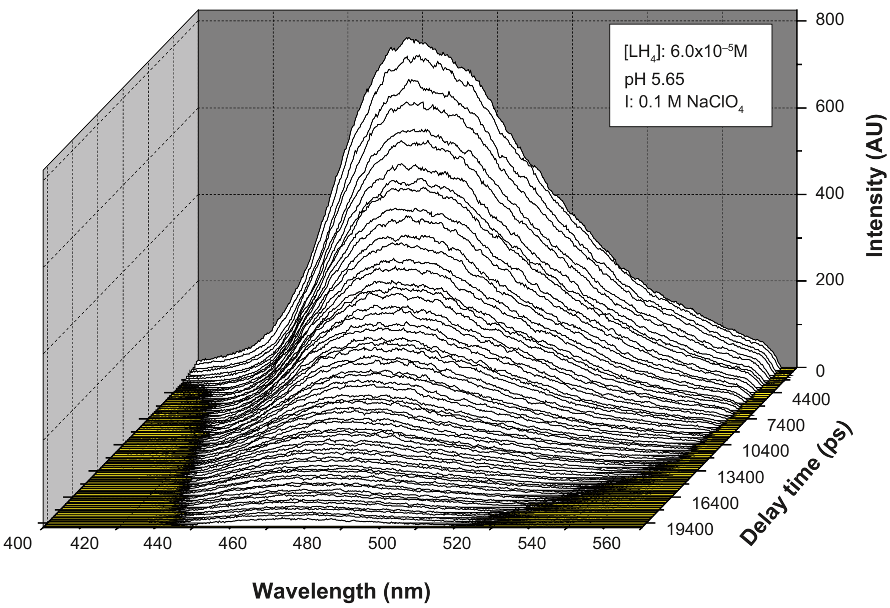


Figure 7-14. *TRLFS spectra of P. fluorescens (CCUG 32456 A) pyoverdins as a function of the delay time.*

Complexation of uranium(VI) with aromatic acids having different functionalities studied by different spectroscopic techniques (UV-vis spectroscopy and time-resolved laser-induced fluorescence spectroscopy (TRLFS))

The complex formation of uranium(VI) with salicylhydroxamic (SHA), benzohydroxamic (BHA) and benzoic acid (BA) was investigated by UV-vis and TRLFS. The different U(VI) species are characterised by their individual absorption spectra and molar extinction coefficients. By using TRLFS at much lower U(VI) concentrations, in all formation was observed. The formation constants of the identified uranium(VI) species, $M_pL_qH_r$, were determined on the basis of the results of both spectroscopic techniques.

To understand the actinide interaction processes in biological systems on a molecular level it is necessary to explore the complexation behavior of actinides with selected bioligands of relevant functionalities as model compounds. The three studied ligands are model compounds for pyoverdins, which are natural bioligands secreted from *Pseudomonas* ssp. possessing a high potential to bind actinides. One objective is if one could detect variations in the absorption spectra due to the different coordination environment of uranyl by using hydroxamic acids and benzoic acid. Another objective is that we want to explore the fluorescence properties of the formed U(VI) species. Moreover we want to compare the formation constants determined using TRLFS with those obtained three systems a static quench process of the uranyl fluorescence due to the complex by UV-vis.

Experimental

The absorption spectroscopy experiments were carried out at a total uranyl concentration of $1\cdot10^{-3}$ M as a function of the ligand concentration (10^{-4} M to $5\cdot10^{-3}$ M) at pH 3 and 4. The ionic strength was adjusted to 0.1 M ($NaClO_4$). The spectra were recorded from 350 to 500 nm using a CARY5G UV-vis-NIR spectrometer (Varian Co.) at 22 ± 1°C. The stability constants were determined using the factor analysis program SPECFIT. Details are summarised in /Glorius et al. 2007/. The TRLFS experiments were carried out at a total uranyl concentration of $5\cdot10^{-5}$ M as a function of the ligand concentration (10^{-5} M to 10^{-3} M) at pH 3 and 4. The ionic strength was adjusted to 0.1 M (NaClO4). The spectra were recorded at 25°C using a pulsed Nd:YAG laser system. The excitation wavelength of the uranyl fluorescence was 266 nm with pulse energy of 100–200 µJ. The stability constants at pH 3 were determined with a slope analysis and at pH 4 using the factor analysis program SPECFIT.

Results

Figure 7-15 shows the measured UV-vis spectra at a uranium concentration of 0.001 M at pH 3 as a function of the SHA (Figure 7-15a) and BA (Figure 7-15b) concentration.

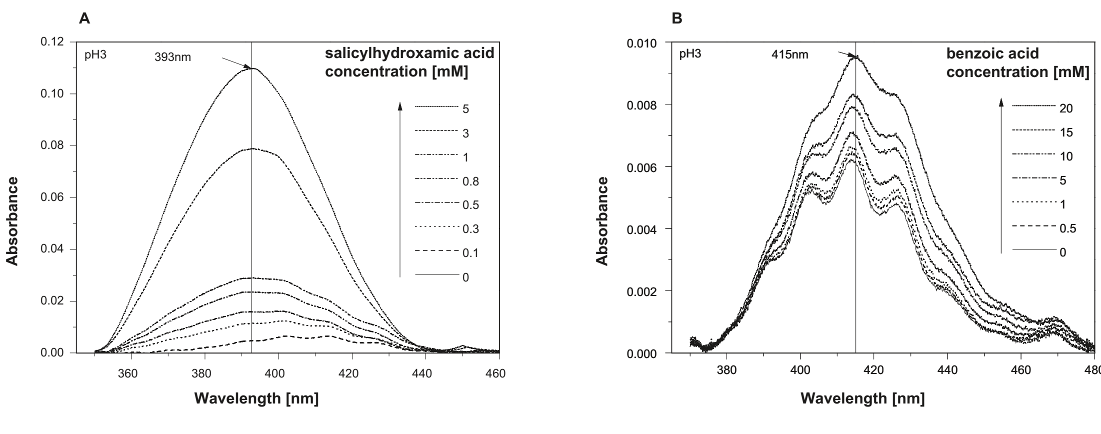


Figure 7-15. *Measured UV-vis spectra at 0.001 M UO_2^{2+} at pH 3 in the (a)) SHA-, (b) BA-system.*

In the SHA- and BHA-uranyl system an increase in the absorbance combined with a blue shift of the absorption maxima of about 25 nm in comparison to the bands of the free uranyl ion was observed. In contrast to the SHA- and BHA-system the spectra of BA shows an increase in the absorbance and a red shift of the absorption maxima of about 2 nm. The changes in the absorption spectra indicate in all three uranyl-ligand systems a formation of uranium(VI)-ligand complexes with a 1:1 stoichiometry. In the SHA-system indications for a 1:2 complex were found. The stability constants of the three systems determined by both methods and extrapolated to infinite dilution are summarised in Table 7-3.

The complex formation constants suggest that SHA forms more stable complexes compared to BHA. Both aromatic hydroxamate compounds form stronger uranyl species than BA. The strength of complex formation decreases generally from SHA via BHA to BA. This dependence is in agreement with results obtained with other metals, e.g. Fe (III) and Cu (II) /O'Brien et al. 2000, Farkas 2000/. Furthermore one can postulate different coordination modes of uranyl from the presented experimental findings. If uranyl is coordinated to hydroxamic acids this results in a blue shift of the absorption maxima. Whereas in the case of coordination to the carboxylic acid group of benzoic acid, a red shift of the absorption maxima was observed. So the uranyl ion is bound to benzoic acid over the oxygen atoms of the carboxylic group and to the hydroxamic acids probably over the oxygen atoms of the hydroxamic acid group. Theoretical calculations are in progress to get a further insight of the coordination environment of U(VI) in the three systems investigated. The differences in the coordination sphere of uranium cause the opposed displacements of the absorption maxima in comparison to the spectrum of the free uranyl ion. Figure 7-16 shows the measured fluorescence spectra at a uranium concentration of $5\cdot10^{-5}$ M at pH 3 as a function of the SHA concentration.

Table 7-3. Complex formation constants of the identified uranium(VI) complexes.

Ligand	Complex species $M_pL_qH_r$ pqr		log β^0 UV-vis	log β^0 TRLFS
SHA	111	$UO_2HOC_6H_4CONHO^+$	16.22 ± 0.10	16.44 ± 0.06
	122	$UO_2[HOC_6H_4CONHO]_2$	~ 30	33.43 ± 0.11
BHA	110	$UO_2C_6H_4CONHO^+$	7.51 ± 0.05	7.47 ± 0.11
	120	$UO_2[C_6H_4CONHO]_2$	14.58 ± 0.11	16.21 ± 0.49
BA	110	$UO_2C_6H_4COO^+$	2.92 ± 0.14	3.11 ± 0.05

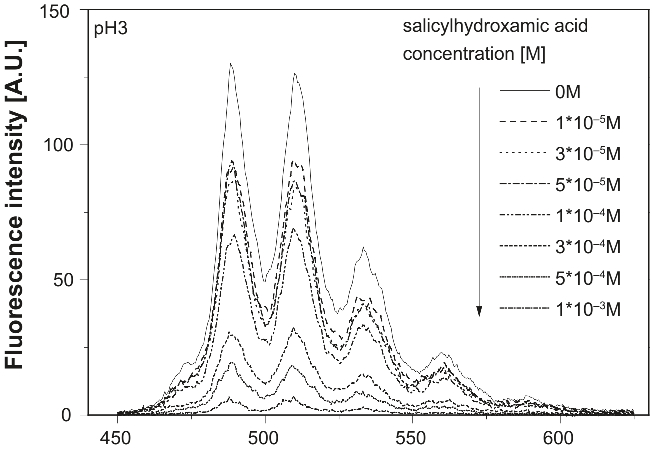


Figure 7-16. *Measured fluorescence spectra of the SHA-uranyl system at $5\cdot10^{-5}$ M UO_2^{2+} at pH 3.*

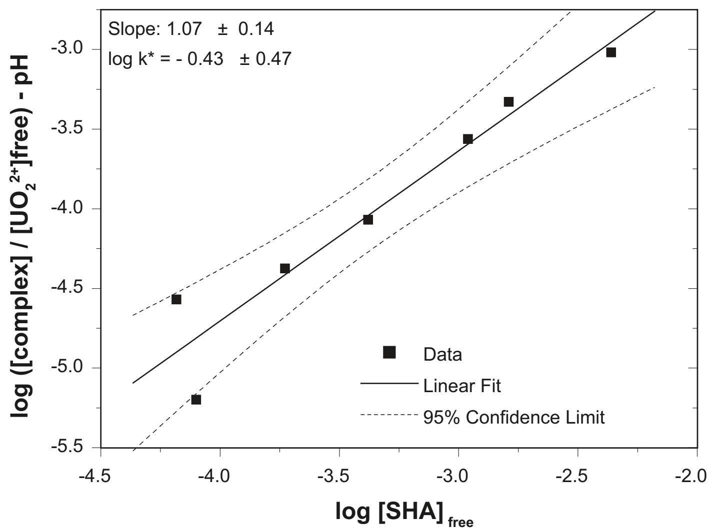


Figure 7-17. *Slope analysis of the uranyl complex formation with SHA at pH 3.*

In all three studied systems we observed a decrease in the fluorescence intensity with increasing ligand concentration at pH 3 and 4, which is typical for static fluorescence quenching due to the complex formation. The lifetimes decrease with increasing ligand concentration, indicating additional dynamic quenching. It follows, that all complexed ligand uranyl species emit no fluorescence light. The determined lifetimes were used to calculate the fluorescence intensity if no dynamic quenching takes place. These corrected fluorescence intensities were then used to calculate the concentrations of the free uranyl ion at pH 3 as a function of the ligand concentration.

To determine the stability constants and to estimate the stoichiometry of the complexes a slope analysis was made using the logarithmic mass action law in its transformed linear form. Figure 7-17 shows the result of the slope analysis of the U(VI)-SHA-system as an example.

The average slope of 0.9±0.2 suggests in all three systems the formation of a 1:1 complex at pH 3. The intersection corresponds to the formation constant log k* of the complex. The stability constant log β was determined using log k* and the protonation constants of the ligands, see Table 7-3. In the SHA- and BHA-system a slope of 1.5 at pH 4 gives evidence for the formation of a second species most likely a 1:2 complex. Because of the occurrence of two complex species, the factor analysis program SPECFIT was used to evaluate the series measured at pH 4. In general, for all ligands the stability constants determined by TRLFS are in agreement with the values measured using UV-vis spectroscopy as shown in Table 7-3. The results of the present work contribute to a better understanding of the uranium(VI) coordination chemistry with aromatic hydroxamate containing bioligands in aqueous solution. The model ligands used in this work simulate the hydroxamate function of the pyoverdins, which is probably the preferred binding place for metals. The higher formation constants of uranyl with the aromatic hydroxamate compounds compared to benzoic acid points to the high potential of the pyoverdins to bind and mobilise U(VI) in the environment. The complexation studies with selected bioligands are essential to explain the actinide interaction processes in biological systems on a molecular level.

7.3.3 Prototype Repository

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

The measuring programme, agreed on by SKB and GRS, includes the monitoring of two electrode arrays in the backfilled drift above the deposition boreholes 3 and 6, an electrode array in the buffer at the top of deposition hole 5, and three electrode chains in the rock between deposition holes 5 and 6, see Figure 7-18.

Special water-tight cables and connectors were selected for connections between the electrodes and the geoelectric monitoring system which was installed in the data acquisition room in the parallel G-tunnel.

In 2006, the measurements have been continued as planned. In Sections I and II a rather homogeneous resistivity distribution around 3 Ωm has been reached in the backfill (see Figure 7-19). Only in the centre of Section II a small region with higher resistivity is maintained, but decreasing in size. In both sections the backfill is close to saturation and the water content in the range of 21–22%.

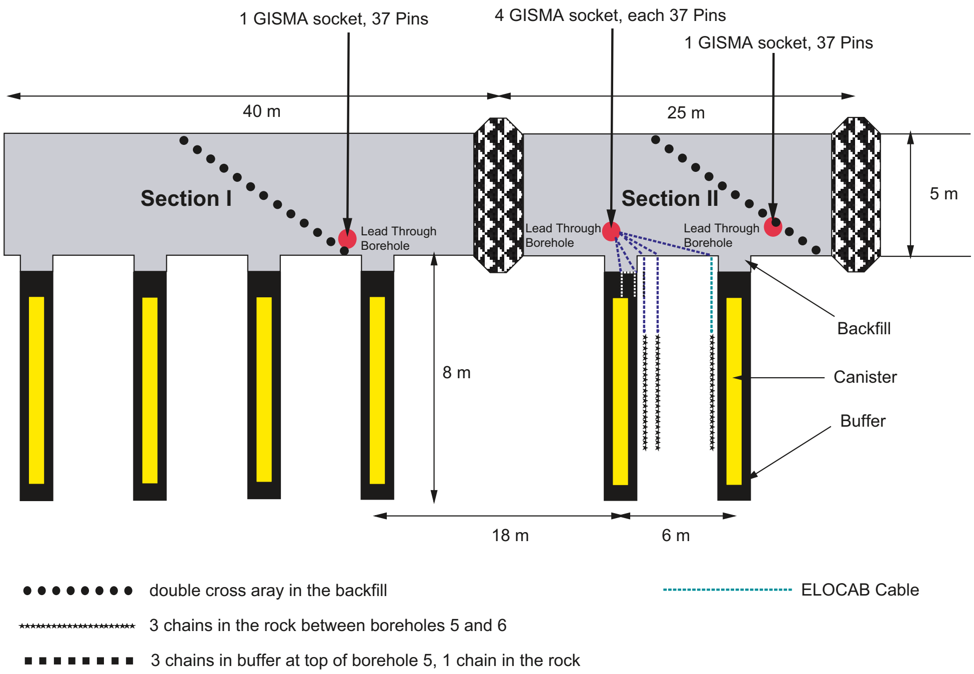


Figure 7-18. Arrangement of electrode arrays in the Prototype Repository

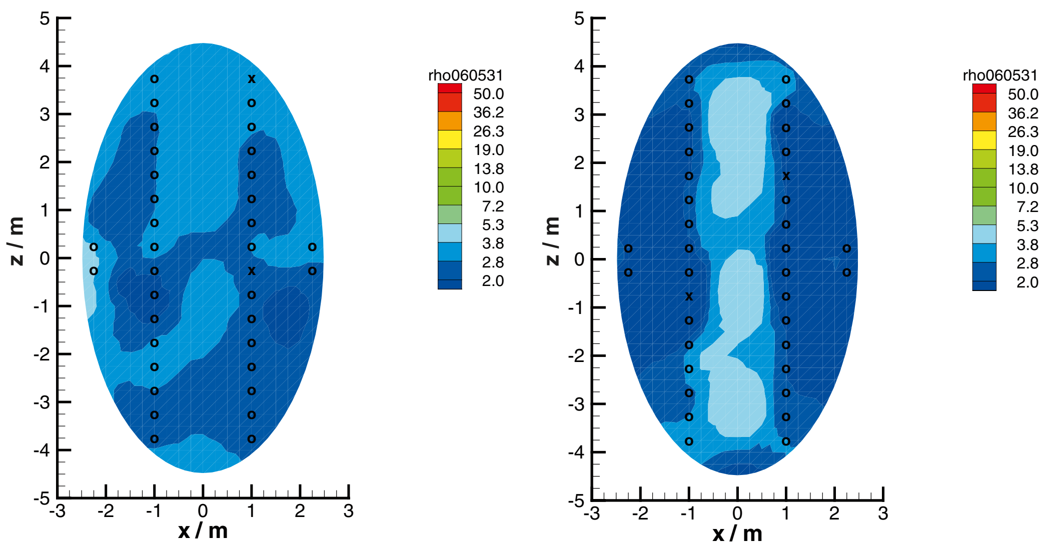


Figure 7-19. Resistivity distribution in backfill Section I (left) and Section II (right).

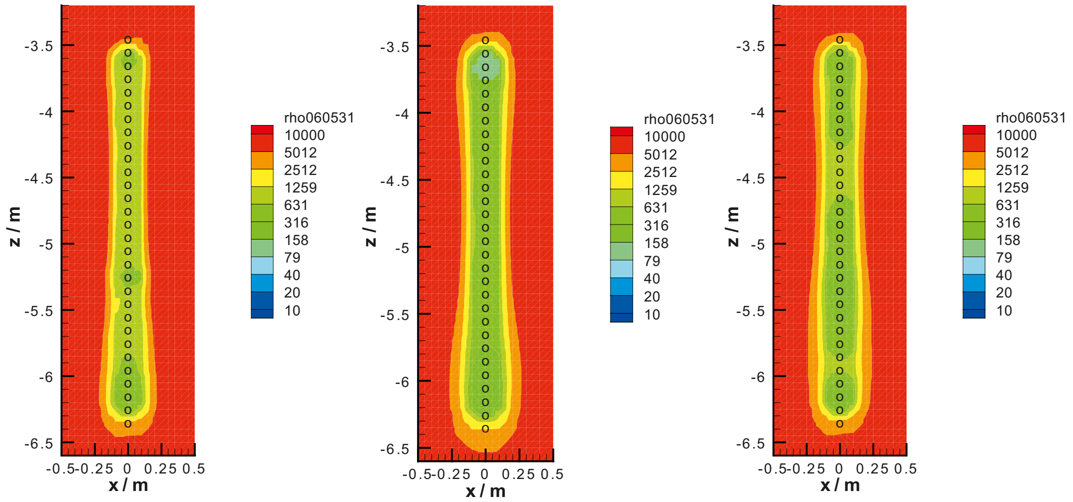


Figure 7-20. Resistivity distribution along the three electrode chains in the rock.

The measurements in the buffer can no longer be evaluated in terms of water content because of the failure of several electrodes at the end of 2005. The reason for the failure is still unclear; an excavation of the electrodes in the course of post-test investigations will yield the necessary information.

The resistivity distributions along the three electrode chains installed in the rock (Figure 7-20) are quite similar to each other. Close to the electrodes, the resistivity is in the range of 200 Ωm. This value characterises the water-saturated concrete used for backfilling the electrode boreholes. Further away from the boreholes, the resistivity rises to values of 2,000 to 7,000 Ωm which is characteristic for saturated granite.

To increase the confidence in the results of the inversions of the apparent resistivities measured in situ, a laboratory experiment has been performed in which controlled progressing water uptake in drift backfill was simulated and monitored by geoelectric measurements. This experiment is currently evaluated. Comparison between the known state of water uptake and the results of the measurements will allow better assessment of the inversion accuracy.

7.3.4 Temperature Buffer Test

Objective of the work DBE Technology is performing in the Temperature Buffer Test (TBT) is to test and evaluate the long-time performance of fibre optic pressure and temperature sensors in an environment with high temperatures and corrosive surroundings. The measurements are accompanied by numerical analyses in order to model and understand the THM-behaviour of the barrier material. Performing numerical analyses were the main activities in 2006.

The temperature distribution in the buffer material is essential when describing the material behaviour since a couple of processes and parameters are dependent on temperature. Thus the main focus was set on analysing the temperature evolution in the buffer material and performing a parameter identification to obtain, as good as possible, the thermal material parameters. The parameter identification has been performed by 3D numerical simulations using the code $FLAC^{3D}$ /Itasca 2005/.

Looking at previous calculation results the temperature evolution around the upper canister was not satisfying. Especially at later times the fitting of the calculated results compared to the measurements was still poor and it was assumed that the thermal parameters of the sand buffer were not correctly chosen. Due to that reason a new and extensive parameter variation has been performed to obtain a unambiguous set of thermal parameters for the different materials resulting in a suitable description of the temperature evolution for the complete 3D configuration.

The current best results of the parameter variation are shown in Figure 7-21 for a couple of temperature sensors at various distances to the heat sources. All failures of the heat sources have been incorporated in the model in order to reduce uncertainties. Keeping in mind the complexity of the 3D system as well as the inhomogeneous boundary conditions due to another heater experiment in the near surrounding the fitting can be seen as good.

In Figure 7-22 the resulting temperature field after 430 days is given together with the current best parameter fit. It was rather surprising that only an unexpected low thermal conductivity of the sand buffer yields a adequate temperature fitting. The temperature field is thus less homogeneous in vertical direction than expected.

After having determined a suitable description of the thermal system a first 2D model has been build to simulate the suction within the bentonite buffer. Besides the pressure induced Darcy flow the capillary pressure (suction) within the bentonite seems to be the dominating force for water uptake of the bentonite next to the outer fluid filled sand filter. The capillary pressure is of coarse temperature dependent. Equation 1 gives the capillary pressure – saturation relation after the van Genuchten model as implemented in FLAC (two-dimensional continuum code). There are two parameters that are temperature dependent: the surface tension σ and the dynamic viscosity μ of the water.

$$P_c = P_0\left[S_e^{-1/a} - 1\right]^{1-a} \qquad P_0 = \frac{\sigma}{\sqrt{k/n}} \qquad k = k_f\,\frac{\mu}{\rho \cdot g} \qquad (1)$$

The 2D simulations are aimed at characterising the effect of temperature on the suction process in the bentonite buffer and to identify a first approach of the van Genuchten parameters to characterise the suction process in the model. A detailed model has been built and first test runs have been performed.

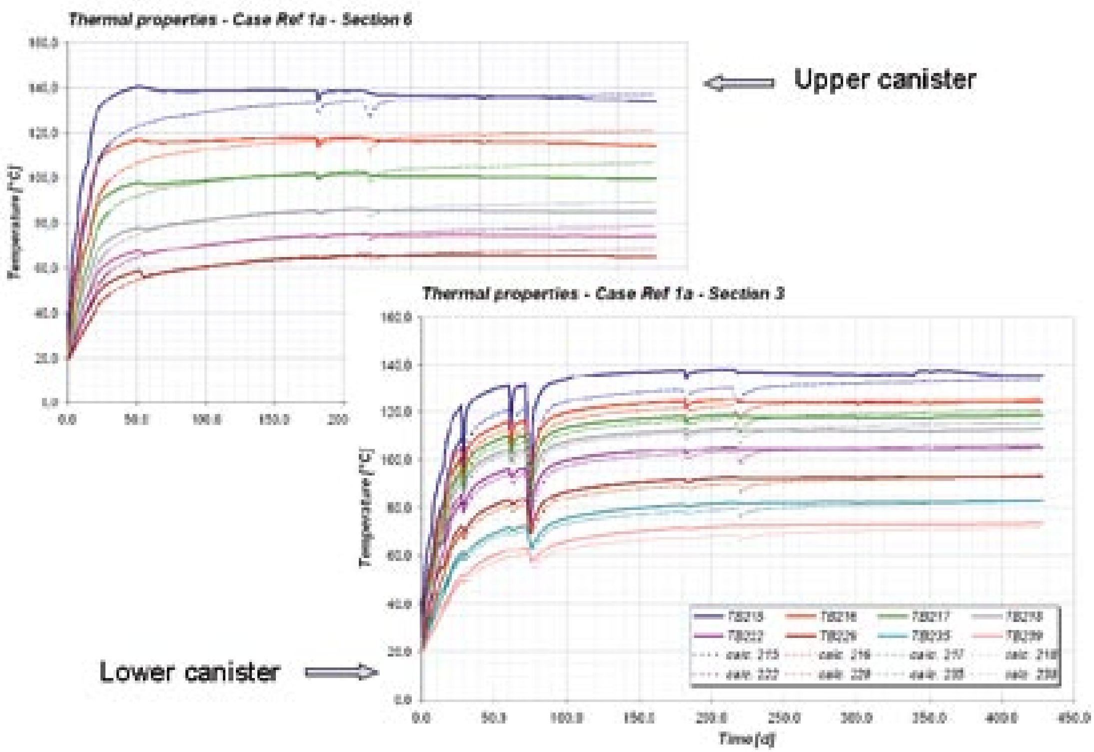


Figure 7-21. Comparison of simulated and calculated temperature evolution around the canisters.

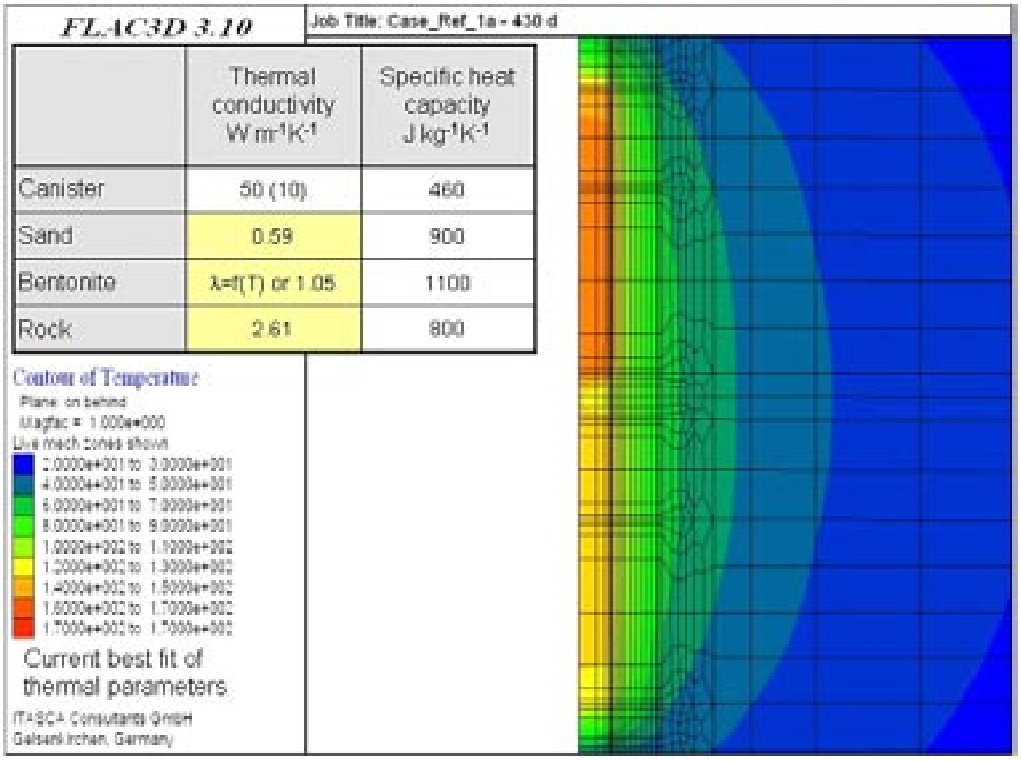


Figure 7-22. *Temperature distribution after 430 days and current best fit thermal parameters.*

7.3.5 Large Scale Gas Injection Test

In 2005 BGR has conducted hydraulic tests in the TBM-excavated A-tunnel in Äspö HRL with the surface packer/mini packer system. The results from these tests could not have been analysed with respect to permeability, but they indicated that the gas entry pressure for the rock matrix is about 1 MPa or higher /Nowak 2005/. For this reason BGR tested those positions again with water as test fluid. The permeability values found in these tests with water do not indicate an interconnected network of microfractures that build a pathway between gallery wall and the rock in a distance of (only) 6 cm. The measured permeability values are below 10^{-20} m^2. Early time test data show a slightly quicker pressure drop which might be interpreted as filling of dead-end microfractures.

Two of these locations have been tested with Helium in gas tracer tests. The analysis of these tests required the assumption af two-phase flow and transport. The necessary parameter values come from the surface packer tests and from literature data, respectively. The multitude of parameter values, but also the measuring technique, cause uncertainties in the interpretation of the gas tracer tests. Nevertheless, the comparison between measured and calculated data can be interpreted as a confirmation that the parameter values that have been used for the calculation are reasonable. The results are documented in /Nowak 2006/.

7.3.6 Task Force on Engineered Barrier Systems

Bauhaus University Weimar, BGR, and GRS are participating in the Task Force. The activities of the team at Bauhaus University Weimar are focused at model identification strategies. The importance of numerical modelling for better understanding the behaviour of complex EBS (engineered barrier systems) and for improving the quality of predictions have increased continuously during the past 15 years. Beside the improvement of modelling features of numerical codes and elaborating more consistent constitutive models, the determination of material and geometrical parameters for the numerical models are of paramount importance for the accuracy of calculation results, and consequently for the model predictions.

For determination of model properties there are several approaches used. On one hand the values can be gained by performing field measurements or laboratory tests. Because these tests often are costly, time consuming or sometimes technically not possible, the data collected rarely may serve for having a fully determined numerical model. Additionally there are cases when the model parameters can not explicitly be determined from the experimental data and field measurements. Optimisation techniques provide very good tool for improving the accuracy of the model and thus for getting more reliable predictions. Back analysis comprises the attempt to minimise the deviation between measured and calculated data by iterative adjustment of model parameters that are used by the forward calculation. In 2006 a software package was finalised and successfully adopted to small scale swelling pressure test and soil column test.

Having successfully demonstrated the applicability of the alternative re-saturation model for compacted bentonite based on the data set of Benchmark 1.1.2 GRS began to extend the model to non-isothermal conditions. Starting with the balance equation for isothermal re-saturation including instantaneous hydration of vapour temperature-dependencies of the parameters and new terms in the equation due to temperature-dependencies were identified. Adequate mathematical formulations can be found in textbooks with one exception. Adsorption isotherms for the bentonite are apparently temperature-dependent. A referring mathematical description has not been formulated yet.

Based on the code VAPMOD, that had been used before, a new experimental code VIPER (Vapour transport In Partially saturated bentonite as Engineered barrier for Repositories) has been developed to solve the temperature-dependent balance equation. At the time a draft version of this code exists that utilises an ad hoc approach for the temperature-dependency of the adsorption isotherm. The transient temperature field is assumed to be known in advance and it is required as input data.

A first check of this code based on the data set of Benchmark 1.1.2 has been performed. The temperature-induced redistribution of moisture in a closed system was simulated in good accordance with the measurements (Figure 7-23). The modelling exercise showed, though, that the formulation of the adsorption isotherms is a rather sensitive element in the model. The results were presented at the EBS Task Force meeting in Barcelona.

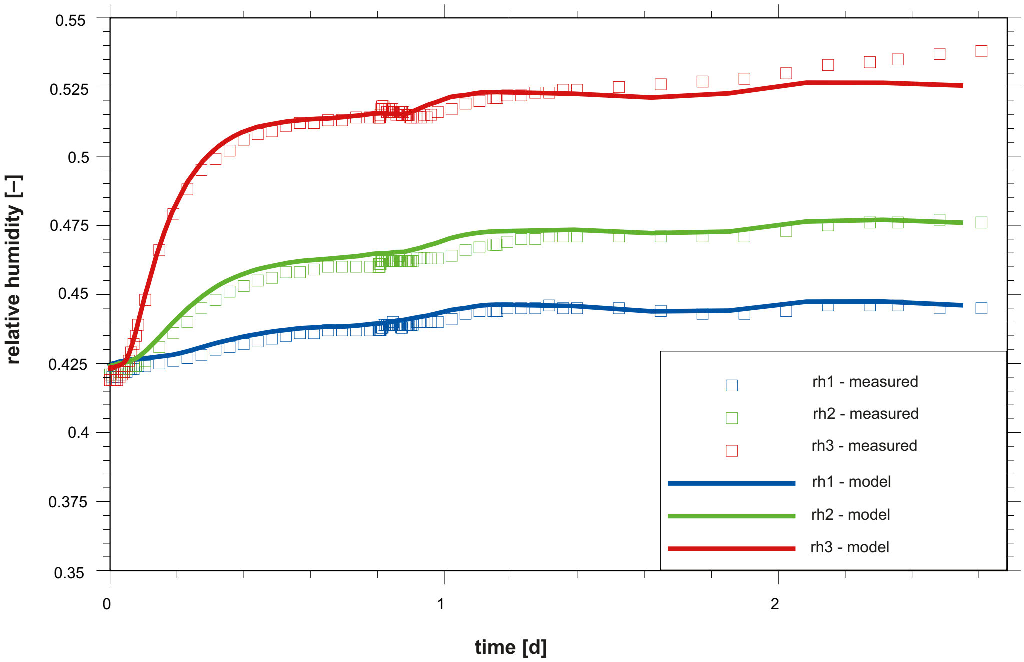


Figure 7-23. *Measured and simulated development of the relative humidity in a bentonite heated at one side.*

BGR participates in Task 1 (THM-coupled processes) and Task 2 (gas migration processes) in the clay-rich buffer materials. At the end of 2006 the processing of the Benchmark 1.1.3 concerning THM-coupled processes in geotechnical barriers (Febex bentonite) has started.

With respect to Task 2 a preliminary two-phase flow study has been conducted on the basis of one of the benchmarks to that task.

7.4 CRIEPI

Central Research Institute of Electric Power Industry (CRIEPI) participates mainly in the modelling activities at Äspö HRL. CRIEPI has participated in the Task Force on Engineered Barrier Systems, tackled benchmark problems and compiled a report on the calculation results. CRIEPI has participated also in the Task Force on Modelling Groundwater Flow and Transport of Solutes and started modelling work for Task 7, long-term pumping test at Olkiluoto in Finland. In addition, CRIEPI has been performing its voluntary project on the impact of microbes on radionuclide retention.

7.4.1 Task Force on Modelling Groundwater Flow and Transport of Solutes

During 2006, CRIEPI performed a numerical analysis for Task 7A which concerns site-scale modelling of long-term pumping test at Olkiluoto in Finland. In the analysis, groundwater flow at site scale was calculated under natural condition as well as during the pumping test. The modelled domain was an approximately 10 km^2 region enclosed by five major hydraulic conductors. 15 fracture zones and 38 boreholes were incorporated into our numerical model. The near-surface background rock from 0–80 metres was also incorporated into our model as porous media. But deeper background rock was not taken into consideration. Figure 7-24 shows the finite element mesh used for the numerical analysis. 1-, 2- and 3-dimensional elements were

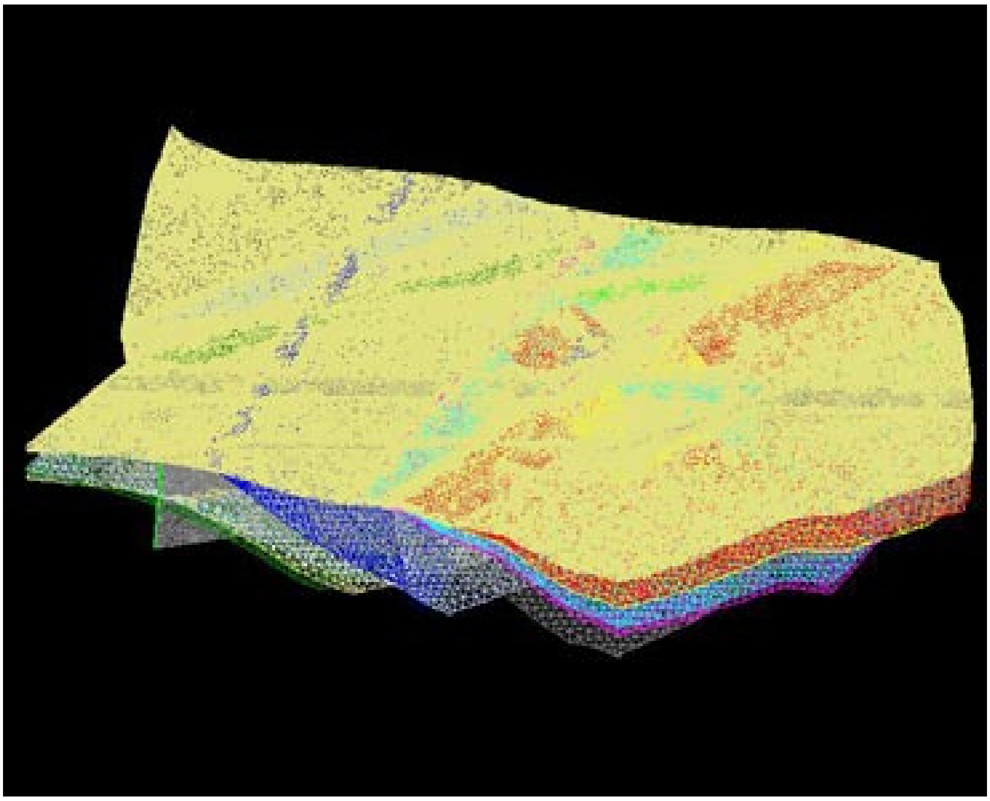


Figure 7-24. *Finite element mesh (overall view).*

used to express the boreholes, the fracture zones and the near-surface rock, respectively. The 2-dimensional elements were subdivided into smaller elements in the neighbourhood of the intersections of a fracture zone with other fracture zones or boreholes (see Figure 7-25). The 3-dimensional elements were also subdivided into smaller elements in the neighbourhood of boreholes (see Figure 7-26). The influence of salinity on groundwater flow was not considered in the analysis.

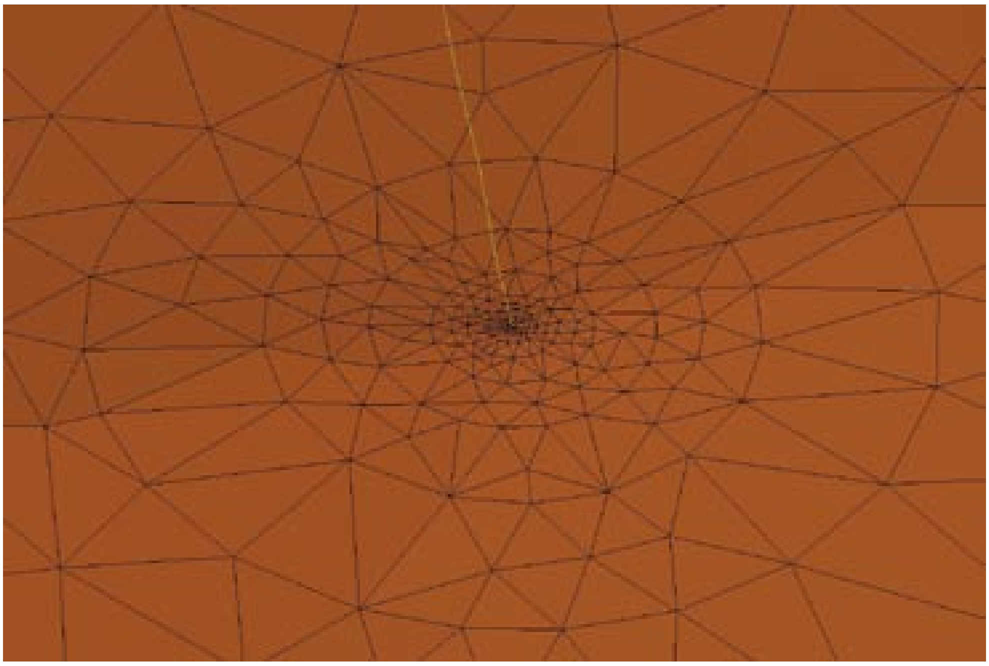


Figure 7-25. *Finite element mesh (2-D elements adjacent to a borehole).*

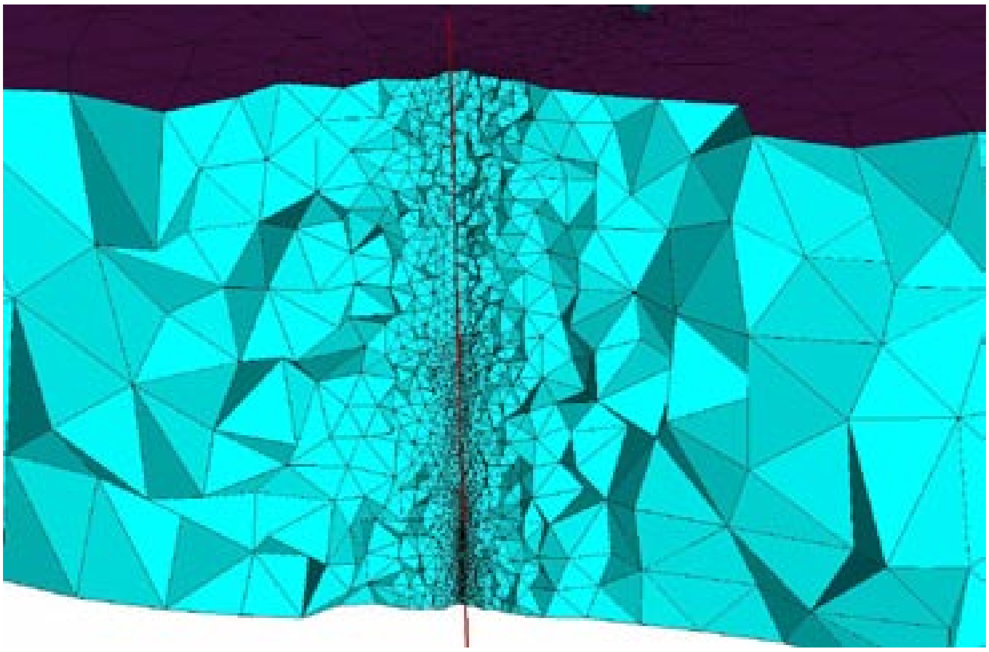


Figure 7-26. *Finite element mesh (3-D elements adjacent to the pumping borehole, OL-KR24).*

Firstly, the groundwater flow under natural conditions was simulated. Transmissivities of the fracture zones were assumed to be basically homogeneous but decreased to one-tenth on the periphery of the fracture zones. Hydraulic conductivity of the near-surface background rock was assumed to be $2 \cdot 10^{-7}$ m/s as recommended. Groundwater recharge from the top surface was calibrated through the numerical analysis. Figure 7-27 shows the hydraulic heads in the open boreholes. Groundwater level under the natural conditions could be almost reproduced in the simulation case in which groundwater recharge was assumed to be 40 mm/year.

Secondly the groundwater flow in the steady state during the pumping test was simulated. Groundwater recharge from the top surface was assumed to be 40 mm/year as calibrated above. Hydraulic conductance of a by-pass pipe in the pumping borehole (OL-KR24), was calibrated through the numerical analysis. Figure 7-28 shows the drawdown in the monitoring boreholes for the best-fit run. Drawdown in the steady state during the pumping test could be reproduced very well in the best-fit run. Figure 7-29 shows the groundwater flows from rock into the boreholes in the same simulation case. The calculated groundwater inflows did not agree with the measured ones. Further calibration is needed to reproduce groundwater levels, drawdown and groundwater inflow simultaneously.

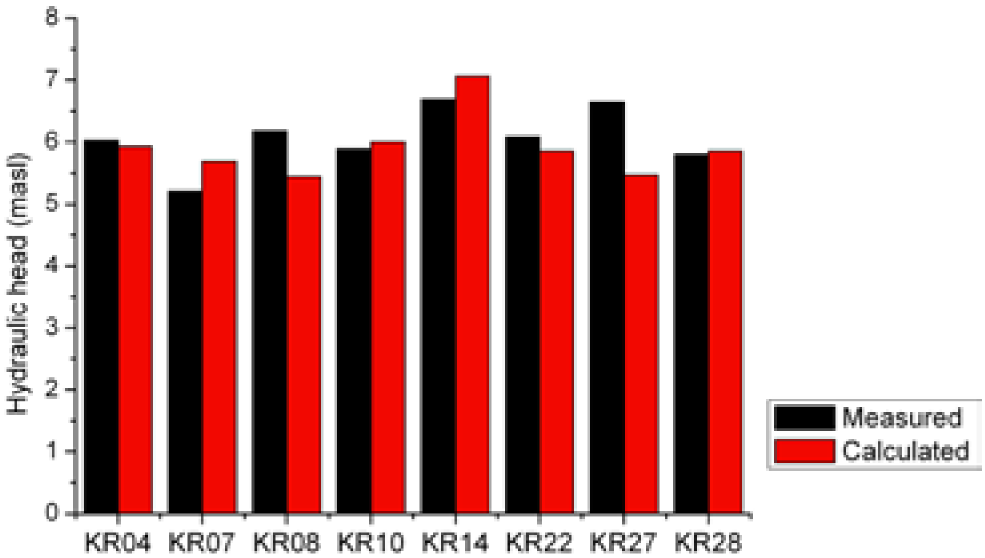


***Figure 7-27.** Hydraulic heads in open boreholes under the natural condition.*

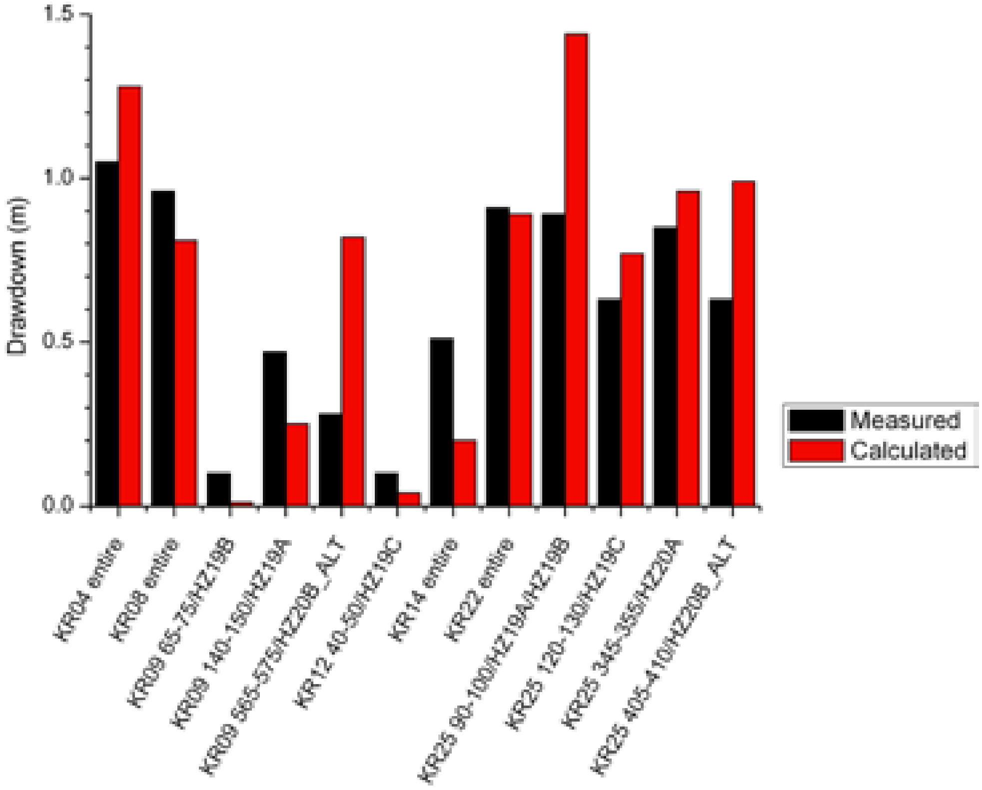


Figure 7-28. Drawdown in monitoring boreholes in the steady state during pumping test.

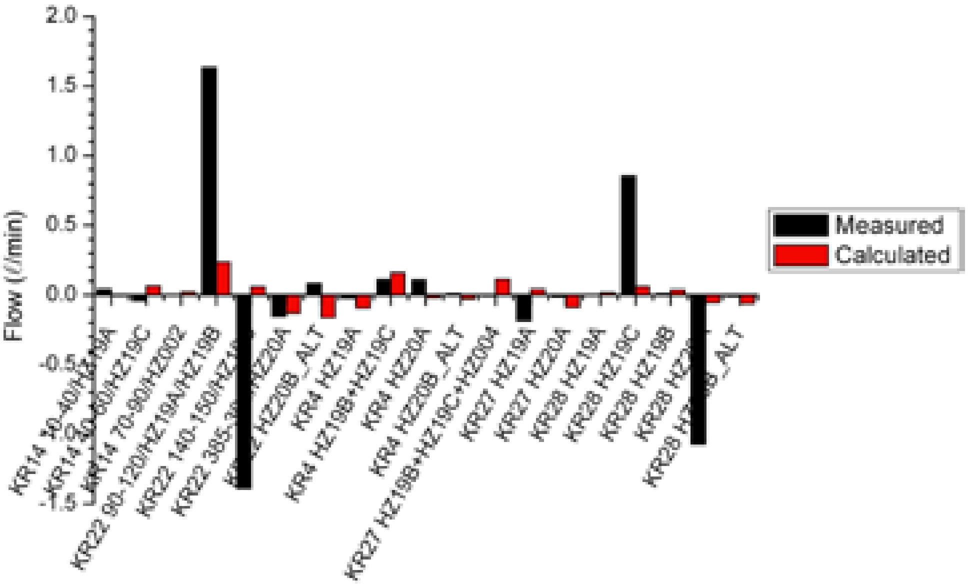


Figure 7-29. Groundwater inflow from rock into monitoring boreholes in the steady state during pumping test.

7.4.2 Task Force on Engineered Barrier Systems

CRIEPI has been developing the thermal-hydrological-mechanical (THM) coupling code Lostuf for evaluating the phenomena that will occur around the engineered barrier system. In 2006, THM Benchmark 1.1.3 of Task Force on Engineered Barrier System was carried out, and Lostuf was applied to the heating test without water infiltration performed by UPC.

Figure 7-30 shows the finite element mesh that was used for Benchmark 1.1.3. The heater and insulation were included in the analytical model as well as the compacted bentonite. Two cases of calculation were conducted. The differences between case-1 and case-2 were values of the intrinsic permeability and the tortuosity factor. They are shown in Table 7-4. The values of case-1 were determined from the experimental and empirical method. On the other hand, the values of case-2 were determined after some calibrations.

Table 7-4. Intrinsic permeability and tortuosity factor of each cases.

	case-1	case-2
Intrinsic permeability	4.34×10^{-21} m^2	2.0×10^{-21} m^2
Tortuosity factor	0.67	0.80

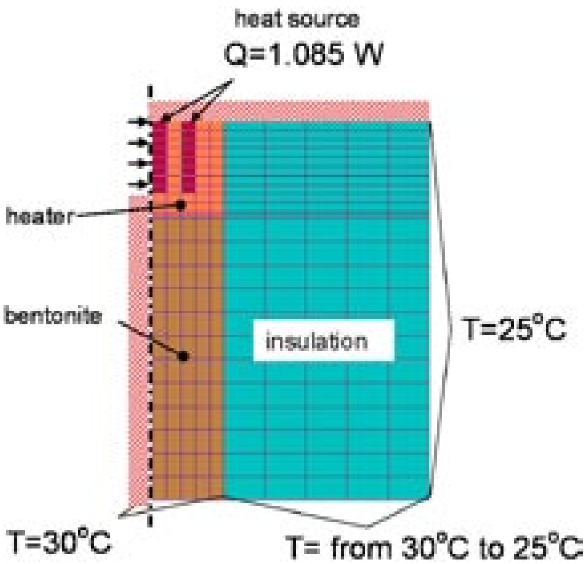


Figure 7-30. *Finite element mesh and thermal boundary conditions for Benchmark 1.1.3.*

Figure 7-31, Figure 7-32 and Figure 7-33 show the comparison between calculated results and measured data. Calculated temperatures were in good agreement with the measured data (see Figure 7-31). The effect of difference in parameters related to liquid flow and vapour diffusion was not important for the prediction of temperature in these analyses. Calculated distributions of the water content were also in good agreement with measured data (see Figure 7-32). The result of case-2 was better than case-1 especially in the drying part. The tendency of diameter increment was reproduced (see Figure 7-33). But the gradients of the distribution curves were different. The positions where the diameter was the same as the initial condition were also different from measured data. In the experiment, those positions were shifted approximately 20 mm from the positions where water contents were the same as the initial values. Further investigation is needed for our swelling and shrinkage model.

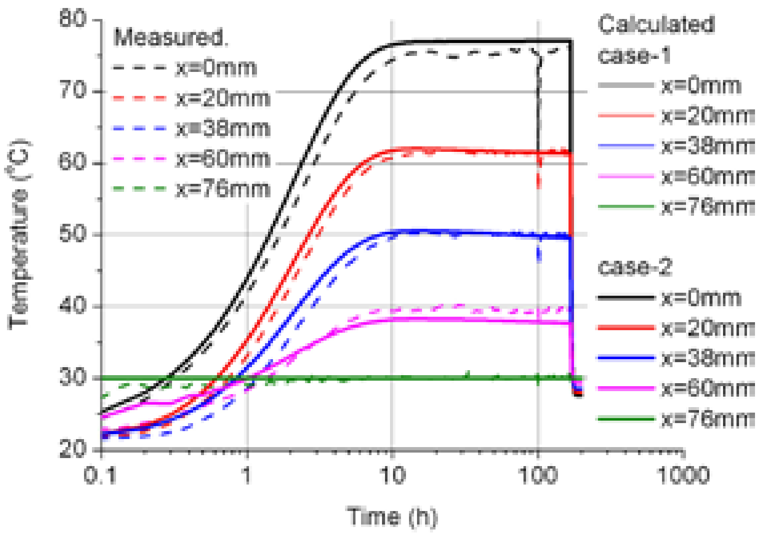


Figure 7-31. *Evolution of temperature versus time.*

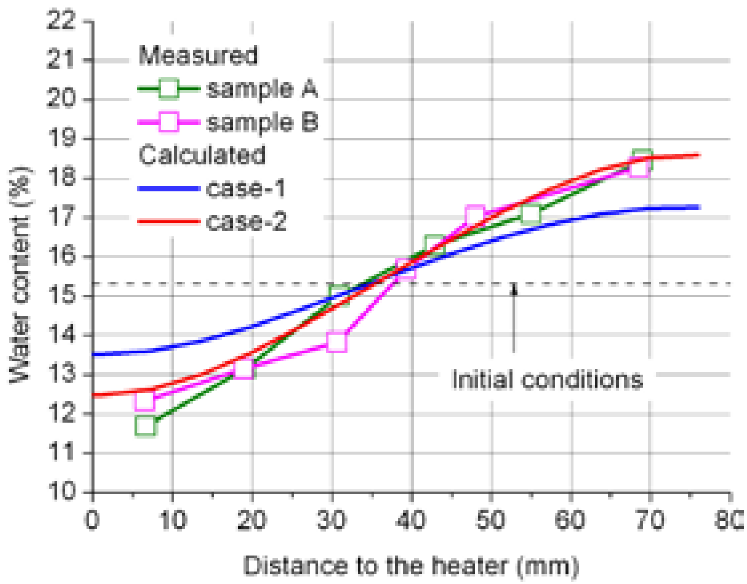


Figure 7-32. *Distribution of water content along the specimen at the end of the test.*

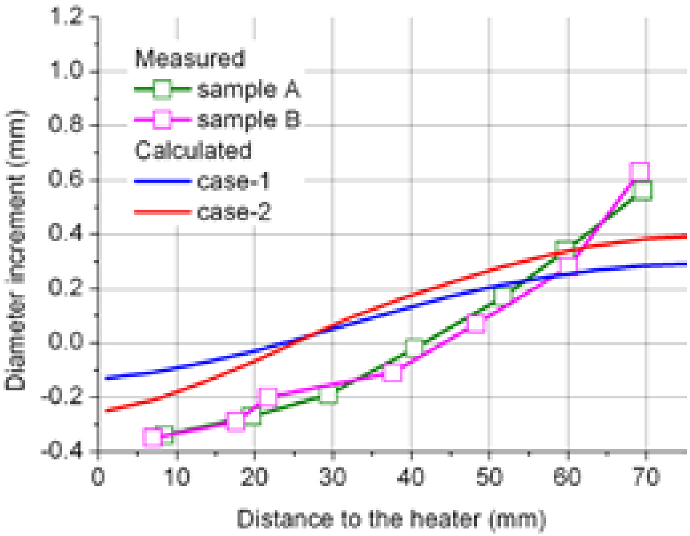


Figure 7-33. *Distribution of diameter increment along the specimen at the end of the test.*

Lostuf has been applied to Benchmark 1.1.2 again, the first time was in 2005, now using the information and parameters obtained from Benchmark 1.1.3. Results of the relative humidity profile are shown in Figure 7-34. Calculated results became better at RH2 and RH3, but could not capture the slow hydration after 10,000 hours passed. It was conceivable that the pore structure of bentonite changed and it became more impermeable especially on heater side during the infiltration because of the swelling pressure from the injection side.

7.4.3 Voluntary project on impact of microbes on radionuclide retention

In order to evaluate the microbial impact on geochemistry of groundwater and radionuclide migration, we have been developing the groundwater circulation system in the experimental laboratory of CRIEPI, Japan. In 2006, the system was further advanced as shown in Figure 7-35. The semi-continuous measurement system of pH and reduction-oxidation potentials (ORP) and injection system for microbe activity inhibitors was placed. The synthetic groundwater and the Äspö groundwater sampled at MICROBE-450 site were circulated with pH and ORP measurements. We have been performing laboratory experiments using the system and working out a report on the microbial impact on groundwater geochemistry.

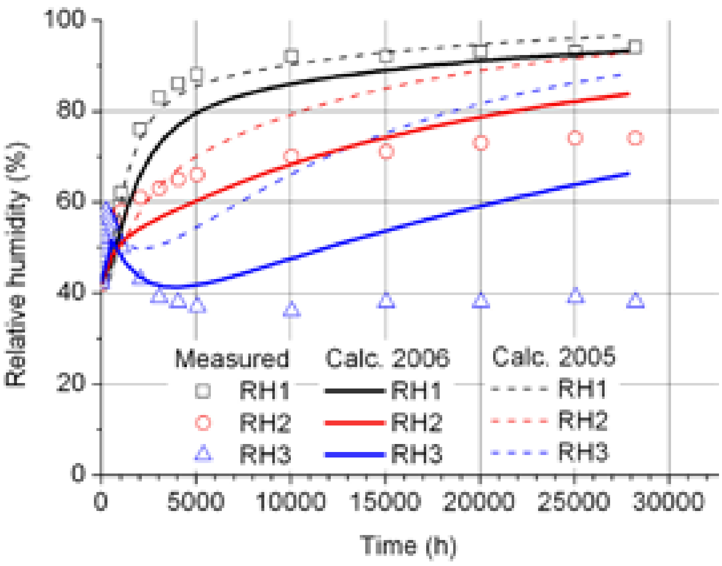


Figure 7-34. *Relative humidity versus time in the follow-up analysis of Benchmark 1.1.2.*

Figure 7-35. *Groundwater circulation system in experimental laboratory of CRIEPI.*

7.5 JAEA

Japan Atomic Energy Agency's (JAEA) role in the Äspö HRL directly contributes to JAEA's mission as providing technical basis for repository site characterisation, safety assessment, and regulation in Japan. The Äspö HRL provides practical information that directly benefits JAEA's underground radioactive waste research laboratories at Horonobe and Mizunami, Japan.

JAEA research objectives at Äspö during 2006 included the following:

- Improve understanding of site characterisation technologies, particularly flow logging and hydraulic interference.
- Improve understanding of flow and transport in fractured rock.
- Improve safety assessment technologies.
- Improve understanding of underground research laboratory experiments and priorities.

7.5.1 True Block Scale Continuation

JAEA has participated in the True Block Scale Project since 1997. During 2006, JAEA assisted in the final reporting for the project, including submission of updated modelling reports and review of technical documents.

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

JAEA participation in the Äspö Task Force on Groundwater Flow and Transport of Solutes during 2006 focused on completion of Task 6, Performance Assessment and Site Characterisation (PASC) and initiation of Task 7, Onkalo Site Hydrogeologic Modelling.

Sub-task 6F2, Performance Assessment and Site Characterisation (PASC)

JAEA carried out sensitivity studies during 2006 to study the effect of aperture laws on transport processes using the sub-task 6F2 "test bench" model. This model studies solute transport in a single fractures with multiple immobile zones based on specific fractures within the sub-task 6C reference hydrostructural model /Dershowitz et al. 2003a/. Case A1 is based on structure "1S" and Case B1 is based on s structure "4S".

JAEA's analyses during 2006 attempted to determine the significance of alternative formulae used to relate fracture transmissivity to aperture. The two formulae studied are the "Doe Law" and the "Cubic Law."

Doe Law:

$e_h = a*T^b$

Where e_h is the aperture, a is a site-specific empirical constant (approximately 0.5 for Äspö Island) and $b = 0.5$ (square root of transmissivity (T)). This relationship was used in the sub-task 6F simulations.

Cubic Law:

Formulation	In Fracture Terms	Aperture
$Q = \frac{b^2 * \rho_w * g}{12\mu_w} * e_h * w * \Delta h$	$Q = T*w*\Delta h$	$e_h = \sqrt[3]{\frac{12\mu_w T}{\rho g}}$

Of these two laws, the "Doe Law" /Dershowitz et al. 2003b/ is the more general, since it includes the "Cubic Law" for specific values of the coefficients a and b (approximately a = 0.1, b = 0.333).

Simulation results from this study are illustrated in Figure 7-36, Figure 7-37 and Figure 7-38. Expressed directly in terms of the solute breakthrough for a "Type 1" (fault) structure with multiple immobile zones, the two laws produce results that are very similar. Results are also similar when expressed in terms of water residence time. As a "Tau-Beta" relationship, however, there are differences between the results for the two different formulae, reflecting the sensitivity of Beta to aperture.

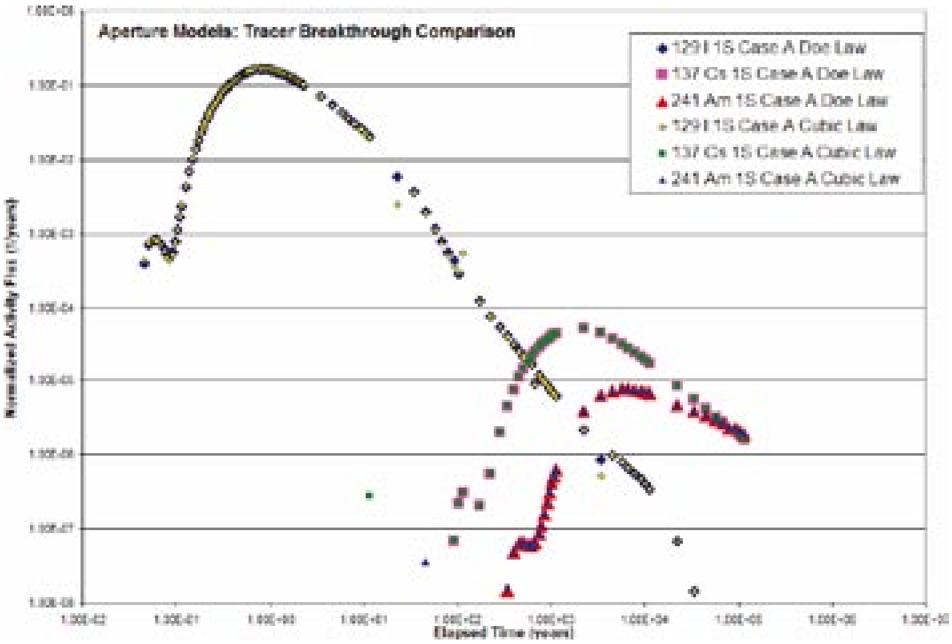


Figure 7-36. *Multiple immobile zone transport breakthrough under sub-task 6F2 PA boundary conditions for alternative aperture-transmissivity relationships.*

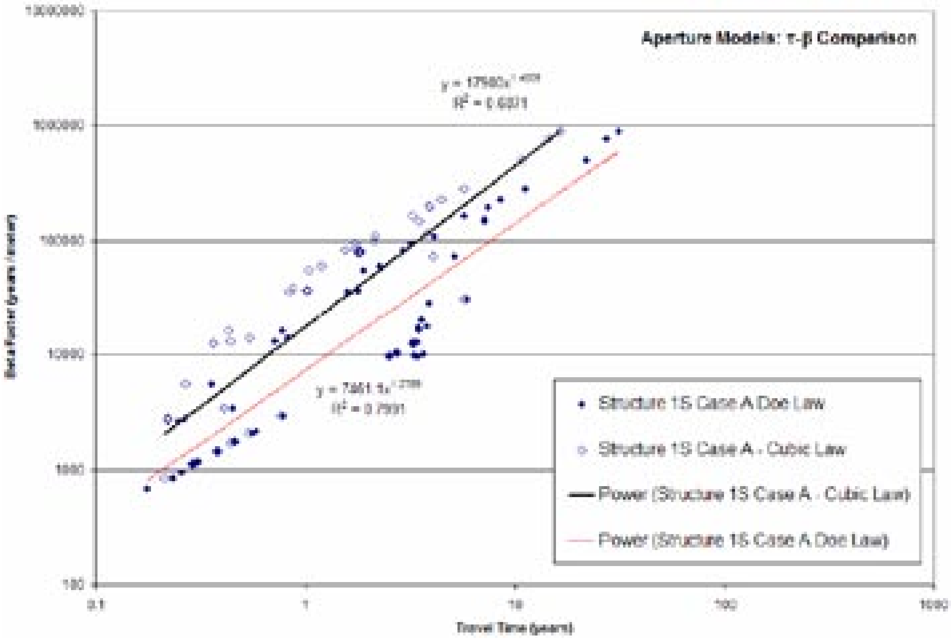


__Figure 7-37.__ Residence time (Tau) – immobile zone interaction parameter (Beta) relationship for "Type I" structure from simulation.

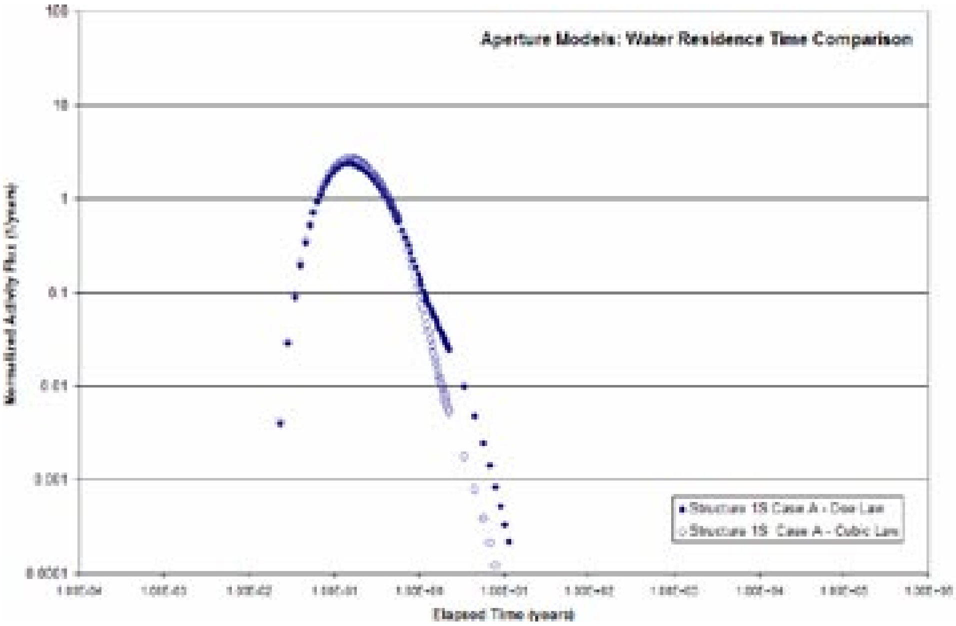


__Figure 7-38.__ Water residence time (Tau) distribution for alternative aperture-transmissivity correlations – "Type I" structure.

This study indicates that for the cases considered, the choice of "Doe Law" or "Cubic Law" apertures is not critical to solute transport modelling. However, from the "Tau-Beta" relationship it can be seen that there is potential that at under conditions in which there are significant variations in transmissivity, the selection of the aperture-transmissivity relationship may become important to performance assessments.

In addition to the sub-task 6F2 simulations, JAEA carried out a review of the progress achieved throughout the Task 6 project. Based on JAEA's assessment, the major achievements of Task 6 are as follows:

- Demonstration of ability of site characterisation (SC) to constrain performance assessment (PA) by constraining transport geometry,
  - tracer tests can be useful for PA by deriving flow wetted surface.
- Demonstrating potential ability of enhanced diffusion area for matrix diffusion through gouge/stagnant zones.
- Introduction and demonstration of concepts of complexity,
  - to handle multiple fracture surfaces in a structure and structure type,
  - using geology to understand immobile zones.
- Initial address to issues of solute transport upscaling (in time, from single fracture to multifracture to fracture network).

JAEA's modelling efforts during Task 6 attempted to address the implementation of microstructural models for transport modelling under PA boundary conditions in terms of channelling and immobile zone geometry (Figure 7-39)

Sub-task 7A, Onkalo Hydrostructural Model

JAEA implemented a preliminary Onkalo hydrostructural model, and carried out demonstration of site characterisation and performance assessment simulations during 2006. These were presented at the Task Force meeting in Paris, March 2006.

The JAEA team implemented the Onkalo hydrostructural model including all of the boreholes and fracture zones in the preliminary sub-task 7A specification. Transmissivities for the zones were based on values provided by Posiva. Storativity and aperture were derived from transmissivity using the relationships of /Dershowitz et al. 2003b/. Boundary conditions were implemented as follows:

- Ground surface, phreatic with infiltration rate of $7.03 \cdot 10^{-9}$ m/s.
- Sides, constant head interpolated from values provided by Posiva.
- Bottom, no flow.

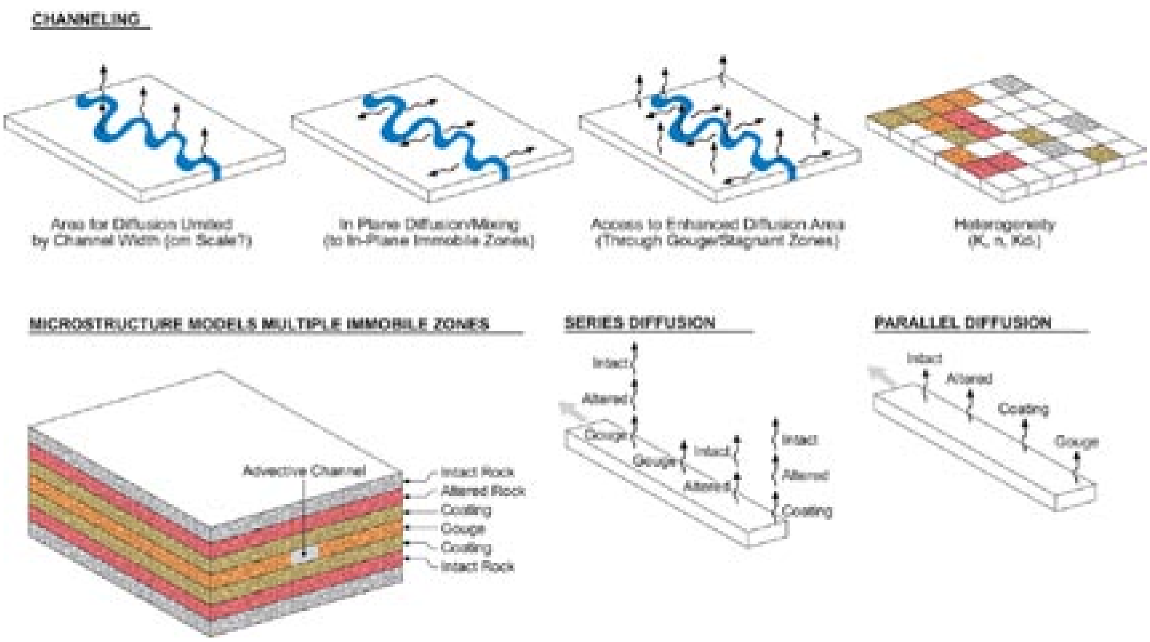


Figure 7-39. *Approaches to implement microstructural models in PA time scale transport models.*

Open boreholes were represented by a "group flux" boundary condition, in which flow is allowed to occur through the well to obtain a single steady state head throughout the well, with a net flow out of the well of zero. Figure 7-40 illustrates the steady state flow simulation for initial conditions.

After convergence of the initial conditions simulation, the OL-KR24 pumping test was simulated with the specified pumping rate of 18.1 L/minute. The results of these simulations are illustrated in Figure 7-41, comparing measured and simulated heads. Based on these simulations it can be concluded that:

- JAEA model simulates drawdown in the pumped section of a borehole (OL-KR24) fairly close to what was observed in situ.
- JAEA model appears to generally over-predict drawdowns in other open boreholes.
- There is likely over-connection in the simplified JAEA model (OL-KR25_T5, OL-KR28, OL-KR26, and OL-KR4 responses to the OL-KR24 pump test).
- OL-KR26, in particular, is probably not well connected to the rest of the deterministic zones.

To demonstrate the potential value of sub-task 7A for safety assessment, JAEA ran a solute transport (particle tracking) simulation in the KR-24 pumping flow field (Figure 7-42) and steady state flow field (Figure 7-43). This simulation demonstrates how sub-task 7A could potentially be used to understand the connection between site characterisation and safety assessment modelling, and how transport pathways under performance assessment boundary conditions differ from those under site characterisation boundary conditions,

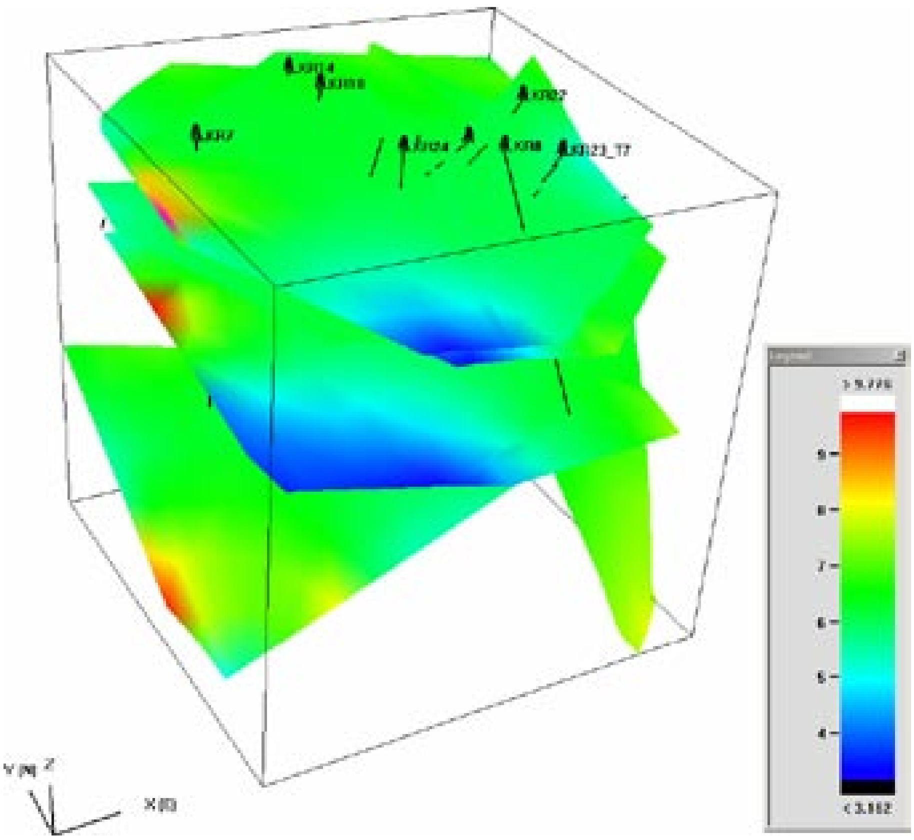


***Figure 7-40.** JAEA FracMan steady state flow simulation of preliminary sub-task 7A Onkalo model.*

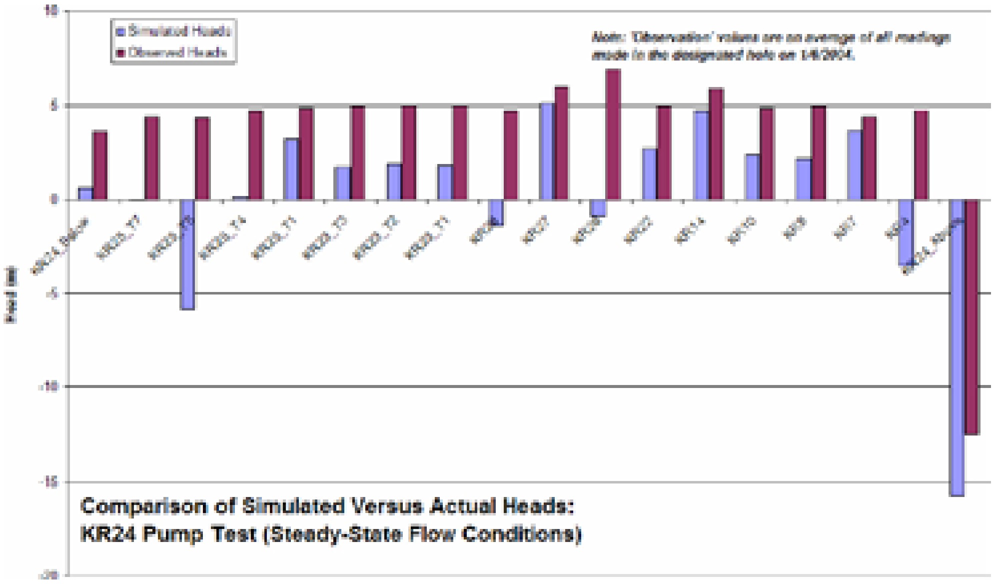


Figure 7-41. *Comparison of measured and simulated heads in JAEA preliminary model for OL-KR24 pump test.*

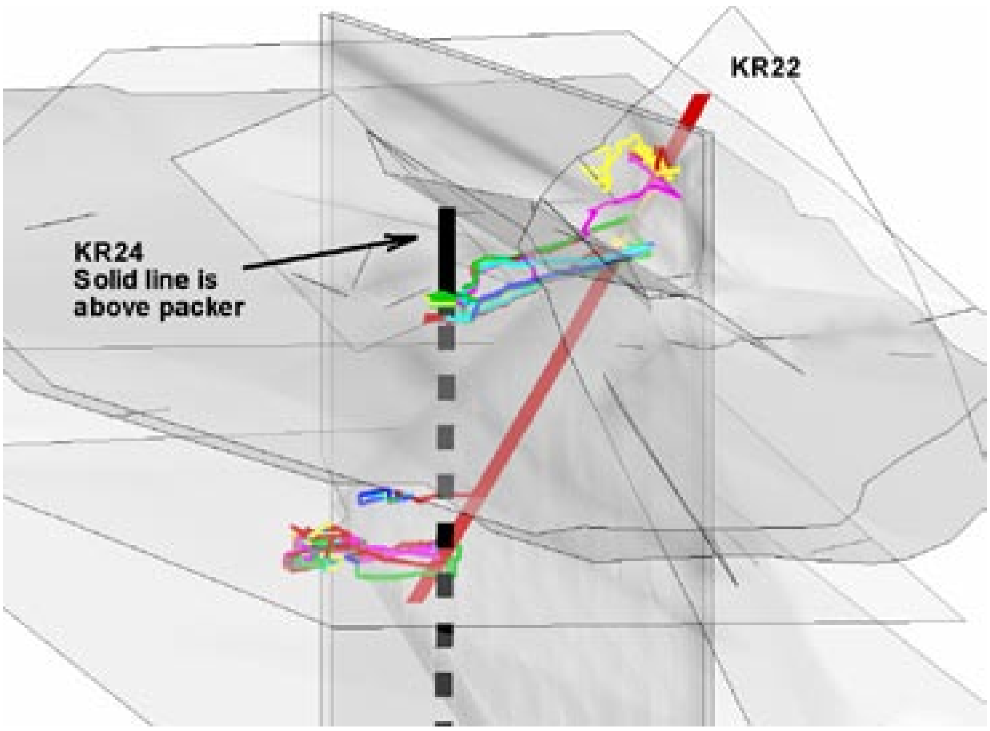


Figure 7-42. *JAEA demonstration transport simulation under OL-KR24 pumping boundary conditions.*

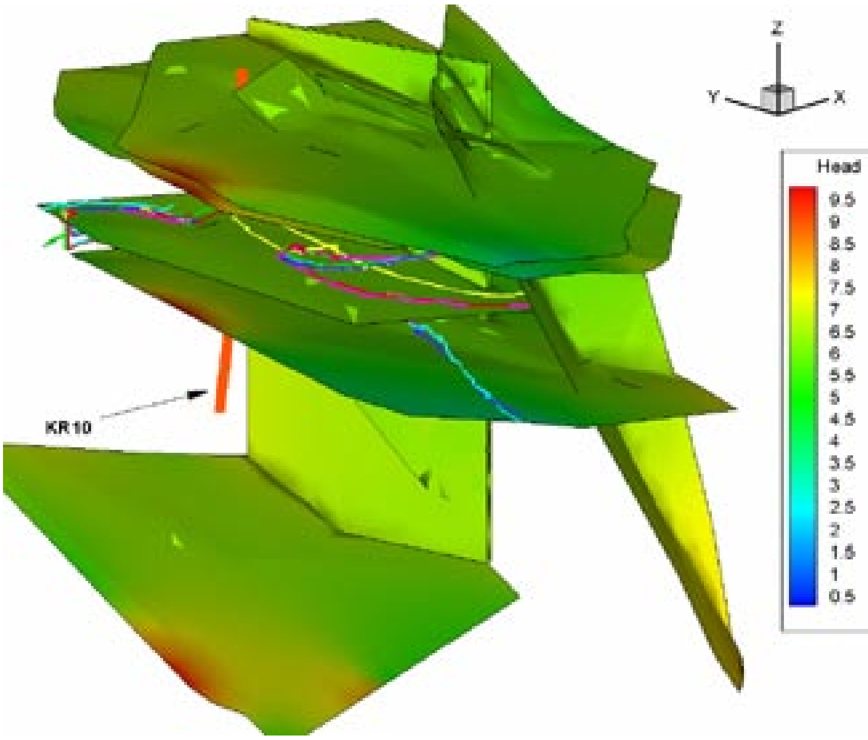


Figure 7-43. *JAEA demonstration transport simulation under OL-KR24 pumping boundary conditions.*

7.6 OPG

Ontario Power Generation (OPG) joined the Äspö HRL in 2004 for a five-year term. In 2006, work was performed on behalf of OPG by AECL, Université Laval and Intera Engineering. The results of this work are briefly described below.

7.6.1 Large Scale Gas Injection Test

OPG is contributing to the gas transport modelling component of Large Scale Gas Injection Test (Lasgit). The gas modelling is being conducted for OPG by Intera Engineering.

Previously, the TOUGH2 code was selected and modified for Lasgit to simulate pressure-induced changes in the properties, such as micro- and macro- fracturing. In 2006, the modified code was applied to experimental data.

Two models were developed: (a) Lasgit experiment model based on the full-scale Lasgit experimental set-up (Figure 7-44) and (b) a laboratory model based on the laboratory-scale experiment of gas transport in bentonite (Test MX-80-10) conducted by /Harrington and Horseman 2003/. The laboratory experiment is essentially a laboratory-scale version of the Lasgit experiment, conducted under controlled boundary conditions. The laboratory experiment was chosen for initial modelling to increase confidence in the parameter set and in the gas-transport modelling approach for the Lasgit experiment model.

Initial modelling focussed on the laboratory experiment, where water injection tests and gas injection tests were simulated. Water injection tests were conducted to confirm the model set-up and refine the model's hydraulic properties. Using "paCalc" as a framework, inverse modelling was conducted to determine optimal values of hydraulic conductivity and pore compressibility, using several flow test injection configurations. Values of $4 \cdot 10^{-22}$ m^2 for permeability and $1 \cdot 10^{-11}$ Pa^{-1} for pore compressibility were determined as appropriate values based on optimisation results. These values are comparable to the modelling results presented by /Harrington and Horseman 2003/.

Only preliminary gas injection tests were conducted. Based on the first deterministic attempts of modelling the gas injection test, the modelling approach to injecting gas requires calibration.

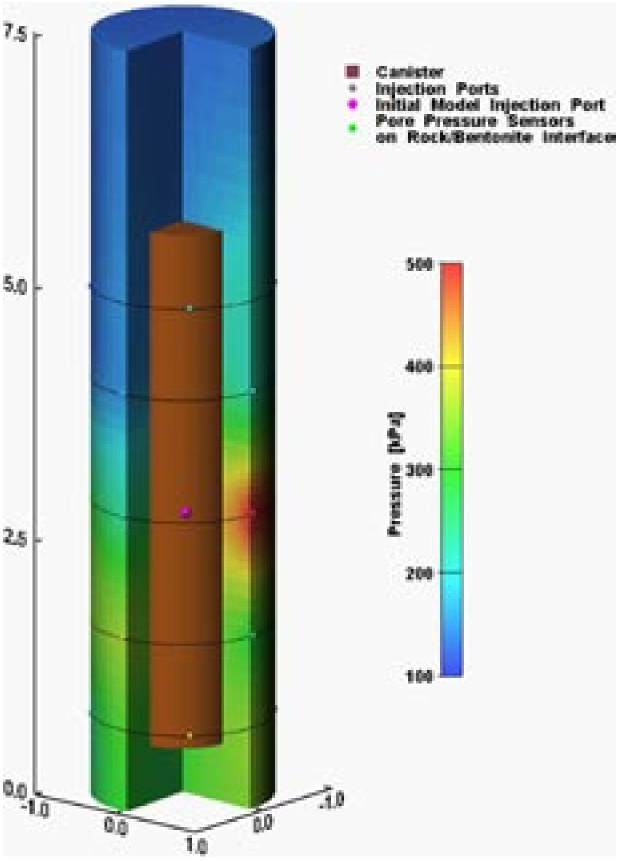


Figure 7-44. Lasgit model initial conditions, interpolated from measured pressures at the side rock/bentonite interface on 31st October 2005.

A first step to calibrating the model will be to adjust the volume of injection elements, to simulate the effects of the injection system on gas injection, using the injection pressure to calibrate the injection element volume.

Future modelling in 2007 will refine the gas-migration modelling of the laboratory experiment, conduct test design analysis of the Lasgit experiment and analyse any preliminary results of the Lasgit experiment.

7.6.2 Task Force on Engineered Barrier Systems

OPG is represented by Atomic Energy of Canada Limited (AECL) in the Task Force. In 2006, AECL used Code_Bright to conduct coupled thermo-hydro-mechanical numerical simulations of the evolution of a laboratory-scale heating test conducted at Universidad Politécnica de Cataluña (Benchmark 1.1.3). The good match in the comparison of the simulated thermal and hydraulic response with the measured data indicates that the thermal parameters (e.g. thermal conductivity) and hydraulic parameters (e.g. hydraulic conductivity of the bentonite and the retention curve) used in this modelling activity are reasonable (see Figure 7-45 and Figure 7-46). A report that detailed the results of the numerical modelling efforts by AECL was submitted to the Task Force Secretariat /Guo 2006/.

The Isothermal Test and Buffer Container Experiment were two full-scale in situ tests previous conducted at AECL's Underground Research Laboratory in Canada. These two tests were selected as large scale field simulations for the modelling activity in 2007. A modelling proposal, descriptions of these two tests, and a data base of thermal, hydraulic and mechanical responses measured from the two underground tests were prepared and submitted by AECL to the Task Force secretariat as inputs for the modelling activity.

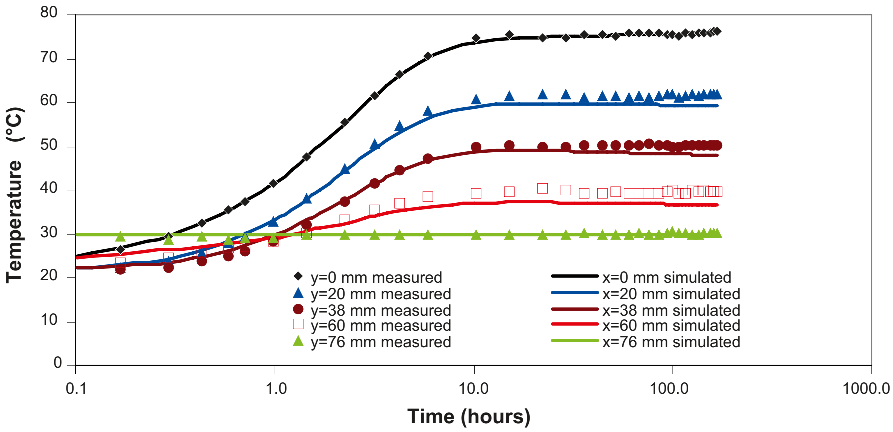


Figure 7-45. *Simulated Temperature and Measurements at Different Locations Along the Axis for EBS Task Force Benchmark 1 /Guo 2006/.*

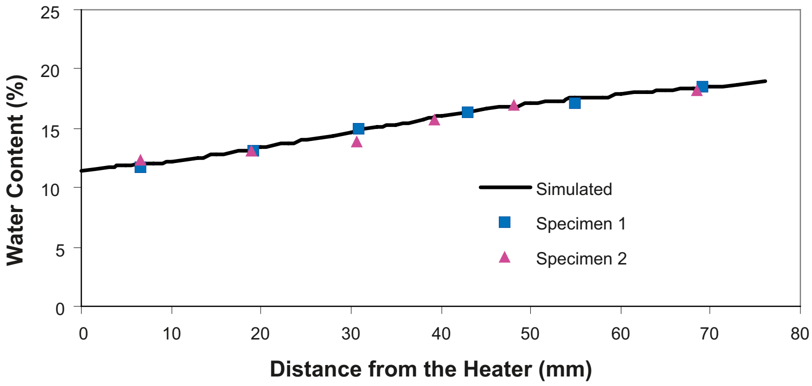


Figure 7-46. *Comparison of Simulated Water Contents versus Distance from the Heater Along the Axis of the Specimen with Measurements for EBS Task Force Benchmark 1 /Guo 2006/.*

7.6.3 Long Term Test of Buffer Materials and Canister Retrieval Tests

Two Long Term Test of Buffer Materials (Lot) samples and nine Canister Retrieval Test (CRT) samples from Äspö HRL were analysed at the AECL Whiteshell Laboratory to establish the culturability and viability of naturally present microbes in these compacted 100% bentonite samples. The results indicate that both culturability and viability of microbes decrease with decreasing water activity and increasing dry density. The microbe viability is always orders of magnitude higher than culturability, suggesting that the majority of microbes present in the bentonite are in a viable, but not culturable state, and are unlikely to be metabolically active in situ. In addition, microbial culturability at the canister-bentonite interface was very low. It is, therefore, unlikely that microbially-influenced corrosion of a copper canister would be significant in these bentonite environments.

7.6.4 Rock Shear Experiment

A full-scale test is proposed by SKB to investigate the effect of earthquake-induced shear on a copper canister emplaced in a vertical borehole in granite rock. Small-scale laboratory testing is required to determine relevant design parameters for the full-scale test. OPG is represented by RSRead Consulting Inc. who reviewed current information on related laboratory tests and developed a laboratory test plan to complement the project.

7.6.5 Long Term Diffusion Experiment

No further supporting laboratory experiments were undertaken in 2006 given that the LTDE field experiments were initiated. A summary report on the completed laboratory programme and associated findings was issued by AECL /Vilks et al. 2005/.

7.6.6 Colloid Project

The Äspö Colloid Project is focused on evaluating the potential ability of bentonite colloids, released from repository buffer and backfill materials, to facilitate radionuclide transport in Äspö groundwaters. In 2006, OPG continued funding bentonite colloid transport experiments at AECL's Whiteshell Laboratory using the Quarried Block (QB) sample, a 1 m × 1 m × 0.7 m block of granite containing a single, complex but well characterised, through-going, variable aperture fracture. The purpose of this experiment was to improve the understanding of physical retardation processes that effect bentonite colloid mobility and support the planning and analysis of field scale experiments undertaken at the Äspö HRL.

It is important to note that bentonite colloids form a polydisperse solution with particle size distributions that can range from a few nm to approximately 2 µm. Through the use of an Ultrafine Particle Size Analyser (UPA) and a two step analysis process involving the removal of particles larger than 0.1 µm, it was determined that the particle size distributions of the bentonite colloid tracer solutions were bimodal, with peaks at approximately 8 nm and between 200 and 300 nm. A methodology to determine particle size distributions at various points along the elution profiles was developed to better understand the transport behaviour of the polydisperse bentonite colloid tracers.

The migration experiments were conducted within a dipole flow field established between two boreholes (L1 to L4 in Figure 7-47) approximately 400 mm apart and terminated at the fracture. Both bentonite and latex colloids (100 nm) were injected sequentially, along with conservative solute tracers. Bentonite colloid migration behaviour was compared to that of the mono-disperse latex colloids and solute tracers using three different flow rates, and ionic strengths representative of dilute and saline waters. Post-test tracer distributions were determined by sampling from all boreholes and mini-plena shown in Figure 7-47.

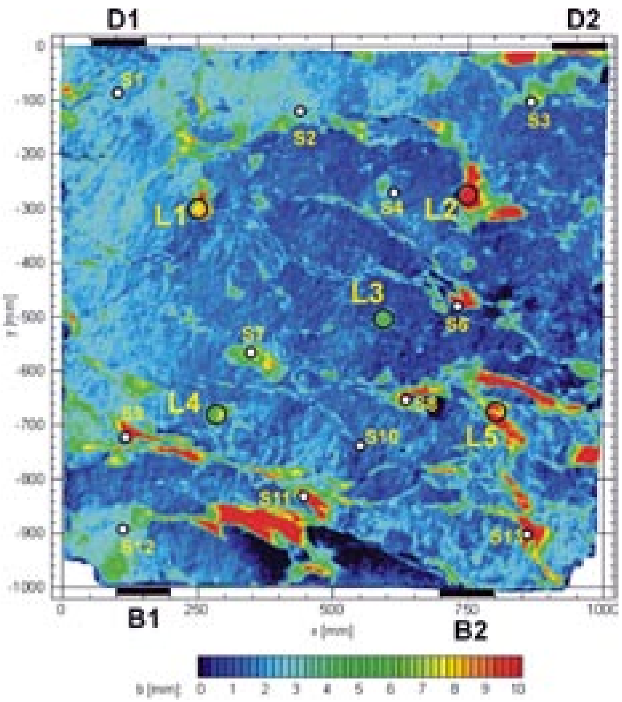


Figure 7-47. Borehole and mini-plena (D1, D2, B1 and B2) locations plotted on digitised aperture distribution for the Quarried Block (QB) fracture.

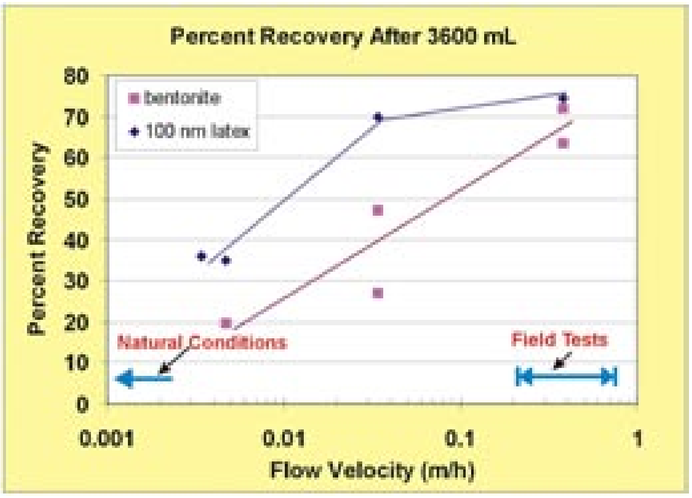


***Figure 7-48.** Comparison of bentonite and latex colloid recoveries at flow velocities representative of the various testing conditions imposed in the Quarried Block (QB) fracture.*

With dilute water and at high flow rates typical of field-scale tracer tests, bentonite colloids and 100 nm latex colloids were mobile and had similar transport behaviour. Differences in transport behaviour of the two colloid types become evident as flow rates were reduced in subsequent transport experiments. The lowest flow rate was considered more typical of natural flow conditions. Decreasing flow velocity reduced colloid transport, with bentonite colloids displaying the most significant reduction in mass recovery as illustrated in Figure 7-48.

Bentonite colloid transport was dominated by small particles (4 to 15 nm), particularly at low flow rates. The larger bentonite colloid size ranges, although present through most of the elution curve at the highest flow rate, were only sporadically detected in the elution curves at the lower flow rates. This finding could be as a result of deposition and retention within the complex fracture, or of partial dispersal of large bentonite colloid flocs into finer sizes during transport.

In saline, Äspö type groundwaters bentonite colloids injected into the fracture were largely not recoverable under intermediate flow conditions, likely due to flocculation and deposition. Approximately 10 percent of the bentonite colloids retained in the fracture under saline conditions were re-mobilised after 3 fracture volumes of dilute water at high flow was directed through the fracture. This latter test, conducted under extreme flow rate conditions, was meant to explore bentonite colloid mobilisation under conditions of reduced ionic strength.

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

A modelling team from the Université Laval is being sponsored by OPG to participate in the Äspö Modelling Task Force's Task 7, which concerns the numerical modelling of hydraulic responses in a fractured crystalline rock environment during a long-term pumping test experiment. The experiment was conducted in borehole OL-KR24, located on Olkiluoto Island at the site of Posiva's Onkalo underground rock characterisation facility. One of the unique aspects of the data set is that it includes Posiva Flow Log (PFL) measurements in several open boreholes, both prior to and during the pumping test.

At the first Task 7 project meeting in 2006, preliminary modelling results were presented based on the initial task description (Figure 7-49). The modelling domain as provided by the Task Force secretariat was 1 km^3, centred on borehole OL-KR24 and included several fracture zones, and open and packed-off boreholes. The results of steady-state and transient groundwater flow simulations using the Frac3DVS code were presented. Preliminary comparisons to hydraulic heads and PFL measurements from boreholes were discussed.

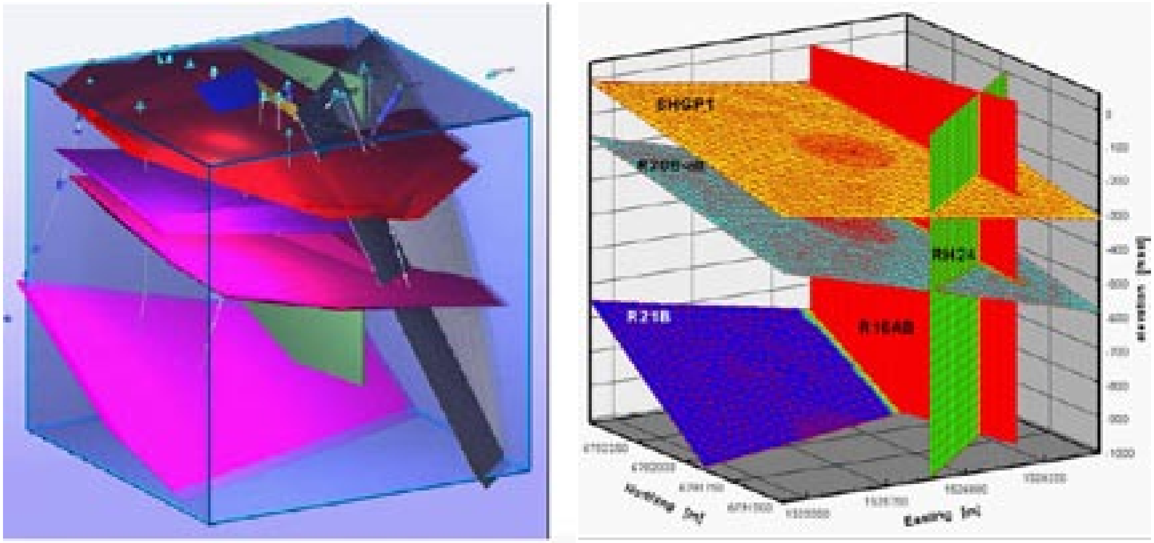


Figure 7-49. *Conceptual fracture zone model around OL-KR24 (left) and initial Frac3DVS implementation (right).*

Based on the discussions at the Task Force meeting, modifications to the task description and the development of performance measures were undertaken by the secretariat. To better discretise non-planar fracture zones with a regular 3D mesh for Frac3DVS, the Laval team has implemented a method that defines new 2D elements, either rectangles or triangles, which can be associated with regular 3D prismatic block elements. These will be used in future Frac3DVS simulations.

7.7 Posiva

Posiva and SKB signed a new co-operation agreement in September. This agreement continues the intensive co-operation within the repository technology, canister and encapsulation technology and site characterisation and long-term safety related research. The participation to the Äspö HRL programme is also included in the agreement.

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

Modelling work in Task 7 of the Äspö Task Force on Groundwater Flow and Transport of Solutes was initiated for sub-task 7A during 2006 by developing software tools and by setting up the numerical model. In particular, a new numerical method was developed to calculate the flowrates between open drillholes and hydrogeological zones. The new method proved out to be considerably faster and more accurate than the previously used method, and it was included as an integral feature of the software package FEFTRA. During the initial phase of the Task it was also found that the flow rates at the open drillholes are extremely sensitive to round-off errors in the numerical solution, forcing to use high precision arithmetic in simulations.

Preliminary simulations were performed using the initial Task Definition v1.2. The results indicated that the initial modelled volume was too small (1 km^3), hence the system was dominated by the boundary conditions. In the updated Task Definition (v2.2b) the hydrogeological model was updated and the modelled area was extended to include the whole Olkiluoto Island. The hydrogeological zones were also extended to the model boundaries. Natural conditions of the groundwater system were now matched appropriately, but the model failed to reproduce the measured strong pressure responses at the deep drillholes, possibly indicating an over-connected model.

Tentative sensitivity analysis showed that the responses of the initial model at deep drillholes were not very sensitive to transmissivities of the majority of hydraulic zones. Only few zones clearly affected the response of the model when the transmissivities of the zones were changed. The influence of the presence of the open drillholes was also studied. The presence of the open drillholes was found to induce a strong change on the flowrates through the pumped borehole (OL-KR24), when compared to results calculated without the open drillholes.

7.7.2 Prototype Repository

This co-operation concentrates on the on-going Prototype Repository experiment, but utilises also the additional results available from the Long Term Test of Buffer Materials (Lot) and other buffer/backfill tests performed at Äspö. In the year 2006 the existing data and knowledge on the subject have been evaluated. Based on this survey it has been decided that VTT will do inverse geochemical modelling of the rock volume in the vicinity of the Prototype Repository installations with the new groundwater data available.

7.7.3 Long Term Test of Buffer Materials

Posiva`s task in this project is to study the pore water chemistry in the bentonite. The task is carried out at VTT Processes. The aim of the work is to obtain data on the chemical conditions, which develop in the bentonite considering the effect of temperature, additives and rock features. The study gives information about the chemical processes occurring in the bentonite, but also supports the other planned studies of the chemical conditions.

The experiment with the Lot parcel A2 was terminated in December 2005. Posiva has published a report /Muurinen 2006/. This report concerns the chemical studies performed on the parcel A2, which was excavated after an experimental time of about five years. Two sample blocks were taken from the hot part of the parcel for studies. One of them was without additives while in the other one cement plug had been placed to represent the adverse conditions.

7.7.4 Alternative Buffer Materials

Posiva will contribute to the project with similar types of experimental studies as already done in the project Long Term test of Buffer material.

7.7.5 KBS-3 method with horizontal emplacement

SKB and Posiva are engaged in an R&D programme over the period of 2002–2007 with the overall aim to investigate whether the KBS-3H concept can be regarded as a viable alternative to the KBS-3V concept. The demonstration phase is on-going since 2004 and it includes test boring at Äspö, planning the construction of the emplacement equipment, and safety evaluations. The programme will end with the evaluation of the potential of the concept in 2007. The project is jointly executed by SKB and Posiva and has a common steering group.

Posiva's main involvement in the project is the evaluation of the long-term safety aspects. During year 2006 Discrete Fracture Network (DFN) models of groundwater flow around a KBS-3H repository situated at Olkiluoto have been produced. Also as a part of the preliminary assessment of long-term safety of a KBS-3H repository, a Process Report and an Evolution Report (evolution for the disposal system from the emplacement of the first canister to the long term timescale) are being produced.

7.7.6 Large Scale Gas Injection Test

This project will be jointly executed by SKB and Posiva and have a common steering group. The gas injection tests will start earliest in spring 2007 depending on the saturation rate of the bentonite buffer.

7.7.7 Cleaning and Sealing of Investigation Boreholes

The on-going Phase 3 of the joint SKB and Posiva programme will be finished in early 2007. The current stage aims at further developing methods and technologies for borehole plugging and at performing field tests with full-scale plugging of a core-drilled investigation hole. Phase 3 is divided into four sub-projects (see Section 4.10). One of the sub-projects comprises plugging of a borehole (OL-KR24) in Olkiluoto.

7.7.8 Task Force on Engineered Barrier Systems

Äspö HRL International Joint Committee has set up a Task Force on Engineered Barrier Systems (EBS) with the objective to develop effective tools for analysis of THM behaviour of buffer and backfill. The objective of the year 2006 was to simulate the THM behaviour of the EBS in the KBS-3V concept, with the canister disposed in a vertical position. The computer code used in the simulations by Posiva was FreeFEM++.

For Task 1 (THM processes) modelling has been performed for the laboratory tests defined in Benchmark 1.1.2 and 1.1.3. The new Benchmark 1.1.3 included volumetric swelling. With the parameters modified for Benchmark 1.1.3, also Benchmark 1.1.2 was revisited.

Benchmark 1.1.3 is based on a test on two cylindrical samples of compacted bentonite symmetrically placed in contact with a heater. No additional water was supplied, so that the test was essentially a water redistribution test with free cylindrical swelling. The results of the Posiva team simulations gave good results on the hydraulic evolution. Also the swelling of the cold end of the samples was simulated well, but the shrinking of the hot end was overestimated.

When the simulations of Benchmark 1.1.2 were rerun with the parameters modified for Benchmark 1.1.3, the results were in good agreement with the measurements until the simulations show stationary state. After that, the measurements show significant wetting of the hot end in contrast to the dry stationary state of calculations.

7.8 Enresa

SKB and Empresa Nacional de Residuos Radioactivos, S.A. (Enresa) signed a project agreement in February 1997 covering the co-operation for technical work to be performed in the Äspö HRL. Both parties renewed the agreement in January, 2002. Due to the decision taken in the Spanish parliament in December 2004 to focus on a central interim storage of spent nuclear fuel before 2010, Enresa in 2004 chose not to renew this agreement and have now left the central and active core of participants.

Enresa is, however, still participating in the Temperature Buffer Test in Äspö HRL. Enresa is also co-ordinating the integrated project Esdred within the 6^{th} EU framework programme. Some of the demonstration work of the integrated project Esdred is carried out in Äspö HRL.

7.9 Nagra

Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle, Nagra, has the task to provide scientific and technical basis for the safe disposal of radioactive waste in Switzerland. Nagra has had agreements with SKB for participation in Äspö HRL since 1994 to include mutual co-operation and participation in Äspö HRL and Grimsel Test Site projects. The last agreement expired 2003 and Nagra has now left the central and active core of participants.

However, Nagra is taking part in the Task Force on Engineered Barriers and the parallel task force that deals with geochemical processes in engineered barriers, chemical modelling of bentonite as well as in the Alternative Buffer Materials project.

7.10 RAWRA

Radioactive Waste Repository Authority, RAWRA, was established in 1997 and has the mission to the ensure the safe disposal of existing and future radioactive waste in the Czech Republic and to guarantee fulfilment of the requirements for the protection of humans and the environment from the adverse impacts of such waste. RAWRA became a participant in the Task Force on Engineered Barrier Systems in 2005 and also participates in the Alternative Buffer Materials project.

8 Literature

8.1 References

Anderson C R, Pedersen K, 2003. In situ growth of *Gallionella* biofilms and partitionating of lanthanids and actinides between biological material and ferric oxyhydroxides. Geobiology 1:169–78.

Anderson C, Jakobsson A-M, Pedersen K, 2006a. Influence of in situ biofilm coverage on the radionuclide adsorption capacity of subsurface granite. Environmental Science and Technology 41:830-6.

Anderson C, Pedersen K, Jakobsson A-M, 2006b. Autoradiographic comparisons of radionuclide adsorption between subsurface anaerobic biofilms and granitic host rocks. Geomicrobiology Journal 23:15–29.

Anderson C R, James R E, Fru E C, Kennedy C B, Pedersen K, 2006c. In situ ecological development of a bacteriogenic iron oxide-producing microbial community from a subsurface granitic rock environment. Geobiology 4:29–42.

Andersson P S, Wasserburg G J, Chen J H, Papanastassiou D A, Ingri J, 1995. U-238-U-234 and TH-232-TH-230 in the Baltic Sea and in river water Earth and Planetary Science Letters 130 (1–4): 217–234 1995.

Andersson P, Billaux D, Byegård J, Cvetkovic V, Dershowitz W, Doe T, Hermanson J, Poteri A, Tullborg E-L, Winberg A (ed) 2006. TRUE Block Scale Continuation Project. Final Report. SKB TR-06-42. Svensk Kärnbränslehantering AB.

Andersson J C, 2007. Äspö Pillar Stability Experiment, final report. Rock Mass Response to Coupled Mechanical Thermal Loading. SKB TR-07-01. Svensk Kärnbränslehantering AB.

Barcena I, Garcai-Sineriz J-L, 2001. Prototype Repository. System for Canisters Displacement Tracking. SKB IPR-02-06. Svensk Kärnbränslehantering AB.

Bath A, Milodowsk A, Ruotsalainen P, Tullborg E-L, Cortés Ruiz A, Aranyossy J-F, 2000. Evidence from Mineralogy and Geochemistry for the Evolution of Groundwater Systems During the Quaternary for Use In Radioactive Waste Repository Assessment (EQUIP Project). Final Report, Contract No FI4W-CT96-0031. Euratom/EC-DG-Research, Report EUR 19613EN. 157 pp. European Commission, Luxembourg.

Baysse C, Budzikiewicz H, Uría Fernández D, Cornelis P, 2002. Impaired Maturation of the Siderophore Pyoverdine Chromophore in Pseudomonas fluorescens ATCC 17400 Deficient for the Cytochrome c Biogenesis Protein CcmC. FEBS Lett. 523, 23–28.

Billaux D, 2005. Analysis of Reactive Transport in a Fault Structure and Associated Background fractures. True Block Scale Continuation project. SKB IPR-05-37. Svensk Kärnbränslehantering AB.

Bono N, Röshoff K, 2003. Prototype Repository. Instrumentation for stress, strain and displacement measurements in rock. SKB IPR-03-19. Svensk Kärnbränslehantering AB.

Bouby M, Billard I, Maccordick H J, 1999. Selective Behavior of the Siderophore Pyoverdine A towards UO_2^{2+}, Th^{4+}, U^{4+} and other Cations. Czechoslovak J. Phys. 49, 147–150.

Boukhalfa H, Reilly S D, Michalczyk R, Iyer S, Neu M P, 2006. Iron(III) Coordination Properties of a Pyoverdin Siderophore Produced by Pseudomonas putida ATCC 33015. Inorg. Chem. 45, 5607–5616.

Byegård J, Johansson H, Andersson P, Hansson K, Winberg A, 1999. Test plan for the long term diffusion experiment. SKB IPR-99-36. Svensk Kärnbränslehantering AB.

Budzikiewicz H, 2004. Siderophores of the Pseudomonadaceae sensu stricto (Fluorescent and Non-Fluorescent Pseudomonas spp.). Fortschr. Chem. Org. Naturst. 87, 83–237.

Budzikiewicz H, Schäfer M, Uría Fernández D, Meyer J-M, 2006. Structure proposal for a new pyoverdin from Pseudomonas sp. PS 6–10. *Z.* Naturforsch. 61c, 815–820.

Budzikiewicz H, Schäfer M, Uría Fernández D, Matthijs S, Cornelis P, 2007. Characterization of the chromophores of pyoverdins and related siderophores by electrospray tandem mass spectrometry. BioMetals, in press.

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

Börgesson L, Hernelind J, 1999. Coupled thermo-hydro-mechanical calculations of the water saturation phase of a KBS-3 deposition hole. Influence of hydraulic rock properties on the water saturation phase. SKB TR-99-41. Svensk Kärnbränslehantering AB.

Börgesson L, Sandén T, 2002. Prototype Repository. Instrumentation of buffer and Backfill in Section II. SKB IPR-03-21. Svensk Kärnbränslehantering AB.

Börgesson L, Sandén T, Johannesson L E, 2006. ROSE, Rock Shear Experiment. A feasibility study. SKB IPR-06-13, Svensk Kärnbränslehantering AB.

Chen J H, Edwards R L, Wasserburg G J, 1986. U-238,U-234 and TH-232 in seawater Earth and Planetary Science Letters 80 (3–4): 241–251 1986.

Cheng H, Cvetkovic V, 2005. Evaluation of the BS2B sorbing tracer tests using the LASAR approach. True Block Scale Continuation Project. SKB IPR-05-39. Svensk Kärnbränslehantering AB.

Christiansen B, 2006. A transformational, structural and natural occurrence study of green rust. SKB IPR-06-24. Svensk Kärnbränslehantering AB.

Collin M, Börgesson L, 2002. Prototype Repository. Instrumentation of buffer and Backfill for measuring THM processes. SKB IPR-02-09. Svensk Kärnbränslehantering AB.

Demange P, Bateman A, Mertz C, Dell A, Piemont Y, Abdallah A A, 1990. Bacterial Siderophores: Unusual 3,4,5,6-Tetrahydropyrimidine-Based Amino Acids in Pyoverdins from Pseudomonas fluorescens. Tetrahedron Lett. 31, 7611–7614

Dershowitz W, Winberg A, Hermanson J, Byegard J, Tullborg E-L, Andersson P, Mazurek M, 2003a. Aspo Hard Rock Laboratory, Aspo Task Force on Modeling of Groundwater Flow and Transport of Solutes, Task 6C, A Semi-Synthetic Model of Block Scale Conductive Structures and the Aspo HRL. SKB IPR-03-13. Svensk Kärnbränslehantering AB.

Dershowitz W S, Doe T W, Uchida M, Hermanson J, 2003b. Correlations between Fracture Size, Transmissivity, and Aperture. Proceedings, Twelfth Pan American Conference on Soil Mechanics and Geotechnical Engineering. P. Culligan, H. Einstein, and A. Whittle, eds. June 22–26, 2003, Cambridge, MA. Verlag Gluckauf Gmbh, Essen. pp 887–891.

Dideriksen K, Stipp S, 2006. Iron Oxides in Fractures at Äspö. A feasibility study to test the possibility of finding a geothermometer or a palaeo-redox indicator. SKB IPR-06-09. Svensk Kärnbränslehantering AB.

Eden P, Björklund A, 1994. Ultra-low density sampling of overbank sediment in Fennoscandia. Journal of Geochemical Exploration 51 (3): 265–289 SEP 1994.

Farkas E, Enyedy E A, Csoka H, 2000. Some factors affecting metal ion-monohydroxamate interactions in aqueous solution. J. Inorg. Biochem. 79, 205–211.

Ferris F G, Konhauser K O, Lyuvén B, Pedersen K, 1999. Accumulation of metals by bacteriogenic iron oxides in a subterranean environment. Geomicrobiology Journal 16:181–92.

Ferris F G, Hallberg R O, Lyvén B, Pedersen K, 2000. Retention of strontium, cesium, lead and uranium by bacterial iron oxides from a subterranean environment. Applied Geochemistry 15:1035–42.

Fox A, Dershowitz W, Ziegler M, Uchida M, Takeuchi S, 2005. BS2B Experiment: Discrete Fracture and Channel Network Modeling of Solute Transport Modeling in Fault and Non-Fault Structures. True Block Scale Continuation Project. SKB IPR-05-38. Svensk Kärnbränslehantering AB.

García-García S, Jonsson M, Wold S, 2006. Temperature effect on the stability of bentonite colloids in water. J. Colloid Interface Sci., Volume 298, Issue 2, pp 694–705.

Gatabin C, Guillot W, 2006. TBT_3 Mock-up Test, Final report, CEA, NT DPC/ SCCME 06-345-A.

Geipel G, Acker M, Vulpius D, Bernhard G, Nitsche H, Fanghänel Th, 2004. An Ultrafast Time-Resolved Fluorescence Spectroscopy System for Metal Ion Complexation Studies with Organic Ligands. Spectrochim. Acta 60, 417–424.

Gipp S, Hahn J, Taraz K, Budzikiewicz H, 1991. Zwei Pyoverdine aus Pseudomonas aeruginosa R. Z. Naturforsch. 46c, 534–541.

Glorius M, Moll H, Bernhard G, 2007. Complexation of uranium(VI) with aromatic acids in aqueous solution – A comparison of hydroxamic acids and benzoic acid. Radiochim. Acta, Oldenbourg Wissenschaftsverlag, ISSN 0033-8230, Volume 95 03/2007, pp 151–157.

Goudarzi R, Johannesson L-E, Börgesson L, 2006a. Backfill and Plug test. Sensors data report (Period 990601–060101) Report No:12. SKB IPR-06-02. Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, Börgesson L, 2006b. Backfill and Plug test. Sensors data report (Period 990601–060701) Report No:13. SKB IPR-06-34. Svensk Kärnbränslehantering AB.

Goudarzi R, Börgesson L, Röshoff K, Edelman M, 2006c. Canister Retrieval Test. Sensors data report (Period 001026–060501) Report No:12. SKB IPR-06-35. Svensk Kärnbränslehantering AB.

Goudarzi R, Åkesson M, Hökmark H, 2006d. Temperature Buffer Test. Sensors data report (Period: 030326–060701) Report No:8. SKB IPR-06-27. Svensk Kärnbränslehantering AB.

Guo R, 2006. Thermo-hydro-mechanical numerical modelling of a laboratory heating test and comparison with measurement. Ontario Power Generation Report 06819-REP-01300-10031-R00.

Harrington J F, Horseman S T, 2003. Gas Migration in KBS-3 Buffer Bentonite: Sensitivity of Test Parameters to Experimental Boundary Conditions. SKB TR-03-02. Svensk Kärnbränslehantering AB.

Haveman S A, Pedersen K, 2002. Microbially mediated redox processes in natural analogues for radioactive waste. Journal of Contaminant Hydrology 55:161–74.

Itasca, 2003. 3DEC – 3 dimensional distinct element code. User's manual. Itasca Consulting Group Inc., Minneapolis.

Itasca, 2005. Flac3D: Fast Lagrangian Analysis of Continua in Three Dimensions, Version 3.0, Minnesota, USA, 2005.

Jansson M, Eriksen T E, Moreno L, 2006. Influence of water radiolysis on the mobilization of Tc(IV) in bentonite clay. Results from field experiments at Äspö. SKB TR-04-22. Svensk Kärnbränslehantering AB.

Jarsjö J, Destouni G, Gale J, 2001. Groundwater degassing and two-phase flow in fractured rock: Summary of results and conclusions achieved during the period 1994–2000. SKB TR-01-13. Svensk Kärnbränslehantering AB.

Johnsson A, Arlinger J, Pedersen K, Ödegaard-Jensen A, Albinsson Y, 2006. Solid-Aqueous Phase Partitioning of Radionuclides by Complexing Compounds Excreted by Subsurface Bacteria. Geomicrobiology Journal 23:621–30.

Karnland O, 2002. Colloid stability in Wyoming bentonite clay. Project contribution to the Äspö Colloid Workshop 5:th of March in Stockholm.

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

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

Laaksoharju M, Wold S, 2005. The colloid investigations conducted at the Äspö Hard Rock Laboratory during 2000–2004. SKB TR-05-20. Svensk Kärnbränslehantering AB.

Ledesma A, Jacinto A, Velasco M, 2006a. TBT_3 Predictive modelling programme, ENRESA Contribution, CIMNE-UPC, DM Iberia.

Ledesma A, Jacinto A, Velasco M, 2006b. TBT_3 Predictive modelling programme – Step 2, ENRESA Contribution, CIMNE-UPC, DM Iberia.

Lindbæk Skovbjerg L, 2005. Reduction of hexavalent chromium by green rust sulphate: Determination of end product and reduction mechanism. SKB IPR-06-25. Svensk Kärnbränslehantering AB.

Löfvendahl R, 1987. Dissolved Uranium in the Baltic Sea. Marine Chemistry 21 (3): 213–227 1987.

Mas Ivars D, 2005. Äspö Pillar Stability Experiment. Hydromechanical data acquisition experiment at the APSE site. SKB IPR-05-21. Svensk Kärnbränslehantering AB.

Mattsson H, 2006. The magnetic anisotropy of rocks across the deformation zone NE-1 at the Äspö HRL. SKB IPR-06-32. Svensk Kärnbränslehantering AB.

Meyer J M, Abdallah M A, 1978. The Fluorescent Pigment of Pseudomonas fluorescens: Biosynthesis, Purification and Physicochemical properties. J. Gen. Microbiol. 107, 319–328.

Moye D G, 1967. Diamond drilling for foundation exploration. Civil Eng. Trans. Inst. Eng. Australia, 95–100.

Muurinen A, 2006. Chemical Conditions in the A2 Parcel of the Long-Term Test of Buffer Material in Äspö. Working Report 2006-83, Posiva Oy.

Neretnieks I, 1982. "Leach Rates of High Level Waste And Spent Fuel. –Limiting Rates as Determined by Backfill And Bedrock Conditions" In: Lutze, W. (Ed.), Scientific Basis for Nuclear Waste Management V, Materials Research Society Symposium Proceedings 11, North-Holland, New York, Amsterdam, Oxford, 1982, pp. 559– 568.

Nowak T, 2005. NF-PRO WP 3.4 Gas effects on the THM behaviour of clay buffer – BGR-Surface Packer Tests, Deliverable 3.4.2. – Federal Institute for Geosciences and Natural Resources; Hanover, 2005.

Nowak T, 2006. NF-PRO WP 3.4 Gas effects on the THM behaviour of clay buffer – BGR-Surface Packer Tests, First data report on gas tracer tests, Deliverable 3.4.4. – Federal Institute for Geosciences and Natural Resources; Hanover, 2006.

Nyberg G, Jönsson S, Wass E, 2006. Äspö Hard Rock Laboratory. Hydro monitoring program. Report for 2005. SKB IPR-06-14. Svensk Kärnbränslehantering AB.

O'Brien E C, Farkas E, Gil M J, Fitzgerald D, Castineras A, Nolan K B, 2000. Metal complexes of salicylhydroxamic acid (H_2Sha), anthranilic hydroxamic acid and benzohydroxamic acid. Crystal and molecular structure of [Cu(phen)$_2$(Cl)]Cl x H_2Sha, a model for a peroxidase-inhibitor complex. J. Inorg. Biochem. 79, 47–51.

Olsson O, 1992. Site characterization and validation – Final report. Stripa Project. SKB TR-92-22. Svensk Kärnbränslehantering AB.

Pedersen K, 2000. The microbe site. Drilling, instrumentation and characterisation. SKB IPR-00-36. Svensk Kärnbränslehantering AB.

Pedersen K. 2001. Diversity and activity of microorganisms in deep igneous rock aquifers of the Fennoscandian Shield. In Subsurface microbiology and biogeochemistry, ed. JK Fredrickson, M Fletcher, pp. 97–139. New York: Wiley-Liss Inc.

Pedersen K, 2002. Microbial processes in the disposal of high level radioactive waste 500 m underground in Fennoscandian shield rocks. In Interactions of microorganisms with radionuclides. Edited by Keith-Roach M.J. and Livens F.R. Elsevier, Amsterdam. pp 279–311.

Pedersen K, 2005. The Microbe framework: Site descriptions, instrumentation, and characterization. Äspö Hard Rock Laboratory. SKB IPR-05-05, pp. 1–85. Svensk Kärnbränslehantering AB.

Poteri A, 2005. Evaluation of the BS2B sorbing tracer tests using the Posiva streamtube approach. True Block Scale Continuation project. SKB IPR-05-36. Svensk Kärnbränslehantering AB.

Puigdomenech I, Sandén T, 2001. Prototype Repository. Instrumentation for gas and water sampling in Buffer and Backfill. Tunnel Section I. SKB IPR-01-62. Svensk Kärnbränslehantering AB.

Pusch R, 2001. Prototype Repository. Selection of THMCB models. SKB IPR-01-66. Svensk Kärnbränslehantering AB.

Pusch R, Svemar C, 2003. Prototype Repository. Predictive modeling of EBS performance in the Prototype Repository Project. SKB IPR-03-26. Svensk Kärnbränslehantering AB.

Rhén I, Forsmark T, 2001. Prototype repository. Hydrogeology – Summary report of investigations before the operations phase. SKB IPR-01-65. Svensk Kärnbränslehantering AB.

Rhén I, Forsmark T, Magnusson X, Alm P, 2003. Prototype Repository. Hydrogelogical, Hydrochemical and Temperature Measurements in boreholes during the operation phase of the Prototype Repository Tunnel Section II. SKB IPR-03-22. Svensk Kärnbränslehantering AB.

Roos M, Åstrom M, 2005. Hydrochemistry of rivers in an acid sulphate soil hotspot area in western Finland. Agricultural and Food Science 14 (1): 24–33 2005.

Rothfuchs T, Hartwig L, Komischke M, Miehe R, Wieczorek K, 2003. Prototype Repository. Instrumentation for resistivity measurements in buffer backfill and rock in Section II. SKB IPR-03-48. Svensk Kärnbränslehantering AB.

Rousset D, Villieras F, Mosser-Ruck R, Pret D, 2006. Analyses of clay material from two LOT test parcels, CREGU-LEM, Andra report n° DRP 0CRE 06002/A.

SKB, 2001. Forsknings-, utvecklings- och demonstrationsprogram för ett KBS-3-förvar med horisontell deponering. SKB R-01-55. Svensk Kärnbränslehantering AB.

SKB, 2004. RD&D-Programme 2004. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste. SKB TR-04-21. Svensk Kärnbränslehantering AB.

SKB, 2005. Äspö Hard Rock Laboratory. Annual report 2004. SKB TR-05-10, Svensk Kärnbränslehantering AB.

SKB, 2006. Äspö Hard Rock Laboratory. Planning Report for 2006. SKB IPR-06-06, Svensk Kärnbränslehantering AB.

Smellie J A T, Waberg H N, Frape S K, 2003. Matrix fluid chemistry experiment. Final report. June 1998–March 2003. SKB R-03-18. Svensk Kärnbränslehantering AB.

Ström A, 1998. The Äspö Task Force on Modelling of Groundwater Flow and Transport of solutes – Issue Evaluation Table 1997/1998, SKB ICR-98-05. Svensk Kärnbränslehantering AB.

Teintze M, Hossain M B, Barnes C L, Leong J, van der Helm D, 1981. Structure of Ferric Pseudobactin, a Siderophore from a Plant Growth Promoting Pseudomonas. Biochemistry 20, 6446–6457.

Thorsager P, Lindgren E, 2004. KBS-3H Summary report of work done during Basic Design SKB R-04-42. Svensk Kärnbränslehantering AB.

Todd D K, 1980. Groundwater hydrology. Second edition. John Wiley & Sons, Inc. New York. ISBN 0-471-87616-X.

Widestrand H, Byegård J, Börjesson S, Bergelin A, Wass E, 2006. Long Term Diffusion Experiment. Functionality tests with short-lived radionuclides. SKB IPR-06-05, in review. Svensk Kärnbränslehantering AB.

Vilks P, Miller N H, Stanchell F W, 2005. Laboratory program supporting SKB's long term diffusion experiment. Report No: 06819-REP-01300-10111-R00, Ontario Power Generation.

Villar M V, Gómez-Espina R, Martín P L, 2006. Behaviour of MX-80 Bentonite at Unsaturated Conditions and under Thermo-Hydraulic Gradient, Informes Técnicos Ciemat, number 1081, Madrid.

Winberg A, Hermanson J, Tullborg E-L, Staub I, 2003. Äspö Hard Rock laboratory. Long-Term Diffusion Experiment. Structural model of the LTDE site and detailed description of the characteristics of the experimental volume including target structure and intact rock section. SKB IPR-03-51. Svensk Kärnbränslehantering AB.

Wold S, Eriksen T, 2002. Formation of inorganic colloids in solutions in contact with bentonite. Project contribution to the Äspö Colloid Workshop 5:th of March in Stockholm.

Åström M, Peltola P, Virtasalo J, Kotilainen A, Salminen R, 2007. Niobium in boreal stream waters and brackish-water sediments. Geochemistry. Exploration, Environment, Analysis (accepted for publication)

8.2 List of papers and articles published 2006

General Äspö HRL

Sjöland K A, Bockgård N, 2006. Present status of the Äspö Hard Rock Laboratory. Proceedings of the 11th International High-Level Radioactive Waste Management Conference, Las Vegas, April 30–May 4, 2006, American Nuclear Society (on CD).

Hydrogeology

Bockgård N, Vidstrand P, Svensson U, Sjöland K A, 2006. Hydrogeological research at the Äspö Hard Rock Laboratory, Sweden. Proceedings of the 11th International High-Level Radioactive Waste Management Conference, Las Vegas, April 30–May 4, 2006, American Nuclear Society (on CD).

Microbe project

Meetings

Pedersen K, 2006. Exploration of microbial activity and diversity in Scandinavian deep hard rock aquifers. Agouron Institute. Deep Biosphere mini-symposium. International Geobiology course, held Wednesday 28th June at the USC Wrigley Institute for Environmental Studies, Catalina Island, CA, USA. (Invited).

Pedersen K, 2006. Geological hydrogen fuels deep intraterrestrial microbial communities via an autotrophic hydrogen-acetate pathway. 2nd FEMS (Federation of European Microbiologists) congress of European microbiologists integrating microbial knowledge into human life. 4–8 July, Madrid, Spain. (Invited).

Pedersen K, 2006. Microbial reduction of carbon dioxide with geological hydrogen to acetate and methane fuels a deep autothrophic intra-terrestrial food chain and poises the oxidation-reduction potential of groundwater. Western Pacific Geophysics Meeting, 24–27 July, Bejing, Kina. (Invited).

Pedersen K, Hallbeck L, Eriksson S, Masurat P, Chi E, 2006. Survival and activity of micro-organisms in compacted Wyoming MX-80 bentonite under extreme conditions relevant to a high level radioactive waste repository. 2006 Western Pacific Geophysics Meeting, 24–27 July, Bejing, Kina. (Invited).

Pedersen K, 2006. Effects of microorganisms upon radionuclide migration. 2nd Annual workshop of the FUNMIG FP6 Integrated project. Fundamental processes of radionuclide migration. 21–23 November 2006, Stockholm, Sweden.

Pedersen K, 2006. Microbial research in the framework of HLW disposal. Seminar given 5th December 2006 at SCK CEN – BRI in MOL, Belgium.

Thesis

Masurat P, 2006. Potential for corrosion in disposal systems for high level radioactive waste by Meiothermus and Desulfovibrio. Thesis, 10th March, 2006, Göteborg University, Department of Cell and Molecuar Biology, Göteborg, Sweden, ISBN 91-628-6773-3.

Chi Fru E, 2006. Molecular charaterisation of the microbial diversity in natural and engineered environments. Thesis, 27th October, 2006, Göteborg University, Department of Cell and Molecuar Biology, Göteborg, Sweden, ISBN 91-628-6955-8.

Johnsson A, 2006. The role of bioligands in microbe-metal interactions. Thesis 3rd November, 2006, Göteborg University, Department of Cell and Molecuar Biology, Göteborg, Sweden, ISBN 91-628-6976-0.

Publications

Anderson C, Jakobsson A-M, Pedersen K, 2006. Autoradiographic comparisons of radionuclide adsorption between subsurface anaerobic biofilms and granitic host rocks. Geomicrobiol. J. 23, 15–29.

Anderson C R, James R E, Fru E C, Kennedy C B, Pedersen K, 2006. In situ ecological development of a bacteriogenic iron oxide-producing microbial community from a subsurface granitic rock environment. Geobiology 4, 29–42.

Anderson C, Jakobsson A-M, Pedersen K, 2006. Influence of in situ biofilm coverage on the radionuclide adsorption capacity of subsurface granite. Environmental Sci ence and Technology, Published on Web 12/22/2006.

Johnsson A, Arlinger J, Pedersen K, Ödegaard-Jensen A, Albinsson Y, 2006. Solid-Aqueous Phase Partitioning of Radionuclides by Complexing Compounds Excreted by Subsurface Bacteria. Geomicrobiol J 23, 621–630.

Kalinowski B E, Johnsson A, Arlinger J, Pedersen K, Ödegaard-Jensen A, Edberg F, 2006. Microbial Mobilization of Uranium from Shale Mine Waste. Geomicrobiol J 23, 157–164.

Nielsen M E, Pedersen K, Fisk M, Istok J, 2006. Microbial nitrate respiration of lactate at in situ conditions in groundwater from a granitic aquifer situated 450 m underground. Geobiology 4, 43–52.

Moll H, Bernhard G, 2006. Complex formation of curium(III) with the amino acids L2-Aminobutyric acid and L-Threonine and the corresponding phosphate ester O-Phospho-L-Threonine. Lecture presented at the 15th Radiochemical Conference Mariánské Lázné, Czech Republic, April 23–28, 2006; Session 6/IV (Separation Methods), Booklet of Abstracts page 223.

Moll H, 2006. Interactions of microbes found at Äspö underground lab with actinides such as curium, plutonium and uranium. Lecture presented at the 2nd Annual Workshop of the IP FUNMIG, Stockholm, Sweden, November 21–23, 2006.

Moll H, Merroun M L, Hennig C, Rossberg A, Selenska-Pobell S, Bernhard G, 2006. The interaction of Desulfovibrio äspöensis DSM 10631T with plutonium. Radiochimica Acta 94, 815–824 (2006).

Glorius M, Moll H, Bernhard G, 2007. Complexation of uranium(VI) with aromatic acids in aqueous solution – A comparison of hydroxamic acids and benzoic acid. Radiochimica Acta, accepted 2006, in press 2007.

Moll H, Bernhard G, 2007. Complex formation of curium(III) with amino acids of different functionalities: L-Threonine and O-Phospho-L-Threonine. Journal of Coordination Chemistry, accepted 2006, in press 2007.

Moll H, Bernhard G, 2006. Complex formation of curium with L-threonine studied by TRLFS. Institute of Radiochemistry Annual Report 2005, FZR-443, 12 (2006).

Moll H, Bernhard G, 2006. Complex formation of curium with O-phospho-L-threonine studied by TRLFS. Institute of Radiochemistry Annual Report 2005, FZR-443, 13 (2006).

Moll H, Merroun M, Selenska-Pobell S, Bernhard G, 2006. Interaction of actinides with Desulfovibrio äspöensis (DSM 10631T). Part IV: Plutonium. Institute of Radiochemistry Annual Report 2005, FZR-443, 32 (2006).

Moll H, Hennig C, Roßberg A, Merroun M, Selenska-Pobell S, Bernhard G, 2005. Desulfovibrio äspöensis (DSM 10631T) and plutonium. XAS results. Institute of Radiochemistry Annual Report 2005, FZR-443, 33 (2006).

True-projects

Cheng H, Cvetkovic V, Winberg A, Dershowitz W D 2006. Estimating retention properties of components of a block scale fracture network – an example from the Äspö Hard Rock Laboratory, Sweden. Paper presented at the American Geophysical Union (AGU) Fall Meeting, San Fransico, CA, December 2006.

Cvetkovic V, Cheng H, Widestrand H, Byegård J, Winberg A, Andersson P, (submitted). Sorbing tracer experiments in a crystalline rock fracture at Äspö (Sweden): 2. Transport model and effective parameter estimation. Paper sumitted to Water Resources Research.

Poteri A, Cvetkovic V, Dershowitz W D, Billaux D, Winberg A, 2006. Illustration of Uncertainties in Assessments of Flow and Transport in a Block Scale Fracture Network – an Example from the Äspö Hard Rock Laboratory, Sweden. Paper presented at the American Geophysical Union (AGU) Fall Meeting, San Fransico, CA, December 2006.

Widestrand H, Byegård J, Cvetkovic V, Tullborg E-L, Winberg A, Andersson P, Siitari-Kauppi M, (submitted). Sorbing tracer experiments in a crystalline rock fracture at Äspö (Sweden): 1. Site description and micro-scale characterisation of retention properties. Paper sumitted to Water Resources Research.

Fe-oxides in fractures

Skovbjerg L, Stipp S, Utsunomiya S, Ewing R, 2006. The Mechanisms of Reduction of Hexavalent Chromium by Green Rust Sodium Sulphate: Formation of Cr-goethite (Resubmitted in February 2006 to Geochimica et Cosmochimica Acta).

Dideriksen K, Christiansen B, Baker J, Frandsen C, Balic-Zunic T, Tullborg E, Mørup S, Stipp S, 2006. Fe-oxide fracture-fillings as a palæo-temperature and redox indicator: Structure, crystal form, REE content and Fe isotope composition (Accepted for publication, May 2006, in Geochimica et Cosmochimica Acta).

Grivé M, Colàs E, Domènech C, 2006. Fe-oxides in fractures: Thermodynamics and trace component uptake. Enviros Progress Report. (under review).

Colloid

Kienzler B, Vejmelka P, Römer J, Luckscheiter B, Kisely T, Soballa E, Walschburger C, Seither A, 2006. Actinide migration experiment in the ÄSPÖ HRL in Sweden: analysis of retained uranium and technetium with core # 7. (Part V). Wissenschaftliche Berichte, FZKA-7196 (Februar 2006).

Kienzler B, Vejmelka P, Römer J, Schild D, Jansson M, 2006. Experiences with underground laboratory experiments. Internat.High Level Radioactive Waste Management Conf. (IHLWM), Las Vegas, Nev.,April 30–May 4, 2006.

Kienzler B, 2006. Radionuklid migration: Chemlab, FUNMIG, PET & Co., Festkolloquium anlässlich der Verabschiedung von Dr.Richter, Inst.f.Interdisziölinäre Isotopenforschung, Leipzig, 20.Oktober 2006.

Hauser W, 2006. A mobile laser-induced breakdown detection system: In situ monitoring of colloid migration and stability of natural ground water colloids. Seminar on Laser-Spectroscopic Methods for Radionuclide Migration, China Institute of Atomic Energy, Beijing, China,April 8–13, 2006.

Hauser W, 2006. Laser-induced photoacoustic spectroscopy with a highly sensitive sensor for trace speciation of aquatic actinides. Seminar on Laser-Spectroscopic Methods for Radionuclide Migration, China Institute of Atomic Energy, Beijing, China,April 8–13, 2006.

8.3 Documents published 2006

During 2006 the following reports and documents have been published in the SKB series.

Technical Reports

SKB, 2006. Äspö Hard Rock Laboratory. Annual Report 2005. SKB TR-06-10. Svensk Kärnbränslehantering AB.

International progress reports

Thorsager P, Börgesson L, Johannesson L-E, Sandén T, 2002. Canister Retrieval Test. Report on installation. SKB IPR-02-30, Svensk Kärnsbränslehantering AB.

Pusch R, Börgesson L, Svemar C, 2004. Prototype Repository. Final report (Deliverable D36). SKB IPR-04-27, Svensk Kärnbränslehantering AB.

Holmen J, Forsman J, 2004. Äspö Task Force. Modelling of Task 6A and 6B2. SKB IPR-04-39, Svensk Kärnbränslehantering AB.

Pusch R, Ramqvist G, 2004. Borehole sealing, preparative steps, design and function of plugs-basic concept. SKB IPR-04-57, Svensk Kärnbränslehantering AB.

Forsmark T, Rhén I, 2005. Prototype Repository. Hydraulic tests and deformation measurements during operation phase. Test campaign 5. Interference tests. SKB IPR-05-18, Svensk Kärnbränslehantering AB.

Lampinen H, 2006. Äspö Pillar Stability Experiment. Detailed geological mapping of the pillar blocks. SKB IPR-05-24, Svensk Kärnbränslehantering AB.

Pedersen K, 2005. MICROBE. Analysis of microorganisms and gases in MICROBE groundwater over time during MINICAN drainage of the MICROBE water conducting zone. SKB IPR-05-29, Svensk Kärnbränslehantering AB.

Haycox J R, Pettitt W S, 2005. Acoustic emission and ultrasonic monitoring during the heating of deposition hole DA3545G01 in the Prototype Repository to March 2005. SKB IPR-05-30, Svensk Kärnbränslehantering AB.

Haycox J R, Pettitt W S, 2005. Acoustic emission and ultrasonic monitoring results from deposition hole DA3545G01 in the Prototype Repository between April 2005 and September 2005. SKB IPR-05-31, Svensk Kärnbränslehantering AB.

Savukoski M, 2005. DECOVALEX. Drill hole KF0066A01 and KF0069A01. Determination of porosity by water saturation and density by buoyancy technique. SKB IPR 05-32, Svensk Kärnbränslehantering AB.

Jacobsson L, Bäckström A, 2005. Unaxial compression tests of intact rock specimens at dry condition and at saturation by three different liquids: distilled, saline and formation water. SKB IPR-05-33, Svensk Kärnbränslehantering AB.

SKB, 2005. Äspö Hard Rock Laboratory. Status Report. July–September 2005. SKB IPR 05-34, Svensk Kärnbränslehantering AB.

Goudarzi R, Börgesson L, Röshoff K, Edelman M, 2005. Canister Retrieval Test. Sensors data report (Period 001026–051101) Report No:11. SKB IPR-05-35, Svensk Kärnbränslehantering AB.

Poteri A, 2005. True Block Scale continuation project. Evaluation of the BS2B sorbing tracer tests using the Posiva streamtube approach. SKB IPR-05-36, Svensk Kärnbränslehantering AB.

Billaux D, 2005. True Block Scale continuation project. Analysis of reactive transport in a fault structure and associated background fractures. SKB IPR-05-37, Svensk Kärnbränslehantering AB.

Fox A, Dershowitz W, Ziegler M, Uchida M, Takeuchi S, 2005. True Block Scale continuation project. BS2B experiment: Discrete fracture and channel network modeling of solute transport modeling in fault and non-fault structures. SKB IPR-05-38, Svensk Kärnbränslehantering AB.

Cheng H, Cvetkovic V, 2005. TRUE Block Scale continuation project. Evaluation of the BS2B sorbing tracer tests using the LASAR approach. IPR-05-39, Svensk Kärnbränslehantering AB.

Forsmark T, 2006. Prototype Repository. Hydraulic tests and deformations measurements during operation phase. Test campaign 6. Single hole tests. SKB IPR-06-01, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, Börgesson L, 2005. Backfill and Plug test. Sensors data report (Period 990601–060101) Report No:12. SKB IPR-06-02, Svensk Kärnbränslehantering AB.

SKB, 2005. Äspö Hard Rock Laboratory. Status Report. October–December 2005. SKB IPR-06-03, Svensk Kärnbränslehantering AB.

Goudarzi R, Åkesson M, Hökmark H, 2006. Temperature Buffer Test. Sensors data report (Period: 030326–060101) Report No:7. SKB IPR-06-04, Svensk Kärnbränslehantering AB.

SKB, 2006. Äspö Hard Rock Laboratory. Planning Report for 2006. SKB IPR-06-06, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson, L-E, 2005. Prototype Repository. Sensors data report (Period: 010917–051201). Report No:14. SKB IPR-06-08, Svensk Kärnbränslehantering AB.

Dideriksen K, Stipp S L S, 2005. Iron oxides in fractures at Äspö. A feasibility study to test the possibility of finding a geothermometer or a palaeo-redox indicator. SKB IPR-06-09, Svensk Kärnbränslehantering AB.

Åkesson M, 2006. Temperature Buffer Test. Evaluation modelling – Field test. SKB IPR 06-10, Svensk Kärnbränslehantering AB.

Åkesson M, 2006. Temperature Buffer Test. Evaluation modelling – Mock-up test. SKB IPR-06-11, Svensk Kärnbränslehantering AB.

SKB, 2006. Äspö Hard Rock Laboratory. Status Report. January–March 2006. SKB IPR-06-12, Svensk Kärnbränslehantering AB.

Börgesson L, Sandèn T, Johannesson L-E, Knutsson H, 2004. ROSE, Rock Shear Experiment. A feasibility study. SKB IPR-06-13, Svensk Kärnbränslehantering AB.

Nyberg G, Jönsson S, Wass E, 2006. Hydro Monitoring Program. Report for 2005. SKB IPR-06-14, Svensk Kärnbränslehantering AB.

SKB, 2006. Äspö Hard Rock Laboratory. Status Report. April–June 2006. SKB IPR-06-16, Svensk Kärnbränslehantering AB.

Haycox J R, Pettitt W S, 2006. Acoustic emission and ultrasonic monitoring results from deposition hole DA3545G01 in the Prototype Repository between October 2005 and March 2006. SKB IPR-06-23, Svensk Kärnbränslehantering AB.

Christiansen B, 2006. A transformational, structural and natural occurrence study of green rust. SKB IPR-06-24, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, 2006. Prototype Repository. Sensors data report (Period: 010917–060601). Report No:15. SKB IPR-06-26, Svensk Kärnbränslehantering AB

Goudarzi R, Åkesson M, Hökmark H, 2006. Temperature Buffer Test. Sensors data report (Period: 030326–060701) Report No:8. SKB IPR-06-27, Svensk Kärnbränslehantering AB.

Äspö Hard Rock Laboratory. Status Report. July–September 2006. SKB IPR-06-33, Svensk Kärnbränslehantering AB.

Technical documents

4 technical documents were produced during 2006.

Bergelin A, Jonsson U, Berg C, Wacker P, 2005. Prototype Repository. Water sampling in Prototype Repository and compilation of water chemistry data from Äspö HRL. SKB TD-05-03, Svensk Kärnbränslehantering AB.

Tullborg E-L, Larsson S-E, 2005. Matrix Continuation. Porosity and density measurements on samplesfrom drillcore KA2599G01. SKB TD-05-04, Svensk Kärnbränslehantering AB.

Pedersen K, 2006. Prototype Repository. Analysis of groundwater microorganisms and gases in buffer and backfill in November 2005. SKB TD-06-01, Svensk Kärnbränslehantering AB.

Bockgård N, 2006. Grundvattenkemidata och grundvattennivåer för privata brunnar 2004–2005. SKB TD-06-02, Svensk Kärnbränslehantering AB.

International technical documents

No international technical documents were produced during 2006.

ISSN 1404-0344
CM Digitaltryck AB, Bromma, 2007