Technical Report

TR-05-10

Äspö Hard Rock Laboratory

Annual Report 2004

Svensk Kärnbränslehantering AB

August 2005

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 2004

Svensk Kärnbränslehantering AB

August 2005

Abstract

The Äspö Hard Rock Laboratory (HRL) is an important part of SKB's work on design and construction of the deep geological repository for the final disposal of spent nuclear fuel. At Äspö HRL, methods for characterising a suitable site for a deep repository are being developed and tested. One of the fundamental reasons behind SKB's decision to construct an underground laboratory was to create an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to repository depth. The underground part of the laboratory consists of a tunnel from the Simpevarp peninsula to the southern part of Äspö where the tunnel continues in a spiral down to a depth of 460 m. Äspö HRL has been in operation since 1995 and the associated research, development, and demonstration tasks, which are managed by the Repository Technology Unit within SKB, have so far attracted considerable international interest. Most of the research is focused on processes of importance for the long-term safety of a future deep repository. A summary of work performed at Äspö HRL during 2004 is given below.

Technology

At Äspö HRL, the goals are 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, 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 carried out at Äspö HRL

The *Canister Retrieval Test*, located in the main test area at the –420 m level, aims at demonstrating the readiness for recovering of emplaced canisters, even after the time when the surrounding bentonite buffer becomes fully saturated. Bentonite rings and blocks, bentonite pellets, and a canister with heaters have been installed in a vertical deposition hole at full repository scale. The test has been running for a little more than four years. The relative humidity sensors indicate that the bentonite between the rock and the canister is water saturated but the bentonite above and below the canister is not. At the beginning, the wetting was a little slower and more inhomogeneous than predicted. Some clogging of the filter mats used for artificial water supply may explain the inhomogeneity. The power in the canister has been maintained at 1,600 W, although only 11 of the 36 heater elements were still working, and the water pressure of the artificial water supply has been kept constant at 850 kPa in the filter mats. Temperature, tension, degree of saturation and swelling have been measured and registered during 2004.

The *Prototype Repository* is a demonstration of the integrated function of the repository and provides a full-scale reference for testing predictive models concerning individual components as well as the complete repository system. It has also been a demonstration of the execution and function of the deposition sequence with state-of-the-art technology at full-scale. The layout involves altogether six deposition holes, four in an inner section and two in an outer. The tunnel is backfilled with a mixture of bentonite and crushed rock. In 2001 the inner section, with four canisters, was installed and the monitoring of processes started. The installation of the outer section took place during 2003 and the surface between the outer plug and the rock was grouted in October 2004. At the beginning of November 2004 the drainage of the tunnel was closed which affected the pressure in the buffers and

the backfill in the two sections. This affected the heaters in two of the canisters negatively and it was decided to reopen the drainage. However, measurements showed that the heaters in canister 2 were so damaged that no power could be applied. The heating of the rest of the canisters started again on January 15, 2004. The drainage of the tunnel has been kept open during 2004. The saturation of the buffer has reached different levels in the six deposition holes due to variation in the access to water. The temperature distributions in the buffer are quite different in the deposition holes mainly due to differences in water content. In a “dry” hole the gap of 10 mm between the buffer and the canister is still filled with air, resulting in a higher temperature on the canister surface compared with a canister in “wet” deposition hole.

The *Backfill and Plug Test* is a test of the function and evolution of the hydraulic and mechanical function of different backfill materials. It is also a demonstration of backfill emplacement methods and installation of a full-scale plug. The experiment is performed in a 28 m long test region which is located in the Zedex drift. The inner part of the tunnel is backfilled with a mixture of bentonite and crushed rock and the outer part is filled with crushed rock. The wetting of the backfill from the rock and filter mats supplying artificial water started at the end of 1999 and continued until autumn 2003 when flow testing in the backfill started. The flow testing has proceeded during 2004. The evaluated hydraulic conductivity in the mixture of bentonite and crushed rock is a little higher than those evaluated from laboratory experiments. The amount of water passing through the plug and the surrounding rock has been measured and the results show that the leakage is slowly reduced with time.

The *Long Term Test of Buffer Material* aims at validating models and hypotheses describing physical properties in a bentonite buffer material and processes related to microbiology, radionuclide transport, copper corrosion, and gas transport under conditions similar to those in a deep repository. The testing principle is to emplace “parcels” containing heater, central copper tube, pre-compacted clay buffer, instruments, and parameter controlling equipment in vertical boreholes with a diameter of 300 mm and a depth of around four meters. The parcels are extracted, after one or five years, and the water distribution in the clay is determined and subsequent well-defined chemical and mineralogical analyses as well as physical tests are performed. Two pilot tests, comprising one parcel each, have been finalised and reported. One parcel from the main test has been extracted and analysed and a report is under production. The remaining four long-term test parcels have functioned satisfactory and temperature, total pressure, water pressure and water content have been continuously measured. The bentonite swelling pressure is still increasing in several parcels, showing that water uptake is still ongoing, although the tests have been running for almost five years.

In the project *Cleaning and sealing of investigation boreholes* the best available techniques for this procedure are to be identified and demonstrated. In the first phase of the project a state-of-the-art report summarising the developments of the techniques during the last 10–15 years was prepared. A final report from the second phase, which focuses on the development of a complete basic concept, has been prepared under 2004. The present design for the borehole seals consists of cylindrical pre-compacted clay blocks contained in perforated copper tubes that are jointed in conjunction with insertion into the boreholes. The planning for a continuation of the project is in progress and the aim is to continue with laboratory tests on potential sealing materials and to perform in situ tests. A number of short boreholes for testing the concept have been drilled under ground in Äspö HRL and a machine for automatic manufacturing of perforated copper tubes is under construction.

It may be necessary to use cementitious products in the repository with leachates with pH ≤ 11. A pre-study concerning this issue was carried out in 2001, followed by a feasibility study in 2002 to mid 2003. In the feasibility study a specific need for development of *injection grouts* both for larger and smaller fractures as well as for testing them in field was identified. In June 2003 a joint project between Posiva, SKB and Numo was initiated. The project is divided into four sub projects: (1) Low-pH cementitious injection grout for larger fractures, (2) Non-cementitious low-pH injection grout for smaller fractures, (3) Field testing in Finland, and (4) Field testing in Sweden. The sub-project connected to Äspö HRL consists of field tests with silica sol, a gel of silica colloids in water. Preparations for the test were initiated in the end of 2003 and the grouting and hydraulic tests took place during the spring of 2004. The sub project is completed and the results indicate a sealing efficiency of 70% in the affected rock mass.

SKB and Posiva in co-operation are carrying through a programme for the *KBS-3 method with horizontal emplacement* (KBS-3H). The outcome from a feasibility study was that the KBS-3H method is worth further development work. The basic design study including e.g. development of technology for excavation of horizontal deposition holes and emplacement of super containers was finalised and reported in 2004. The excavation for the full scale demonstration at Äspö HRL is in progress. The demonstration comprises two deposition holes – one short hole (15 m) which will be used for construction and testing of a low-pH shotcrete plug and one long hole (95 m) which will primarily be used for demonstration of the deposition equipment and for evaluation of the chosen excavation method. At the end of 2004 the excavation of the short hole was completed, laser scanned and approved by SKB and the pilot hole for the longer hole was finished.

The aim of the *Large Scale Gas Injection Test* is to perform gas injection tests in a full-scale KBS-3 deposition hole. The current understanding of the gas transport process through compacted bentonite indicates that the buffer would open for gas passage before any harmful pressures are reached. However, there are still large uncertainties about the gas migration process which have to be verified in large-scale experiments. The experiments will be performed in Äspö HRL in a bored full-size deposition hole with a canister without heaters and a surrounding bentonite buffer. At the end of 2004 the installation phase was more or less finalised and the deposition of canister and buffer is planned to take place in the beginning of 2005. Water will be artificially supplied as soon as the installation is completed and the gas injection tests start when the buffer is fully saturated, which is expected to take two years.

The *Temperature Buffer Test* aims at improving the current understanding of the thermo-hydro-mechanical behaviour of buffers with a temperature around and above 100°C during the water saturation transient. The French organisation Andra is running this test in co-operation with SKB. Two heater probes are installed in one deposition hole in the same test area as the Canister Retrieval Test. The upper probe is surrounded by an ordinary bentonite buffer and the other probe has a ring of sand as a thermal protection between it and the bentonite buffer. The operation phase, including heating, artificial pressurised saturation of the buffer and monitoring of temperature, humidity, pressure and displacement started in March 2003. Monitoring and sampling of experimental data are continuously ongoing and the information is transferred via a data link to Andra's head office in France. The dense arrays of thermocouples enable the evaluation of thermal conductivity distribution, which in turn give an indication of the saturation process. The results indicate that the buffer around the upper heater was close to full saturation at the end of 2004. Such evaluations have confirmed that the conceptual description of these processes is basically correct.

The *Rock shear experiment* aims at observing 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. Such a displacement is considered to be caused by an earth-quake, and the test set-up needs to provide a shearing motion along the fracture that is equal to a shearing motion expected in real life. A feasibility study, which has been running since summer 2004, is finished and a preliminary experiment design has been made up based on a predicted test evolution. The predictions show that the effect of the rock shear is not detrimental for the canister after a rock shear of 200 mm.

The *Task Force on Engineered Barrier Systems* was put in a stand-by position in 2001. As the European Commission funding of the Prototype Repository project ceased in early 2004 it was judged most convenient to activate the Task Force and continue the modelling work in the Prototype Repository project within this frame, where modelling work on all other experiments also can be conducted. The Task Force was established in 2004 and a kick-off meeting was held in October. The Task Force starts with a first phase that comprised of four years. This phase addresses two tasks: (1) THM processes in buffer material, and (2) gas migration in buffer material. The focus is on the use of numerical codes for predicting the conditions in the buffer at specified milestones in the repository evolution.

Geo-science

Geo-scientific research is a basic activity at Äspö HRL. Studies are ongoing with the major aim of increasing the understanding of the rock mass properties and increasing the amount of information about measurements that can be used in site investigations.

A feasibility study to investigate the possible need for a new system for *Geological mapping and modelling* to be used in the deep repository has been started and will be performed during 2005. The major reasons for this investigation are aspects concerning time requirements, precision and traceability in mapping. The project name Rock Characterisation System (Rocs) has been accepted. The feasibility study is a joint project with Posiva and European experts participate in the scientific committee. The geological 3D-model of Äspö rock volume has been improved, mainly with local models of smaller rock volumes inside the Äspö volume. For example, a preliminary model of the KBS-3H rock volume has been established which will be improved during early 2005. In addition, the lithological terminology has been improved so that the names used in the Äspö and Oskarshamn site investigation are compatible.

Rock stress measurements with different measuring techniques have been performed over the years and numerical modelling of the stress has been performed. To be able to make correct assessments of the in situ stress field of results from different types of measurement it is important to know the limitations and shortcomings of the different techniques. Methods for transient strain analysis of stress measurements using an over-coring method for isotropic conditions have been developed and published. The method is used as a standard procedure in the ongoing site investigations in Sweden. A continuation of the project to investigate the possibility of transient strain analysis on anisotropic rock was agreed upon between Posiva and SKB late 2004.

The objective of the *Rock Creep Project* is to develop better conceptual models for the evaluation of the influences of the rock damaged zone and rock creep on rock stability in a tunnel. A literature study and scoping numerical modelling with a three-dimensional coupled hydromechanical computer code (3Dec) were performed already in 2003. The reporting of the results is in progress and will soon be published.

Äspö Pillar Stability Experiment was initiated to demonstrate the capability of predicting spalling in a fractured rock mass on the propagation of micro-cracks in the rock mass closest to the deposition hole. During 2003, a new drift was excavated to ensure that the experiment was carried out in a rock mass with a virgin stress field. Two vertical holes at a distance of one metre were drilled in the floor of the tunnel. The pillar between the two holes is heated to induce spalling. The major part of the field work has been accomplished, resulting in a large and interesting data set. The year began with the final preparatory work in the experiment volume before the heating and monitoring phase was initiated. In May the heaters were turned on which quickly initiated spalling in the pillar wall. The spalling progressed about five metres down the hole. The experiment was carried out as planned during 2004 which was a successful year for the experiment. During the autumn and winter the post characterisation programme was started and the monitored results began to be summarised.

The project on *Heat transport* aims at decreasing the uncertainties in the estimates of the temperature field in the repository. Less uncertain estimates of the temperature field around a repository makes it possible to optimise the distance between canisters in the repository layout. The heat evolution in the Prototype Repository has been used to analyse thermal properties of the rock and to verify prognoses. The present work to analyse uncertainties and the scale dependency in data on thermal rock properties will be evaluated and reported during the beginning of 2005.

Seismic influence on the groundwater system can be studied by analysing and comparing data in the Äspö HRL Hydro Monitoring System (HMS) database with other databases, e.g. SKB's site investigation database (Sicada) and the national seismological database. Data from 2004 has been stored in the HMS database pending analysis.

Natural barriers

At Äspö HRL, experiments are performed under the conditions that are expected to prevail at repository depth. The aim is to gain knowledge about the long-term function of the repository barriers. The bedrock with available fractures and fracture zones, its properties and the ongoing physical and chemical processes that affect the integrity of the engineered barriers and the transport of radionuclides, are denoted the natural barriers. The experiments are related to the rock, its properties, and in situ environmental conditions. The strategy for the ongoing experiments is to concentrate the effort on those experiments that are of importance for the site investigations. Tests of numerical 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 of evaluating the usefulness and reliability of different numerical models and to developing and testing methods for determination of parameters required as input to the 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 increase the understanding of the processes which govern retention of radionuclides transported in crystalline rock, and to increase the credibility of models used for radionuclide transport calculations. During 2004, work has been performed within two sub-projects; True Block Scale Continuation and True-1 Continuation.

The objectives of the *True Block Scale Continuation Project* are to improve the understanding of transport pathways at the block scale, including assessment of effects of geometry, macro-, and micro-structure. During 2004 in situ tracer tests were performed by establishing a radially converging flow field with a constant withdrawal rate in a selected sink section. The in situ efforts were paralleled by model predictions employing four different modelling approaches. A close scrutiny of the predictions compared with the experimental outcome show that most modelling teams provide equitable predictions of the least sorbing tracer, whereas differences become highly visible in the case of more sorbing tracers. Evaluation and reporting of the project will be made during 2005.

One of the principal objectives of the *True-1 Continuation Project* is to map the porosity of the earlier investigated Feature A at the True-1 site. Results from the True-1 Continuation project are available from the Fault Rock Zones Characterisation project and the Complementary laboratory tests of the sorption characteristics of fracture rim zone and fault gouge materials relative to the assembly of radioactive sorbing tracers employed in the True Programme. A planned injection of epoxy resin at the True-1 site will be preceded by complementary cross-hole hydraulic interference tests combined with tracer dilution tests. These tests are intended to shed light on the possible three-dimensional aspects of transport at the site.

The *Long Term Diffusion Experiment* constitutes a complement to diffusion and sorption experiments performed in the laboratory, and is a natural extension of the True-experiments. The difference is that the longer duration (approximately four years) of the experiment is expected to enable an improved understanding of diffusion and sorption in the vicinity of a natural fracture surface. The experiment will be performed in a core stub with a natural fracture surface isolated in the bottom of a large diameter telescoped borehole. The installation-test and pre-test programmes performed during 2004 showed that some modifications were necessary. The modifications are ongoing and the injections of radioactive tracers are planned for the first half of 2005. In addition, laboratory experiments, comprising radial diffusion and porosity measurements on core samples from the LTDE borehole, were initiated at AECL in Canada.

Radionuclide Retention Experiments are carried out with the aim of confirming results from laboratory experiments in situ, where conditions representative for the properties of groundwater at repository depth prevail. The experiments are carried out in special probes placed in boreholes. Radiolysis experiments, intended to investigate the influence of radiolysis on the migration of oxidised technetium, were performed with the Chemlab 1 probe. The field experiment and the evaluation of collected data are finished, and the final report will be printed in 2005. Migration of actinides in a natural rock fracture in a drill core is studied in the Chemlab 2 probe. The last field experiments of the actinide project, with the tracers uranium and technetium, started in 2004 and have been prolonged due to a somewhat unexpected increase in uranium concentration in the outlet solution. Two new experiments will be started in the Chemlab probes during 2005. Both of the experiments are still in the design phase. The radionuclide transport resistance at the buffer-rock interface will be studied in Chemlab 1 and experiments on spent fuel leaching under relevant repository conditions will be started in Chemlab 2.

The *Colloid Project* includes studies of the stability and mobility of colloids, measurements of the colloid concentration in the groundwater at Äspö, bentonite clay as a source for colloid generation, and the potential of colloids to enhance radionuclide transport. The laboratory experiments, background measurements and borehole specific measurements to measure the generation of colloids from bentonite will be compiled in a final report. The report is in progress and will be ready in spring 2005. The planning and preparation of dipole colloid experiments, which study the change in colloid content in the groundwater prior and after its transport through a natural fracture, has continued during 2004.

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 and are studied in the *Microbe Project*. The main activities during 2004 have been focused on bio-immobilisation of radionuclides, microbial effects on the chemical stability of the ground water, and microbial corrosion of copper. The radionuclide adsorption capacity of biofilms grown under in situ geological nuclear waste repository conditions is compared with the capacity of rocks from the same environment. The biofilms actually isolate the rock surface from the groundwater and diffusion to the rock surface must first proceed through the biofilms.

The numbers of microorganisms, their biomass and the metabolic diversity of the organisms in the Microbe 450-m circulations have been determined during 2004. The data suggest that microbial populations in deep groundwater at Äspö are stable and in a steady state with their deep aquifer environment. Copper corrosion from sulphide, produced by sulphate reducing bacteria in was monitored in bentonite compacted to different densities. Measured mean sulphide production decreased exponentially with increasing bentonite density when exposed to unfiltered groundwater.

The first phase of the *Matrix Fluid Chemistry* experiment (1998–2003) was published in 2004. The results from this phase gave information about matrix pore space fluids/groundwaters from crystalline rocks of low hydraulic conductivity, which complemented the hydrogeochemical studies already conducted at Äspö. The continuation phase focuses on the small-scale micro-fractures in the rock matrix which facilitate the migration of matrix waters and quantifying the hydraulic parameters of the host rock. The understanding of the migration of groundwater, and its changing chemistry, is important for repository performance. In 2004 a study to evaluate the potential impact of the tunnel excavation at the Äspö Pillar Stability Experiment site in the vicinity of the Matrix Fluid Experiment borehole was initiated. The scope of work for 2005 will very much depend on the impact of the tunnel excavation. If there is no significant impact, resampling of groundwaters and dissolved gases from borehole sections will be made followed by hydraulic testing of the sampled sections.

The activities at Äspö HRL include projects with the aim of evaluating the usefulness and reliability of different models and developing and testing methods for determination of parameters required as input to the models. An important part of this work is performed in the *Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes*. The work in the Task Force is closely tied to ongoing and planned experiments at the Äspö HRL. Specified tasks are defined where several modelling groups work on the same set of field data. The modelling results are then compared to the experimental outcome and evaluated by the Task Force delegates. The ongoing Task 6, Performance assessment modelling using site characterisation data, was initiated in 2001.

Padamot (Palaeohydrogeological Data Analysis and Model Testing) is an EC-project that includes developments of analytical techniques and modelling tools to interpret data, but also focusing research on specific processes that might link climate and groundwater in low permeability rocks. The term palaeohydrogeology is used as a common name for information from fracture minerals that is used for interpretations of past hydrogeochemical and hydrogeological systems. The EC-project was initiated in the beginning of 2002 and was finalised at the end of 2004. A continuation is being discussed.

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. The behaviour of trace component uptake can be obtained from natural material as well as through testing in the laboratory. The three year project on Fe-oxides started late autumn 2003 and a pilot study has been going on during 2004.

Äspö facility

An important part of the Äspö facility is the administration, operation, and maintenance of instruments as well as development of investigation methods. The availability of the underground-related systems (ventilation, hoist, lightning, pumps etc) has been more than 99% during 2004. Other tasks are to keep the stationary hydro monitoring system (HMS) continuously available and to carry out the programme for monitoring of groundwater head and flow and the programme for monitoring of groundwater chemistry.

International co-operation

Seven organisations from six countries have participated in the co-operation at Äspö HRL during 2004. One organisation, Ontario Power Generation of Canada, became a new participant, and one, Nagra, has left the central and active core of participants. Most of the participating organisations are interested in groundwater flow, radionuclide transport and rock characterisation. Several organisations are participating in the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes, which is a forum for co-operation in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock.

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 recourses available for national and international environmental research. SKB's economic engagement in the foundation was concluded in 2003 and the activities are now concentrated on the Äspö Research School. The School started in 2002 and is the result of an agreement between SKB and Kalmar University. The research activity focuses on biogeochemical systems, in particular on the identification and quantification of dispersion and transport mechanisms of contaminants (mainly metals) in and between soils, sediments, water, biota and upper crystalline bedrock. There are currently a variety of research activities at sites outside Äspö HRL.

Sammanfattning

Äspölaboratoriet är en viktig del i SKB:s arbete med utformning, byggande och drift av ett djupförvar för slutlig förvaring av använt kärnbränsle samt för utveckling och testning av metoder för karakterisering av en lämplig plats för ett djupförvar. Ett av de grundläggande skälen till SKB:s beslut att anlägga ett underjordslaboratorium var att skapa förutsättningar för forskning, utveckling och demonstration i en realistisk och ostörd bergmiljö på förvarsdjup. Underjordslaboratoriet utgörs av en tunnel från Simpevarpshalvön ner till södra delen av Äspö där tunneln fortsätter i en spiral ner till 460 m djup. Äspölaboratoriet har varit i drift sedan 1995 och verksamheten där, vilken leds av avdelningen förvarsteknik inom SKB, har väckt stort internationellt intresse. Forskningen är till stor del fokuserad på de processer som har betydelse för den långsiktiga säkerheten hos ett framtida djupförvar. Här följer en sammanfattning av det arbete som bedrivits vid Äspölaboratoriet under 2004.

Förvarsteknik

Verksamheten vid Äspölaboratoriet har som mål att demonstrera funktionen hos djupförvarets delar och visa att teknik finns för att bygga och driva ett djupförvar. 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 djupförvar. Det är viktigt att möjligheter 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.

Återtagsförsöket, ligger i försöksområdet på 420 m djup och syftar till att prova teknik för att återta kapslar efter det att den omgivande bentonitbufferten har vattenmättats. En fullstor kapsel med elektriska värmare, bentonitblock och bentonitpellets har installerats i ett vertikalt deponeringshål. Försöket har varit i drift i lite mer än fyra år och sensorer som mäter fukthalten indikerar att bentonitblocken som omger själva kapselröret är vattenmättade men inte bentonitblocken över och under kapseln. Uppmättnaden av bentonitblocken har gått långsammare och den är mer ojämn än förväntat. En rimlig förklaring är att de filtermattor som används för den konstgjorda bevätningen av bentoniten tidvis har satt igen. Under 2004 har vattentrycket i filtermattorna varit konstant, 850 kPa, och den tillförda effekten i kapseln har varit 1 600 W trots att endast 11 av de 36 värmeelement fungerar. Temperatur, spänning, mättnadsgrad och svällning i bentonitbufferten mäts och registreras fortlöpande.

I *Prototypförvaret* pågår en demonstration av den integrerade funktionen hos djupförvarets barriärer. Prototypförvaret utgör dessutom en fullskalig referens för prediktiv modellering av utvecklingen i förvarssystemet och dess delar. Den utförda inplaceringen av buffert, kapsel, återfyllning samt förslutning av deponeringstunneln i Prototypförvaret utgjorde en demonstration av tillgänglig teknik i full skala. Prototypförvaret omfattar totalt sex deponeringshål, fyra i en inre tunnelsektion och två i en yttre. Tunneln är återfylld med en blandning av krossat berg och bentonit. Den inre sektionen, med fyra kapslar, installerades under år 2001 och då startade moniteringen av viktiga processer. De två kapslarna i den yttre sektionen deponerades under 2003 och den slutliga injekteringen av den yttre pluggen i tunnelmynningen genomfördes i oktober 2004. I november stoppades dräneringen av tunnlarna vilket innebar att trycket ökade i buffert och tunnelåterfyllnad i de två sektionerna. Detta påverkade värmarna i kapslarna negativt och man beslutade att hålla tunneldränaget öppet. Mätningar visade att värmarna i kapsel 2 inte fungerar. Uppvärmningen av de övriga kapslarna påbörjades igen den 15 januari 2004. Tunneldränaget har hållits öppet under hela året. Vattenmättnadsgraden i bufferten är olika i de sex deponeringshålen beroende på att tillgången på vatten varierar. Även temperaturfördelningen i bufferten är olika i hålen huvudsakligen beroende på skillnaderna i mättnadsgrad. I ett så kallat ”torrt” hål är spalten mellan kapsel och buffert fortfarande fylld med luft vilket medför att temperaturen på kapselytan blir hög i jämförelse med ett ”vått” hål.

I *Återfyllningsförsöket* undersöker man den hydrauliska och mekaniska utvecklingen hos olika återfyllnadsmaterial. Försöket är också en demonstration av olika metoder för inplacering av återfyllnad och installation av tunnelförslutning. Försöket genomförs i en 28 m lång testsektion som ligger i Zedextunneln. Sektionens innersta del är återfylld med en blandning av krossat berg och bentonit medan den yttre delen är återfylld med krossat berg. Bevätning av återfyllnaderna har skett både naturligt från berget och konstgjort via permeabla mattor. Den startade i slutet av år 1999 och har pågått fram till och med hösten 2003 då flödestester startade. Dessa har pågått under hela 2004. Den hydrauliska konduktiviteten som utvärderats för blandning av krossat berg och bentonit från fältförsöken är något högre än den som utvärderats från laboratorieförsök. Mängden vatten som passerar pluggen och omgivande berg mäts och resultaten från dessa indikerar att utläckaget minskar sakta med tiden.

I *Lotförsöket* genomförs långtidsförsök av buffertmaterial som syftar till att validera modeller och hypoteser som beskriver buffertens fysikaliska egenskaper och processer relaterade till mikrobiologi, radionuklidtransport, kopparkorrosion och gastransport i ett djupförvar. Lotförsöket innebär att ”paket” som innehåller ett kopparrör med elektriskvärmare, kompakterad bentonit, instrumentering och kontrollutrustning placeras i 4 m djupa borrhåll med en diameter på 300 mm. Paketen sitter i borrhålen under ett eller fem år och därefter tas de upp och vattenmättnaden i bentoniten bestäms, kemiska och mineralogiska analyser genomförs och fysikaliska tester utförs. Två pilotförsök, som omfattat ett paket var, har avslutats och rapporterats. Från huvudförsöket har ett paket tagits upp, undersökts och rapporteringen pågår. De återstående fyra paketen har fungerat bra och vattentryck, total tryck, temperatur och mättnadsgrad mäts kontinuerligt. Trots att försöket pågått i nästan fem år fortsätter svälltrycket i bentoniten att öka i flera paket, vilket är ett tecken på att vattenuppmättnaden fortgår.

För att identifiera och demonstrera bästa möjliga tillgängliga teknik för *rensning och förslutning av undersökningsborrhål* genomförs ett projekt vid Äspölaboratoriet. Under projektets första fas gjordes en inventering av teknikutvecklingen inom område under de senaste 10–15 åren vilken sammanfattades i en statusrapport. Den andra fasen av projektet, som syftade till att utforma ett fullständigt referenskoncept för förslutning av borrhål, slutrapporterats under 2004. I det föreslagna konceptet består borrhålsförslutningen av perforerade kopparrör fyllda med kompakterade bentonitblock. Rören sammanfogas vid installationen i borrhålen. Planeringen av en fortsättning av projektet pågår, vilket ska omfatta fortsatta laboratoriestudier av kandidatmaterial för förslutning samt tester i fält. Vid Äspölaboratoriet har ett antal korta borrhål borrats och en maskin för automatisk tillverkning av perforerade kopparrör är under tillverkning.

I ett djupförvar kan det bli nödvändigt att använda cement och betong som ger lakvatten med pH $\leq$ 11. Två studier, med avseende på denna fråga, genomfördes under 2001 respektive 2002–2003. I den senare studien identifierades ett behov av att utveckla och prova *lågalkaliska injekteringsmaterial* för tätning av både större och mindre sprickor i berget. I juni 2003 initierade SKB, Posiva och Numo som består av fyra delprojekt:
(1) cementbaserade lågalkaliska injekteringsmaterial för tätning av större sprickor,
(2) ej cementbaserade lågalkaliska injekteringsmaterial för tätning av mindre sprickor,

(3) fältförsök i Finland och (4) fältförsök i Sverige. Fältförsöken i Sverige innebär att silica sol, en vattengel av kiselkolloider, injekteras i Äspölaboratoriet. Förberedelserna för detta startade i slutet av 2003 medan injektering och hydrauliska tester genomfördes under våren 2004. Delprojektet är avslutat och resultaten visar på en tätningseffekt på 70 % i den injekterade bergmassan.

Ett forskningsprogram för ett *KBS-3-förvar med horisontell deponering* (KBS-3H) genomförs som ett samarbetsprojekt mellan SKB och Posiva. I den genomförda förstudien drogs slutsatsen att KBS-3H-konceptet bör vidareutvecklas. Fortsatt utveckling av teknik för drivning av horisontella deponeringshål och inplacering/deponering av kapselpaket avslutades och avrapporterades under 2004. Bergarbeten 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 lågalkalisk cement och (2) ett långt hål (95 m) som huvudsakligen ska användas för demonstration av deponeringsutrustning men även för utvärdering av berguttagsmetod. I slutet av 2004 var det korta hålet färdigställt liksom ett pilothål för det långa deponeringshålet.

Syftet med ett *gasinjekterinsförsök i stor skala* är att studera gastransport i ett fullstort deponeringshål (KBS-3). Nuvarande kunskap om gastransportprocessen visar att bentonitbufferten kommer att släppa igenom gas innan skadligt höga gastryck utvecklas. Det finns dock stora osäkerheter i förståelsen av gastransportprocessen vilka behöver studeras i fullstor skala. Detta görs i Äspölaboratoriet där ett experiment genomförs i ett deponeringshål med en kapsel utan värmare och en omgivande bentonitbuffert. Installationsfasen var mer eller mindre avslutad i slutet av 2004 och deponering av kapsel och buffert förväntas kunna ske i början av 2005. Bufferten väts på konstgjord väg och gas kommer att tillsättas via munstycken i kapseln när bufferten är vattenmättad, vilket beräknas ta cirka två år.

Syftet med *TBT-försöket* är att förbättra förståelsen av buffertens termiska, hydrologiska och mekaniska utveckling under vattenmättnadsfasen vid temperaturer runt eller högre än 100°C. Den franska organisationen Andra ansvarar för experimentet vid Äspölaboratoriet vilket genomförs i samarbete med SKB. Två värmare har installerats ovanpå varandra i ett deponeringshål beläget bredvid återtagsförsöket. Den undre värmaren är omgiven av en bentonitbuffert medan den övre är omgiven av en buffert bestående av sand närmast värmaren och bentonit utanför sanden. Sanden är tänkt att fungera som ett termisktskydd mellan värmaren och bentoniten. Projektets driftfas som omfattar uppvärmning och konstgjord bevätning av bufferten samt övervakning och mätning av temperatur, fuktighet, tryck och rörelser startade i mars 2003. Övervakningen och insamlingen av data sker kontinuerligt och data överförs direkt till Andras huvudkontor i Frankrike. De termiska givarna i bufferten har placerats tätt vilket underlättar utvärdering av hur den termiska konduktiviteten utvecklas, vilken är en indikation på uppmättnadsförloppet. Mätningarna indikerade att bufferten runt den övre värmaren var nära vattenmättad i slutet av 2004. Utvärderingarna ger stöd för att den konceptuella beskrivning som gjorts för de processer som styr bevätningen i stort sett är riktiga.

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. Försöksinstallationen måste utformas så att en skjuvrörelse motsvarande den som kan uppkomma i en verklig spricka kan simuleras. I en avslutad förstudie, som initierades sommaren 2004, har en preliminär försöksutformning tagits fram vilken är baserad på predikteringar. Dessa visar att en skjuvrörelse på 200 mm inte skulle orsaka några skador på kapseln som innebär att dess isolerande förmåga hotas.

Ett internationellt samarbetsprojekt, *Task Force on Engineered Barrier Systems,* sattes i vänteläge år 2001. När Europeiska kommissionens finansiering av Prototypförvaret tog slut 2004 var det lämpligt att återuppta samarbetsprojektet för att kunna fortsätta modellering av Prototypförvaret och andra experiment. Ett uppstartsmöte hölls i oktober 2004. Den första fasen av projektet, som beräknas vara fyra år, omfattar huvudsakligen två områden: (1) THM-processer i buffertmaterial och (2) gasmigration i buffertmaterial. Projektet fokuserar på användandet av numeriska koder för att förutsäga förhållandena i bufferten under betydelsefulla skeden i förvarets utveckling.

Geovetenskap

Forskning inom geovetenskap är en viktig del av arbetet vid Äspölaboratoriet. Studier pågår med syfte att öka förståelsen för bergmassans egenskaper och öka kunskaperna om vilka mätmetoder som kan användas vid platsunderökningar.

En förstudie för att undersöka behovet av nya system för *Geologisk kartläggning och modellering* för djupförvaret har startat och kommer att gemomföras under 2005. De huvudsakliga motiven för denna utredning är att minska tidsåtgången samt att förbättra precision och spårbarhet vid kartläggning av berg. Förstudien, som har fått namnet Rocs (Rock Characterisation System), är ett samarbetsprojekt mellan SKB och Posiva där Europeiska experter deltar i en vetenskaplig kommitté. Den geologiska 3D-modellen av Äspös bergvolym har förbättrats, framförallt genom lokala modeller av mindre bergvolymer. En preliminär modell över bergvolymen för KBS-3H-försöket, vilken kommer att förbättras under 2005, har utvecklats. Dessutom har den litologiska terminologin fastställts så att namngivningen vid Äspölaboratoriet och platsunder-sökningen i Oskarshamn överensstämmer.

Mätning av bergspänningar har under årens lopp genomförts i fält med hjälp av olika mättekniker och bergspänningar har simulerats med numeriska modeller. För att kunna utvärdera fältmätningarna är det viktigt att ha god kunskap om de olika mätteknikernas begränsningar och brister. En ny metod för att genomföra transienta spänningsmätningar genom överborrning under isotropa förhållanden har utvecklats och publicerats. Metoden används som standard i de pågående platsundersökningarna i Sverige. I slutet av 2004 kom SKB och Posiva överens om ett fortsatt samarbete för att undersöka möjligheten att använda metoden på anisotropiskt berg.

Målet med projektet om *krypörelser i berget* är att utveckla en bättre konceptuell modell för utvärderingen av de effekter den störda zonen och bergkryp har på bergstabiliteten i en tunnel. En litteraturstudie och inledande modellering med en tredimensionell kopplad hydromekanisk datorkod (3DEC) genomfördes under 2003. Rapportering av resultaten från modelleringen pågår och de kommer inom kort att publiceras.

Syftet med *Pelarförsöket* är att undersöka möjligheterna att förutsäga spännings-inducerade bergbrott runt deponeringshål i sprickigt berg. Under 2003 drevs en ny tunnel för att säkerställa att experimentet genomförs i berg med jungfruliga spänningsfält. Två deponeringshål i full skala med ett avstånd av 1 m har borrats i golvet på tunneln så att en pelare bildas mellan dem. Pelaren utsätts för spänningar genom att bergmassa värms upp. Under början av 2004 genomfördes de sista förberedelserna innan uppvärmning- och moniteringsfasen inleddes. I maj slogs värmarna på vilket snabbt ledde till att små bergskivor släppte i pelarväggen. Spjälkbrotten fortsatte cirka fem meter ner i hålet. Experimentet genomfördes som planerat under 2004 och med stor framgång. Den största delen av fältarbetet är avslutat och har resulterat i en stor mängd intressanta data. Under hösten och vintern har efterkarakteriseringsprogrammet startat och sammanställning av moniterade data påbörjats.

Ett projekt som syftar till att minska osäkerheterna i de uppskattningar av *värmetransport* i berg och temperaturfältet runt ett djupförvar som görs pågår vid Äspölaboratoriet. Om osäkerheterna kan reduceras innebär det att avstånden mellan kapselpositioner kan optimeras. Värmeutvecklingen i Prototypförvaret har utnyttjats för att analysera bergets termiska egenskaper och för att verifiera gjorda prognoser. Pågående arbete med att analysera osäkerheterna och skalberoendet i termiska bergdata kommer att utvärderas och rapporteras i början av 2005.

Seismisk påverkan på grundvattensystem kan studeras genom att analysera och jämföra data insamlade i hydromoniteringssystemet HMS, som finns vid Äspölaboratoriet, med andra data så som SKB:s databas för platsundersökningar (Sicada) och den nationella seismologiska databasen. Under 2004 har data lagrats i HMS i väntan på analys.

Naturliga barriärer

I Äspölaboratoriet genomförs experimenten vid förhållanden som liknar de som förväntas i ett djupförvar. Experimenten kopplar till berget, dess egenskaper och in situ förhållanden. Målen med de pågående experimenten är att öka den vetenskapliga kunskapen om säkerhetsmarginalerna i djupförvaret och att ta fram data för funktions- och säkerhetsutvärderingar och därigenom tydligt förklara geosfärens roll och dess betydelse för barriärernas funktion: isolera, fördröja och bidra till utspädning. Ett viktigt syfte med verksamheten vid Äspölaboratoriet är att testa beräkningsmodeller för grundvattenströmning, radionuklidtransport och kemiska/biologiska processer. I programmet för testning av modeller ingår att utvärdera användbarheten av och tillförlitligheten hos de olika modellerna samt att utveckla och prova metoder för 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. Under 2004 har arbete bedrivits inom två delprojekt: ”True Block Scale Continuation” och ”True-1 Continuation”.

Målet med ”*True Block Scale Continuation*” är att öka kunskapen om transportvägar i blockskala i berget med avseende på bland annat betydelsen av geometri, macro- respektive mikrostrukturer. Under 2004 har spårämnesförsök genomförts i berget i ett radiellt flödesfält där avsänkningssektionen pumpades med konstant flöde. Fältförsöket har kompletterats med beräkningar där fyra modellgrupper har använt olika beräkningsmodeller. En jämförelse av resultat från modellgruppernas beräkningar och experimentet visar att transporten av lågsorberande spårämnen kunde predikteras bra medan skillnaderna var stora för de mer sorberande spårämnena. Utvärdering och rapportering av projektet kommer att ske under 2005.

Ett av målen med ”*True-1 Continutaion Project*” är att kartlägga porositeten i en tidigare undersökt sprickzon, ”Feature A”. De underlag som finns att tillgå omfattar resultat från ett tidigare genomfört delprojekt, ”Fault Rock Zone Characterisation”, och laboratorieförsök genomförda för att bestämma sorptionsegenskaperna hos sprickfyllnadsmaterial och sprickytor. Den planerade injekteringen av epoxyharts i en struktur kommer att föregås av hydrauliska interferenstester mellan två borrhål vilka kombineras med spårämnesförsök. Syftet med dessa tester är att belysa betydelsen av platsens tredimensionellitet för spårämnestransporten.

LTDE-försöken är ett komplement till de sorptions- och spårämnesförsök som genomförts i laboratoriet, det är också en utvidgning av de experiment som genomförts inom

True-programmet. Experimentet pågår under längre tid (omkring 4 år) och förväntas därför ge en bättre förståelse av diffusion och sorption på och i närheten av naturliga sprickytor. Experimentet genomförs i en borrhålskärna i botten av ett teleskopformat borrhål. De installations- och förtester som genomfördes under 2004 visade att vissa modifieringar av experimentet var nödvändiga. Modifieringsarbetet pågår och injicering av radioaktiva spårämnen planeras kunna äga rum under första halvåret 2005. Dessutom har laboratorieexperiment, som omfattar radiell diffusion och porositetsmätningar, på borrkärnor från LTDE-borrhålet initierats vid AECL i Kanada.

Fördröjning av radionuklider i geosfären studeras i *RNR-försöket*. Syftet med experimenten är att bekräfta resultat från tidigare laboratorieexperiment som genomförts vid förhållanden som liknar de som råder på förvarsdjup. Experimenten genomförs i borrhål med två specialutvecklade sonder. För att studera hur radiolysprodukter påverkar rörligheten hos teknetium har experiment genomförts i Chemlab 1. Fältexperimenten och utvärderingen av insamlade data har avslutats och slutrapporten kommer att tryckas under 2005. Migration av aktinider i naturliga sprickor i borrkärnor studeras i Chemlab 2. Det sista fältförsöket med spårämnena uran och teknetium startade 2004. Tiden för experimentet har förlängts då oväntat höga halter av uran uppmätts i utgående lösning. Två nya experiment som för närvarande är i en utformningsfas beräknas starta 2005. Transportmotståndet för radionuklider i gränsytan mellan bentonitbuffert och berg ska studeras i Chemlab 1 och i Chemlab 2 ska lakningsförsök på använt kärnbränsle under förvarsförhållanden genomföras.

Kolloidprojektet omfattar studier av kolloiders stabilitet och rörlighet, mätning av kolloidkoncentrationen i grundvattnen på Äspö, studier av bentonitens betydelse som källa för bildandet av kolloider samt studier av risken för att radionuklider transporteras med kolloider. Den slutliga rapporteringen av genomförda laboratorieexperiment, mätningar av bakgrundshalter av kolloider i grundvattnet och de senaste mätningarna av kolloidbildning från bentonit gjorda i borrhål pågår. Under 2004 har planering och förberedelser gjorts för nya kolloidexperiment. I dessa så kallade dipolförsök ska kolloidkoncentrationen i grundvatten studeras före respektive efter passage genom en naturlig spricka.

Mikroorganismer samverkar med sin omgivning och kan i vissa fall ge stor påverkan på förhållandena där. Sådan samverkan kan ha betydande påverkan på funktionen hos ett framtida djupförvar och detta studeras i *Mikrobprojektet.* De huvudsakliga aktiviteterna under 2004 har varit bio-immobilisering av radionuklider, mikrobiell påverkan på den kemiska stabiliteten hos grundvattnet samt mikrobiell korrosion av koppar. Kapaciteten hos biofilmer som växt under in situ geologiska förhållanden att adsorbera radionuklider jämförs med kapaciteten hos berg från samma miljö. Det visar sig att biofilmen isolerar bergytan från grundvattnet och nukliderna måste diffundera genom biofilmen innan de adsorberar på bergytan. Antalet mikroorganismer, deras biomassa och skillnader i metabolism hos organismer i det installerade cirkulationssystemet för grundvatten på 450-m nivån har undersökts under 2004. Data indikerar att de mikrobiella populationerna i de djupa grundvattnen i Äspölaboratoriet är stabila och anpassade till miljön på detta djup. Sulfidjoner, som bildas av sulfatreducerande bakterier i bentonit, orsakar korrosion av koppar. Omfattningen av kopparkorrosionen har moniterats på kopparbitar som ligger inbäddade i bentonit med olika densiteter. Den uppmätta sulfidkoncentrationen i bentonit som utsätts för ofiltrerat grundvatten minskar exponentiellt med ökande densitet.

Den första fasen av *Matrisförsöket* (1998–2003), som har givit ökad kunskap om matrisvattnet i kristallint berg med låg hydraulisk konduktivitet, publicerades under 2004. Detta utgör ett viktigt komplement till tidigare hydrogeokemiska studier som genomförts vid Äspölaboratoriet. Grundvattnets transport och dess kemiska förändringar är av betydelse för förvarets funktion och förståelsen av dessa är viktig. Nästa fas av projektet kommer att fokusera på hur småskaliga mikrosprickor i berget bidrar till rörelsen av matrisvatten och att kvantifiera bergets hydrauliska parametrar. En utvärdering av hur tunnelarbeten i närheten av matrisförsöket har påverkat grundvattnet i matrisborrhålet initierades 2004. Resultatet av denna utvärdering har betydelse för omfattningen av arbetet inom Matrisförsöket under 2005. Visar det sig att påverkan har varit obetydlig kommer provtagning av grundvatten och lösta gaser i borrhålssektioner att genomföras liksom hydraulisk provtagning av de aktuella sektionerna.

Aktiviteterna vid Äspölaboratoriet omfattar projekt med syfte att utvärdera användbarheten och tillförlitligheten hos olika beräkningsmodeller samt 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. Flera internationella modelleringsgrupper arbetar med definierade uppgifter och använder samma fältdata. För närvarande bedrivs arbetet huvudsakligen inom ”Task 6” som initierades redan 2001. ”Task 6” omfattar modellering med både med beräkningsmodeller som används för att göra säkerhetsanalyser och med modeller som används för platskarakterisering. Under 2004 har två internationella möten ägt rum där resultaten från modelleringsarbetet har presenterats och diskuterats.

Projektet *Padamot* är ett EU-projekt som omfattar utveckling av analysteknik och modelleringsverktyg för att utvärdera palaeohydrogeologiska data. Palaeohydrogeology är en benämning som används för att beskriva den information om förflutna hydrogeokemiska och hydrogeologiska system som erhålls vid utvärdering av sprickfyllnadsmaterial. Inom projektet bedrivs dessutom forskning med syfte att undersöka de specifika processer som beskriver hur klimatet påverkar grundvattenkemin i berg med låg permeabilitet. EU-projektet initierades i början av 2002 och avslutades i slutet av 2004. För närvarande diskuteras möjligheterna att starta ett fortsättningsprojekt.

I projektet *Järnoxider i sprickor* undersöks järnoxidbeklädda sprickytor för att utvärdera lämpliga palaeoindikatorer och beskriva deras bildningsförhållande. Upptaget av spårämnen kan erhållas både från mätningar på naturliga material och från laboratoriestudier. Projektet, som ska pågå under tre år, startade sent 2003 och under 2004 har en förstudie pågått.

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. Driften av anläggningen under 2004 har fungerat programenligt och tillgängligheten på servicerelaterade system i anläggningen och underjordslaboratoriet har varit mer än 99 %. Andra aktiviteter är underhåll av det stationära hydromonoteringssystemet (HMS) för att det ska vara kontinuerligt tillgängligt, att genomföra programmen för mätning av grundvattentryck och -flöden samt programmet för grundvattenkemi.

Internationellt samarbete

Under 2004 har sju organisationer från sex länder deltagit i det internationella samarbetet vid Äspölaboratoriet förutom SKB. Den kanadensiska organisationen OPG blev ny medlem och den schweiziska organisationen Nagra lämnade den aktiva och centrala gruppen av deltagare under året. Flertalet av de deltagande organisationerna är intresserade av grundvattenströmning, radionuklidtransport och karaktärisering av berg. Flera av organisationerna deltar både i det experimentella arbetet vid Äspölaboratoriet och i modelleringsarbetet inom ”Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes”.

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. SKB:s ekonomiska engagemang i Miljöforskningsstiftelsen avslutades under 2003 och ansträngningarna fokuseras nu i stället till Äspö forskarskola. Skolan grundades år 2002 och är ett resultat av en överenskommelse mellan SKB och Kalmar universitet. Forskningen fokuserat på biokemiska system, särskilt identifiering och kvantifiering av spridnings- och transportmekanismer för föroreningar (huvudsakligen metaller) i och mellan mark, sediment, vatten, biota och den övre kristallina berggrunden. För närvarande pågår en mängd aktiviteter dock mestadels utanför Äspölaboratoriet.

Contents

1 General

1.1 Background

The Äspö Hard Rock Laboratory (HRL), in the Simpevarp area in the municipality of Oskarshamn, constitutes an important part of SKB's work to design and construct a deep geological repository for spent nuclear fuel and to develop and test methods for characterisation of a suitable site. One of the fundamental reasons behind SKB's decision to construct an underground laboratory was to create an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to repository depth. Most of the research is focused on processes of importance for the long-term safety of a future deep repository and the capability to model the processes taking place. Demonstration addresses the performance of the engineered barriers, and practical means of constructing and operating a repository for 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 last 400 m have been excavated by a tunnel boring machine (TBM) with a diameter of 5 m. The first part of the tunnel has been excavated by conventional drill and blast technique. The underground tunnel is connected to the ground surface through a hoist shaft and two ventilation shafts. On the ground surface office buildings, factories, and laboratories supporting the underground activities are located.

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 and the construction of the Äspö Research Village were completed.

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

1.2 Goals

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

1. *Verify pre-investigation methods*. Demonstrate that investigations on the ground surface and in boreholes provide sufficient data on essential safety-related properties of the rock at repository level.
2. *Finalise detailed investigation methodology.* Refine and verify the methods and the technology needed for characterisation of the rock in the detailed site investigations.
3. *Test models for description of the barrier functions at natural conditions*. Further develop and at repository depth test methods and models for description of groundwater flow, radionuclide migration, and chemical conditions during operation of a repository and after closure.
4. *Demonstrate technology for and function of important parts of the repository system.* Test, investigate and demonstrate on full-scale different components of importance for the long-term safety of a deep repository and to show that high quality can be achieved in design, construction, and operation of repository components.

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

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

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

- Provide information to the general public on technology and methods that are being developed for the deep repository.

1.3 Organisation

SKB's work is organised into five departments: Technology, Site Investigation, 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.

Repository Technology (TD), one of five units organised under the Technology department is responsible for development and testing of deep repository technology and in situ research on repository barriers at natural conditions. The unit is also responsible for the operation of the Äspö facility and the co-ordination of the research performed in international co-operation. The Repository Technology unit was during 2004 organised in three operative groups, see Figure 1-2:

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

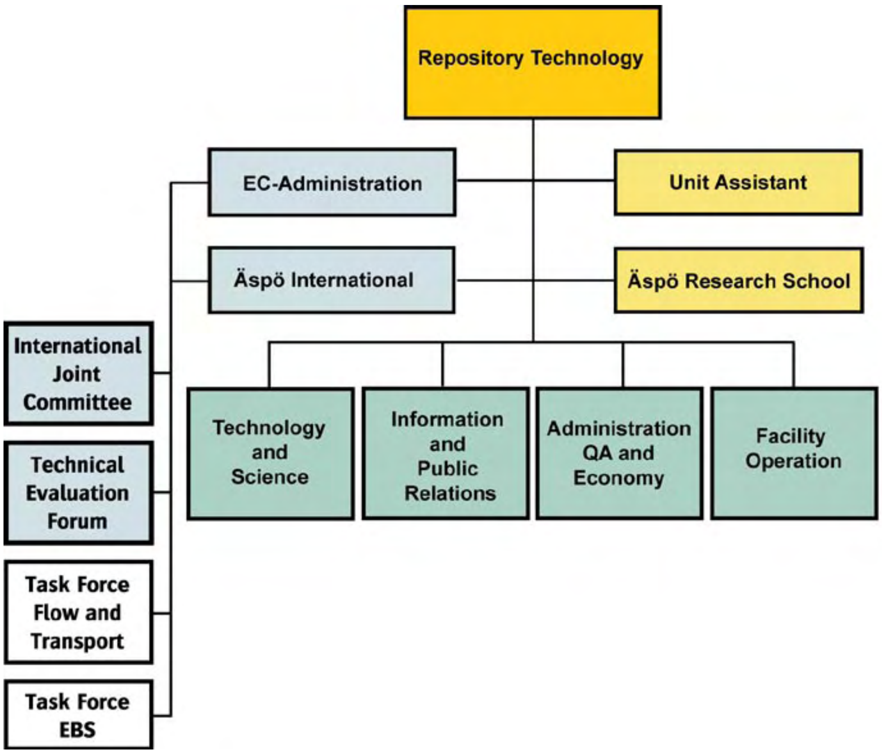


Figure 1-2. *Organisation of Repository Technology and Äspö HRL during 2004.*

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

1.4 International participation in Äspö HRL

The Äspö HRL has so far attracted considerable international interest. Seven organisations from six countries participated during 2004 in the Äspö HRL in addition to SKB. The participating organisations were:

- Agence Nationale pour la Gestion des Déchets Radioactifs (Andra), France.
- Bundesministerium für Wirtschaft und Arbeit (BMWA), Germany.
- Central Research Institute of Electric Power Industry (CRIEPI), Japan.
- Empresa Nacional de Residuos Radiactivos (Enresa), Spain.
- Japan Nuclear Cycle Development Institute (JNC), Japan.
- Ontario Power Generation Inc. (OPG), Canada.
- Posiva Oy, Finland.

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

Specific technical groups, so called Task Forces, are another form of organising the international work. A Task Force on Groundwater Flow and Transport of Solutes in fractured rock has been working since 1992 and a Task Force on Engineered Barrier Systems has been on stand-by but was activated during 2004.

Some EC projects have been co-ordinated by the Director of Repository Technology and administrated by the Repository Technology staff. Examples are EC projects concerning the Prototype Repository that have a direct coupling to the test set-up at Äspö and the CROP project that is coupled to experiments carried out in the Äspö HRL. The EC projects were in the stage of finalisation in the end of 2004. However, the continued operation of the Prototype Repository is funded by SKB.

1.5 Allocation of experimental sites

The rock volume and the available underground excavations have to be divided between the experiments performed at the Äspö HRL. It is essential that the experimental sites are allocated so that interference between different experiments is minimised. The allocation of experimental sites within the Äspö HRL is shown in Figure 1-3.

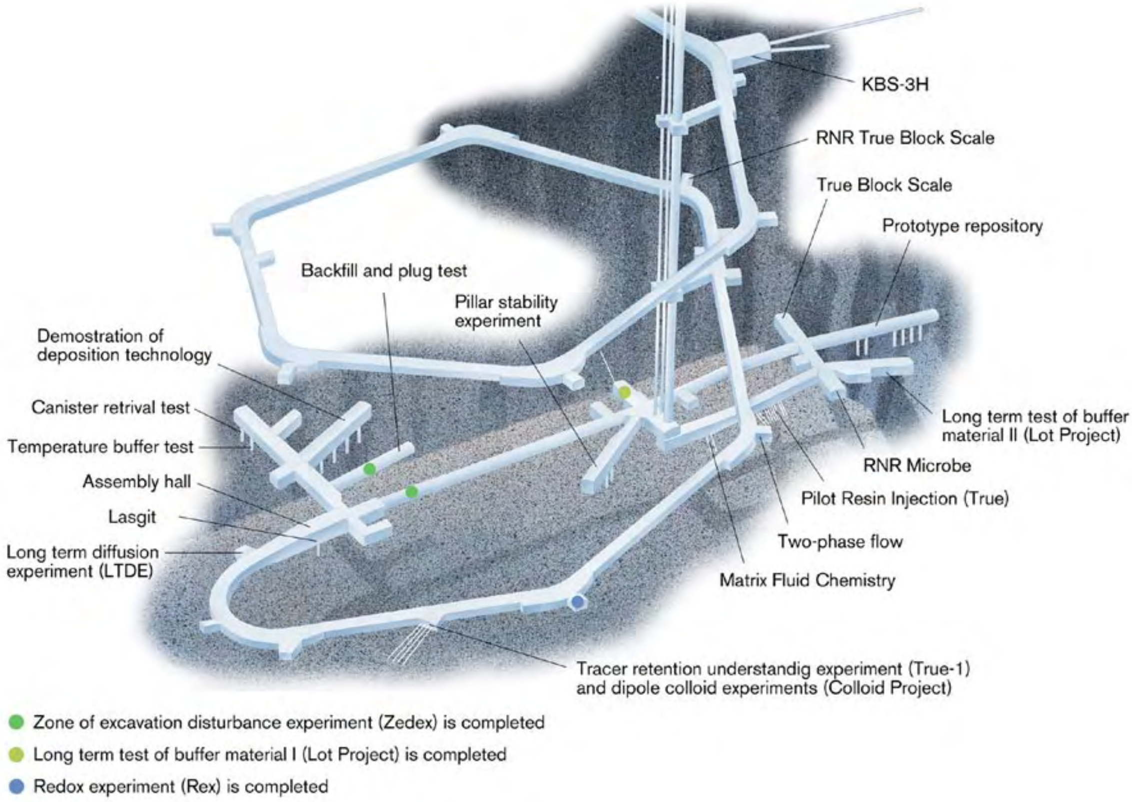


Figure 1-3. *Allocation of experimental sites from –220 m to –450 m level.*

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 2002–2007 are presented in SKB's RD&D-Programme 2001. The information given in the RD&D-Programme related to Äspö HRL is detailed in the Äspö HRL Planning Report /SKB, 2004/ 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 four times a year. The current report describes the achievements during 2004.

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	Director Repository Technology	SKB
Planning Reports – Detailed plans covering each calendar year	Contributors	Director Repository Technology
Annual Reports – Summary of work covering each calendar year	Contributors	Director Repository Technology
Status Reports – Short summary of work covering each 3 month period	Principal Investigators or Project Managers	Director Repository Technology
Technical Reports (TR)	Project Manager	Director Repository Technology
International Progress Reports (IPR)	Project Manager	Director Repository Technology
Internal Technical Documents (ITD)	Case-by-case	Project Manager
Technical Documents (TD)	Case-by-case	Project Manager

1.7 Management system

SKB is since 2001 certified according to the Environmental Management System ISO 14001 and also to the Quality Management Standard ISO 9001, and since 2003 also 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 document for issues related to management, quality and environment are written as routines. The documentation can be accessed via SKB's Intranet, where policies, common routines for SKB as well as specific routines for Äspö HRL can be found.

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

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

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

- Safety.
- Efficiency.
- Sensitivity.

Project Model

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

Environmental management

SKB 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 ongoing operations and activities on the environment. This environmental work is goal-oriented and the progress versus goals is assessed each 3rd 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 2004 is described in six chapters in this report:

- Technology – demonstration of technology for and function of important parts of the repository system.
- 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.
- Äspö facility – operation, maintenance, data management, and monitoring etc.
- International co-operation.
- Environmental research.

2 Technology

2.1 General

To meet stage goal 4, to demonstrate technology for and function of important parts of the repository 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 real repository.

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

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 emplacement, backfilling, sealing, plugging, monitoring and canister retrieval.
- Integrate these methods and procedures into a disposal sequence, which can be demonstrated to meet quality requirements in relation to relevant standards, as well as practicality.

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

The main experiments that are installed in Äspö HRL are:

- Canister Retrieval Test.
- Prototype Repository.
- Backfill and Plug Test.
- Long Term Test of Buffer Material.
- KBS-3 Method with Horizontal Emplacement.
- Large Scale Gas Injection Test.
- Temperature Buffer Test.

2.2 Canister Retrieval

2.2.1 Background

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

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.

2.2.2 Objectives

The overall aim of the Canister Retrieval Test is to demonstrate to specialists and to the public that retrieval of canisters is technically feasible during any phase of operation. 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 concern also other tests in the Äspö HRL. In addition to the retrieval test, the results of monitoring and laboratory testing of parts of the buffer will be used to increase the understanding of the THM processes in a deposition hole.

2.2.3 Experimental concept

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

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

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

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

The buffer was installed in the form of blocks of highly compacted Na-bentonite, with a full diameter of 1.65 m and a nominal height of 0.5 m. Instruments for measuring temperature, relative humidity, total pressure, and pore pressure were installed in many of the bentonite 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 one metre from the tunnel floor. On top the hole was sealed with a plug made of concrete and a steel plate as cover. The plug was secured against heave caused by the swelling clay with 9 cables anchored to the rock. The tunnel will be left open for access and inspections of the plug support. The experimental set-up is shown in Figure 2-1.

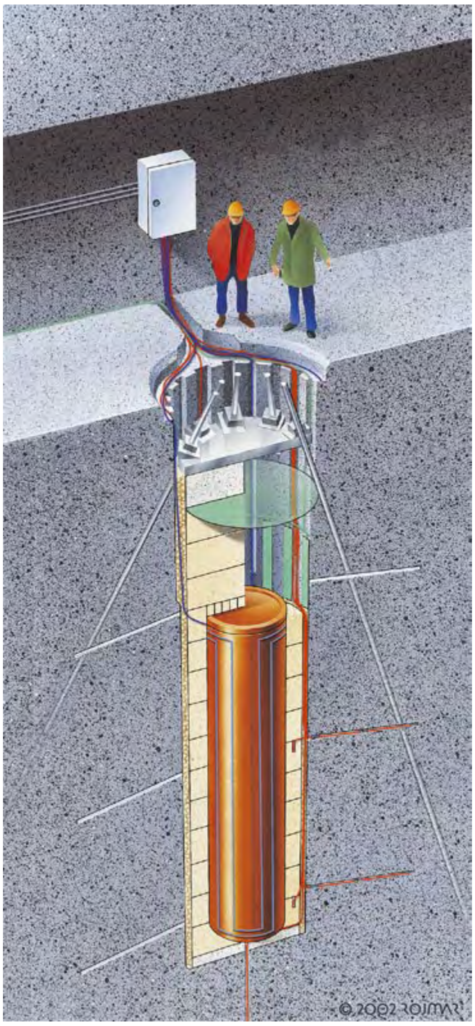


Figure 2-1. Illustration of the experimental set-up of the Canister Retrieval Test.

Artificial addition of water is 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 is 2–3 years in the 350 mm thick buffer along the canister and 5–10 years in the buffer below and above the canister. Decision on when to start the retrieval tests is dependent on the degree of saturation in the buffer. The instrumentation in the buffer is similar to the instrumentation in the Prototype Repository and yield comparable information during the saturation period.

2.2.4 Results

Status

The installation of the buffer material and the canister with instrumentation and heaters started mid September 2000 and was completed during October 2000 including the in situ casting of the concrete plug on top of the bentonite buffer. The heaters were turned on and the artificial watering of the buffer started in October 2000. The test has thus been running for a little more than 4 years with continuous measurement of the wetting process, temperature, stresses and strains. The general conclusion is that the measuring systems and transducers seem to work well with exception of several relative humidity sensors that have failed due to water saturation and the sensors inside the canister, which all have failed. Data reports are produced twice a year.

The relative humidity sensors indicate that the bentonite between the rock and the canister is close to water saturation although the wetting seems to be somewhat uneven and the total pressure has not reached the expected values yet. Some clogging of the filters may explain the inhomogeneous appearance. However, back flushing of the mats is done regularly in order to avoid clogging.

In order to increase the rate of saturation the water pressure in the mats was increased in steps to 800 kPa during the autumn 2002 and in order to reduce the risk of heater failure the power of the canister was reduced from 2,600 to 2,100 W in September 2002 In December 2003 the power was further reduced to 1,600 W.

During 2004 the water pressure in the mats has been kept constant at 850 kPa and the power at 1600 W. Power failure occurred in September, October and November. At the end of the year only 11 of 36 heater elements were still working.

Measurements

A large number of parameters are measured during the test to provide a basis for modelling purposes. Two data reports covering the period up to 2004-05-01 /Goudarzi et al. 2004a/ and the period up to 2004-11-01 /Goudarzi et al. 2004b/ have been released. Table 2-1 shows the parameters that are measured. Selected characteristic values from 2000-10-26 until 2004-12-30 are shown in the figures below. Figure 2-2 and Figure 2-3 show the total pressure and the relative humidity in the buffer in different horizontal planes. Figure 2-4 shows the anchor forces. The forces were measured in three of the nine anchors and the forces are multiplied by three in the figure in order to reflect the total forces.

The relative humidity sensors indicate that the bentonite between the rock and the canister is water saturated but not the bentonite above and below the canister. The wetting was in the beginning a little slower and more inhomogeneous than predicted. Entrapped air and clogging of the filters may explain the appearance. The filters have been flushed regularly since 2002 in order to avoid such effects.

Table 2-1. Measurements in Canister Retrieval Test.

Type of measurement	Number of sensors	Comments
Temperature inside canister.	18	
Temperature on canister surface	4 loops of optic cables	
Temperature in the buffer	32 (+in many sensors)	
Temperature in the rock	40	
Rock stress + strain	8 + 9	
Total pressure in buffer	27	Example in Figure 2-2
Pore pressure in buffer	14	
Relative humidity in buffer pores	55	Example in Figure 2-3
Heater effect	1	
Artificial watering volume	1	
Artificial watering pressure	1	
Vertical displacement of plug (mm)	3	
Forces in rock anchors (kN)	3	Example in Figure 2-4

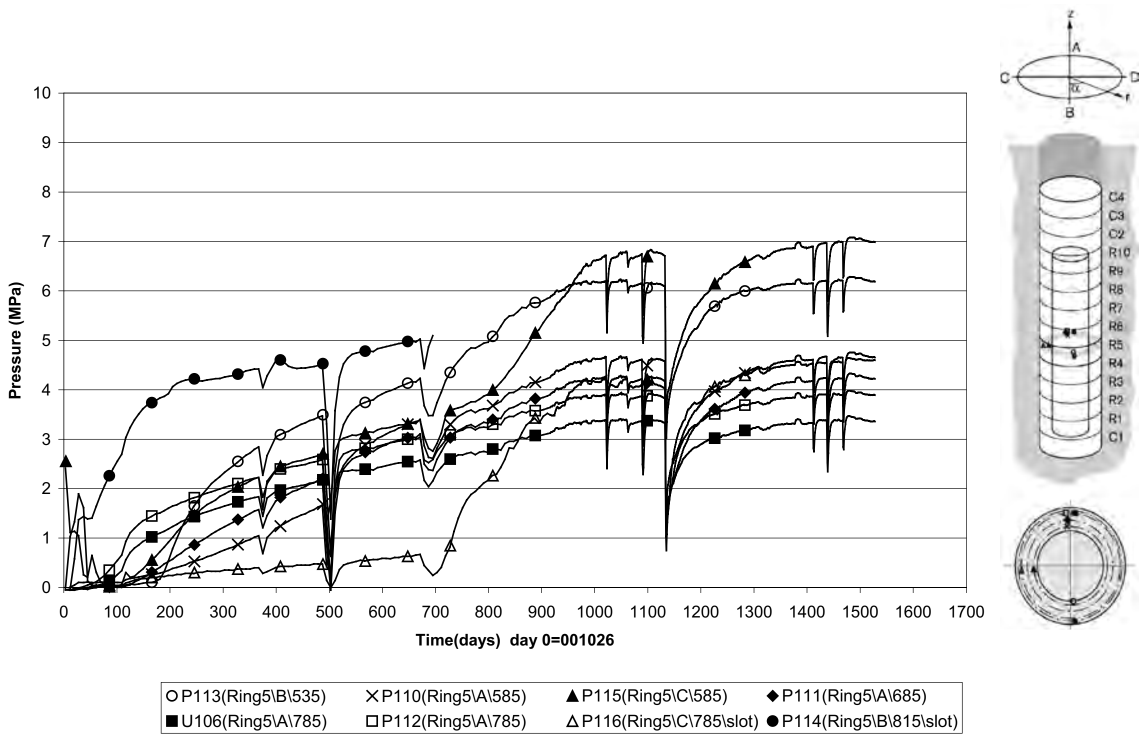


Figure 2-2. *Measured total pressure in the buffer in a horizontal plane located in the centre of the canister (Ring 5, 2000-10-26 to 2005-01-01).*

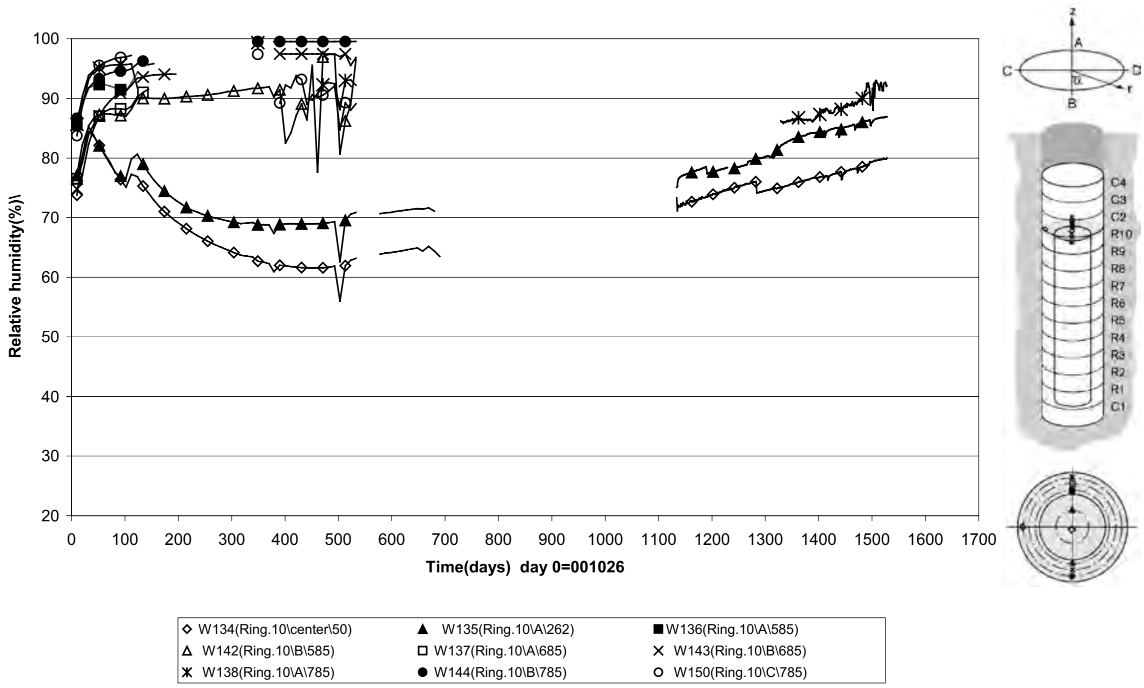


Figure 2-3. *Measured relative humidity in the buffer in a horizontal plane located about 10 cm above the canister (Ring 10, 2000-10-26 to 2005-01-01).*

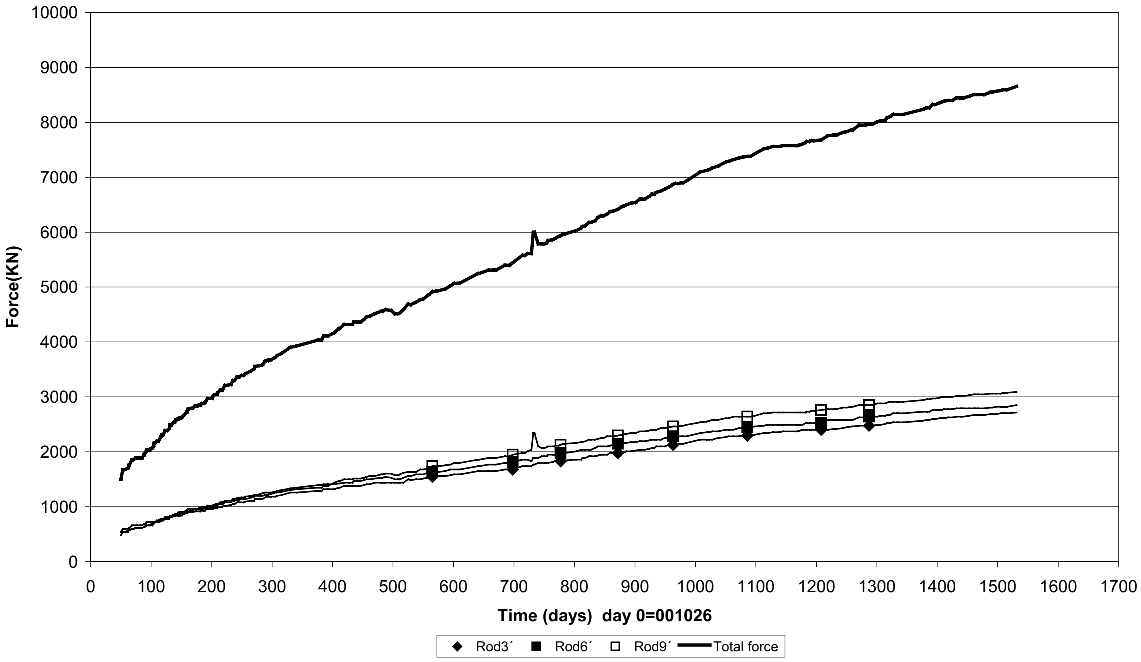


__Figure 2-4.__ Measured anchor forces (multiplied by 3) on the plug in three of the nine anchors. The solid line is the total force in all nine anchors (2000-10-26 to 2005-01-01).

The swelling pressure and the forces on the anchors are somewhat lower than predicted. The reason is not clear but an early displacement of the bentonite blocks (before the plug was anchored) may have decreased the density. Sampling at excavation will hopefully explain the behaviour.

2.3 Prototype Repository

2.3.1 Background

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

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

The Prototype Repository has been co-funded by the European Commission with SKB as co-ordinator. The EC project started in September 2000 and was concluded in February 2004.

2.3.2 Objectives

The main objectives for the Prototype Repository are to:

- Test and demonstrate the integrated function of the deep repository components under realistic conditions in full-scale and to compare results with 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.

2.3.3 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 2-5. 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 will in practice provide two more or less independent test sections. Canisters with dimension and weight according to the current plans for the deep repository and with heaters to simulate the thermal energy output from the waste are positioned in the holes and surrounded by bentonite buffer. The deposition holes are with a centre distance of 6 m. This distance is evaluated considering the thermal diffusivity of the rock mass and the 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, and results successively gained. It is envisaged that the outer test section will be decommissioned after approximately five years to obtain interim data on buffer and backfill performance. Instrumentation 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.

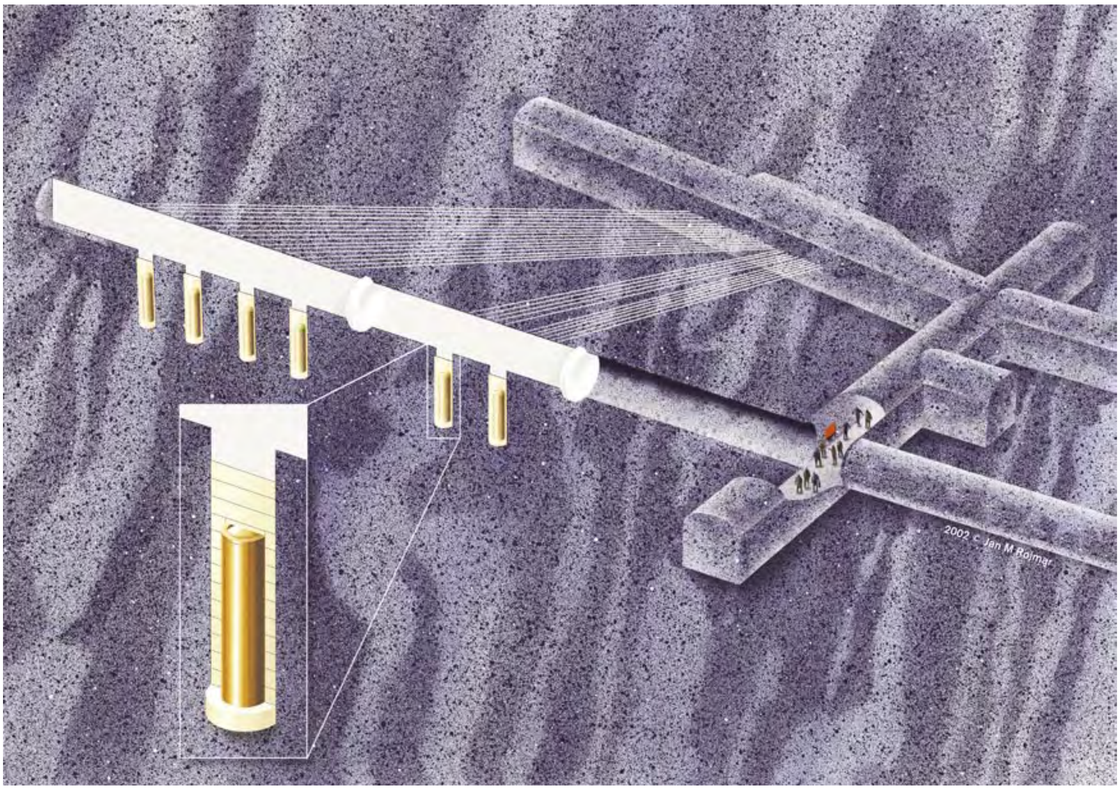


Figure 2-5. *Schematic view of the layout of the Prototype Repository (not to scale).*

2.3.4 Results

The installation of Section I was done during summer and autumn 2001. The heating of the canister in hole1 started with an applied constant power of 1,800 W at September 17, 2001. This date is also marked as start date. The backfilling started in September and was finished in November and the plug was cast in December that year. 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 holes 1–4 was decreased with about 30 W to 1,710 W.

The installation of Section II 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 on May 8, 2003. This date is also marked as start date. The backfilling started in April and was finished in June and the plug was cast in September. In the beginning of September 2004 the power in holes 5 and 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 November 2004 the drainage of the inner part of Section I and the drainage trough the outer plug were closed. This affected both the total and pore pressures 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 2-6. The maximum pressures were recorded around January 1, 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, also damages on canister 6 were observed. The drainage of the tunnel was then opened again. During the next week further investigations on 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 on January 15, 2004. The drainage of the tunnel has been kept open during 2004.

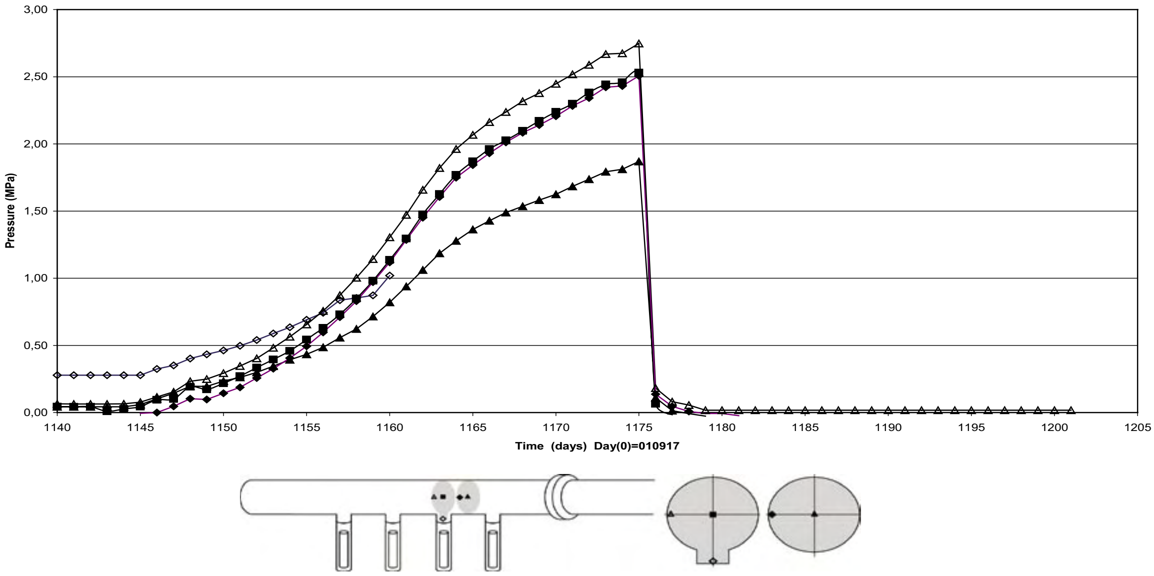


Figure 2-6. *Measured total pressure in the backfill around deposition hole 3 (2004-11-01 to 2005-01-01).*

In the following sections performed measurements are presented. In Chapter 6 additional work performed by participating organisations i.e. measurements, evaluations of data, and modelling are presented.

Measurements in rock, backfill and buffer

Altogether more than 1,000 transducers were installed in the rock, buffer and backfill /Collin and Börgesson, 2002; Börgesson and Sandén, 2002; Rhén et al. 2003/. The transducers measure the temperature, the pore pressure and the total pressure in different part 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.

Furthermore transducers were installed for recording the displacement of the canisters in 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 out come 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 with 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 also ongoing /Rhén et al. 2003/. The measurements are made in boreholes which are divided into sections with packers. In connection with 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 by 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 samples and tests have already 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 November 1, 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.

Hole 1 can be considered a "wet" deposition hole while hole 3 is very "dry". In Figure 2-7 to Figure 2-10 measurements of relative humidity (RH) and total pressure in the two deposition holes are plotted as 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 (bentonite block R5). The measurements in hole 1 indicate a rapid increase both in total pressure and relative humidity. The RH-transducers have at the end of the measuring period 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 of the still working transducers are at the end of the measuring period (December 4, 2004) 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 the same level as before the closure of the drainage. Corresponding measurements in 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.

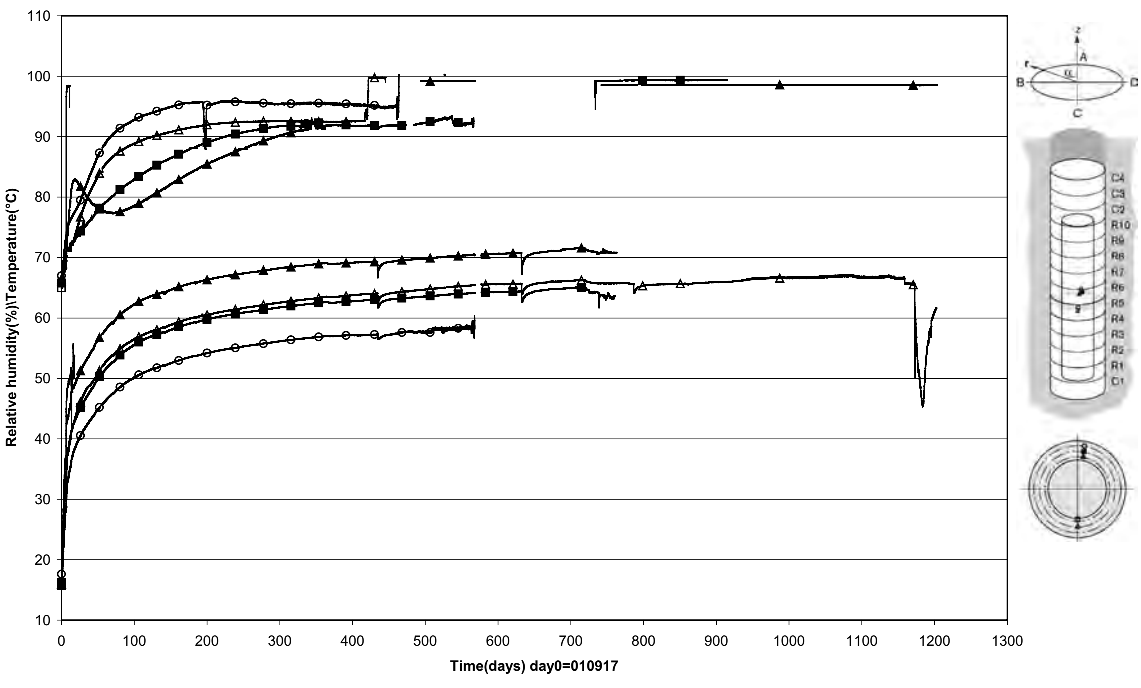


***Figure 2-7.** Measured relative humidity (the lower curves are temperature measurements made with the RH sensors) in deposition hole 1 (Ring 5, 2001-09-17 to 2005-01-01).*

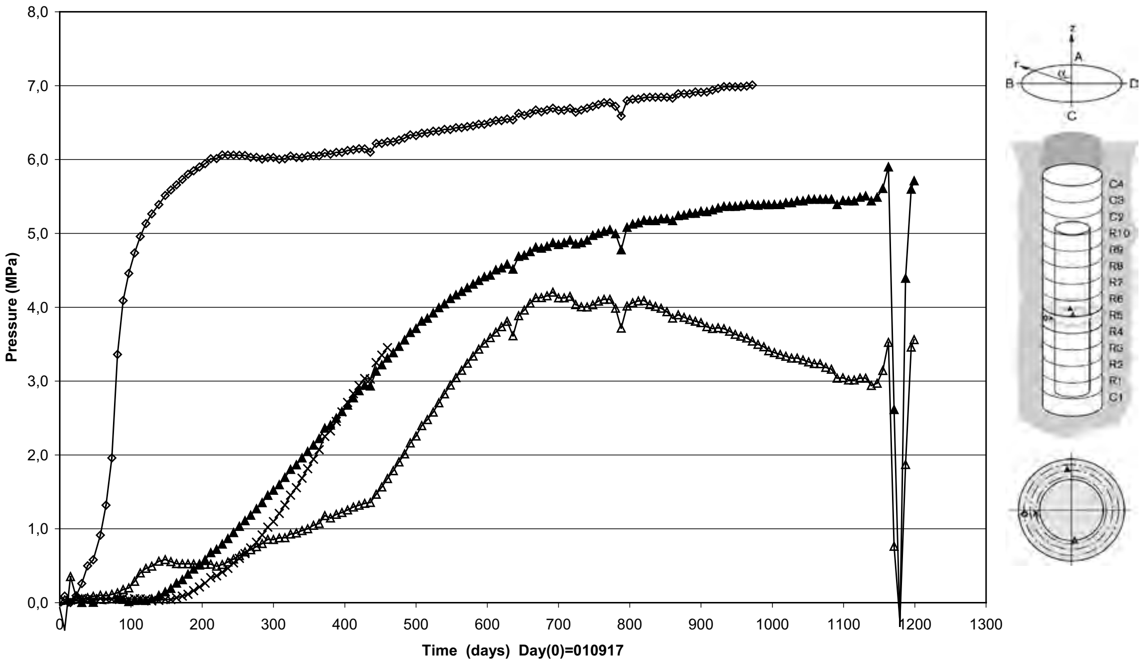


Figure 2-8. *Measured total pressure in deposition hole 1 (Ring 5, 2001-09-17 to 2005-01-01).*

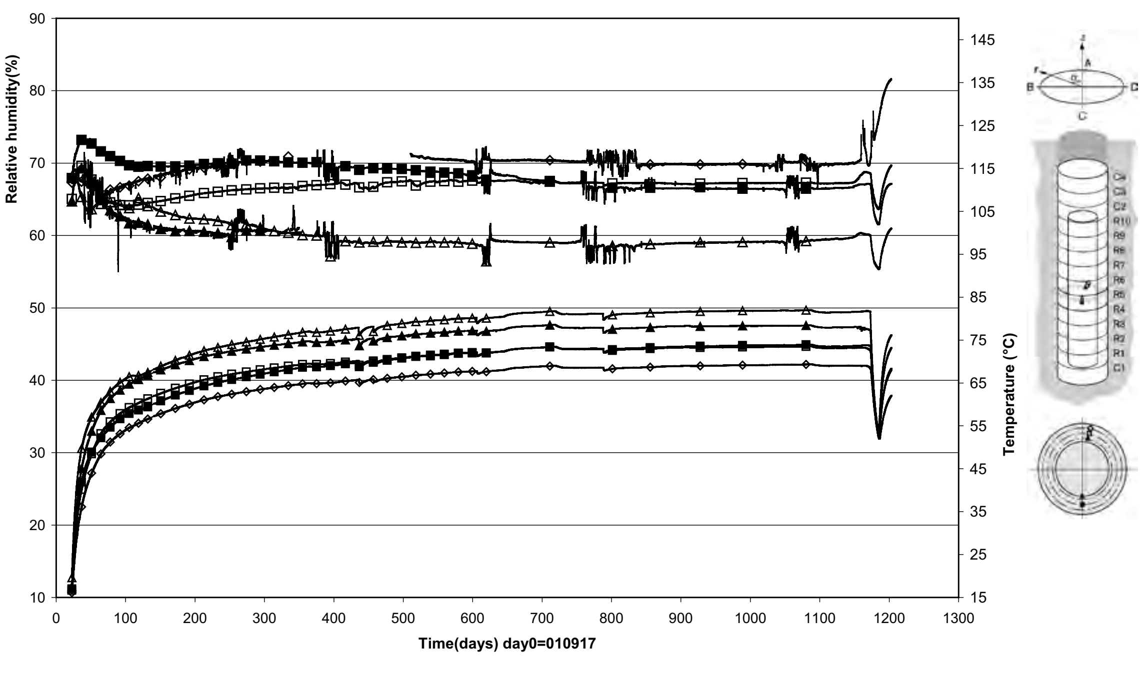


Figure 2-9. *Measured relative humidity (the lower curves are temperature measurements made with the RH sensors) deposition hole 3 (Ring 5, 2001-09-17 to 2005-01-01).*

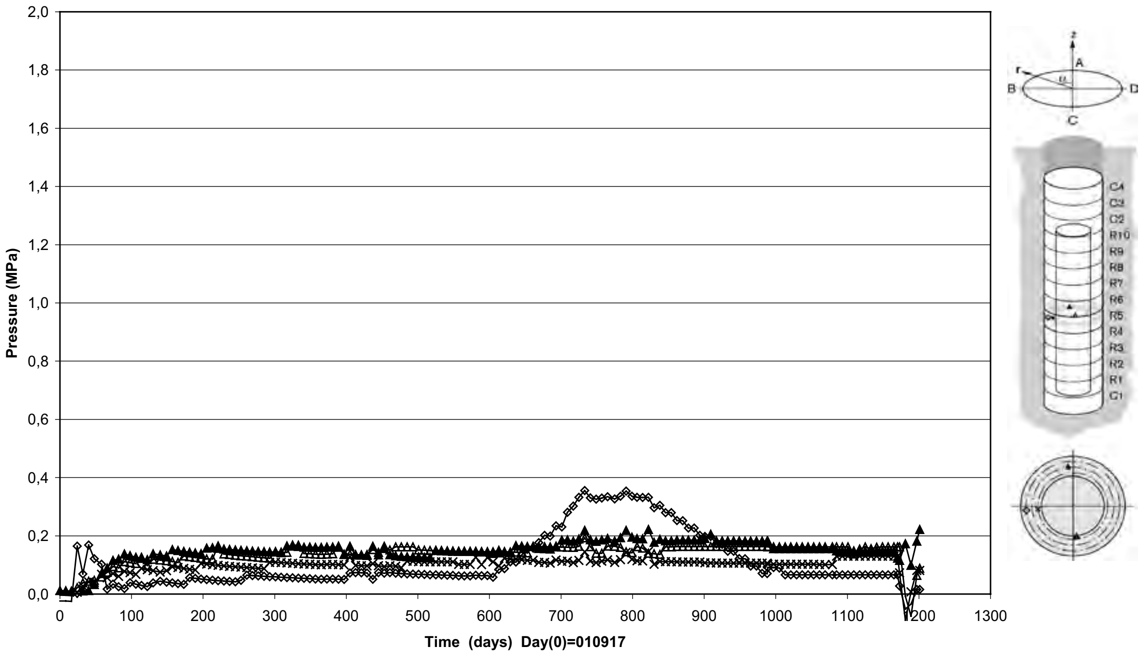


***Figure 2-10.** Measured total pressure in deposition hole 3 (Ring 5, 2001-09-17 to 2005-01-01).*

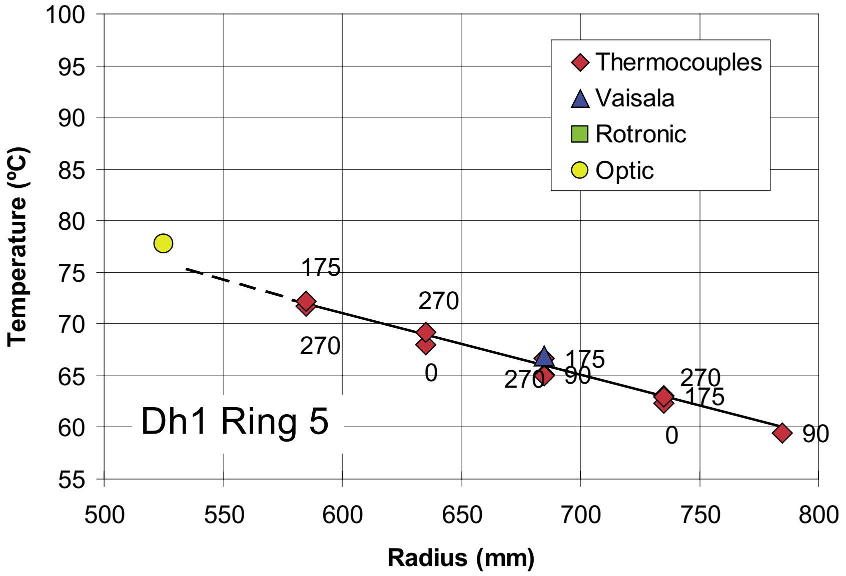
Comparison of the temperature in a "wet" and a "dry" hole

In Figure 2-11 temperature at mid height of the canister is plotted as function of distance from the centre of the deposition hole for holes 1 and 3. The measurements are made at mid height of the canisters at September 1, 2004. The data from the plots are also summarised in Table 2-2. Although the power applied to the two canisters is the same the temperature distributions in the buffer are quit different. In the dry hole 3 the gap of 10 mm between the buffer and the canister is still open, resulting in a higher temperature on the canister surface compared with the canister in hole 1 where the gap is closed. In the gap in hole 3 the temperature drops about 17°C. The maximum temperature in the buffer is somewhat higher for hole 3, about 7°C. Also the temperature close to the outer slot, filled with pellets, is higher in hole 3, about 9°C. The temperature gradients over the buffer calculated for the central part of the blocks are similar for the two deposition holes, indicating similar thermal conductivity for the bentonite in the two holes. This can be explained by a loss in density due to swelling that thermally compensates the increase in water content of the buffer in the wet hole.

Table 2-2. Temperatures measured in deposition holes 1 and 3.

Dep hole	Max temp on the canister surface	Max temp in the buffer	Min temp in the buffer	Temperature grad over the buffer	Temperature drop over the inner gap
	(°C)	(°C)	(°C)	(°C/cm)	(°C)
No:1	78*)	75	59.5	0.60	0
No:3	100*)	82.5	68	0.55	17

*) These values might be adjusted after recalibration of the optical cables.



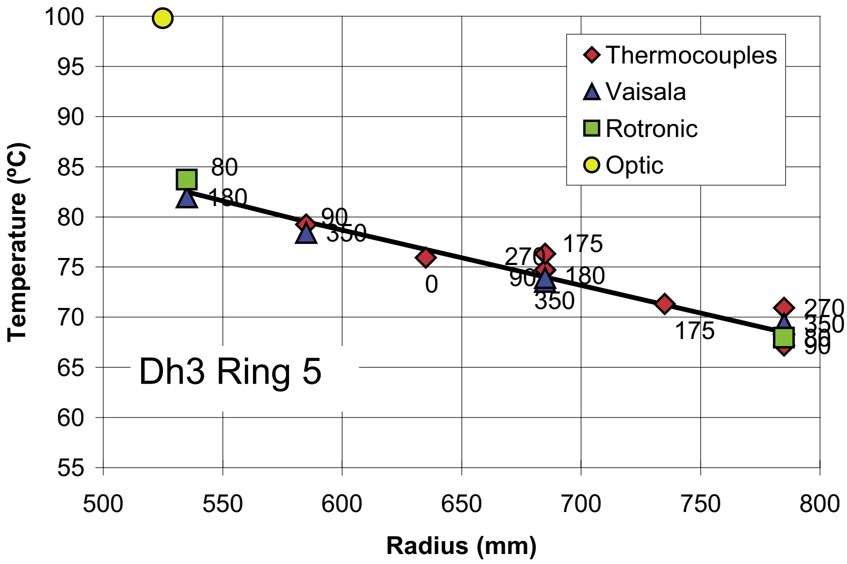


Figure 2-11. *Temperature measured in the buffer as function of the radius in the two deposition holes 1 and 3. The measurements are made with different type of transducers. The numbers above the dots show the direction in the deposition hole which the transducers are installed (angle from the west-east direction).*

Hydration of the backfill in Section I

Figure 2-12 shows some results from measurements of suction in the backfill of Section I over holes 1 and 3. 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 gave similar values as before the closing of the drainage.

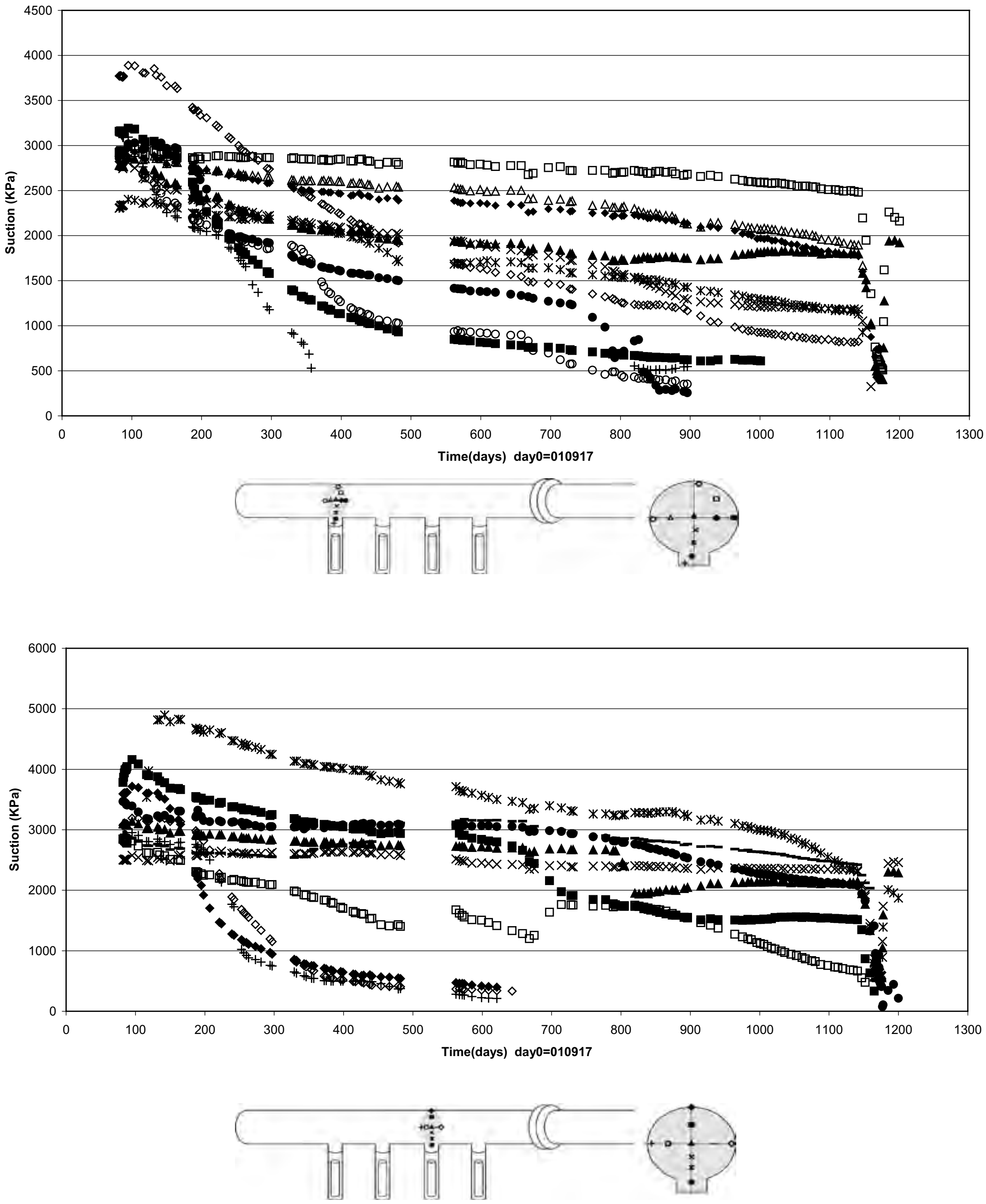


Figure 2-12. Suction measured in the backfill in tunnel sections above deposition holes 1 and 3 (2001-09-17 to 2005-01-01).

Stress and strain measurements in the rock around deposition holes 5 and 6

The monitoring programme consists of 80 sensors measuring compressive and tensile stresses, movements, deformations, strains and temperatures both inside the canister holes and in the surrounding area. In addition there are 24 sensors monitoring the plug.

A schematically layout of the two deposition holes in section II indicating the location of sensors used to measure stress and strain is shown in Figure 2-13.

SECTION II

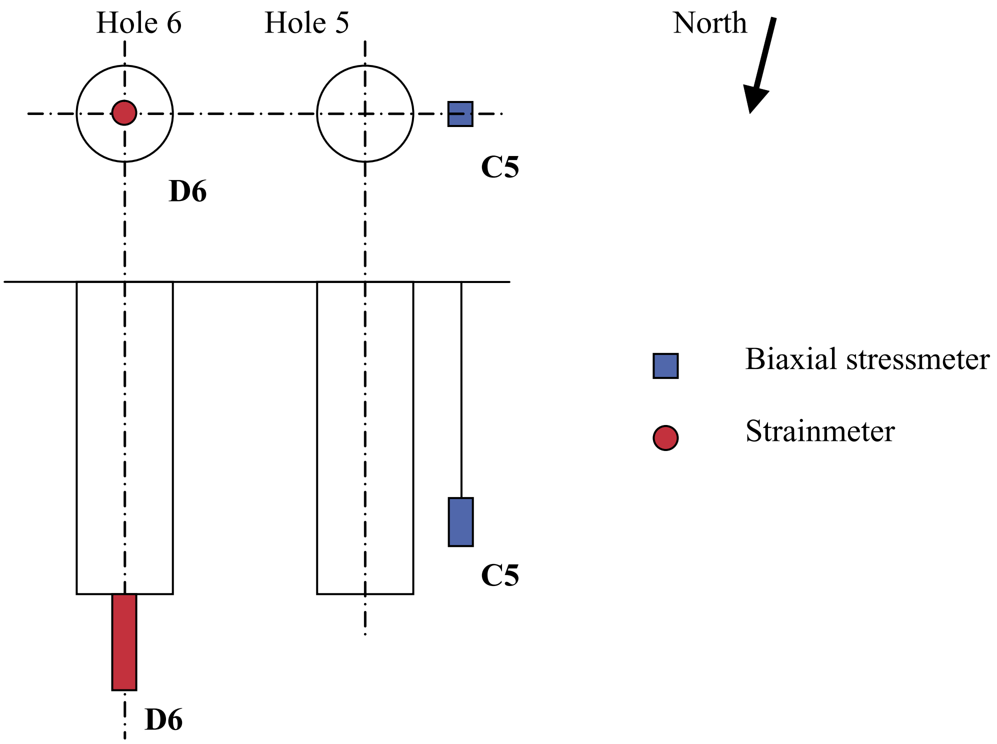


Figure 2-13. *Layout of deposition hole 5 and 6 in Section II showing location of sensors in the vertical boreholes (D6 and C5).*

There are a few sensors that show signs of noise and disturbances, mainly towards the end of the year. However, in general the sensors present reliable and stable readings.

Changes in stress caused by the heating of the rock

There has been a small increase in temperature with about 5°C from January 2004 until late November 2004. The stress increase has been less then 5 MPa during this period. In general the changes in stress in Section II caused by the heating of the rock are negligible. However, the closing of the drainage in beginning of November caused both the temperature sensors and the stress sensors to show rapid changes in values. During a few weeks in December the temperature dropped with about 7°C, and then immediately increased. Figure 2-14 is an illustrative example.

Changes in strain caused by the heating of the rock

The strain monitoring has showed small changes in value caused by the heating, but the measurements stabilised when the power was decreased in September. As described in the above section, the closing of the drainage in the beginning of November caused rapid changes in strain in deposition hole 6. This can be seen in Figure 2-15.

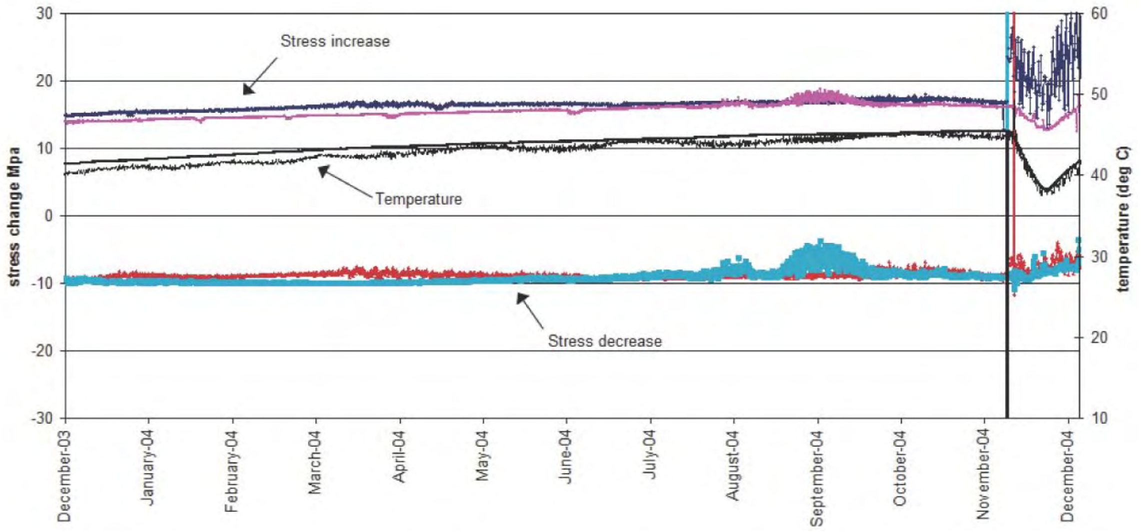


Figure 2-14. *Changes in stress measured in vertical borehole C5 close to deposition hole 5.*

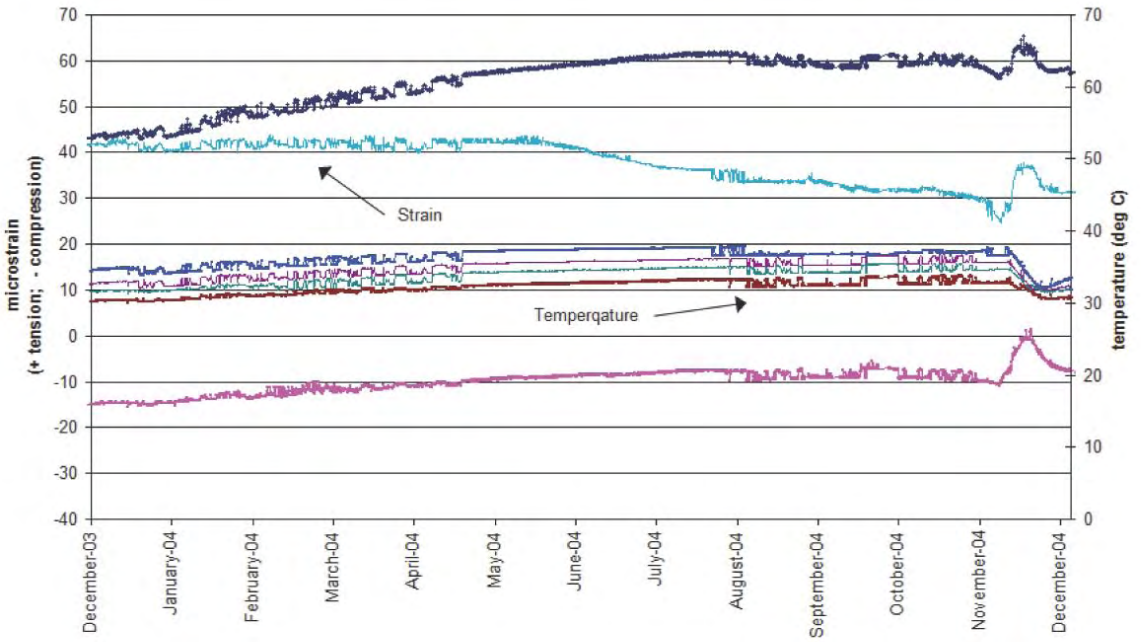


Figure 2-15. *Changes in strain measured in vertical borehole D6 below deposition hole 6.*

Modelling of THM processes

The model used to predict and evaluate the various processes in the Prototype Repository buffer and backfill has been described in detail /Pusch, 2001/ and the results of the predictive modelling has been reported /Pusch and Svemar, 2003/. The major features of the models used for predicting the THM evolution can shortly be described as:

- 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 following codes have been employed:

- Compass – (H R Thomas and P J Cleall, Cardiff University).
- Code Bright – (A Ledesma, CIMNE, Enresa).
- Rockflow – (L Liedke, BGR).
- Thames – (Y Sugita, JNC).
- Abaqus – (L Börgesson, Clay Technology AB, SKB).

2.4 Backfill and Plug Test

2.4.1 Background

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

2.4.2 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.

2.4.3 Experimental concept

The test region for the Backfill and Plug Test is located in the old part of the Zedex drift. Figure 2-16 shows a three dimensional 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.

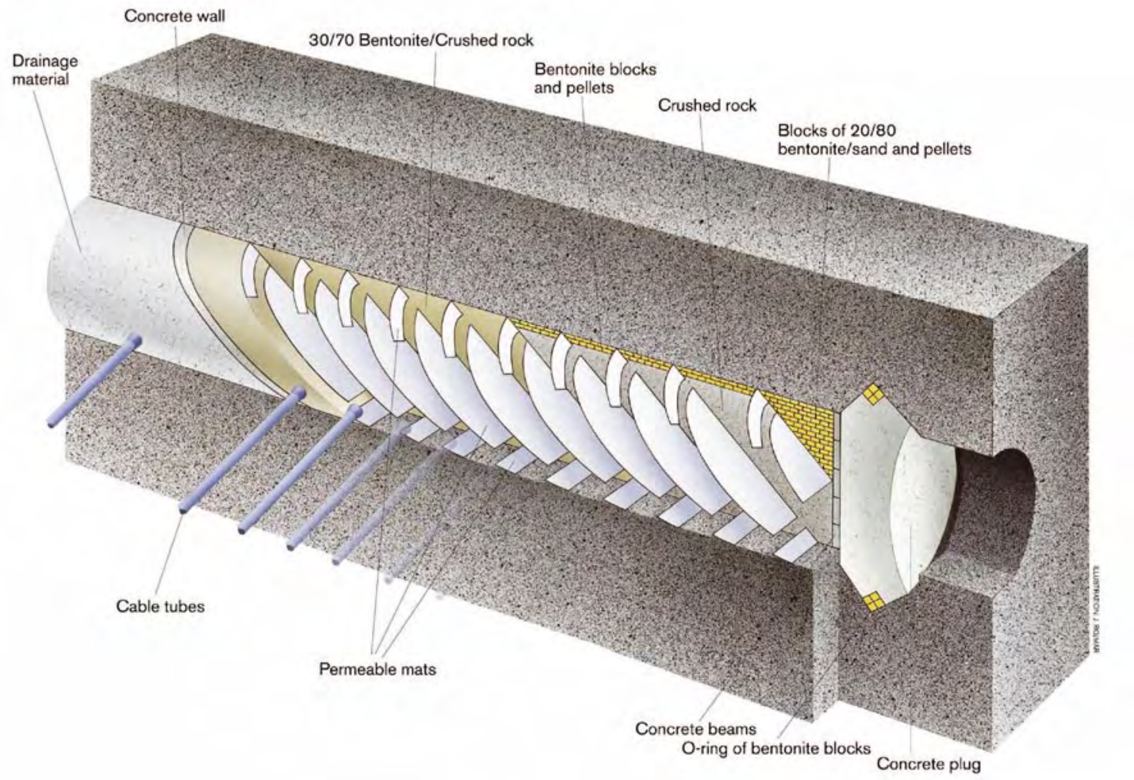


Figure 2-16. *Illustration of the experimental set-up of the Backfill and Plug Test.*

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. The crushed rock has no swelling potential but may instead settle with time. In order to ensure a good contact between the backfill and the rock a slot of a few dm was left between the backfill and the roof and filled with a row of highly compacted blocks with 100% bentonite content. The remaining irregularities between these blocks and the roof were filled with bentonite pellets.

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 2.2 m. Each mat section was divided in three units in order to be able to separate the flow close to the roof from the flow close to the floor and also in order to separate the flow close to the rock surface from the flow in the central part of the backfill.

The outer 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 will after water saturation be tested by applying a water pressure gradient along the tunnel between the mats and measuring the water flow. All cables from the instruments are enclosed in Tecalan tubes in order to prevent leakage through the cables. The cables are led through the rock in boreholes drilled between the test tunnel and the neighbouring demonstration tunnel hosting the data collection room.

2.4.4 Results

The installation was completed and the wetting of the backfill from the permeable mats 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. During 2004 the flow testing of the test sections with bentonite/crushed rock mixture has proceeded.

The flow testing is done by decreasing the water pressure in the permeable mats sections (one by one) to 400 kPa and measuring the flow between the mat sections, starting with the filter at the plug. The results from measurements in the backfill containing a mixture of 30% bentonite and 70% crushed rock are summarised in Table 2-3. Both 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.

The evaluated hydraulic conductivity is a little higher than expected from the laboratory results, which yielded values between 10^{-9} and 10^{-10} m/s for a dry density of 1,700 kg/m^3 and 1.2% salt content in the water. The high conductivity values in the bottom of the backfill are judged to be caused by flow in the fractured rock floor while the high values through the top mats are most likely caused by low density at the roof.

The amount of water passing through the plug and the surrounding rock has been measured by collecting water outside the plug. The results show that the leakage is slowly reduced with time, see Figure 2-17.

Logging of measured results from all sensors have continued during 2004 except for the relative humidity sensors, which were disconnected since all those sensors showed full water saturation. Two data reports covering the period up to July 1, 2004 /Goudarzi et al. 2004c/ and the period up to January 1, 2005 /Goudarzi et al. 2005a/ have been released.

Table 2-3. Hydraulic conductivity of 30/70 backfill evaluated from the flow results.

Layer	Top K (m/s)	Centre K (m/s)	Bottom K (m/s)
A5	$1.5 \cdot 10^{-8}$	$1.4 \cdot 10^{-9}$	$2.1 \cdot 10^{-8}$
A4	$9.1 \cdot 10^{-8}$	$1.2 \cdot 10^{-9}$	$7.9 \cdot 10^{-9}$
A3	$6.7 \cdot 10^{-8}$	$3.3 \cdot 10^{-9}$	$1.8 \cdot 10^{-8}$
A2	$4.4 \cdot 10^{-8}$	$1.0 \cdot 10^{-9}$	$1.4 \cdot 10^{-8}$
A1	$3.2 \cdot 10^{-8}$	$8.8 \cdot 10^{-11}$	$7.7 \cdot 10^{-9}$
Average	$5.0 \cdot 10^{-8}$	$1.4 \cdot 10^{-9}$	$1.4 \cdot 10^{-8}$

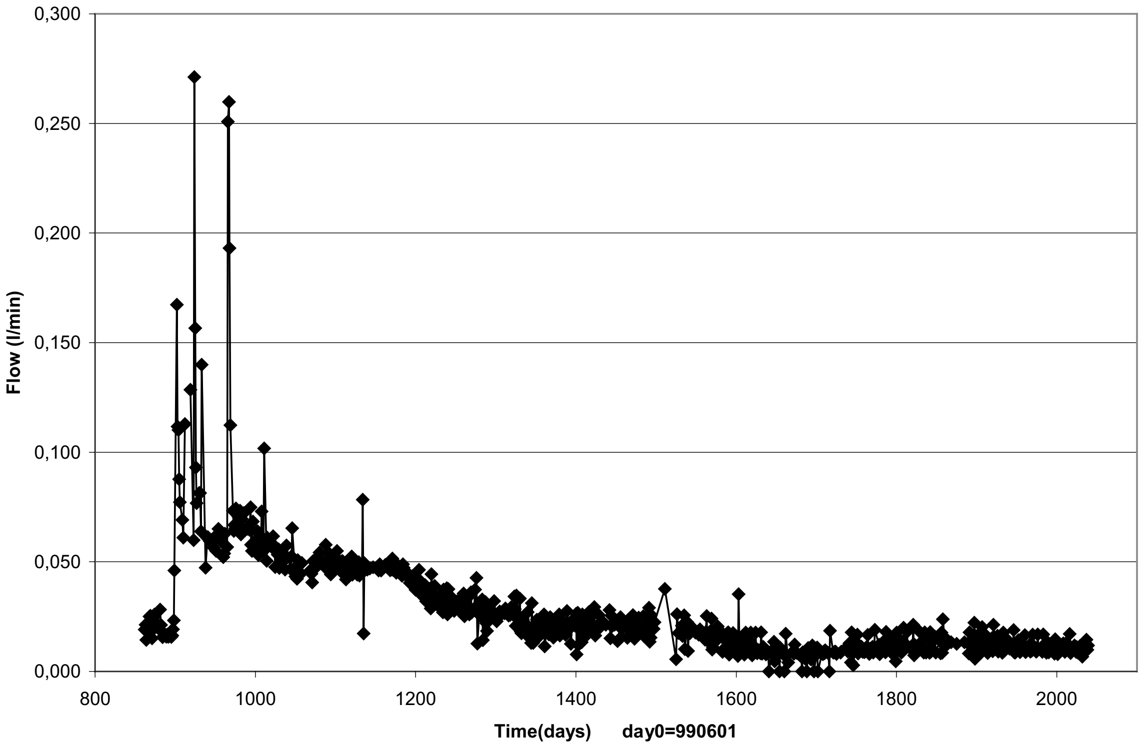


Figure 2-17. Measured water flow past the plug and its surroundings. 500 kPa has been kept inside the plug from day 965 to day ~ 1,320, when the pressure was reduced to 400 kPa (1999-06-01 to 2004-12-30).

2.5 Long Term Test of Buffer Material

2.5.1 Background

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

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

2.5.2 Objectives

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

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

2.5.3 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 2-18.

The test series see Table 2-4, concern realistic repository conditions (S) and controlled adverse conditions (A). 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 are regulated or kept constant at values calculated to give a maximum clay temperature of 90°C in the standard tests and in the range of 120°C to 150°C in the adverse condition tests.

Table 2-4. Layout of the Long Term Test series.

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

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

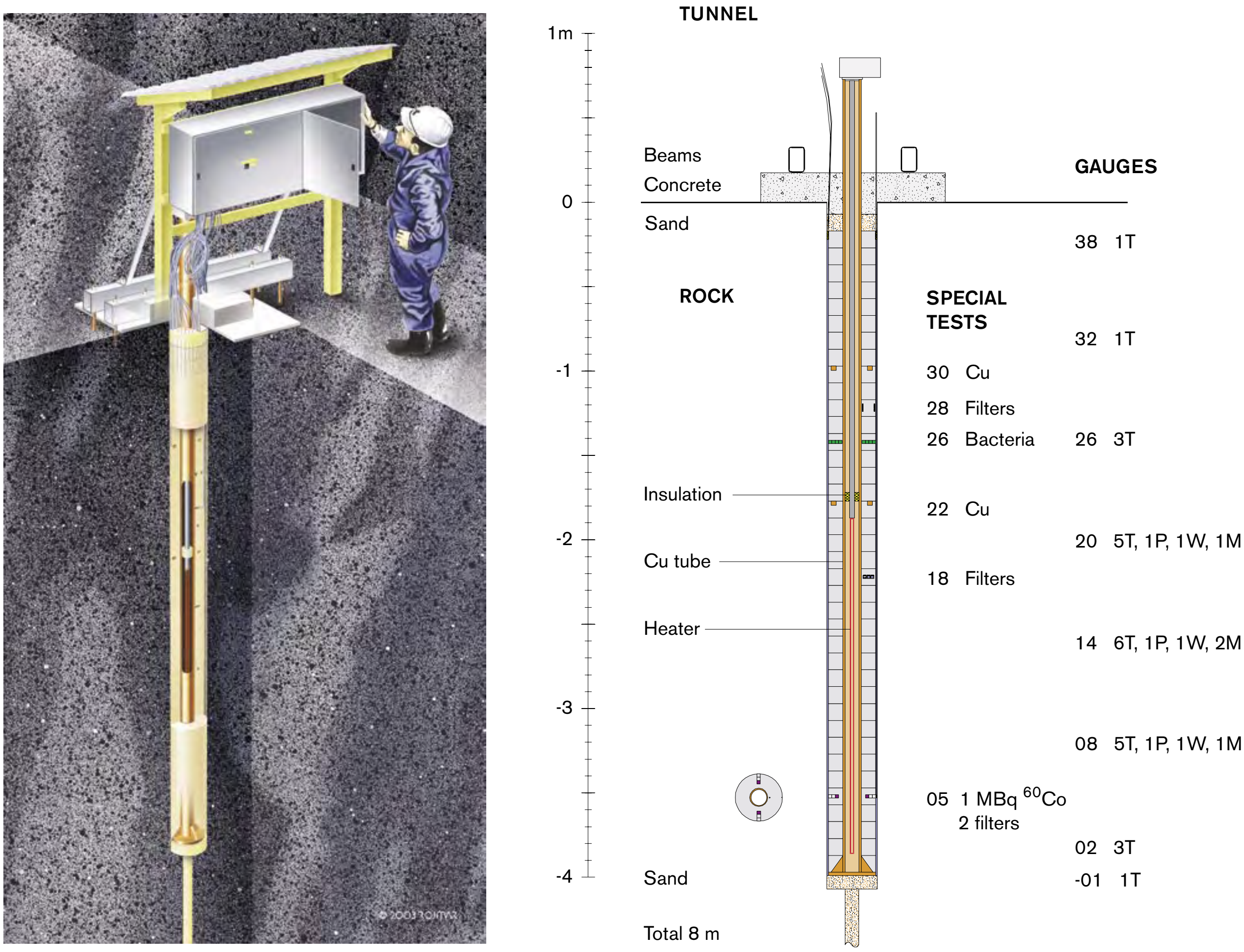


Figure 2-18. *Illustration of the experimental set-up in the Long Term Test of Buffer Material (left) and a cross-section view of an S-type parcel (right). The first figures in column denote block number and second figures denote the number of sensors. T denotes thermocouple, P total pressure sensor, W water pressure sensor, and M moisture sensor.*

Temperature, total pressure, water pressure and water content, are measured during the heating period. At termination of the tests, the parcels are extracted by overlapping core-drilling outside the original borehole. The water distribution in the clay is determined and subsequent well-defined chemical, mineralogical analyses and physical tests are performed.

2.5.4 Results

Chemical and mineralogical analyse data from the A0 parcel have been used for improvement of mineralogical modelling. Thermo-hydro modelling with Code Bright has been made of the bentonite water uptake process against the prevailing temperature gradient.

The ongoing four long-term test parcels have functioned satisfactory, and temperature, total pressure, water pressure and water content have been continuously measured and registered every hour. The incoming data are automatically monitored, and all recorded data are followed up monthly. The evolution of the temperature and the total pressure in test parcel A2 are shown in Figure 2-19 and Figure 2-20 respectively. The bentonite swelling pressure is still increasing in several positions, showing that water uptake is still ongoing, although the tests have been running for almost five years.

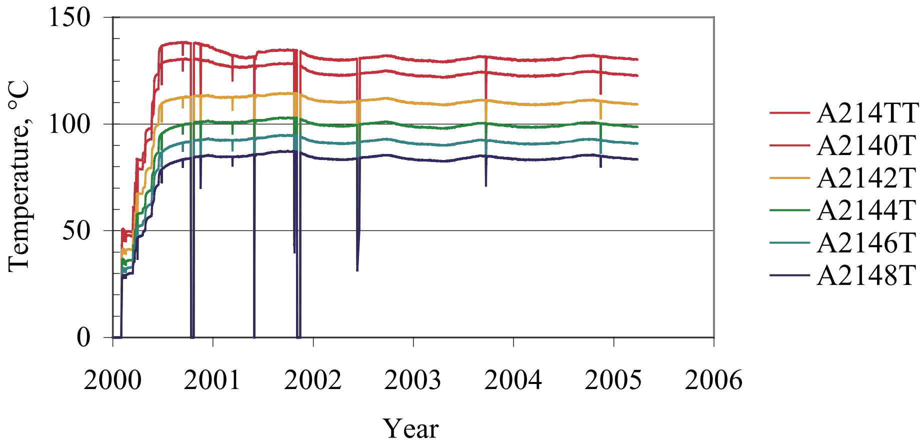


***Figure 2-19.** Measured temperatures in the warmest section in parcel A2. A214TT denotes copper tube surface temperature, and the next curve shows the temperature 2 cm outwards into the bentonite, etc. A2148T shows the temperature at the interface with the rock.*

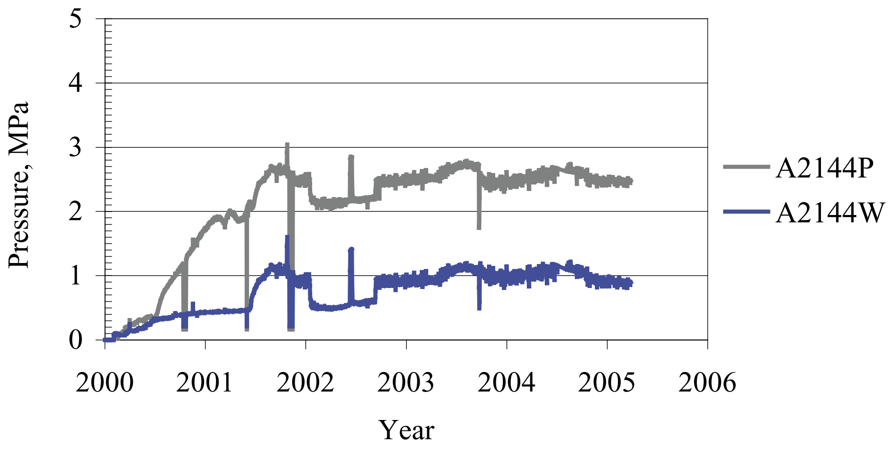


***Figure 2-20.** Measured total pressure (grey) and water pressure (blue) in the bentonite halfway between the copper tube and the rock in the warmest section of parcel A2.*

2.6 Cleaning and sealing of investigation

2.6.1 Background

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

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

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

2.6.2 Objectives

The main objective of this project is to identify and to demonstrate the best available techniques for cleaning and sealing of investigation boreholes. Phase 1 of the project, mainly an inventory of available techniques, was finalised in the end of 2003. The project has now come to Phase 2, including the development of a complete cleaning and sealing concept and to demonstrate it. In addition, the planning for a continuation, Phase 3, is in progress. In Phase 2 the work is divided in the four main areas described below:

- Laboratory studies on potential materials and combinations of different materials. Laboratory tests on selected candidate materials to evaluate if the criteria set on hydraulic conductivity, shrinkage, and physical and chemical long-term stability can be fulfilled.
- Cleaning of the borehole to be used at a later stage in the project. Identification of the type of equipment left in the borehole and investigations of the distribution of equipment along the borehole. Specification of methods and equipment needed to catch and bring up the left equipment in the borehole. Finally, select methods and equipment to be applied for cleaning the hole.
- Preparations for full-scale testing in the field. Present the requirements to be set on preparations to be made before plugging the borehole. Specify the requirements to be fulfilled by equipment and material to be used for plugging of long and short boreholes from the surface and from underground.
- Compile a complete “Basic concept” for sealing of boreholes. The concept should include measures to be taken before plugging, evaluation of long-term stability of selected materials, and techniques for manufacturing and installation of plugs in boreholes. In addition, recommendation should be made on full-scale tests of the concept.

2.6.3 Results

The major conclusion, from the completed phase 1, was that smectite clay is recommended as main candidate material for sealing of boreholes in the forthcoming work. The second phase, which focuses on the development of a complete basic concept for cleaning and sealing of boreholes, will be documented in a final report. The report is now being reviewed before printing.

The basic concept for surface-based boreholes (see Figure 2-21) comprises the following materials at different depths:

- On the ground surface, filling of 3 m well compacted moraine from the site.
- 3–50 m, well fitting rock cylinders pressed down in the precision-drilled (reamed) uppermost part of the hole. The cylinders are from the site. Silica gel is used as mortar.
- 50–60 m, fill of well compacted moraine from the site. It constitutes a transfer from the effective underlying ductile clay seal to the overlying stiff borehole plug.
- 60–100 m, fill of smectite pellets of bentonite applied and compacted layer wise.
- Below 100 m, highly compacted smectite clay contained in perforated copper tubes (2–4 mm thick walls and degree of perforation is approximately 50%). Tubes are jointed to form a continuous clay column.

Tunnel-based boreholes are filled with highly compacted smectite clay contained in perforated copper tubes that are jointed to form a continuous clay column. These boreholes will be plugged with concrete at the tunnel.

Laboratory studies of material for plugging boreholes are in progress, test of bentonite with different water content and density are going on. The construction of a machine for automatic manufacturing of copper tube has started, and will be tested in full scale during February.

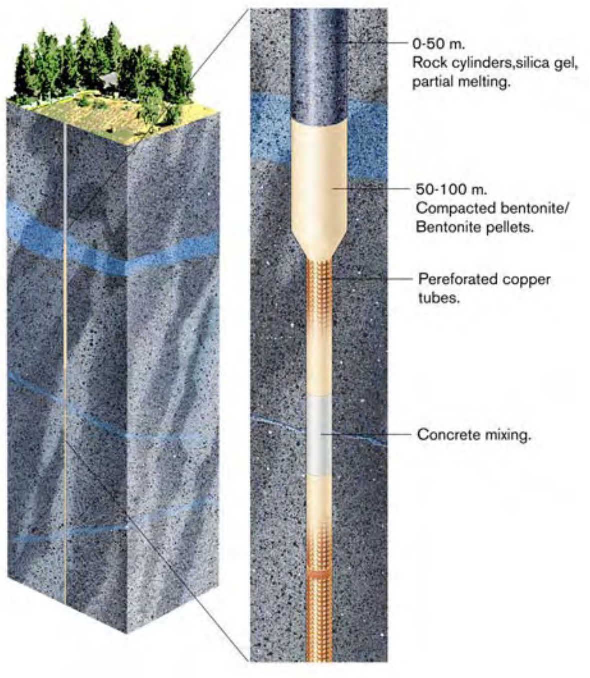


Figure 2-21. *Illustration showing the basic concept for sealing of surfaced-based investigation boreholes.*

A number of short boreholes for testing the concept have been drilled under ground. The testing will give information of the maturation rate, i.e. the time required for a clay plug of basic type to become at least as tight as the surrounding rock. Boreholes with 200 mm diameter have also been drilled to a depth of 1.5 m. They will be used for testing potential sealing methods of the upper part of the boreholes.

One part of the project is a full-scale field test at Äspö where two deep candidate investigation boreholes, KAS06 and KAS07, have been investigated as a preparation for potential field test. The conclusion was that KAS06 might be used in a later stage of the project but needs to be re-bored to increase the diameter.

2.7 Injection grout for deep repositories

2.7.1 Background

Use of common construction materials, as steel and concrete, are foreseen in the deep repository. With respect to the repository long-term safety a suitable chemical environment is vital. The use of low-pH products is necessary in order to get leachates with a sufficiently low pH (≤ 11). A pre-study in 2001 was followed by a feasibility study in 2002–mid 2003. The current project aims at achieving some well quantified, tested and approved low-pH injection grouts to be used from the start of the construction of the underground rock characterisation facility Onkalo. The project is a joint project between SKB, Posiva and Numo. The project is divided into four sub projects:

SP1 Low-pH cementitious injection grout for large fractures.

SP2 Non-cementitious low-pH injection grout for small fractures.

SP3 Field testing in Finland.

SP4 Field testing in Sweden.

The work to be carried out at the Äspö HRL is part of sub project 4, Field testing in Sweden, and started in December 2003. The sub projects SP1 and SP2 have been carried out by Posiva, see Section 6.8.4.

2.7.2 Objectives

The objective of the field test in Äspö HRL is to investigate if it is possible to estimate/predict the penetration of silica sol based on transmissivity and hydraulic aperture, resulting from hydraulic tests. The evaluation will increase the knowledge concerning the behaviour of silica sol, which will be useful for predictions and selection of grouting strategies.

2.7.3 Experimental concept

The sub-project connected to Äspö HRL consists of a field test with silica sol. The test site at section 0/670 in the access tunnel is a rock pillar that has been grouted earlier with cement in a similar test. The fracture is well characterised and has a small hydraulic aperture (~ 40–50 µm), hence suitable for tests of penetrability of silica sol. Further, not connected to Äspö HRL, is an evaluation of possibilities to couple the behaviour of grout in sand column tests to the behaviour when grouted in a rock fracture.

2.7.4 Results

Preparations of the site prior to the grouting test were initiated already in 2003 and hydraulic pre-tests were carried out at the site in February. Grouting test with silica sol, was performed in March and a minimum grout spread of 0.4 m was observed in an adjacent hole. The grouting was followed up by complementary hydraulic testing during May. The hydraulic tests showed a sealing efficiency of 70% in the affected rock mass. The sub-project SP4 (Field testing in Sweden) has been completed as part of the ordinary construction work. The grouting was accompanied by extra investigations and analysis during operation /Emmelin et al. 2004/.

2.8 KBS-3 method with horizontal emplacement

2.8.1 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 deposition holes (KBS-3H) instead of vertical emplacement of single canisters in the deposition hole (KBS-3V) has been considered since early nineties. In the KBS-3H method the copper canister and its buffer material is emplaced together in the long deposition holes as a prefabricated super container, see Figure 2-22.

Late 2001 SKB published an R&D programme for the KBS-3 method with horizontal emplacement /SKB, 2001b/. The programme, carried out by SKB in co-operation with Posiva, is divided into four parts: Feasibility study, Basic design, Full scale demonstration of the concept at Äspö HRL, and Evaluation. Parts of the full scale demonstration receive contribution from the EC project Esdred.

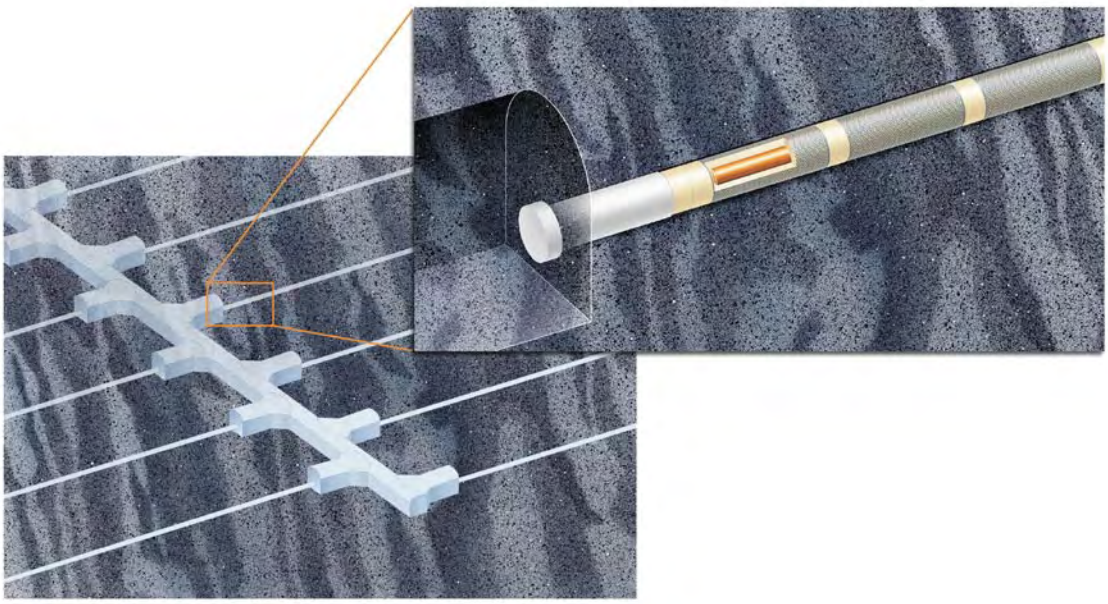


Figure 2-22. *Schematic illustrations of KBS-3 method with horizontal emplacement (KBS-3H).*

2.8.2 Objectives

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

The objective of the first part of the project 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 the excavation of horizontal deposition holes, the deposition technique and the function of the buffer.

The objectives of the second part of the project, Basic Design, were continued technical development, preparation of the full scale demonstration and studies of the barrier performance /Thorsager and Lindgren, 2004/.

The objectives of the third part of the project are realisation of the full scale demonstration, continued buffer research and preparation and compilation of a safety case.

2.8.3 Experimental concept

The site for the demonstration of the method is located at 220 m depth in Äspö HRL. A niche, with a height of about 8 m and a bottom area of 25×15 m that will form the work area, has been excavated. Two horizontal deposition holes, one short with a length of 15 m and one long with a length of 95 m will be used for the tests. Originally, three horizontal holes were planned. It has been decided that the deposition holes will be excavated by blind horizontal raise boring and that the straightness of the pilot hole will be guaranteed by the use of active steering device.

The short hole will be used for construction and test of a full scale low pH shotcrete plug. The long hole will be used for demonstration of the deposition equipment, see Figure 2-23.

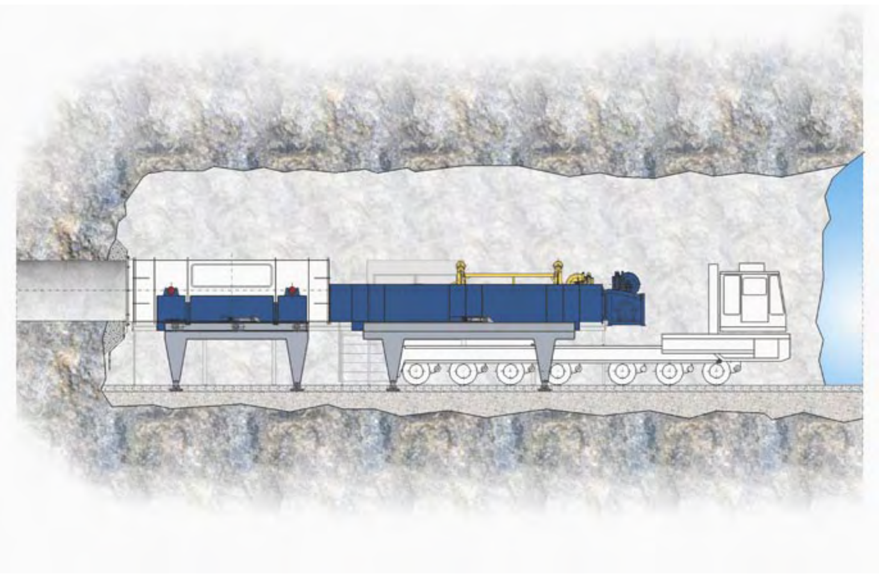


Figure 2-23. *Illustration of KBS-3H deposition equipment.*

2.8.4 Results

During 2004 the finalisation of test niche at –220 m level at Äspö HRL including hydraulic characterisation of the rock mass and preparation of the invert were made.

The excavation of the short deposition hole (15 m), including drilling of a pilot-hole and up-reaming with Indau equipment of that hole to the desired deposition hole diameter (1.85 m) was finished in the beginning of November. The quality achieved was investigated by a number of methods for instance by laser scanning. Preliminary results indicate that a high quality has been achieved, but in some places the required tolerances have been exceeded. However, the deposition hole can be used as planned.

The drilling of the pilot-hole for the long deposition hole (95 m) started in the middle of November, with an active steering device. The drilling was, however, stopped due to problem with the equipment. A decision was taken that the drilling of the pilot-hole should be carried out with the same equipment as was used for the short pilot hole. Thus the Indau drilling machine was moved into place and a 311 mm wide hole was drilled. During drilling the alignment and direction of the hole was measured at an interval of about 15 m and the inclination was also checked by reading the altitude of the crone with water based vertical control technique. The drilling was successfully completed in the end of December and the up-reaming of the pilot-hole to a 1.85 m deposition hole will start in January.

An overview of other activities performed during 2004 is given below:

- A manufacturer of deposition equipment has been contracted and the manufacturer has started the detailed design work.
- Detailed design of super container completed.
- Detailed design of container and bentonite block completed.
- Continued analysis of buffer and long-term safety.
- Motives for a future full scale buffer test have been identified.
- Presentation of experimental and modelling results and findings obtained during 2004.

2.9 Large Scale Gas Injection Test

2.9.1 Background

The aim of the large scale gas injection test (Lasgit) is to perform a large scale gas injection test in a full-scale KBS-3 deposition hole.

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 on the buffer material is to not cause any harm to the other barriers. Gas build up from 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 de-hydrate the buffer.

The small scale experiments that have been performed over the last ten years indicate that the effects described above do not occur. The current understanding of the gas transport process through compacted bentonite indicates that the buffer would open for gas passage before any harmful pressures are reached. However, there are still large uncertainties around the gas migration process and all these findings have to be verified in a large scale experiment. The project is conducted as a SKB and Posiva joint project.

2.9.2 Objectives

The objective of this experimental programme is to undertake a large-scale gas injection test to provide data to improve process understanding and test/validate modelling approaches which might be used in performance assessments. 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 gas migration process.
- Provide high-quality 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.

2.9.3 Experimental concept

The experiment will be performed in a bored full-size deposition hole in Äspö HRL. A full scale canister, without heaters, and a surrounding bentonite buffer is installed, see Figure 2-24. Water will be artificially supplied to the buffer and the gas injection tests will start when the buffer is fully saturated. The operation of the test is divided into the *hydration phase* and the *gas injection phase*.

The aim with the *hydration phase* 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 clay 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 measurements 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* starts when the buffer is considered to be fully saturated. Gas injection might be accomplished using a combination of controlled flow rate and constant pressure test stages.

Figure 2-24. *Illustration of experimental set-up of the Large Scale Injection Test.*

2.9.4 Results

During 2004 a full scale canister with gas injection equipment was manufactured and leak tested. The installation of the test in an earlier drilled deposition hole (DA3147G01) at the –420 m level in Äspö HRL was more or less finalised in the end of 2004. The information available on the hole was sufficient and no additional characterisation was needed.

The installation comprised the following activities:

- Installation of rock anchors.
- Installation of the buffer.
- Lowering of the canister into the hole and connection of all instrumentations and equipments.
- Filling of pellets in the slot between buffer and rock.
- Grouting of a concrete plug on the top of the buffer.
- Installation of a steel lid.
- Tension of anchor cables.

In the project problems with instrumentation and pumps have caused delays in the project and the wetting of the buffer is now planned to start in January 2005.

In Section 6.3.2 analyses of performed hydraulic tests in surrounding boreholes and predictive modelling of the saturation process are presented.

2.10 Temperature Buffer Test

2.10.1 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.

The scientific background to the project relies on results from large-scale field tests on engineered barrier system (EBS) 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).

2.10.2 Objectives

The Temperature Buffer Test (TBT) 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.

2.10.3 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 2-25.

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, with a thickness of 0.23 m, 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 components in the deposition hole, starting from an initial unsaturated state under thermal transient and ending with a final saturated state with a stable heat gradient.

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.

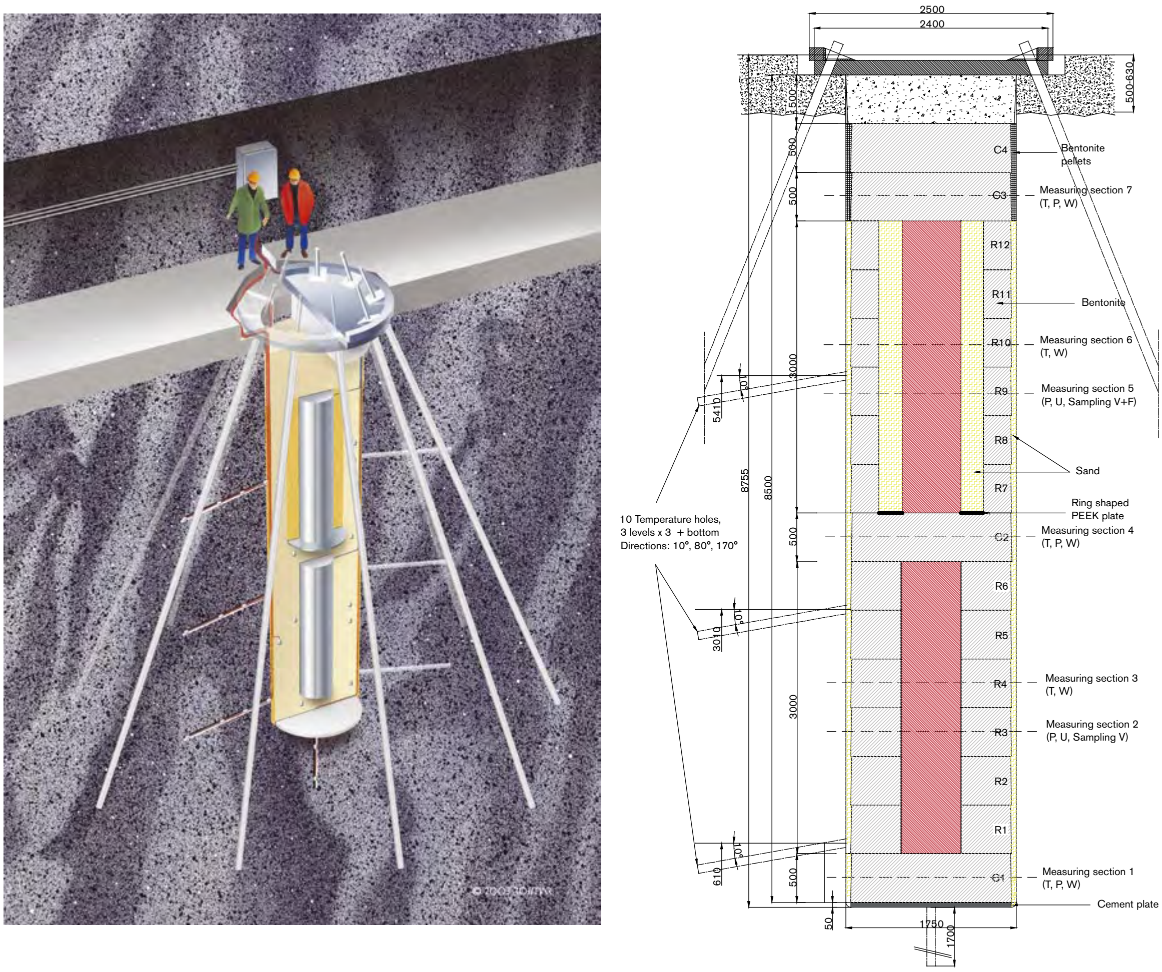


Figure 2-25. *Principle design and experimental set-up of the Temperature Buffer Test.*

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

2.10.4 Results

Experimental results

The experiment has generated data since the start in March 2003. The results include measurements of temperatures, relative humidities, stresses, pore pressures and cable forces in 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. 2005b/.

The thermal conditions in the experiment at the end of 2004 are illustrated in Figure 2-26. The dense arrays of thermo-couples enable a continuous evaluation of thermal conductivity distribution, which in turn give an indication of the saturation process. Such evaluations have confirmed that the conceptual description of these processes is basically correct /Hökmark et al. 2005/.

The hydration of the buffer is illustrated in Figure 2-27. The results indicate that the buffer around the upper heater was close to full saturation at the end of 2004. This process was fairly well captured in the predictive modelling task, whereas the predictions of the hydration around the lower heater varied for different codes /Hökmark et al. 2005/.

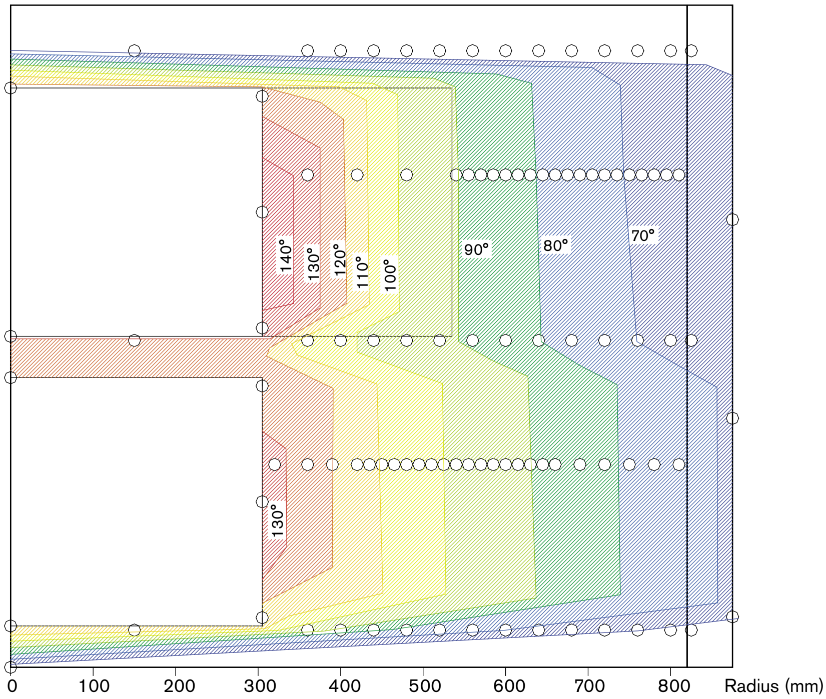


***Figure 2-26.** Temperature distribution at day 645.*

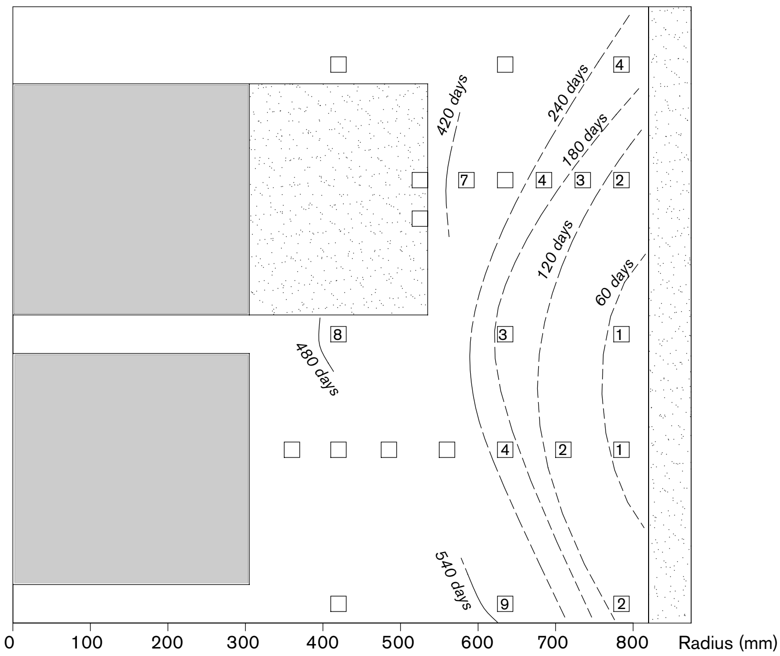


***Figure 2-27.** Occurrences of saturation as indicated by RH ≈ 100% and active Wescor sensors (RH > 95%). Numbers (1–8) denote periods of 60 days.*

A noticeable draw-back was the failure of several RH-sensors in the inner section of the buffer around the lower heater. This was probably a consequence of high temperature in this part.

Recorded stresses were at the end of 2004 in the order of 6–8 MPa and tended to level out. The developments of axial stresses and cable forces on the lid area (assuming an even distribution) are shown in Figure 2-28. A significant part of the swelling pressure is apparently balanced by shear stresses at the periphery.

The function of the sand filter has received some attention during 2004. From the onset of the test, water was injected in the lower section of the sand filter only. Since the flow rate was observed to diminish in the winter of 2003/2004 (Figure 2-29), the injection points in the upper section were pressurised in April 2004. After this, the experiment has been wetted from both sections and two hydraulic tests have been performed. These have confirmed that the flow capacity of the four lower injection points was much lower than the four upper injection points and therefore indicated that the flow resistance of the filter tips tends to increase dramatically with time. Since mid-October 2004 (day 568), six injection points are used to inject water and two are used to measure the pressure in the sand filter. The injection pressure monitored in the main tube is only representative of the pressure in the injection system, whereas the actual pressure in the sand filter is only measured at non-pressurised injection points, see (Figure 2-30).

Unexpected results were recorded during the period, day 234 to day 373, when the recorded developments of stresses and suction levels around the upper heater reversed, with increasing suction levels (Figure 2-31) and decreasing pressure (see also Figure 6-1 in Section 6.2.1). The end of the period coincided with the pressurisation of the upper injection points in April 2004, and an explanation for these deviations has therefore been sought in the hydraulic conditions in the sand filter (see below).

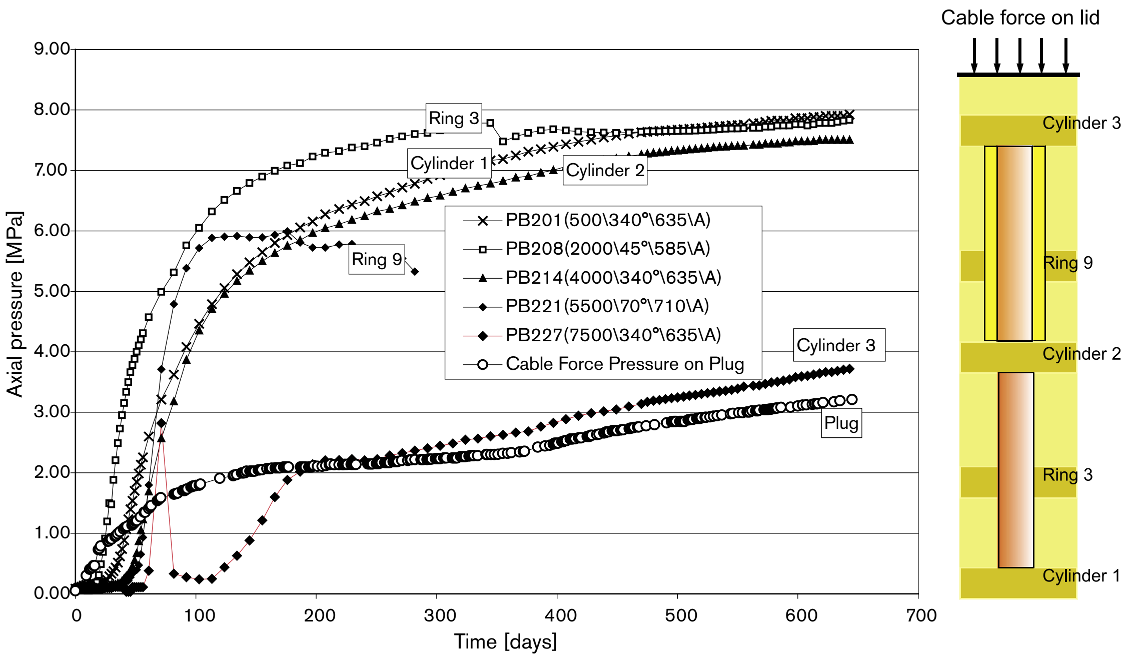


Figure 2-28. *Axial stresses and cable force distributed on lid area (plug).*

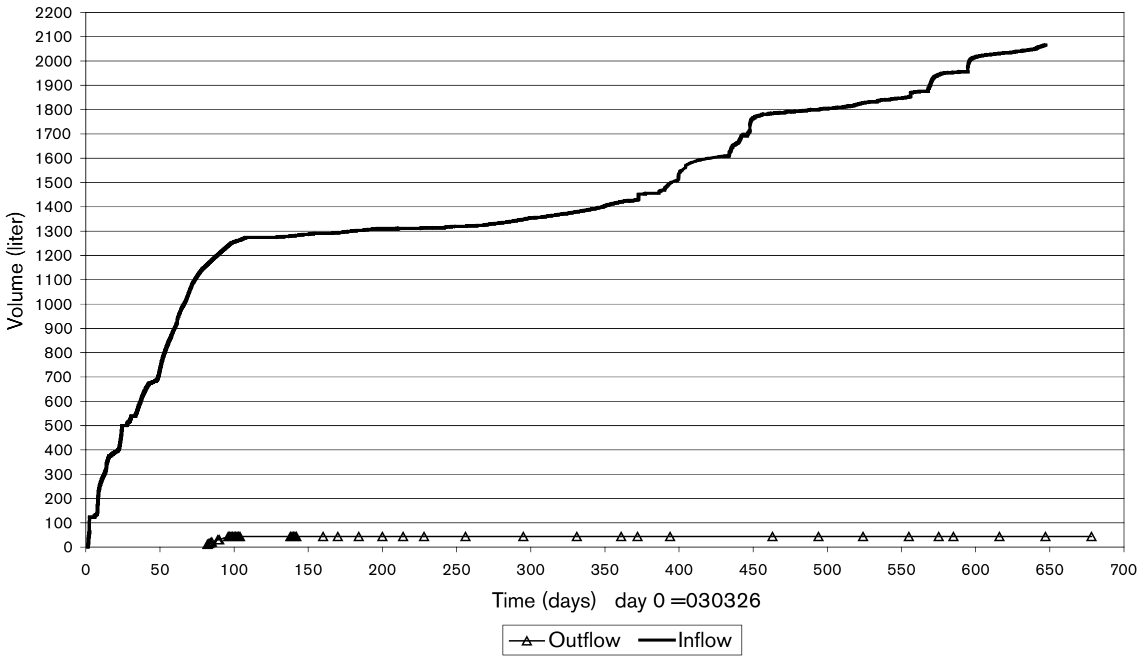


***Figure 2-29.** Water out- and inflow (2003-03-26 to 2005-01-01).*

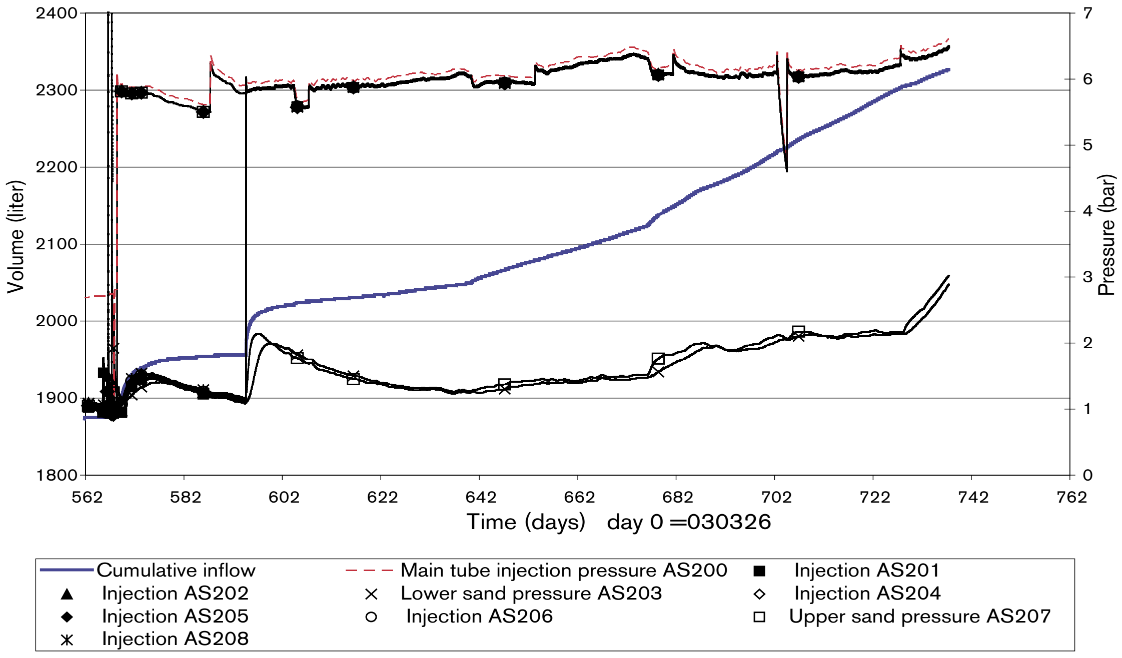


***Figure 2-30.** Pressurisation and flow rate measured (2004-10-08 to 2005-04-01) after second hydraulic test mid October 2004 (day 568). AS200 is the main tube. AS201–AS208 is individual injection tubes.*

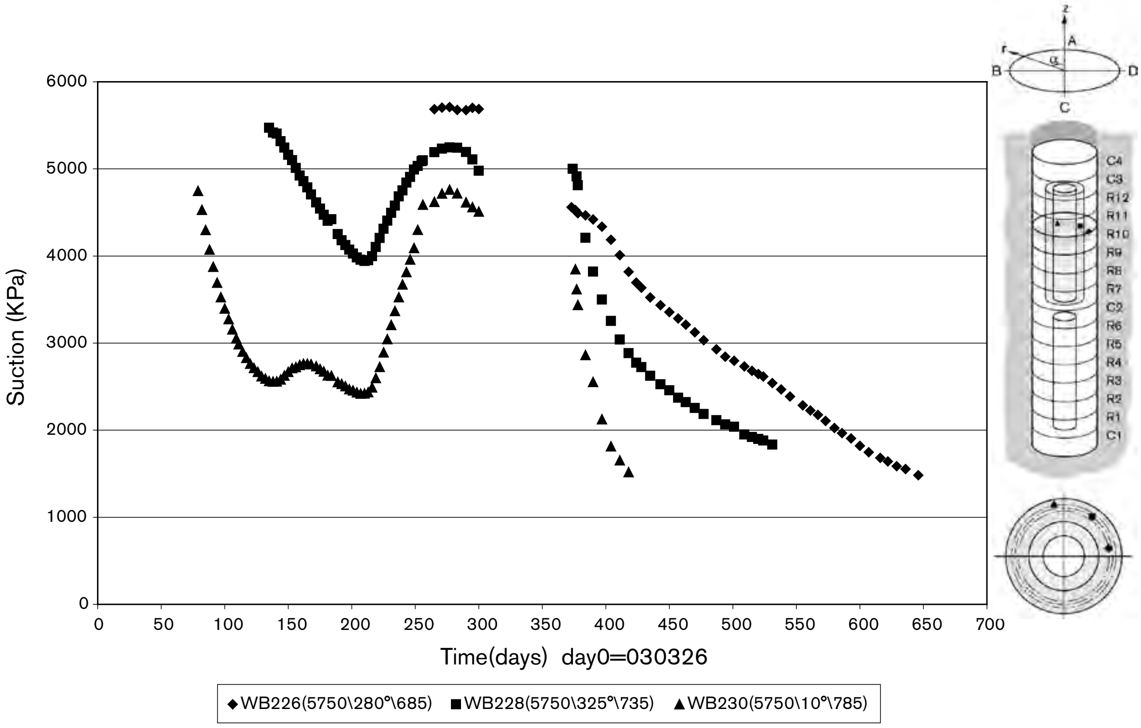


***Figure 2-31.** Suction measured in Ring 10 (2003-03-26 to 2005-01-01).*

Modelling results

Two issues for evaluation modelling tasks have been addressed during 2004:

- The possibility to reverse the hydration of the buffer around the upper heater through increase of heating power.
- Explanation of deviating hydro-mechanical trends around the upper heater during the winter 2003/2004 described above.

Both tasks were carried out by modelling groups from UPC (Spain), EDF (France) and Clay Technology (Sweden).

Results from the first task showed that a power increase from 1,500 W to 2,250 W would affect the hydration process to a minor extent only. This and the notion that boundary conditions should be kept as constant as possible motivated a decision not to increase the power.

Results from the second task showed that the deviating trends were a consequence of a lack of water in the sand filter. The same conclusion was found in a specifically designed mock-up test performed by CEA, see Section 6.2.1. The numerical models, that included mechanical processes and elasto-plastic descriptions of the buffer material, were able to reproduce measured stress and suction levels with a fairly high degree of precision. Of special interest are the achievements by the UPC-team, which were able to reproduce a substantial part of the measured trends for the whole geometry, with a hydraulic boundary based on the injected water volumes only. The ability to reproduce plastic shear strains, demonstrated by the team from Clay Technology, should also be mentioned.

2.11 Rock Shearing Experiment

2.11.1 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 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 theses 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 (small up to 1:10 scale). The results need, however, 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.

2.11.2 Objectives

The project aims at observing the forces that would 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 mid-height (worst case scenario). Such a displacement is considered to be caused by an earthquake, and the test set-up need to provide a shearing motion along the fracture that is equal to an expected shearing motion in real life.

2.11.3 Experimental concept

The test set-up is planned to use the site of the Äspö Pillar Stability Experiment (Apse, see Section 3.5) when the rock mechanics test there has been completed. Two full scale deposition holes then exist with a rock pillar of 1 m in between. Figure 2-32 illustrates the present, schematic idea for a test set-up. The left hole is used for the buffer and canister, while the right hole is used for the shearing equipment. Half of the rock between the holes is removed (is partly fractured after the Apse experiment) and replaced by concrete 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 concrete 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 (shown in the figure) or by cable bolts as in Canister Retrieval Test and Temperature Buffer Test.

The shearing may not be done before the buffer has saturated, but this time can be reached after two years by using highly saturated bentonite blocks, 95–98% saturation, and lining the hole with permeable mats for artificial water supply. Needed shearing speed is between 0.1 and 1 m/s. If the lower speed is chosen pistons may be used as shown in Figure 2-32, but if the higher speed is required another technique is probably more favourable.

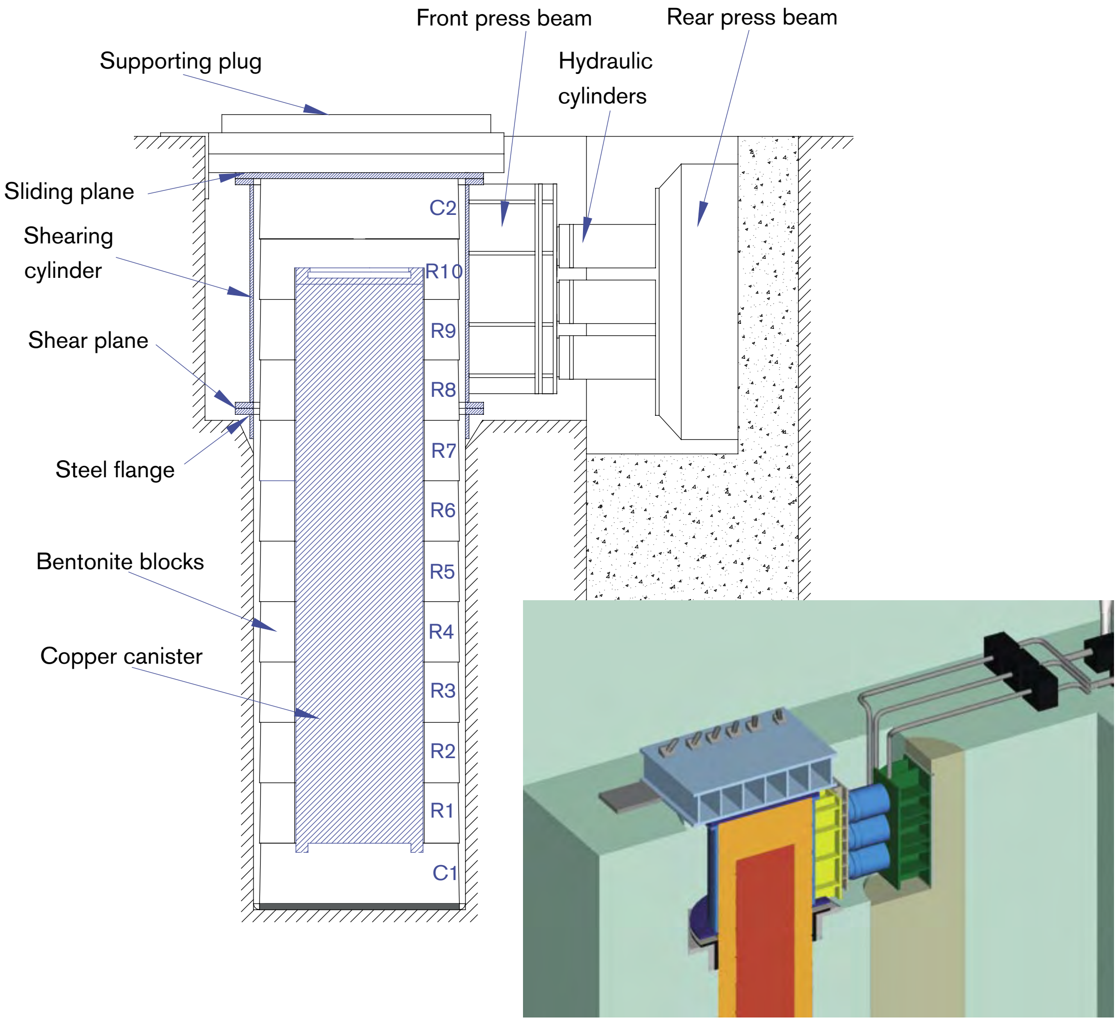


Figure 2-32. *Schematic illustration of a possible test set-up for verification of the stress and strain a canister may exhibit during an instant shearing of 100–200 mm.*

2.11.4 Results

The feasibility study has been running since summer 2004 and is now finished. A preliminary design based on the predicted test evolution has been made. The equipment for attaining the required force and shear rate has been drawn up.

The conclusion from the feasibility study is that the test can be accomplished with the desired demands for simulating the effect of a critical rock shear. Predictive modelling shows that the maturation can be fulfilled in about two years if the bentonite blocks are compacted to a high degree of saturation and if wetting of the buffer in the deposition hole is supplied from filter mats attached to the rock surface. The modelling shows that the effect of the rock shear is not detrimental for the canister. In Figure 2-33 the results from predictive modelling of a rock shear of 20 cm are given, in the figure the buffer, copper canister and steel insert in a longitudinal section through the deposition hole (tilted 90 degrees) are shown.

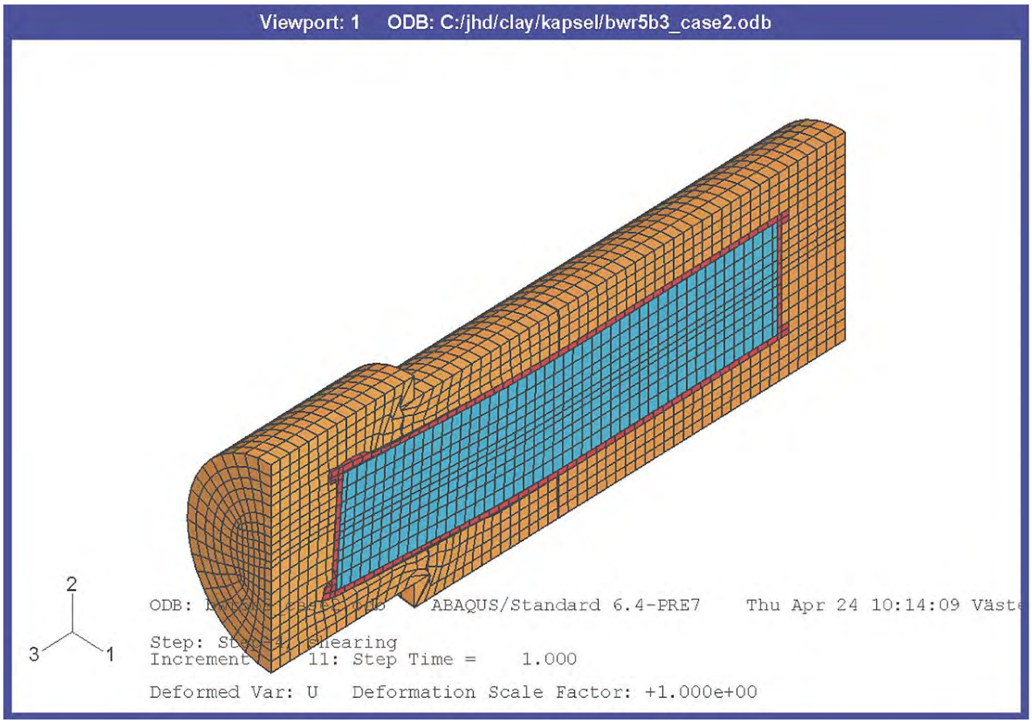


Figure 2-33. *Results from predictive modelling. The buffer (orange), copper canister (red) and steel insert (blue) in a longitudinal section through the deposition hole (tilted 90 degrees) after a rock shear of 20 cm.*

2.12 Learning from experiences

2.12.1 Background and objectives

In this project, reference techniques for emplacement of buffer and canisters, backfilling, and closure of a deep repository are to be identified. Several large-scale experiments have during the years been installed in Äspö HRL and methods and machines used have provided experiences for refinement and evaluation of limits of the methods applied.

Emplacement of buffer and canisters, and backfilling of tunnels have been experienced in the Canister Retrieval Test, the Prototype Repository and the Backfill and Plug Test. These experiences are all well documented and the results have been evaluated with respect to possible improvements as well as limits with respect to water inflows. This knowledge is worth considering in future work.

The aims are to identify techniques by:

- Compilation of the results from more than ten years of performed engineering experiments in Äspö HRL.
- Compilation and evaluation of experience from emplacement of buffer and canisters, backfilling of tunnels, and estimation of acceptable water inflows for the applied methods.

2.12.2 Results

A report that describes the large series of experiments related to engineered barrier systems that have been conducted in SKB's underground laboratories and construction sites during the time period 1981 to 2003 is available in a draft version. The review of the draft report is in progress and the report will be published as an international progress report (IPR) in Äspö's report series.

2.13 Task Force on Engineered Barrier Systems

2.13.1 Background

The Task Force on Engineered Barrier Systems, which was initiated in 2000 to focus on the water saturation process in buffer, backfill and rock, has been on stand-by as long as the Prototype Repository EC project was operative, i.e. through the first quarter of 2004. However, the Task Force on EBS has now been activated to continue the modelling work in the Prototype Repository project within this frame, where also modelling work on other experiments can be conducted.

2.13.2 Results

A Task Force related meeting on buffer and backfill modelling was held in Lund in March /Pusch and Svemar, 2004/. The participants were modellers representing waste-handling organisations in Europe, Japan and North America. The overall conclusion from the workshop was that modelling of some of the major physical processes in buffers and backfills can be made with sufficient accuracy. A number of important issues for further research in the framework of the Task Force were identified, e.g. prediction of access to water from the bedrock is required for adequate modelling of the hydration of buffers and backfills.

A planning meeting for the project took place in September and a kick-off meeting was held in October. At that meeting two tasks were chosen for the Task Force work, namely: (a) THM processes in buffer materials and (b) Gas migration in buffer material, having the objectives to:

- Verify the capability to model THM and gas migration processes in unsaturated as well as saturated bentonite buffer.
- Refine codes that provide more accurate predictions in relation to the experimental data.
- Develop the codes to handle three dimensions as standard (long-term objective).

3 Geo-science

3.1 General

Geo-scientific research is a part of the activities at Äspö HRL as a complement and an extension of the stage goals 3 and 4. Studies are performed in laboratory and field experiments as well as by modelling work. For rock mechanics is all SKB's work directed from the staff of Repository Technology having Äspö as its base. The major aims are to:

- Establish and maintain geo-scientific 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 measurements that can be used in site investigations.
- Determine the rock mechanics characteristics at potential repository depths at candidate sites.
- Develop methods for numerical modelling of stress and strain evolution, and methods for in situ stress measurements.

3.2 Geological mapping and modelling

3.2.1 Background and objectives

Geological mapping of all exposed rock surfaces is performed, in order to achieve a successively better picture of the geology in the Äspö rock volume. Also drill cores are logged and mapped. This increasing amount of data contributes to an improved three dimensional RVS-model of the Äspö geology

A feasibility study concerning geological mapping techniques is performed in addition to the regular mapping. The aims of the feasibility study are to investigate the possible need for a new method for underground geological mapping in a future deep repository. The major reasons for performing this feasibility study and possibly identify a new rock characterisation system are aspects on the objectivity of a more automatic method. In addition, time required, precision in mapping and traceability are considered important parameters. At this initial stage in the feasibility study, the major objective is to identify different alternative methods and techniques that could be used as a base for a new rock characterisation system.

3.2.2 Results

During 2004 new deposition holes have been drilled and geological mapping has been performed in deposition holes in TASQ and data has been reported into the SKB Sicada database. A discrepancy in the lithological terminology was identified with respect to rock names used in Äspö and in the site investigation in Oskarshamn and the lithological terminology has therefore been improved so that the names are compatible between Äspö and Oskarshamn site investigation.

The geological 3D-model of Äspö rock volume has been improved, mainly by local models of smaller rock volumes inside the Äspö volume. For example, a preliminary model of the KBS-3H rock volume has been established that will be improved during early 2005.

Investigations to identify suitable experiment rock volumes have been undertaken at several localities in Äspö HRL, for instance at the –450 m level for a borehole plug-test.

An undergraduate thesis from Lund University, which focused on structural control on fine-grained granite dykes in Äspö, was completed during the spring 2004. The results show that many of the dykes have been structurally controlled when intruded and that Äspö HRL is divided into different volumes of controlling structures. A new undergraduate thesis has been initiated that focuses on the genesis, geochronology and structural relations of a set of water conductive brittle fractures running in a northwest-southeast direction. Field work has been completed and results will be presented before summer 2005.

A feasibility study with the objective to investigate the possible need for a new method for underground rock characterisation has been started, the project Rocs (Rock Characterisation System). The feasibility study will be performed as a joint project with Posiva and with European experts as participants in the scientific committee. In order to investigate possible methods as alternative to the present manual mapping, tests have been performed on laser scanning. The scanning has been performed in drilled tunnel, blasted tunnel and in vertical and horizontal deposition holes.

3.3 Rock stress measurements

3.3.1 Background

To be able to make correct assessments of the in situ stress field from results from different types of rock stress measurement techniques it is important to know the limitations and shortcomings of the different measurement techniques. Rock stress measurements with different techniques (bore probe, doorstopper and hydraulic fracturing) have during the years been performed as well as numerical modelling of the stresses.

3.3.2 Results

Method for transient strain analyse of stress measurements by an over-coring method for isotropic conditions has been developed and published. The method is used as a standard procedure in the ongoing site investigations in Sweden. A project plan for the possibility to also do transient strain analyse on anisotropic rock was agreed upon between Posiva and SKB late 2004.

Positive experiences from back analyse of stresses based on convergence measurements was gained during tunnelling for the Apse project in 2003 /Staub et al. 2004/. The applied method covers a much larger volume than any borehole method, and seems to be reliable. However, it is also known that a significant deformation has occurred already when the installation for the convergence measurements can be done.

3.4 Rock creep

3.4.1 Background

The understanding of the material properties of rock and rock-mass are being developed. The objective with the work is to be able to develop better conceptual models for the influence of the rock damaged zone and rock creep on rock stability.

3.4.2 Results

A literature study and scooping numerical modelling with a three-dimensional coupled hydromechanical computer code (3Dec) have been performed. The reporting of the results from the modelling and the literature study is ongoing. The review of the literature study is finalised.

3.5 Äspö Pillar Stability Experiment

3.5.1 Background

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

A Pillar Stability Experiment 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.

3.5.2 Objectives

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

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

3.5.3 Experimental concept

To achieve the objectives a new drift was excavated in Äspö HRL to ensure that the experiment is carried out in a rock mass with a virgin stress field. In the new drift a vertical pillar is constructed in the floor between two large boreholes, each with a diameter of 1.8 m. The pillar is 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 was 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, LVDT's, thermistors and an acoustic emission system were used to monitor the experiment. The experiment drift has a rounded floor to concentrate the stresses in the centre of the drift, see Figure 3-1.

Figure 3-1. The experimental TASQ drift shortly after the excavation.

3.5.4 Results

It has been a successful year for the Pillar Stability Experiment. The major part of the field work has been accomplished resulting in a large and interesting data set. The year begun with the final preparatory work in the experiment volume before the heating and monitoring phase was initiated. During the autumn and winter the post characterisation programme was started and the monitored results begun to be summed up. Photographs of the spalling as it reaches one instrument level and a photograph from the removal of the spalling slabs are shown in Figure 3-2 and Figure 3-3.

Preparatory works

The first large hole was drilled in the end of 2003. In the beginning of 2004 the confinement equipment was installed in it and pressurised with a 0.7 MPa overpressure. The second large hole, in deposition hole scale, was then drilled so that a one metre wide pillar was created between the holes. There were spalling along the pillar wall in the second hole down to two metres depth. This was excellent news since the exact location of the equilibrium between the stress and rock strength now was known. The instruments for temperature and displacement monitoring were installed in the second hole as well as the electrical heaters in the four boreholes just outside the pillar. The acoustic system which was installed in 2003 was checked and calibrated.

Figure 3-2. *Photograph of spalling precisely as it has reached one instrument level.*

Figure 3-3. *Photograph of the pillar wall as the slabs are being removed from the bottom and up.*

Heating and monitoring

The power to the electrical heaters was turned on May 14. A few days thereafter acoustic emission counts were monitored at the notch and soon thereafter displacements were recorded at the first instrument level at 2.5 m depth. As the temperature increased in the pillar the spalling propagated down the hole. Displacements well correlated with acoustic emission responses were recorded at all the instrument levels located at approximately 2.5, 3.0, 3.5 and 4.1 m depth in the hole.

In mid July the spalling had propagated down to approximately 5 m depth. The acoustic emission frequency was low and the deformations had ceased. The experiment was now in a steady state and it was time to test the effect of the confining pressure. The pressure was dropped in steps of 50 kPa. The new pressure level was held until the acoustic emission associated with the pressure drop ceased. Another 50 kPa drop was then made.

Approximately one week after the removal of the confining pressure the heaters were turned off. All instruments were logging during the cooling of the rock, the displacements were thought close to zero during that period and the acoustic emissions very limited.

At regular intervals throughout the heating of the rock visits were made in the hole during which photographs were taken and sketches of the spalling propagation was made.

Post characterisation

After the rock had cooled down the slabs created during the spalling phase was removed from the open hole and stored. The hole was then laser scanned to provide a detailed survey of the final geometry of the damaged pillar.

At the end of the year the pillar should be sawn into five one metre high blocks that would be additionally characterised. To prevent the wire-saw from getting jammed a de-stressing slot had to be drilled outside the pillar volume. Modelling of the slot geometry was made and it was realised that the work was non trivial. The model indicated that there was a risk for damage of the pillar as the stresses re-distributed. The slot geometry giving the least damage was chosen but during the drilling the open hole was quite damaged. The spalled zone was deepened and the information about the notch geometry in 3D could not be retrieved. The blocks were though sawn out anyway to be able to create a detailed geological model. The sawing and removal of the blocks were not completely finished at the end of 2004.

3.6 Heat transport

3.6.1 Background

The deposit canisters generate heat due to radioactive decay. The temperature field in the repository depends on the thermal properties of the rock and the generated heat. The layout of the repository is dependent on the temperature field. The design criterion is the maximum temperature allowed on the surface of the canisters. A low thermal conductivity in the rock leads primarily to a larger distance between canisters than in the case of a high thermal conductivity.

3.6.2 Objectives

The aim of the heat transport project is to develop a strategy for site descriptive thermal modelling to decrease the uncertainties in the estimates of the temperature field in a repository. Less uncertain estimates of the temperature field make it possible to optimise the distance between canisters in the repository layout. The work includes measurements of thermal properties of the rock, examinations of the thermal conductivity distributions, analyses of thermal properties at different scales, and inverse modelling of thermal properties from the measured temperature – time relationship in the rock mass at the Prototype Repository. In order to determine the significant scale for the variation of thermal properties in a repository, a large number of numerical simulations are included in the work.

3.6.3 Results

The results of the project are going to be reported during 2005. However, some of the results from the project are presented below.

Thermal conductivity measurement with different sensor size

Measurements in laboratory of the two properties thermal conductivity (λ) and thermal diffusivity (κ) have been conducted using the TPS (Transient Plane Source) method. The purpose of the measurements was to study scale effects of the thermal properties and thereby two different sensor sizes have been used.

The sampling layout was designed to serve the requirements to examine scale factors of thermal properties. The chosen part of the drill core was determined as Ävrö granite. Three sample groups with five samples in each were taken along the drill core. The individual samples were taken 0.1 m apart and the sample groups were placed approximately 10 m apart. The results of the measurements with two different sensor sizes are illustrated in Figure 3-4.

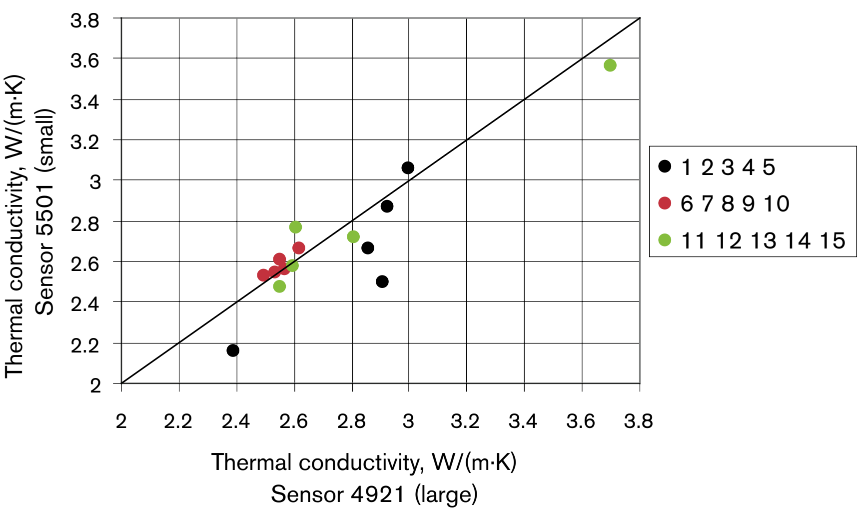


Figure 3-4. *Comparison of thermal conductivity measured with two sensor sizes. Presentation with sample numbers separated in sample groups.*

For thermal conductivity there is a tendency that the large sensor gives a slightly higher value than the small sensor. This difference is however not significant at the 5% level (paired t-test). For heat capacity there is also a non-significant tendency for larger values with the large sensor. There is no significant difference in variance between the small and large sensor for the thermal conductivity measurements. However, for heat capacity there is a significant difference in variance.

Methodology of thermal domain modelling

A methodology for lithological domain modelling and modelling of scale dependency has been developed. This was not originally in the plan for 2004.

The methodology takes into account:

- The decrease in variance due to up scaling from small to larger scales.
- The variance contribution due to spatial variability within rock type. The spatial variability is determined by a relationship between density and thermal conductivity /Sundberg, 2002; 2003/.
- Variability due to the presence of different rock types in the lithological domain. The variability is more pronounced where the difference in thermal conductivity is large between the most common rock types of the domain.
- Different modelling approaches have been conducted. The main modelling approach for a lithological domain where borehole density loggings are possible to use is illustrated in Figure 3-5.

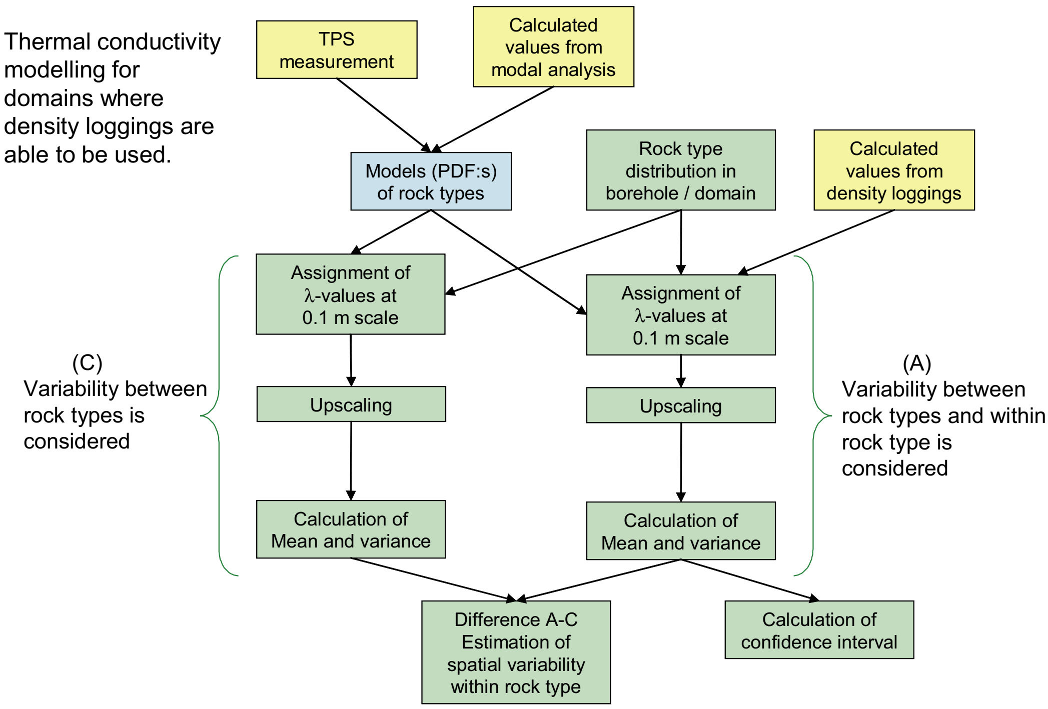


Figure 3-5. Main approach (A) and (C) for modelling of thermal conductivity for domains where density loggings are able to be used. Yellow colour indicates the data level, blue the rock type level and green the domain level.

3.7 Seismic influence on the groundwater system

3.7.1 Background and objectives

The Hydro Monitoring System (HMS) registers at the moment the piezometric head in 409 positions 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.

The data in the database are assumed to bear witness of different seismic activities in Sweden but also abroad, dependent on the magnitude of the event, as well as the position of the epicentre. By analysing the data on changes in the piezometric head at Äspö connections to specific seismic events are expected to be established.

3.7.2 Results

Data from the HMS are stored in the database pending analysis. A special computer code is under development that may run and compare the HMS database with other databases, like Sicada or the national seismological database. For example, the earthquake in the Indian Ocean on the December 26 was registered by the HMS system after 23 minutes.

4 Natural barriers

4.1 General

To meet Stage goal 3 for the work at Äspö HRL, 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, and 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. Processes that influence migration of species along a natural rock fracture are shown in Figure 4-1. The programme includes projects with the aim to evaluate the usefulness and reliability of different models and to develop and test methods for determination of parameters required as input to the models. The overall purposes are to:

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

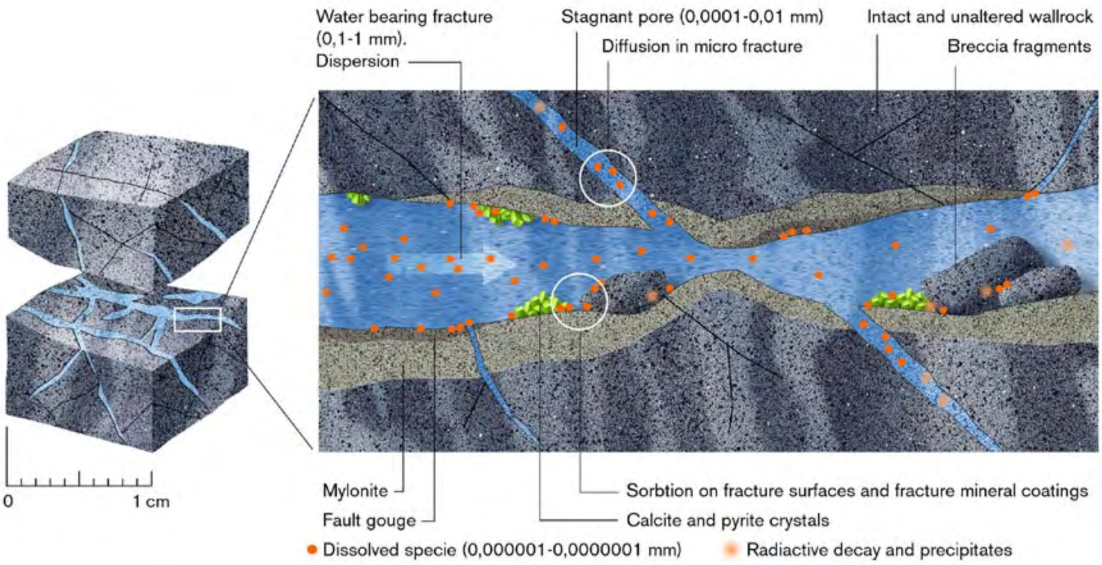


Figure 4-1. *Processes studied in the True experiments that influence migration of species along a natural rock fracture.*

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

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

4.2 Tracer Retention Understanding Experiments

During the year significant progress has been made on three different fronts – in the laboratory, in the field and predictive modelling. In the laboratory, sorption experiments have been successfully conducted on fracture rim zone and fault gouge materials which experimentally corroborate earlier calculated estimates. In the field, and subsequently in the laboratory, resin-impregnated sections in boreholes as part of the Fault Rock Zones Characterisation Project have been over cored, successfully retrieved and finally sectioned and analysed, producing an improved visualisation of the internal structure of conductive fractures similar to those investigated in the True in situ test programmes. In addition, predictions of the True Block Scale in situ tests with radioactive sorbing tracers in a new part of the True Block Scale rock volume have been successfully carried out using the accumulated geological knowledge base from the True programme, and compared with experimental outcome.

With these elements most of the important open issues remaining at the time of termination of True Block Scale project have been successfully addressed. Furthermore, with the successful application of the Fault Rock Zones Characterisation programme, the True team is ready to return to the True-1 site to investigate the internal pore space of the investigated Feature A.

4.2.1 True Block Scale Continuation

Background

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 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 without developed wall rock alteration and fault gouge signatures.

Results

Results from True Block Scale Continuation are available from the BS2b in situ tests and the model predictions of the in situ tests with radioactive sorbing tracers.

In situ tests

During the year the premises for carrying out experiments with radioactive sorbing tracers have been substantiated and demonstrated. The results of the underlying Pre-tests are documented /Andersson et al. 2004/. The results identified section KI0025F03:R3 (Structure #19) as the most suitable pumping section. Injection sections were established in KI0025F03:R2 (Background fracture BG#1, formerly named Structure #25) and in section KI0025F02:R3 (Structure #19). The specific objectives for the BS2b tracer tests were to study /Andersson et al. 2005/:

- Sorbing tracer transport in a single Type 1 (fault) structure /Dershowitz et al. 2003/ over length scales of tens of metres. The 19.5 m long flow path between sections KI0025F02:R3 and KI0025F03:R3 in Structure #19 was used.
- Sorbing tracer transport in a flow path involving a single background fracture of Type 2 (non-fault, cf /Dershowitz et al. 2003/) connected to a major Type 1 structure. The only flow path available for tracer experiment addressing this type of transport was the 22 m long flow path between section KI0025F02:R2 (Background fracture BG#1) and section KI0025F03:R3 (Structure #19).

To fulfil the demand of having tracers of different sorption strength, it was considered as advantageous if a palette of sorbing tracers of variable sorption strength could be used for each flow path. Based on available isotopes, the following selection was done:

- Slightly sorbing tracers: $^{85}Sr^{2+}$ for the fast flow path (KI0025F02:R3 to KI0025F03:R3) and $^{22}Na^{+}$ for the slow flow path (KI0025F02:R2 to KI0025F03:R3).
- Moderately sorbing tracers: $^{86}Rb^{+}$ for the fast flow path and $^{133}Ba^{2+}$ for the slow flow path.
- Strongly sorbing tracers: $^{137}Cs^{+}$ for the fast flow path and $^{54}Mn^{2+}$ for the slow flow path.

The sorbing tracers were also complemented by two non-sorbing tracers in each flow path:

- $^{131}I^{-}$ together with ^{160}Tb-DTPA as tracers for the fast flow path.
- HTO together with ^{155}Eu-DTPA as tracers for the slow flow path.

The tracer tests were performed by establishing a radially converging flow field with a constant withdrawal rate in the selected sink section KI0025F03:R3 (Structure #19). The withdrawal rate was established using the maximum sustainable flow (2.3–2.5 l/min).

Radioactive tracers were injected in the selected injection sections KI0025F02:R2 (BG#1) and KI0025F02:R3 (Structure #19) as decaying pulses with simultaneous injection of water (unlabelled formation water) creating a slight excess pressure and thus, a weak dipole flow field. Samples were automatically withdrawn both in the injection and withdrawal sections and on-line γ-detectors were used. Examples of breakthrough curves for the flow path in Structure #19 are presented in Figure 4-2.

Model predictions

Predictions have been carried out by four independent modelling teams representing the True Block Scale Continuation partners. The modelling groups are briefly presented in Table 4-1. More details on the underlying numerical codes and their underlying assumptions may be found in /Poteri et al. 2002/.

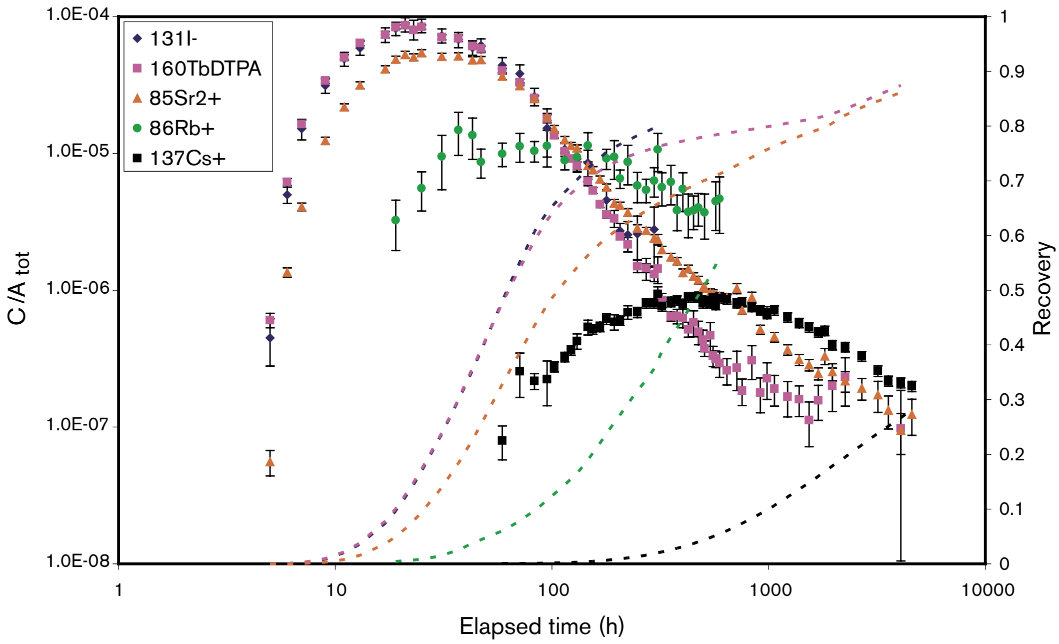


Figure 4-2. *Tests with radioactive sorbing tracers between KI0025F02:R2 and KI0025F02:R3 (both in Structure #19). Shown are breakthrough curve and cumulative breakthrough.*

Table 4-1. Overview of modelling approaches.

Modelling team	Basic modelling approach
Posiva – VTT Energy (Finland)	Posiva stream tube approach /Poteri et al. 2002/, Transport model takes into account advection along the fractures, matrix diffusion and sorption in the immobile pore space. Surface sorption on the fracture walls was not modelled but the diffusion into the pore space of the fracture coating and sorption in the pore space of the coating was directly modelled.
ANDRA-Itasca (France)	Channel Network/Discrete Fracture Network approach (3FLO) with a regular grid of pipes on each feature. Feature intersections are also described as pipes. Full mixing at pipe intersections and no longitudinal dispersion in pipes assumed. Matrix diffusion: from each pipe, infinite medium, homogeneous.
JNC-Golder Associates (Japan/USA)	Channel Network/Discrete Fracture Network approach employing conventional advection-dispersion-diffusion and multiple immobile zones.
SKB KTH-WRE (Sweden)	Lagrangian stochastic advection-reaction framework /Cvetkovic et al. 1999/.

As a basis for the predictions, the modelling teams made use of all the accumulated wealth of geological information from the True-1 and True Block Scale projects. Specifically, the project team provided details on the intercepts of the injection and pumping sections and the results of the tracer pre-tests. Furthermore, the modelling teams had access to early results from the laboratory sorption experiments on fracture rim zone and fault gouge (see below) and results from the Fault Rock Zones Characterisation Project (see below). The blind predictions were presented, discussed and compared with in situ test results at a Technical Committee meeting early November 2004. The predictions for the test in Structure #19 involving injection of the sorbing tracers Sr, Rb, and Cs are presented in Figure 4-3.

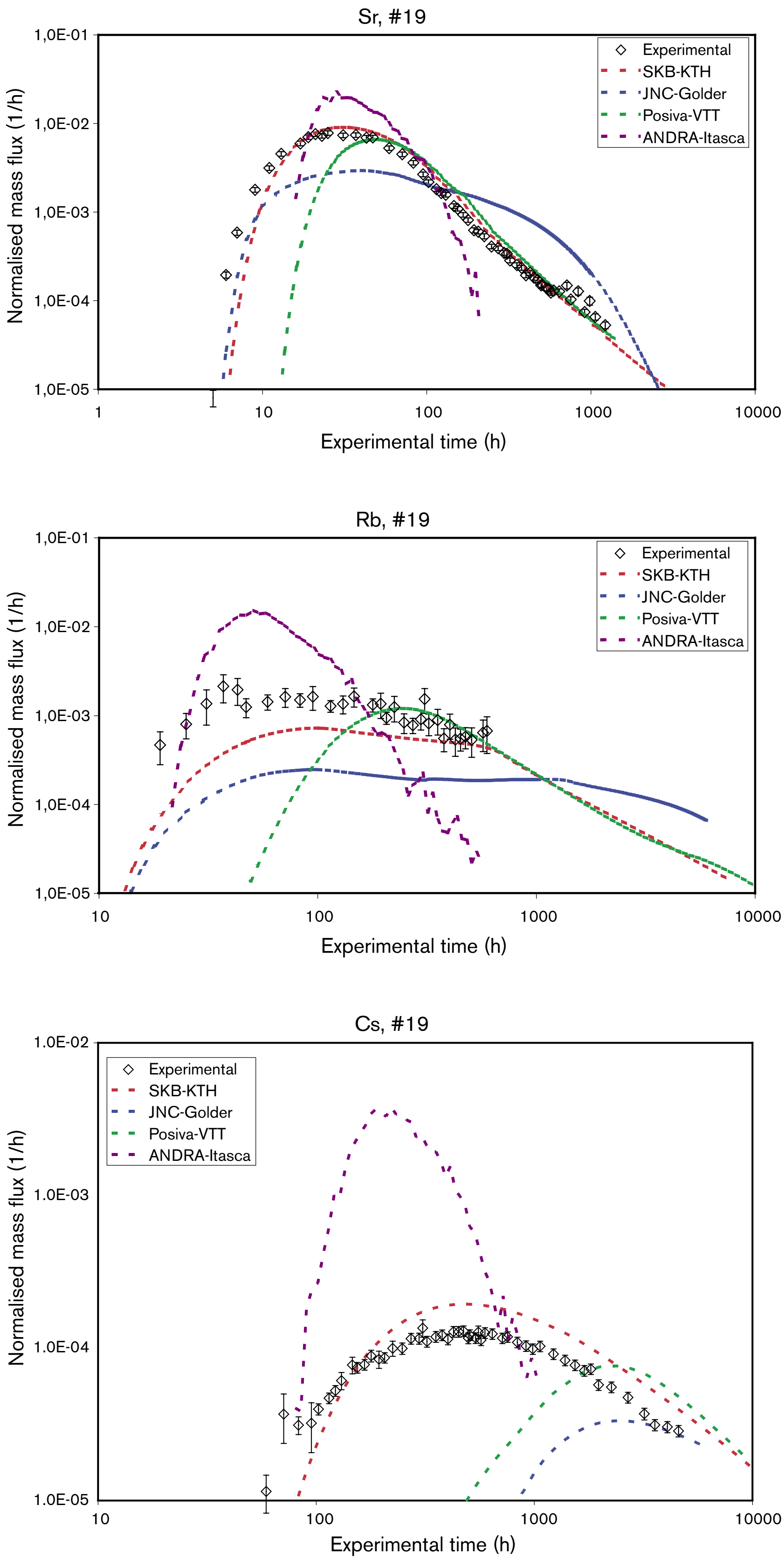


Figure 4-3. *Model predictions of BS2b Sorbing experiment in the single structure flow path between KI0025F02:R3 –> KI0025F03:R3 (both in Structure #19) over a distance of 19.5 m. In order of increased sorbtivity: a) Strontium, b) Rubidium, c) Caesium.*

A close scrutiny of the predictions compared with the experimental outcome show that most modelling teams provide equitable predictions of the least sorbing tracer (Sr), whereas differences become highly visible in the case of Caesium (^{137}Cs), where the predictions by the SKB-KTH-WRE team shows a very good correspondence with the measured breakthrough. ^{137}Cs has previously been employed in True-1 /Winberg et al. 2000/ and in True Block Scale /Andersson et al. 2002a; Poteri et al. 2002/. The predictions for the flow path which involve a background fracture (BG#1) and the larger structure (#19) show a surprisingly large spread in the predictions for the low-sorbing ^{22}Na. For the more strongly sorbing tracers, ^{133}Ba and ^{54}Mn, the predictions also show a significantly larger spread, flanking the experimental breakthrough.

4.2.2 True-1 Continuation

Background

The True-1 Continuation project is a continuation of the True-1 experiments, and the experimental focus is here placed on the True-1 site. The discussion and outcome of the 4th International Äspö Seminar (focused on the First True Stage) re-emphasised the need for conducting the planned injection of epoxy resin at the True-1 site. However, before conducting such an impregnation, some complementary cross-hole hydraulic interference tests combined with tracer dilution tests are foreseen. These tests are intended to shed light on the possible three-dimensional aspects of transport at the site. The planned tests would employ both previously used sink sections and some not employed in the already performed tests.

A complication for the scheduling of planned future work lies in the fact that the True-1 and Long Term Diffusion Experiment (LTDE, see Section 4.3.1) sites are hydraulically connected. In view of the urge for a relative hydraulic tranquillity on the part of LTDE, a priority for advancing LTDE has been set by SKB. Consequently, the resin impregnation at the True-1 site will be postponed until vital parts of LTDE have been accomplished. According to the present plans resin injection will be possible 2006 at the True-1 site.

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.
- Provide an improved understanding of the constitution, characteristics and properties of fault rock zones (including fault breccia and fault gouge).
- Provide insight into the three-dimensionality of the rock block studied as part of the First True Stage such that the role and effects of the fracture network connected to Feature A on the performed tracer tests can be assessed.
- Test a methodology to estimate fracture aperture from radon concentration in groundwater and radon flux from geological materials.
- 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 identified remaining field and laboratory activities related to the True-1 site includes:

- Complementary cross-hole interference, tracer dilution, and tracer tests with conservative tracers.
- Water sampling and analyses including analyses of radon concentration in groundwater and measurements of radon flux from various geological materials and subsequent evaluation.
- 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.
- Batch sorption experiments on rim zone and fault gouge materials from the True Block Scale site and from other locations along the access tunnel, including zones investigated as part of the Fault Rock Zone characterisation project.
- Injection of epoxy resin into the previously investigated Feature A, with subsequent excavation and analyses.

Results

Results from the True-1 Continuation project are available from the Fault Rock Zones Characterisation project and from the complementary laboratory tests of the sorption characteristics of fracture rim zone and fault gouge materials using the radioactive sorbing tracers employed in the True Programme. Furthermore, progress has been made on production of three scientific articles in a series accounting for the True team analysis of the True-1 experiment.

Fault Rock Zones Characterisation

Resin injection with uranine-tagged epoxy was conducted in packed-off sections hosting identified conductive structures in 7 of 16 original 76 mm near-horizontal exploration boreholes drilled at four localities distributed along the Äspö access tunnel. These 7 boreholes are summarised in Table 4-2, cf /Mærsk Hansen and Staub, 2004/. A comprehensive preparation process preceded the subsequent over-coring process. This included design and manufacturing of core barrels of variable length, hydraulic core-sectioning devices to be applied in the borehole and tools to be employed in the reclamation of the cores from the boreholes. The weight of the cylindrical overcore is some 150 kg/m.

Table 4-2. Borehole-specific data for the seven injection holes that have been over cored.

Hole ID	Pilot length (m)	Target Zone position (m)	Packer position (m)	Grouted length (m)	Grout take (litres)	Specif grout take (l/m)	Over-coring length (m)	Target core length (m)
KA1596A02	5.62	4.32–5.00	3.45–3.63	1.99	0.1214	0.06	6.15	4.3–6.15
KA1596A04	4.1	2.05–3.05	1.10–1.28	2.82	0.1387	0.05	3.2	1.9–3.2
KA2169A01	3.62	2.30–2.65	1.90–2.08	1.54	1.054	0.68	3.6	1.9–2.6
KA2169A02	4.32	2.70–3.35	2.60–2.78	1.54	0.44	0.29	4.4	No core
KA2169A03	4.28	3.70–4.20	3.50–3.68	0.6	0.26	0.43	4.4	3.55–4.4
KA2423A03	2.93	2.20–2.65	1.80–1.98	0.95	0.5635	0.59	3.1	1.9–3.1
KA2549A01	3.69	1.67–2.24	1.35–1.53	2.16	0.690	0.32	2.4	1.3–2.4

Furthermore, a careful drilling scheme was set up for the over-coring and core retrieval, adapted to the conditions of the individual borehole /Mærsk Hansen and Staub, 2004/. Despite the detailed planning, there was a call for improvisation, in particular when facing the problem of sectioning the core within an epoxy impregnated section, including a polyethene dummy cylinder. The latter with its plastic behaviour proved more difficult to section than expected. Apart from this latter generic problem a very clear correlation was found between the resin take and the competence of the retrieved core. For example, the over-coring of the impregnated parts of Zone NE-2 in boreholes KA1596A02 and KA1596A04 did not succeed, as was the case for borehole KA2169A02. This was attributed to high clay content and the fact that the relative resin take was so small, as shown in Table 4-2, reflecting the low hydraulic conductivity of the material. The outcome of the over-coring of the remainder of the boreholes was successful in terms of integrity of the retrieved core and also with regards to resin impregnation. However, the most successful outcome was obtained for borehole KA2423A03 where an almost 10 cm wide structure, featured by a mylonitic precursor, was successfully impregnated. Figure 4-4 shows a composite of the impregnated core, the result of a fold-out mapping of the mantle surface

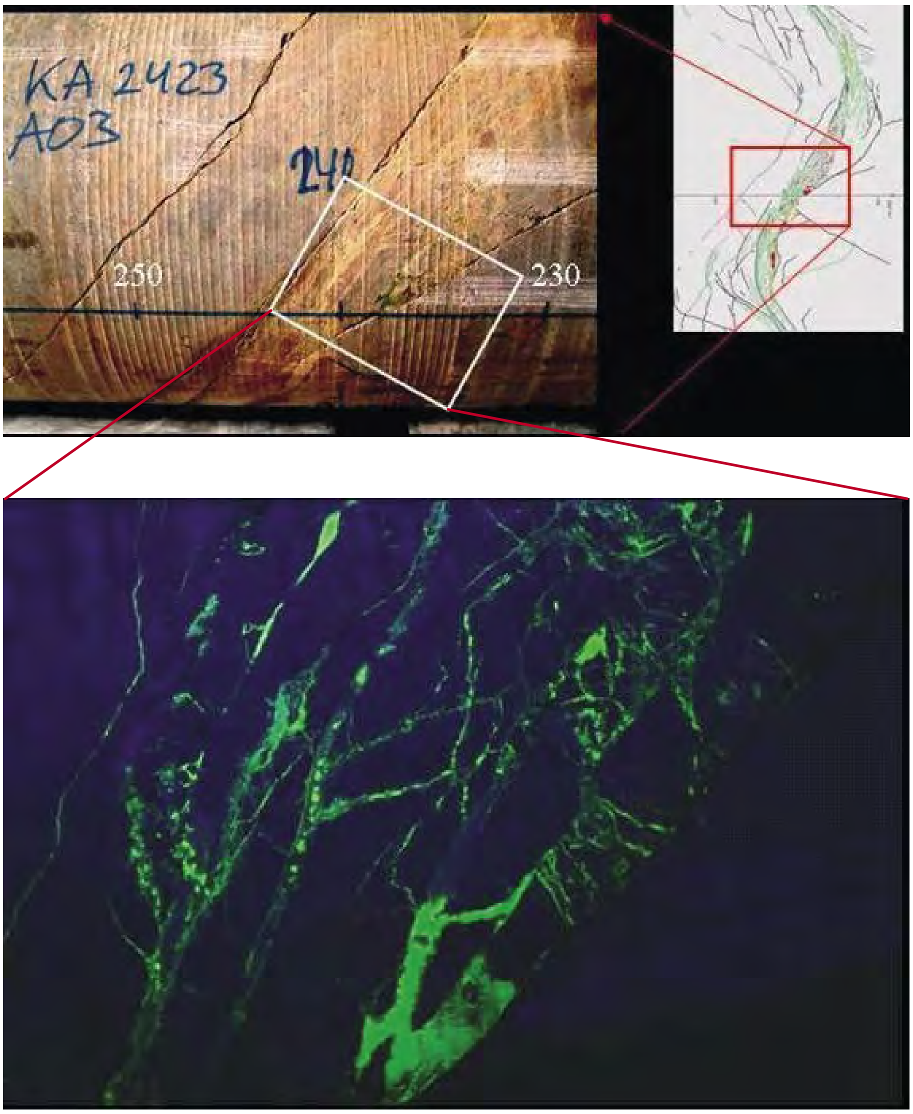


Figure 4-4. *Composite showing mantle surface of overcore, geological mapping on transparent foil and blow up under UV light.*

using transparent foil, and a detailed image of the core under UV light. The photograph in no way can make justice to the result of the impregnation. In fact, a close scrutiny shows pore spaces ranging in size from microscopic fabrics and textures to filled discrete fractures on the sub centimetre scale. Subsequently, sectioning plans were devised for all cores in order to facilitate easy access and transport of the core pieces. An archive "half-core" was in all cases left at the Äspö HRL.

Core material (fault gouge) from the damaged KA1596A04 core was immediately put into plastic bags which were subsequently put under water to ensure no or minimal exchange with atmosphere. Materials of variable size were taken to the Swedish National Testing and Research Institute (SP) and to the University of Helsinki for porosity determination. The analysis at SP was conducted as ordinary water saturation tests. At the University of Helsinki Radiochemistry department, a trial PMMA (Poly-methyl methacrylate) impregnation was attempted on one sample. The results from the SP indicated porosities in the order of 5 to 15% (by volume), whereas the PMMA injection of one sample indicated an average porosity in the order of 3% (by volume).

The cores, and particularly the core from KA2434A03, were analysed using image analysis techniques. Figure 4-5 shows a sequence of images, from normal light, UV light through binary imaging and a Ferret box. The latter box defines the volume over which porosity is defined. The latter is done across a series of slabs, by which a 3D estimation of the porosity is obtained. For the B2 sample a 3D porosity of 18% (by volume) is obtained whereas the B3 sample shows a porosity of about 8%. Apart from the porosity, various other attributes

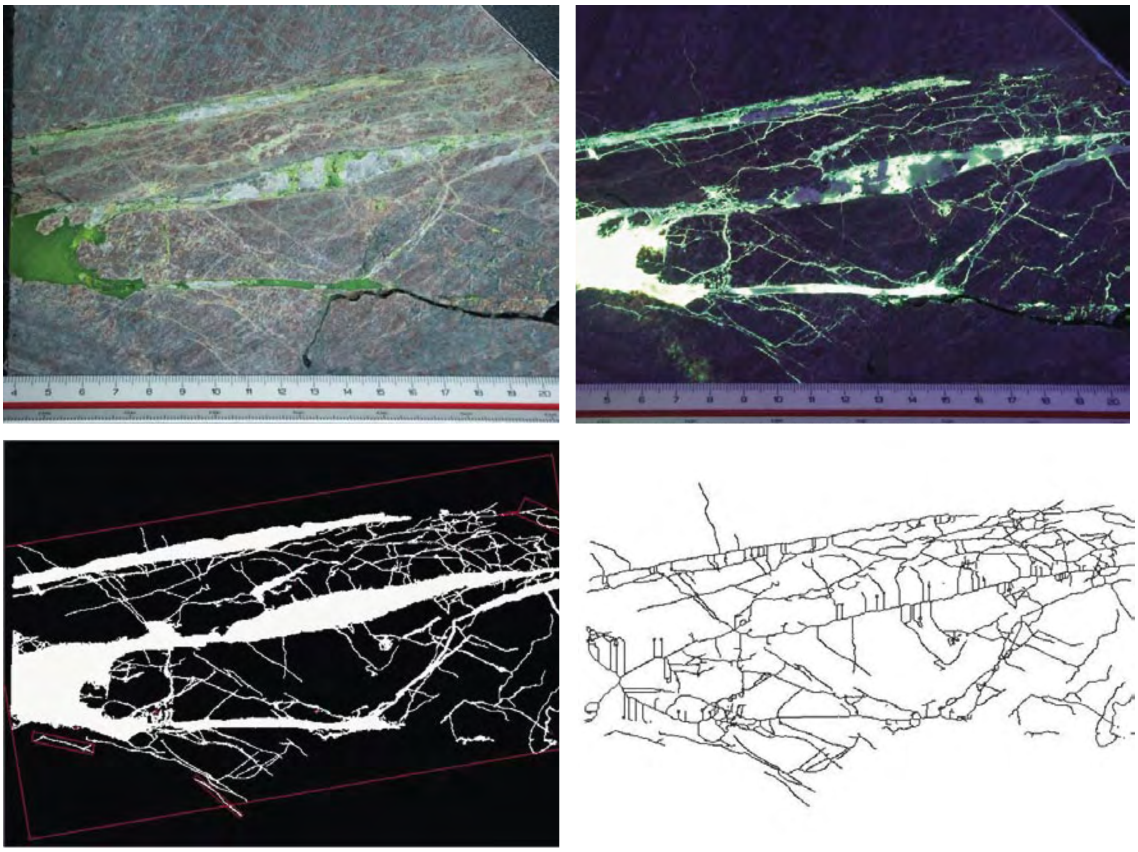


***Figure 4-5.** Example representation of image analysis of photographs of Sample B2-a1 from KA2423A03. a) Original image under ordinary light (169×127 mm), b) UV light, c) Binary image with Ferret box and d) Network image.*

for the fracture network and the individual fractures are investigated; Fracture branch number and distribution, Junction and fracture block boundary co-ordinates, fracture data in 3D such as corner co-ordinates, orientation and thickness etc, mineral size and shape distribution inside the network. The analysis also potentially allows mapping of entities related to radionuclide retention (a_r, i.e. the fracture surface area per volume of rock, but here in terms of the mapped fracture length per unit area).

The pore space analysis will be supplemented by detailed structural analysis and mineralogical and geochemical analyses of selected sections (slabs) of the epoxy-impregnated cores.

True-1 articles

Complete drafts have been produced for the first two of the planned scientific articles accounting for the True team analysis of the True-1 experiments /Winberg et al. 2000/; (1) Test results, modelling and effective parameter estimation, (2) Characterization of in situ retention properties, and (3) Interpretation of tracer test results using prior information on retention properties. All three titles are to be regarded as tentative at this stage.

Complementary laboratory sorption experiments

Geological material from fracture rim zones and in particular from unconsolidated fine-grained fault gouge is scarce. Laboratory sorption characteristics of these materials were non-existent for Äspö rock. Significant retention effects were attributed to these types of materials by /Mazurek et al. 2002/ for the interpretation of the True-1 experiments /Winberg et al. 2000/. In the case of the True Block Scale experiments /Winberg et al. 2003a; Andersson et al. 2002b/ the sorption coefficient (K_d) of the fracture rim zone material and fine-grained fault gouge were calculated using the mineralogical composition, CEC of pure mineral phases, selectivity coefficients and groundwater chemistry. These calculations were used for the predictions and evaluations of the True Block Scale experiments with sorbing tracers /Poteri et al. 2002/. In the currently conducted laboratory sorption experiments, site-specific materials from multiple localities of conductive structures of variable dignity and texture have been analysed. These include Structures #19, #20 and #22 at the True Block Scale site, and the major fracture zones NE-1, NE-2 and EW-1. The experimental details, which are described in /Byegård, 2005/, involve the tracers Na^+, Ca^{2+}, Rb^+, Cs^+, Ba^{2+} and Mn^{2+}. The experiments were evaluated in terms of sorption coefficients (K_d and K_a). Figure 4-6 shows an example graphical comparison between measured and calculated sorption coefficients (K_d) for the fault gouge material (< 0.125 mm). The results show that the calculated predictions overall compare well with the evaluated sorption coefficients based on the laboratory experiments. This finding is highly satisfactory in relation to the prediction and evaluation work performed in conjunction with the True Block Scale Project, but also its further use in conjunction with work on Task 6 in the Äspö Task Force work, cf Section 4.8.

In summary, the results underway within the Fault Rock Zones Characterisation and complementary laboratory sorption work fills many of the voids in terms of supporting in situ and laboratory data identified at the conclusion of the True Block Scale project.

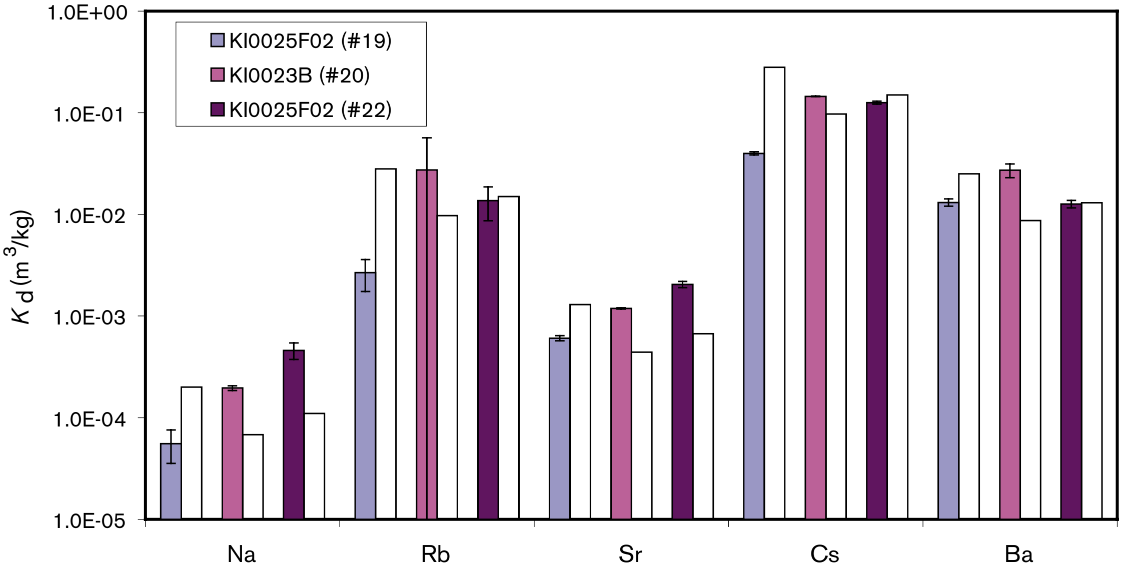


Figure 4-6. *Comparison between predicted K_d (hatched) and K_d evaluated from laboratory experiments. From /Byegård, 2005/.*

4.3 Long Term Diffusion Experiment

4.3.1 Background

The Long Term Diffusion Experiment (LTDE) constitutes a complement to performed diffusion and sorption experiments in the laboratory, and is a natural extension of the performed in situ experiments, e.g. the True-1 and the True Block Scale experiments. The difference is that the longer duration (approximately 4 years) of the experiment is expected to enable an improved understanding of diffusion and sorption both in the vicinity of a natural fracture surface and in the matrix rock.

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

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

4.3.2 Objectives

The objectives of the Long Term Diffusion Experiment project are to:

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

4.3.3 Experimental concept

A core stub with a natural fracture surface is isolated in the bottom of a large diameter telescoped borehole. 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. A cocktail of non-sorbing and sorbing tracers are circulated in the test section for a period of approximately 4 years after which the core stub is over-cored, and analysed for tracer content and tracer fixation, see Figure 4-7.

The experiment is focussed on a typical conductive fracture identified in a pilot borehole (KA3065A02). A telescoped large diameter borehole (300/197 mm) (KA3065A03) is 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 mantel surfaces of the two boreholes.

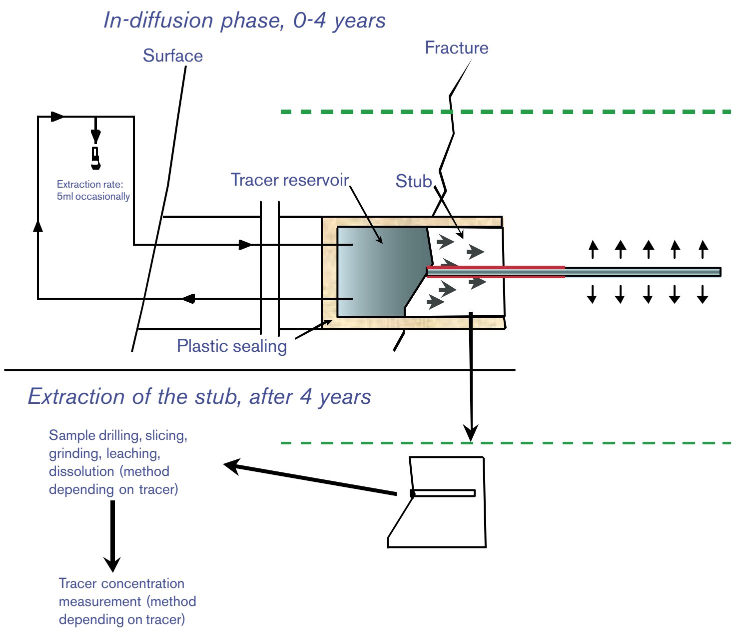


***Figure 4-7.** LTDE experimental concept including injection borehole in contact with a fracture surface.*

The natural fracture as seen on the surface of the stub is sealed off with a polyurethane cylinder and a peek lid, which constitutes a "cup-like" packer. The remainder of the borehole will be packed off with a system of one mechanical and two inflatable packers. The small diameter (36 mm) borehole is packed off using a double packer system leaving a 300 mm long section that will be exposed for the radionuclides. The system of packers and an intricate pressure regulating system will be used to eliminate the hydraulic gradient along the borehole, see Figure 4-8.

During the circulation of tracer, samples of water will be collected at various times over the duration of the experiment. The redox situation in the circulation loop will be monitored continuously with a flow through an electrochemical cell, which will measure pH, Eh and temperature. Strategically positioned filter will ensure limited build-up of microbes in the water circulation loop. After completion of tracer circulation, the core stub is over-cored, sectioned and analysed for different radionuclide tracers.

The project also involves a variety of mineralogical, geochemical and petrophysical analyses. In addition, laboratory experiments with the core material from KA3065A03 (Ø 277, 177 and 22 mm) and the fracture "replica" material will be performed. Both "batch" sorption and through diffusion experiments are planned.

The drilling of the telescoped large diameter experimental borehole was performed with a high degree of interactivity between; careful iterative drilling in short uptakes (particularly in the inner part of the borehole), BIPS imaging, core examination and on-site structural modelling/updating of structural model. Despite these the resulting stub turned out three times longer (150 mm) than originally planned. The situation was analysed in a series of in situ and laboratory measurements and modelling, which showed that the core stub effectively is disturbed throughout its entire length.

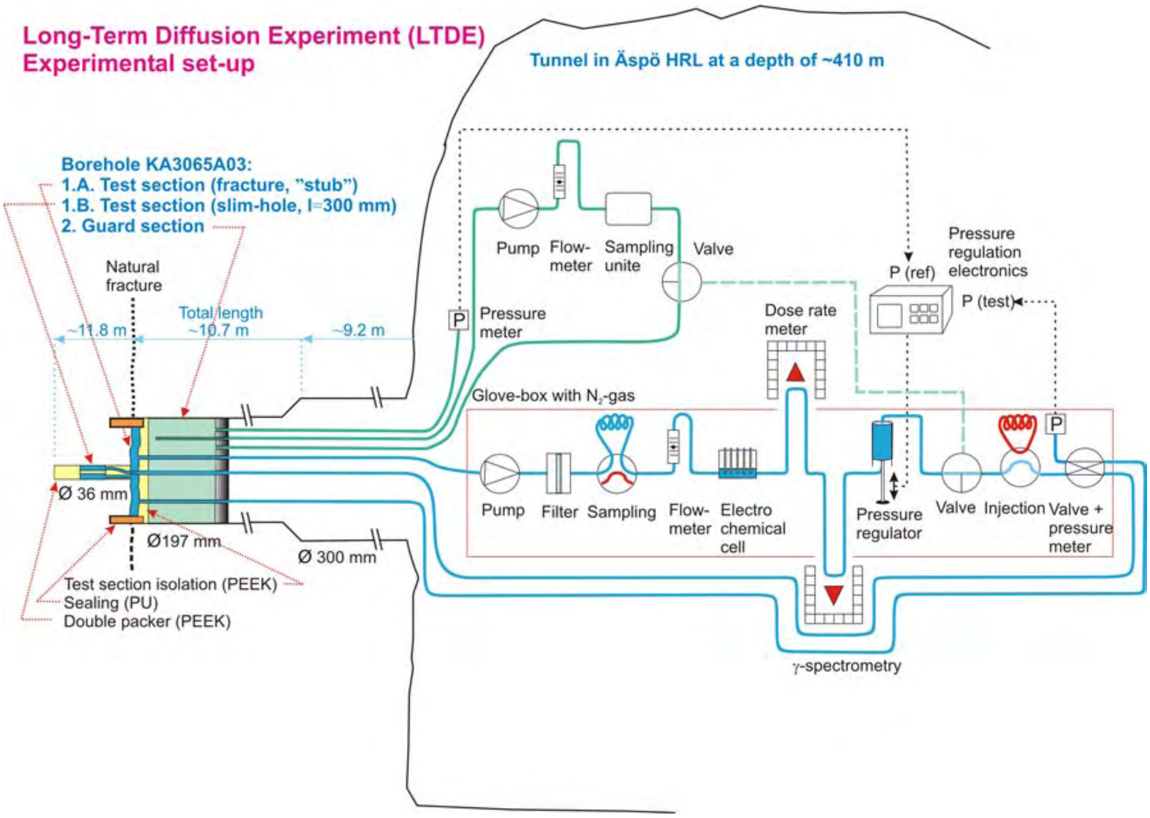


Figure 4-8. LTDE experimental set-up in the experimental borehole including the water circulation system to the test-section and the hydraulic pressure control system.

A 36 mm borehole was drilled in 2001 as an extension of KA3065A03 into the intact matrix rock. Characterisation of the experimental borehole KA3065A03 and a structural model of the LTDE site based on boreholes KA3065A02 and KA3065A03 is presented in a separate report /Winberg et al. 2003b/.

4.3.4 Results

During 2004 a hydrogeological pre-test programme was completed. The programme included evaluation of the hydrological conditions in the vicinity of the experimental borehole, KA3065A03, and possible hydraulic interferences from other activities in Äspö HRL. Results showed that it is possible to keep the hydraulic conditions under control, i.e. small pressure changes, at the LTDE site if boreholes intersecting the NW-2 zone are kept closed during the course of the experiment. It was also demonstrated that in the case of a leakage of radioactive tracers from the test section in borehole KA3065A03, the radioactive leakage can be withdrawn in the pilot borehole, KA3065A02.

Within the framework of the Äspö HRL collaboration between SKB and OPG supporting laboratory experiments on core samples from the LTDE borehole KA3065A03 has been initiated at AECL in Canada. The experimental programme consists of a radial diffusion experiments, diffusion cell experiments, porosity measurements, and permeability measurements. The radial diffusion experiment and porosity measurements started in December. The complete set of laboratory experiments are planned to be accomplished in 2005.

The installation test programme focused on system function control and simulations of extreme experimental conditions have been accomplished. The tests resulted in some necessary modifications in the electronics of the pressure regulation device and in the electronics for the electrochemical cell. The modifications are in progress.

4.4 Radionuclide Retention Experiments

4.4.1 Background

The retention of radionuclides in the rock matrix is one of the mechanisms that contribute to retardation of radionuclides released from the waste form in a deep repository. 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 very difficult to conduct. Even though the experiences from different scientists are uniform it is of great value to be able to demonstrate the results of the laboratory studies in situ, where the natural contents of colloids, of organic matter, of bacteria etc are present in the groundwater used in the experiments. A special borehole probe, Chemlab, has been designed for different kinds of in situ experiments where data can be obtained representative for the properties of groundwater at repository depth.

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

4.4.2 Objectives

The objectives of the radionuclide retention experiments are to:

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

4.4.3 Experimental concept

Chemlab 1 and 2 are borehole laboratories built into probes, in which in situ experiments can be carried out under ambient conditions with respect to pressure and temperature, and with the use of natural groundwater from the surrounding rock, see Figure 4-9. 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 4-10 the principles of the Chemlab 1 and Chemlab 2 borehole laboratories are given.

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

- Diffusion of cations (Cs^{+}, Sr^{2+}, and Co^{2+}) and anions (I^{-} and TcO^{4-}) in bentonite (completed and reported /Jansson and Eriksen, 1998; 2001; 2004/).
- The influence of primary and secondary formed water radiolysis products on the migration of the redox-sensitive element technetium (completed and reported /Jansson et al. 2004/).
- Migration of actinides (americium, neptunium, and plutonium) in a rock fracture (in progress /Kienzler et al. 2003a;b/).

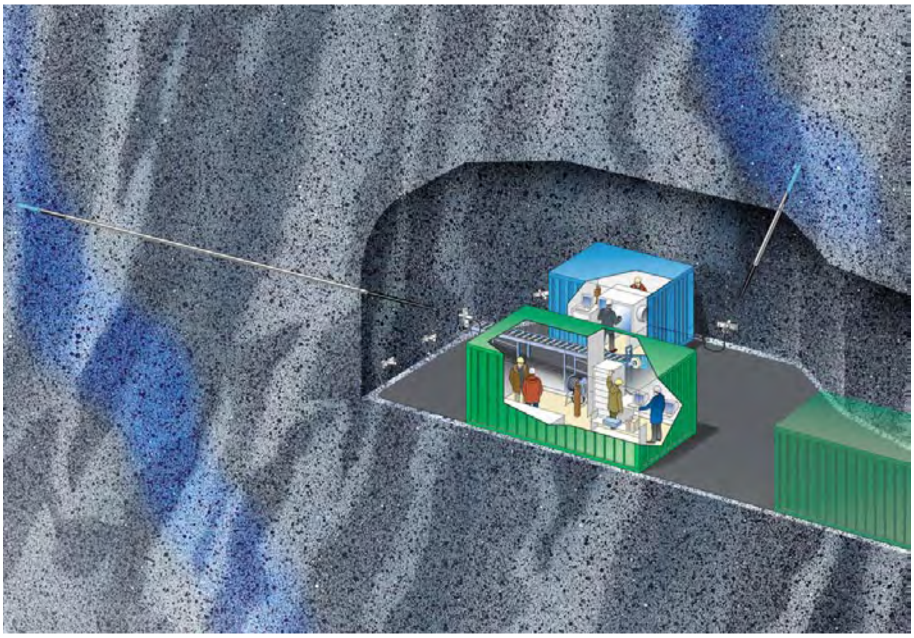


Figure 4-9. *Illustration of the experimental site of the Radionuclide Retention Experiments.*

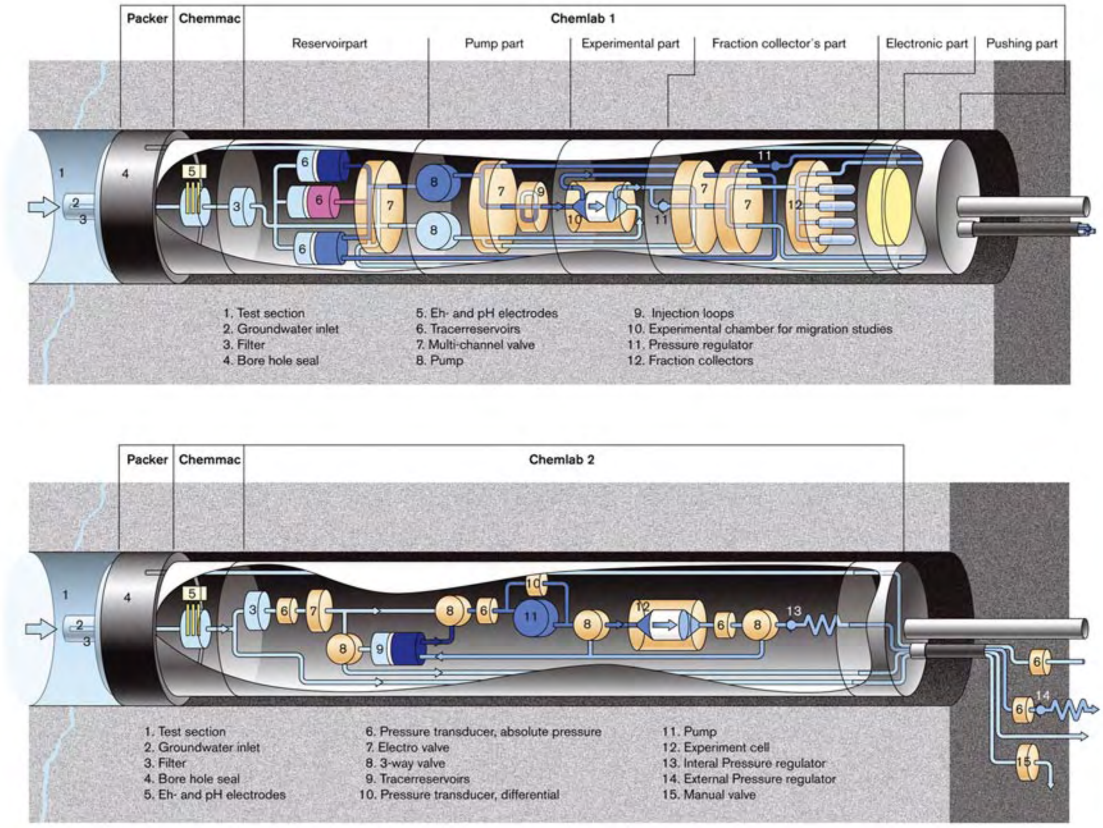


Figure 4-10. *Schematic illustration of Chemlab 1 and 2 borehole laboratories.*

4.4.4 Results

Radiolysis experiments

In the end of 2002, two kinds of radiolysis experiments in Chemlab 1 were started. In the indirect radiolysis experiments the groundwater is irradiated before it comes in contact with the experiment cell containing bentonite and reduced technetium. Radicals produced from water radiolysis will not reach the experiment cell, but the molecular products (H_2O_2, O_2, and H_2) will influence the redox chemistry in the cell. In the other type, direct radiolysis experiments, the irradiation source is placed in the experiment cell, close to the reduced technetium, and thereby the radicals produced will play a role.

The major conclusions are that technetium was to some extent oxidised in the direct radiolysis experiment and had started to diffuse whereas in the indirect radiolysis experiment technetium was only found in its reduced form. The results are published in a technical report /Jansson et al. 2004/

Migration of actinides

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

In these experiments a cocktail containing actinides is added to groundwater before pumping it through a longitudinal natural fracture in a drill core placed in Chemlab 2. The rock samples are analysed with respect to the flow-path and to the actinides sorbed onto the solid material. Non-destructive and destructive techniques are applied, such as x-ray computer tomography and cutting the samples after injection of fluorescent epoxy resin. The distribution of actinides along the flow-path is determined from the abraded material gained by cutting, as well as by coupled laser ablation ICP-MS techniques of the slices.

The field experiments are preceded by thorough laboratory investigations. Some results from the sorption experiments have been published /Kienzler et al. 2003c; 2004/.

The first three field experiments comprised migration of the actinides americium, neptunium, and plutonium. The last in situ experiment (in borehole KJ0044F01) was performed during 2004 using uranium and technetium. The experiment will be terminated mid 2005. The fraction collectors as well as the rock core will be analysed at FZK/INE during fall 2005. The final report on the actinide migration experiment is planned to be published in the beginning of 2006.

4.5 Colloid Project

4.5.1 Background

Colloids are small particles in the size range 10^{-6} to 10^{-3} mm. The colloidal particles are of interest for the safety of a repository for spent nuclear fuel because of their potential to transport radionuclides from a defect waste canister to the biosphere. SKB has for more than 10 years conducted field measurements of colloids. The outcome of 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 ground-water and strong sorption onto rocks. Field experiments at the Nevada Test Site, where hundreds of underground nuclear tests were conducted, indicate however that plutonium is associated with the colloidal fraction of the groundwater. The $^{240}Pu/^{239}Pu$ isotope ratio of the samples established that an underground nuclear test 1.3 km north of the sample site is the origin of the plutonium /Kersting et al. 1999/.

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

4.5.2 Objectives

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

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

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

4.5.3 Experimental concept

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

Laboratory experiments

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

Background measurements

The natural background colloid concentrations were measured in eight different boreholes during 2002, representing groundwater with different ionic strength, along the Äspö HRL-tunnel.

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

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

A complementary campaign for determining the background colloid concentration in different Äspö waters was performed in October–November, see also Figure 4-11.

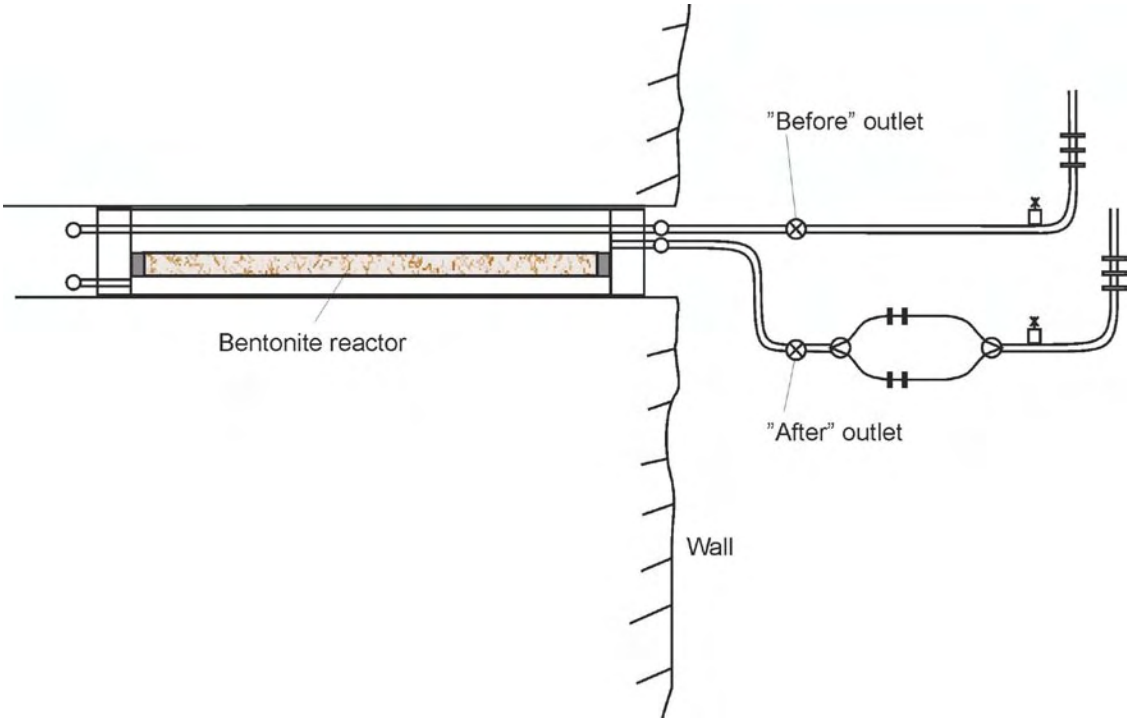


Figure 4-11. *The natural groundwater is in contact with the bentonite clay surrounded by a filter textile. The water flowing by the reactor is sampled and analysed. A bypass allows colloid determination of the natural groundwater. The aim is to determine the colloid generation potential from the bentonite in contact with the water.*

Borehole specific measurements

The aim of the measurements is to determine the colloid generation properties of bentonite clay in contact with groundwater prevailing at repository depth. For this purpose laboratory tests were carried out in order to optimise the "colloid reactor" (filter textile with bentonite clay) design. For the borehole specific measurements 4 boreholes along the Äspö tunnel and 2 boreholes at Olkiluoto in Finland were investigated. The boreholes were selected so the natural variation in the groundwater composition at Fennoscandia was covered. The groundwater is in contact with the bentonite clay adapted in a packer equipment in the borehole and the colloid content is measured prior and after contact with the bentonite clay. The bentonite reactor is 50 cm long and installed in boreholes with a diameter of 36 mm, see Figure 4-11. The colloid content was measured by using conventional filtering and ultra filtration at different flow conditions. The results indicate that the colloid release from the bentonite clay at prevailing groundwater conditions is small and the increased flow did not increase the colloid release from the bentonite reactor.

Dipole colloid experiments

The dipole colloid experiment is a fracture specific experiment with the aim to study the stability of colloids in different Äspö-waters and to establish if colloidal transport of actinides is realistic in the groundwater environment at Äspö.

The following topics will be covered in the project:

- Bentonite as a source of colloids.
- Stability and mobility of bentonite colloids in granitic groundwater.

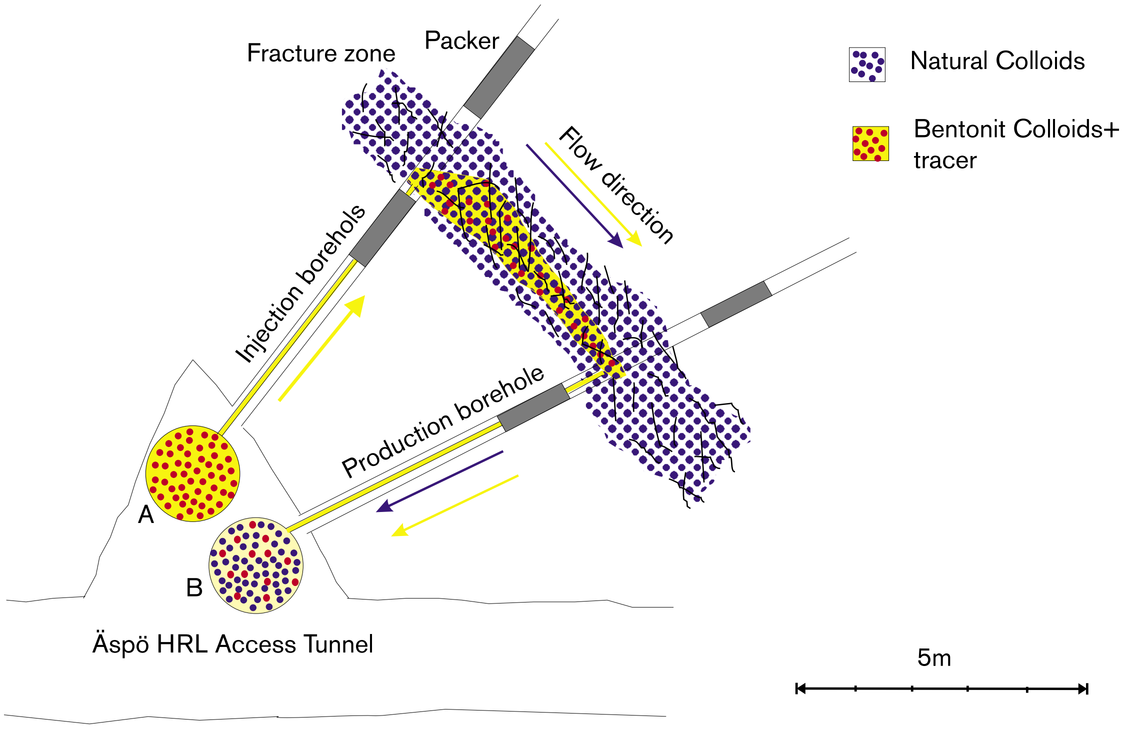


Figure 4-12. Dipole colloid experiments – injection of bentonite colloids and monitoring of the injected and natural colloids in the production borehole.

- Stability and mobility of other types of colloids in granitic groundwater.
- Colloidal mobilisation and transportation of radionuclides in a water bearing fracture in granitic rock.
- Monitoring of background concentrations of colloids in granitic groundwater.

The results from the Colloid Dipole project complement the results from the colloid and radionuclide retention experiment (CRR project) performed in Grimsel, Switzerland where colloidal transport of actinides was found in waters with low ionic strengths and high pH. Such conditions are known to increase the stability of colloids. The pump rates in the experiment are also considered to be quit high. Äspö waters, with higher ionic strengths and lower pH, should result in low stability conditions for colloids.

The Colloid Dipole experiment will be conducted at the True-1 site in Feature A in close collaboration with True-continuation. The choice of True-1 is very beneficial since the infrastructure and instrumentation is already there. Also the site is well examined.

According to present plans two nearby boreholes intersecting the same fracture having the same basic geological properties will be 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. After assessing the natural colloid content in the groundwater, bentonite clay will be dissolved in ultra pure water to form colloidal particles.

A cocktail with fluorescent latex colloids of different sizes as well as bentonite colloids will be injected. The mixture will be injected into the injection borehole, see Figure 4-12. The result of major interest is the changes in colloid content prior and after the transport through the fracture. The outcome of the experiment will be used to check performed model calculations and to develop future colloid transport modelling.

4.5.4 Results

A final report (covering the laboratory experiments, background measurements, and the borehole specific measurements) for the Colloid Project is in process and will be ready in spring 2005. The experimental data from the bentonite reactors at Äspö and Olkiluoto are under evaluation. A complementary campaign for determining the background colloid concentration in different Äspö waters was performed in October–November 2004. Planning of the Colloid Dipole Project started in September 2004. The Colloid Dipole Project will end with a final report in December 2007.

Colloid Dipole Project

The in situ experiments is planned to start in September 2005. Modelling of the system is performed to get realistic start conditions concerning colloid concentrations, injection and pump rates etc. Stability experiments to examine what bentonite colloid concentrations can be stable in the specific groundwater conditions will finish before the time for in situ experiments. The latex colloid concentration will be analysed by a flourometer and the bentonite colloids with a SPC (Single Particle Counter).

4.6 Microbe Project

4.6.1 Background

Micro-organisms interact with their surroundings, and commonly have a significant effect on the geochemical record. Microbial processes could thus significantly influence the functioning of any future high-level radioactive waste repository /Pedersen, 2002a/. The study of microbial processes in the laboratory can provide valuable information about possible microbial effects on such a repository. However, the effects suggested by laboratory studies must, for several reasons, be tested in a repository-like environment. First, at repository depth, hydrostatic pressure approaches 50 bars, a level that is very difficult to reproduce in the microbiology laboratory. Such high pressure influences chemical equilibria and the amount of gas that can be dissolved. Second, the geochemical environment of deep groundwater, on which microbial life depends, is complex. Dissolved salts and trace elements, and in particular the redox chemistry and carbonate system, are characteristics that are very difficult to mimic in a research laboratory located on the ground surface level. Third, natural ecosystems, such as those in deep groundwater, comprise many different species in various mixes /Pedersen, 2001/. The surface-level laboratory is, however, best suited for studies of pure cultures and the effect of processes arising from many contributing species in natural ecosystems can therefore not easily be investigated there.

The aforementioned limitations of surface-level investigations motivated the establishment of microbiological investigation sites in the Äspö HRL tunnel. The main site is the Microbe laboratory at the 450-m level, but several other sites along the tunnel have been in use since the start of Microbe.

4.6.2 Objectives

The main objectives for the Microbe sites are to:

- Provide in situ conditions for studying the bio-mobilisation of radionuclides.
- Present a range of conditions relevant for studying the bio-immobilisation of radionuclides.

- Provide the proper conditions for research of the effect of microbial activity on the long–term chemical stability of the repository environment.
- Enable investigation of the bio-corrosion of copper under conditions similar to those of a high-level radioactive waste repository.

4.6.3 Microbial processes

Microbial processes can significantly alter the mobility of radionuclides in the environment. The multi-disciplinary research conducted at sites operating within the Microbe framework combines microbial physiology, ecology, and molecular biology with nuclear chemistry, geochemistry, and geology in order to explore how microbial processes may influence the repository and migration of radionuclides.

Table 4-3 and Figure 4-13 summarise the microbial processes that can influence the speciation and thereby the migration behaviour of radionuclides. Microbial processes can have either immobilising or mobilising action, depending on the type of process and the state of the microbes involved. Microbes in biofilms will, with the exception of those which produce complexing agents, be immobilising. Planktonic cells that biosorb or bioaccumulate radionuclides will have a mobilising effect on radionuclides. These processes can act directly or indirectly in affecting radionuclide transport in the geosphere. Direct action involves contact between a microbe and the radionuclide, with a resulting change in radionuclide speciation. Indirect action is caused by changes in the environment generated by microbial metabolism, which in turn influence radionuclide behaviour. Finally, all microbial processes except biosorption require an active, energy-driven metabolism. The modelling of microbial processes must, therefore, include a proper understanding of microbial energy turnover rates in deep rock aquifers. All processes presented in Table 4-3 are being or will be investigated to various degrees of detail within the framework of the Microbe research project. The emphasis is on their importance for understanding geosphere mobilisation and immobilisation phenomena in the safety assessment of radioactive waste disposal. The processes are briefly introduced below.

Table 4-3. Microbial processes can directly or indirectly influence retention of radionuclides in several ways. The most important variables in such processes are the state of attachment (i.e. whether the microbes are attached or unattached) and whether the microbes are metabolically active or dormant and inactive.

Microbial processes that influence radionuclide migration	Microbes in this process are in the following state(s):		The action of this microbial process on radionuclides is:		This process requires an active microbial energy-driven metabolism:	
	Planktonic	Biofilm	Direct	Indirect	Yes	No
Immobilisation processes						
Biosorption		X	X			X
Bioaccumulation		X	X		X	
Biotransformation	X	X	X		X	
Biomineralisation	X	X		X	X	
Metabolic redox reactions	X	X		X	X	
Mobilisation processes						
Biosorption	X		X			X
Bioaccumulation	X		X		X	
Production of complexing agents	X	X	X		X	

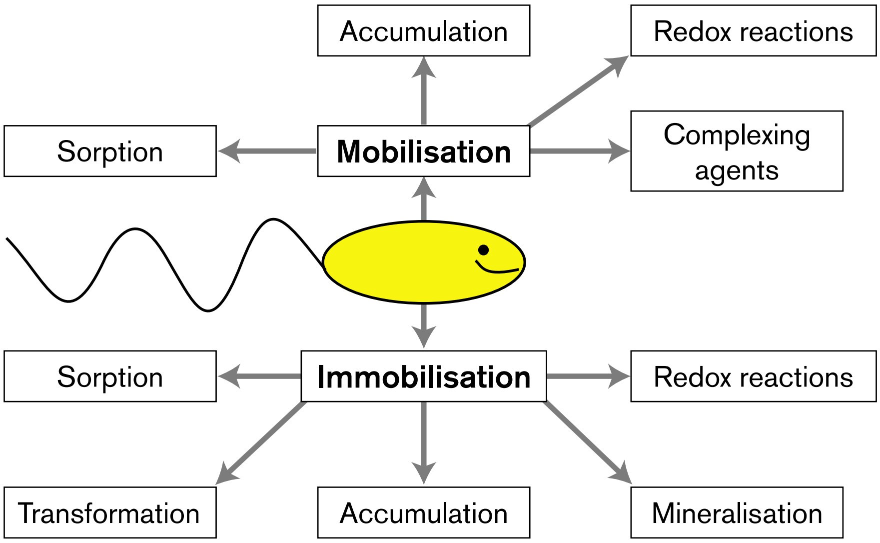


Figure 4-13. *Schematic representation of microbial processes that may influence radionuclide migration.*

Bio-immobilisation of radionuclides

Biosorption

The term biosorption (Table 4-3) is used to describe the metabolism-independent sorption of heavy metals and radionuclides to biomass, i.e. microbial cells. Biosorption can be summarised as the sorption and accumulation of trace elements to the surface of microbial cells. Both living and dead biomass are capable of biosorption, and the ligands involved in metal binding include carboxyl, amine, hydroxyl, phosphate, and sulphydryl reactive groups on the cell wall.

Microbe numbers as high as 10^{11} cells/m^2 have been reported in biofilms in Fennoscandian shield rock groundwater /Pedersen, 2001/. Biofilm micro-organisms commonly excrete extra-cellular material supporting attachment which also creates the three-dimensional shape of a growing biofilm. As this extra-cellular material is organic in nature, it adds a biosorption capacity to the cell's surfaces. In conclusion, biosorption to attached microbes in biofilms can have an immobilising effect on radionuclides (Table 4-3). Very few in situ experimental data exist regarding the importance of biofilm biosorption processes in understanding geosphere retention phenomena in the safety assessment of radioactive waste disposal. In response to this lack, ongoing experiments within the Microbe framework are attempting to elucidate these processes.

Bioaccumulation and biomineralisation

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 oxides (Bios) will have a retardation effect on many radionuclides. Typically, those 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 a water content of up to 99%. The microbes contribute to the exposure of a large oxide area to trace elements flowing past in the groundwater. Also the organic biological material has a strong retention capacity of its own, in addition to that of the iron oxides. The retention effect of Bios (bioaccumulation and mineralisation, Table 4-3) is being studied in the Microbe framework.

Bio-mobilisation of radionuclides

Microbes need metals for their metabolism, as do multicellular living organisms, and both bacteria and microscopic fungi share this need. Such metals are often available only in small quantities or, as with the case with iron in surface waters, are not bio-available at all due to low solubility under aerobic conditions. Therefore, microbes produce various kinds of chelating compounds to increase the bioavailability of essential elements needed for metabolism. These ligands are not always highly specific, and several of them will also mobilise other elements such as heavy metals and radionuclides. In the process of capturing the metal-ligand complex, microbes sort toxic metals from essential ones and expel the toxic elements back to the environment. The potential for the mobilisation of radionuclides from repository environments by bacterially produced ligands is unknown; it is thus a concern in safety analysis that warrants exploration. This process has been investigated in the laboratory using micro-organisms isolated from the deep groundwaters of the Äspö HRL. In situ experiments will follow the laboratory experiments. Fungi have the ability to produce large amounts of complexing agents, for example, via fermentation processes. The presence of fungi in deep groundwaters has been noted in earlier work. A detailed survey of fungi found in Äspö groundwaters was performed by /Ekendahl et al. 2003/.

Microbial effects on the chemical stability of deep groundwater environments

Micro-organisms can have an important influence on the chemical conditions in groundwater /Haveman and Pedersen, 2002/. In particular, they may execute reactions that stabilise the redox potential of groundwater at a low and thus 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. Energy metabolisms of hydrogen, and possibly also of carbon monoxide and methane, generate secondary metabolites such as ferrous iron, sulphide, and organic carbon. The metabolic activity of these species lowers the redox potential and they will act reducing on possibly introduced oxygen. Circulation systems and analytical instrumentation for studying gas dissolved in groundwater have been installed at the deepest (450 m) Microbe site.

Microbial energy metabolism requires a reduced electron and energy donor and an oxidised electron acceptor (Table 4-4). The energy donor can be an organic or an inorganic compound. The electron acceptor is generally an inorganic compound, except in fermentation, where both the electron donor and electron acceptor are the same organic compound. Electron donors and acceptors can be combined in redox couples according to the difference in free energy. Any redox couple that releases energy via a reaction is a possible source of energy for microbes. The result of microbial harvesting of energy from redox couples is an oxidised donor and a reduced acceptor. Notably, microbial metabolism generally lowers the redox potential of the environment.

Microbial corrosion of copper

The bio-corrosion of copper canisters, if any, can result from microbial sulphide production. Two important questions have been identified and studied within the Microbe framework. Can sulphide-producing microbes survive and produce sulphide in the bentonite that surrounds the canisters? Can microbial sulphide production in the neighbouring rock exceed a performance safety limit? A series of laboratory and field experiments has indicated that the answers to both these questions are negative /Pedersen et al. 2000a;b/. However, the results have been criticised for not accounting for natural conditions, such as high pressure and the natural population of sulphate-reducing bacteria in deep groundwater. This issue has now been studied under in situ conditions.

Table 4-4. The most common energy and electron donors and electron acceptors in microbial metabolism are summarised. The respective atom that donates or accepts one or several electrons is underlined.

Organic energy sources and electron donors		Inorganic energy sources and electron donors		Electron acceptors	
Reduced	**Oxidised**	**Reduced**	**Oxidised**	**Oxidised**	**Reduced**
Carbohydrates	$\underline{C}O_2$			$\underline{O}_2$	$H_2\underline{O}$
Amino acids	$\underline{C}O_2$	$\underline{N}H_4^+$	$\underline{N}O_3$	$\underline{N}O_3$	$\underline{N}_2$
Organic acids	$\underline{C}O_2$	$\underline{Mn}^{2+}$	$\underline{Mn}^{4+}$	$\underline{Mn}^{4+}$	$\underline{Mn}^{2+}$
Fat	$\underline{C}O_2$	$\underline{Fe}^{2+}$	$\underline{Fe}^{3+}$	$\underline{Fe}^{3+}$	$\underline{Fe}^{2+}$
		$H_2\underline{S}$	$\underline{S}O_4^{2-}$	$\underline{S}O_4^{2-}$	$H_2\underline{S}$
		$\underline{C}H_4$	$\underline{C}O_2$	$\underline{S}^0$	$H_2\underline{S}$
		$\underline{C}O$	$\underline{C}O_2$	$\underline{U}^{6+}$	$\underline{U}^{4+}$
		$\underline{H}_2$	H_2O	$\underline{C}O_2$	$\underline{C}H_4$

4.6.4 Experimental concept

Four sites along the tunnel have been in operation. However, at present, only two sites are active. The main site is the Microbe 450-m site where also the research efforts are being focussed. Some tasks require settings that cannot be achieved at the 450-m site and therefore a site was configured along the tunnel at 2,200 m tunnel length.

The Microbe 450-m site

The main Microbe site is on the –450 m level in the F-tunnel (Figure 4-14). A laboratory container has been installed with laboratory benches, an anaerobic gas box and an advanced climate control system. A gas chromatograph (Kappa-5) and a gas extraction system are installed. This system can analyse the following gases (detection limit): hydrogen (1 ppb), carbon mono-oxide (1 ppb), carbon dioxide (1 ppm), methane (1 ppm), ethane (1 ppm) and ethylene (1 ppm). Three core drilled boreholes, KJ0050F01, KJ0052F01 and KJ0052F03, intersecting water conducting fractures at 12.7, 43.5 and 9.3 m, respectively, are connected to the Microbe laboratory via 1/8 " PEEK tubing. The boreholes are equipped with metal free packer systems that allow controlled circulation of groundwater via respective fracture /Pedersen, 2000/. Each borehole has been equipped with a circulation system offering a total of 528 cm^2 of test surface in each circulation for biofilm formation at in situ pressure, temperature and chemistry conditions. The systems operate at the pressures 24, 32 and 24 bars in KJ0050F01, KJ0052F01 and KJ0052F03, respectively. The flow through the flow cells is adjusted to about 15–20 ml per minute, which corresponds to a flow rate over the surfaces of 0.5 mm per second. Temperature is controlled and kept close to the in situ temperature at around 15–16°C. Remote alarms have been installed for high/low pressure, flow rate and temperature.

It was deemed important to determine how much water was flowing in the respective fracture. This was performed via saturation experiments. Replacement of distilled water in the circulations was followed and the results showed an exponential saturation function that asymptotically approached the original concentration before the start of the experiment. Plotting the logarithm of the measured parameters against time ideally generates straight lines in which the inclination equals the dilution rate Figure 4-15 and Figure 4-16 gives the results for KJ0052F01 and Table 4-5 summarises the data. It was found that the residence time was relatively short, less than a day. This makes the circulations excellent for the planned experiments with microorganisms.

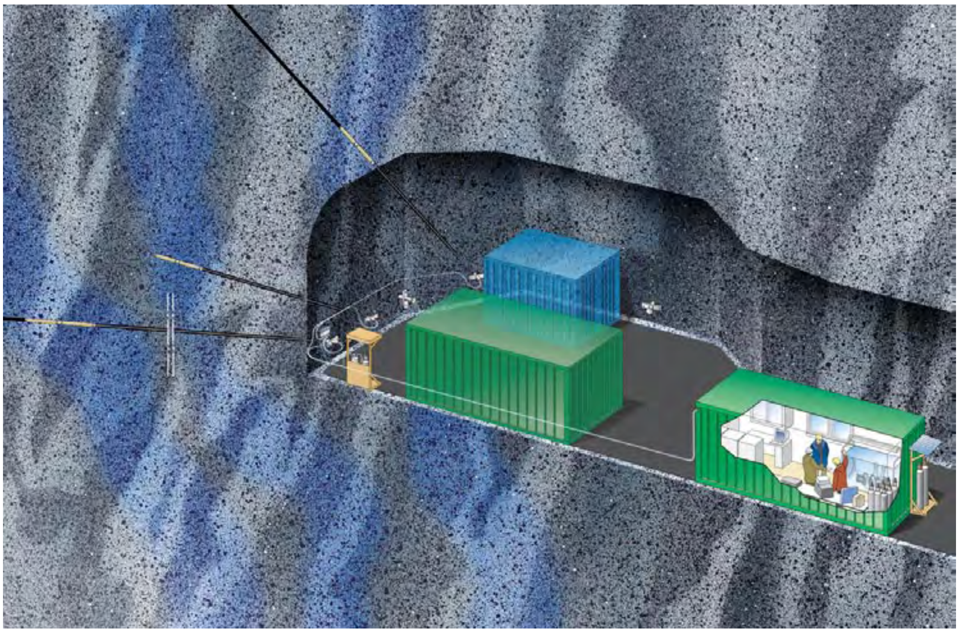


Figure 4-14. The artists view of the Microbe 450-m site and the metal free packer configuration. The laboratory is situated in a steel container and connected to three discrete fractures in the rock matrix. PEEK tubing connects the systems in the lab with the groundwater (See text for details).

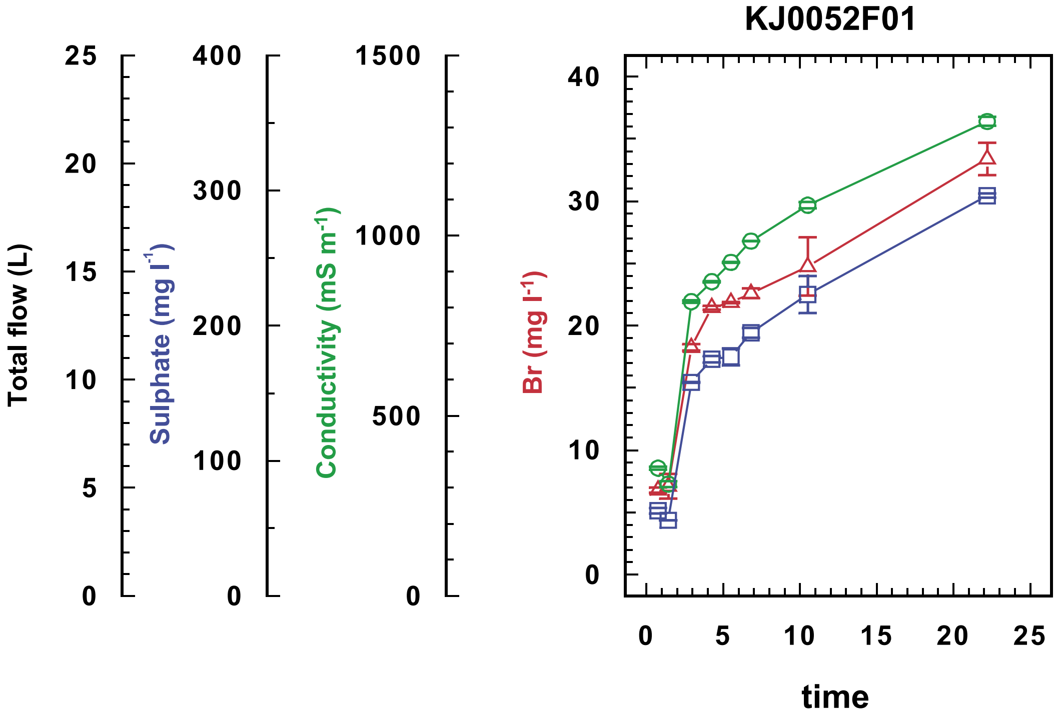


***Figure 4-15.** Results of the dilution rate tests (linear scales). See text for details.*

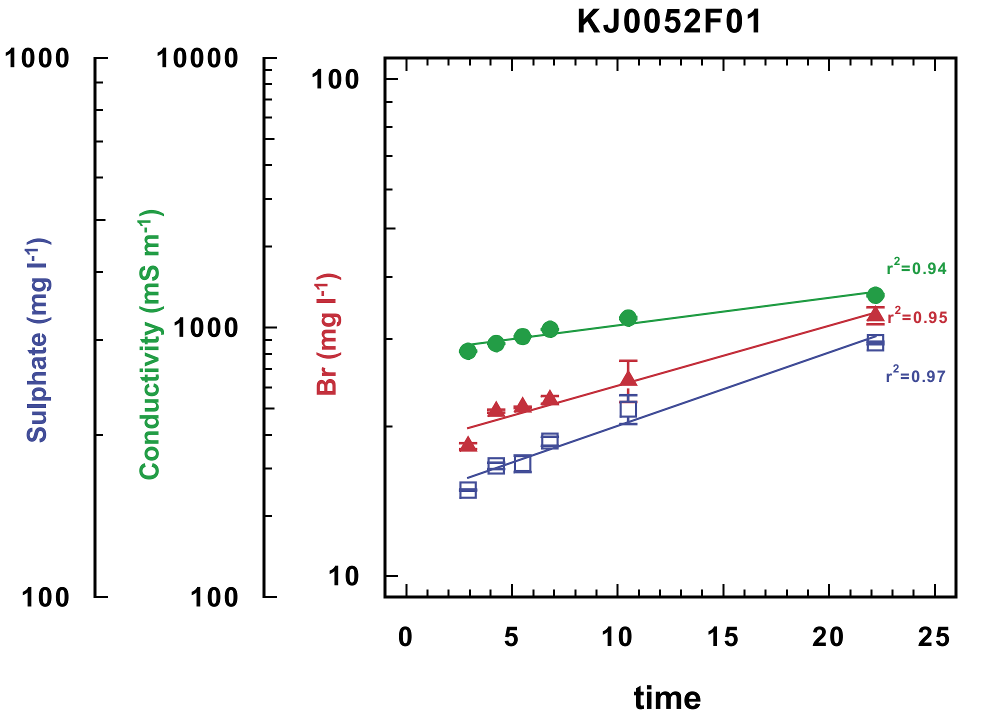


Figure 4-16. *Results of the dilution rate tests (logarithmic scales). See text for details.*

Table 4-5. Calculated maximum dilution rates and theoretical residence time of the groundwater in the respective circulation with test piles and diffusers installed.

Borehole	Volume of circulation (ml)	Maximum dilution rates (hr^{-1}) calculated from		Residence time (hr) calculated from	
		SO_4^{2-}/ Br^{-1}	Conductivity	SO_4^{2-}/ Br^{-1}	Conductivity
KJ0050F01	916	0.069	0.053	10	13.1
KJ0052F01	1,057	0.072	0.056	9.6	12.4
KJ0052F03	862	0.047	0.039	14.7	17.8

Principal component analysis (PCA) analysis was performed to compare the groundwater geochemical composition situation at Microbe 450 m in April 2000 with that in September 2003. The Microbe groundwater samples lie in the central area of the PCA plot shown in Figure 4-17. This indicates that these waters do not have an extreme groundwater composition, but rather are affected by the mixing of several reference waters. The plot shows that all three Microbe groundwater samples have moved towards a deeper brine signature. KJ0050F01 shows the largest move and has approached the position of KJ0052F01, suggesting that deep groundwater is up-coning towards the positions of the Microbe sites.

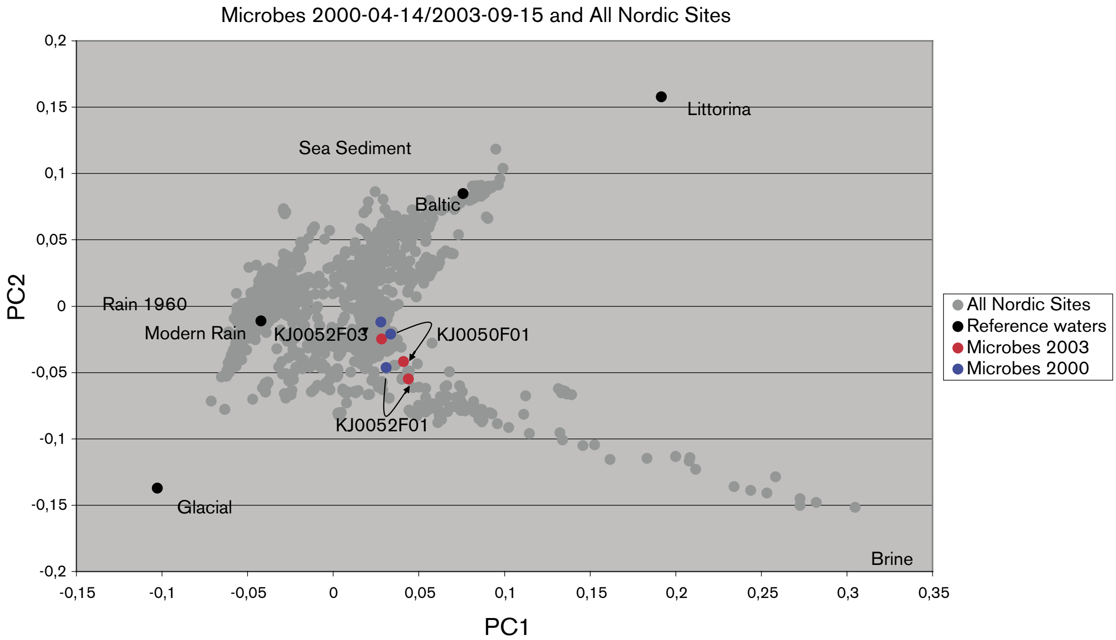


***Figure 4-17.** Principal component plot showing groundwater chemical data from the Microbe 450-m site in comparison to data from other Nordic sites (including data from the site investigations).*

The BIOS-site at 2,200 A m tunnel length

Organic surfaces and iron oxides have been identified as important factors in radionuclide transport modelling. Several microorganisms oxidise ferrous iron to ferric iron resulting in a mix of organic material (microbes) and iron oxides, here denoted Bios (biological iron oxide systems). Bios can be found everywhere along the Äspö HRL tunnel system. This Bios is mainly produced by the stalk-forming bacterium *Gallionella ferruginea* /Hallbeck and Pedersen, 1990; 1991; 1995; Hallbeck et al. 1993/. One particularly good site for investigations has been identified at tunnel length 2,200 m, on the A side. A vault is reaching about 10 m into the host rock perpendicular to the tunnel and it has a borehole in the front that delivers groundwater rich in ferrous iron and iron oxidising bacteria. The borehole has been connected to two 200×30×20 cm artificial channels (Brics) that mimic ditches in the tunnel. The channels have rock and artificial plastic support that stimulate Bios formation (Figure 4-18). A research project studying the retention of naturally occurring trace elements in the groundwater by the BIOS was completed and published during 2003 /Anderson and Pedersen, 2003/. New experiments on the succession of Bios over time were performed during 2004.

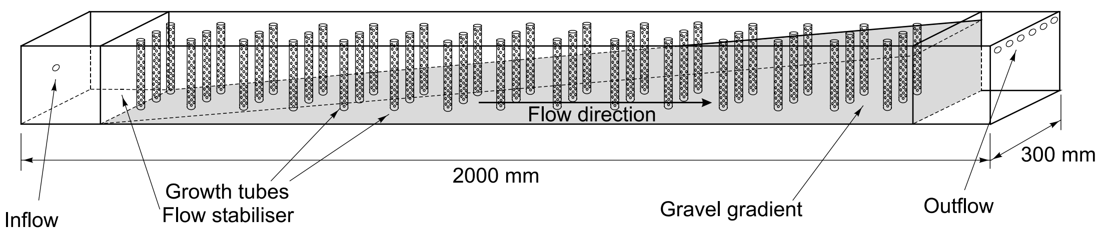


***Figure 4-18.** Schematic diagram of an artificial channel (Bric) installed at the Bios site.*

4.6.5 Results

Bio-mobilisation of radionuclides

There has not been activity in the tunnel on this objective during 2004. Research is planned for 2005.

Bio-immobilisation of radionuclides

Bio-sorption

In new experiments the radionuclide adsorption capacity of biofilms grown under in situ geological nuclear waste repository conditions are compared with the capacity of rocks from the same environment. Radionuclides with different oxidation states were chosen, Co(II), Pm(III), and Mo(VI). The predominant interest is the effect of different charges (Co^{2+}, Pm^{3+}, MoO_4^{2-}) on the distribution of metals between different phases present in a far-field repository environment. Flow cells were left to develop natural biofilms under in situ conditions for 8 to 16 months at the Microbe 450 m site. The in situ conditions were maintained until the slides were transferred from the flow cells to the experimental vessels. The activity of ^{147}Pm was determined in the aqueous phase using liquid scintillation. The ^{60}Co activity was determined in aqueous phase using a NaI γ counter. The spatial distribution of solid phase adsorption for all radionuclides was imaged on one set of replicates at the end of the experiments using an electronic autoradiography machine (Figure 4-19). The radionuclides were measured separately and exposure time was set at 30 minutes for ^{147}Pm and 10 minutes for ^{60}Co. The counts per minute (CPM) recorded by this machine was ≤ 10% of the actual disintegrations per minute (DPM).

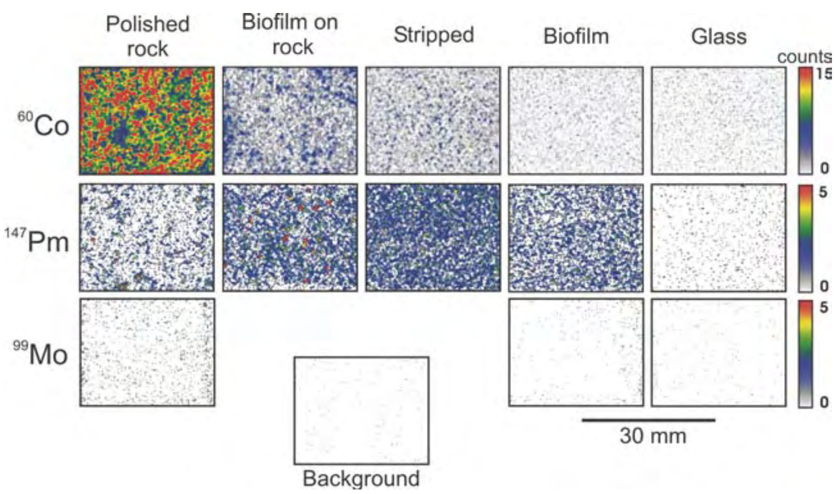


Figure 4-19. *Five sorption surfaces were tested for each radionuclide. The sorption surfaces were as follows: polished granite rock slides (Polished rock), biofilms attached to rock slides (Biofilm on rock), biofilms attached to glass slides partially stripped of metals (Stripped), biofilms attached to glass slides (Biofilm),and glass slides (Glass).*

The results indicate that these surfaces adsorb up to 50% of the radionuclides in natural conditions with a surface sorption coefficient (K_a) approaching 10^5 and 10^6 m 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 definitely not for Co. Desorption of Co and Pm from biofilm surfaces proceeds more rapidly than from rock surfaces. Further, complex stability differs between rock and biofilms due to the surface functional groups available and competition for those groups. The biofilms actually isolate the rock surface from the groundwater and diffusion to the rock surface must first proceed through the biofilms. High ionic strength of the groundwater and the chemical properties of the radionuclide species used reduce the adsorption to biofilm surfaces. The effects of biofilm coverage on radionuclide adsorption and migration in subsurface environments cannot be ignored. Suppression of adsorption by biofilms should be accounted for in performance safety assessment models.

Microbial effects on the chemical stability of deep groundwater environments

The numbers of microorganisms, their biomass and the metabolic diversity of the organisms in the Microbe 450-m circulations have been determined during 2004.

The total numbers of cells were similar to those found in the repository site investigation programme, i.e. between 10^4 and 10^6 cells/ml (Figure 4-20). KJ0052F01 was found to contain significantly more cells than the two other circulation systems. This difference was confirmed by the ATP analysis (Figure 4-20). The amount of ATP has been recalculated in the form of cells/ml using the relationship 2 amol ATP = 1 cell, which represents an upper limit for healthily growing cells. The relationship approaches 1 amol per cell in some cases. The ATP values correlate reasonably well with the total numbers. The analysis of ATP in deep groundwater is still a new application of this method, and a separate paper (in preparation) will discuss the rationale behind ATP analysis in much greater detail.

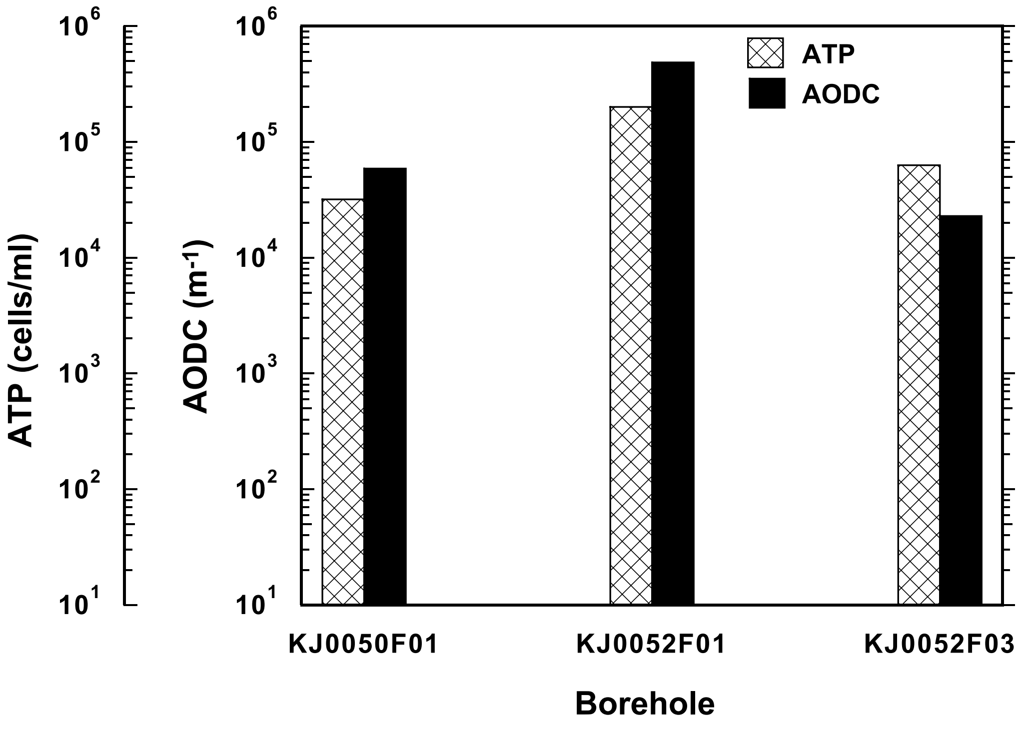


Figure 4-20. *Total number of cells measured as ATP and using microscopy (the AODC method).*

Figure 4-21 show the metabolic diversity of the circulations. All groups analysed for were found, except for iron-reducing bacteria (albeit, manganese-reducing bacteria were not found in KJ0052F01). The dominant groups of micro-organisms were the acetogens followed by sulphate-reducing bacteria and methanogens. KJ0052F03 contained significantly lower numbers of microbes, generally about 100 times lower, than did the other two boreholes. This is possibly explained by the fact that the PCA signature of this borehole was shallower than the other two (Figure 4-17). All microbes analysed, except for iron reducing bacteria (IRB) and manganese reducing (MRB), are stimulated by a very low redox potential (–400 to –250 mV). The redox potential is usually lower in groundwater with a deep signature, than in shallower groundwaters.

The obtained data for acetogens and methanogens correlate excellently with the MPN data obtained from the Äspö HRL tunnel between 1994 and 1996 (cf Figure 3 in /Kotelnikova and Pedersen, 1998/). At a depth of 400–450 m, acetogens averaged around 1,000 cells per ml of groundwater, while methanogens averaged around 100 cells per ml groundwater.

The estimates of most probable number (MPN) demonstrate the robustness of the MPN method. The data also suggest that microbial populations in deep groundwater at Äspö are stable and in a steady state with their deep aquifer environment.

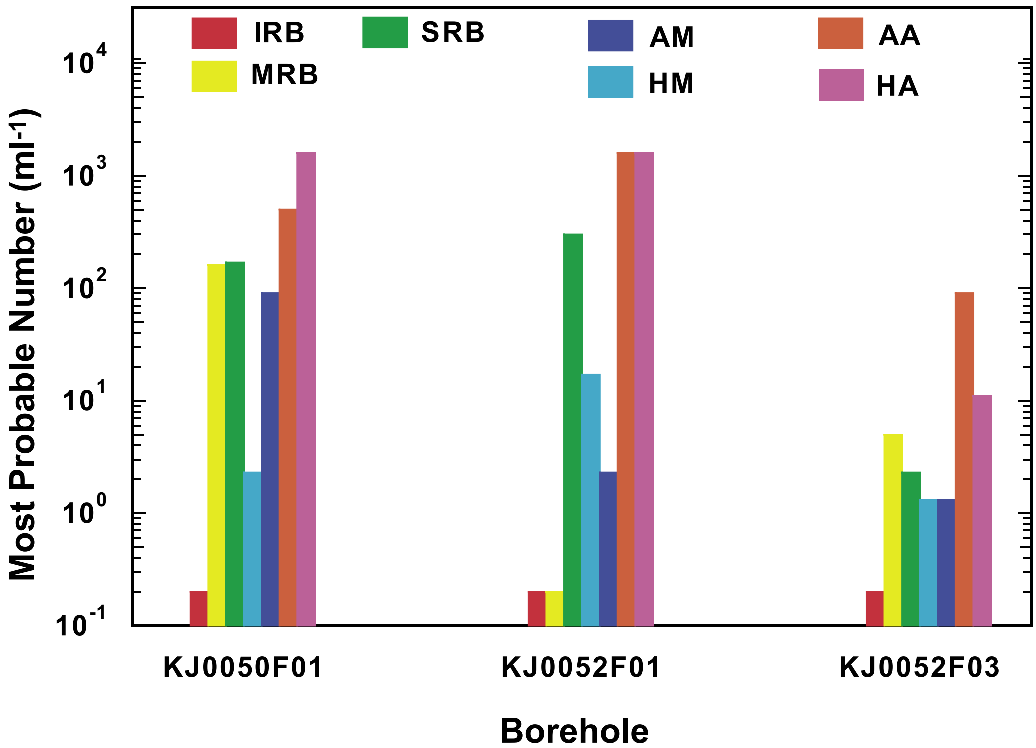


Figure 4-21. *Most probable numbers of different physiological groups of micro-organisms in the Microbe circulations. Abbreviations: MRB (Manganese Reducing bacteria), AA (Autotrophic Acetogens), AM (Autotrophic Metanogens), IRB (Iron Reducing Bacteria), SRB (Sulphate Reducing Bacteria), HA (Heterotrophic Acetogens), HM (Heterotrophic Metanogens).*

Bio-corrosion

The in situ sulphide production by sulphate reducing bacteria (SRB) in bentonite compacted to different densities was investigated. In the investigations the in situ conditions such as hydraulic pressure and anaerobic conditions were maintained throughout the entire experiment and a stable swelling pressure in the bentonite. The experiments were performed without laboratory bacterial strains. The results show that the Microbe-450 m site groundwater resulted in sulphide production.

Copper corrosion from sulphide, produced by SRB, was monitored with radioactive sulphur as tracer in $^{35}SO_4^{2+}$. Amount and distribution of radioactive copper sulphide was analysed with electronic autoradiography in two dimensions. The sources of SRB were deep groundwater and possibly the bentonite. Measured mean sulphide production decreased exponentially with increasing bentonite density when exposed to unfiltered groundwater. One example of results is shown in Figure 4-22. As swelling pressure is directly related to bentonite density, a good correlation between the sulphide production and the swelling pressure was found. The data are presently in preparation for publication.

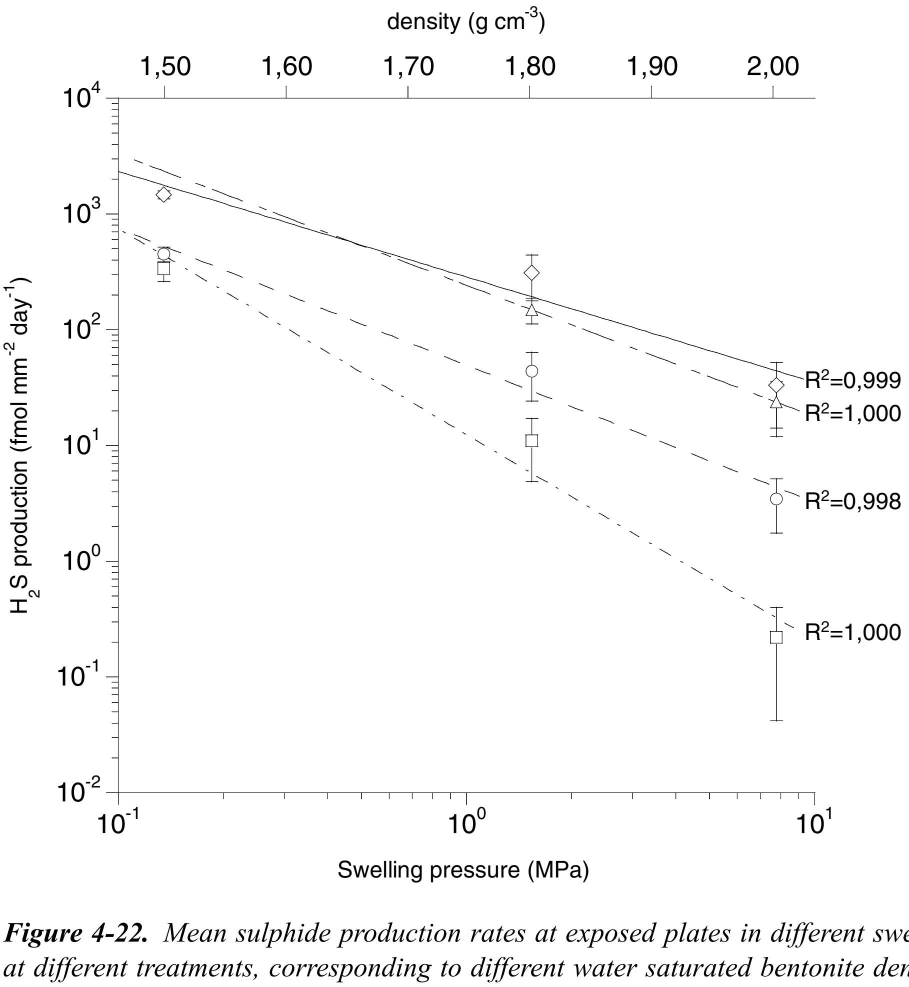


Figure 4-22. *Mean sulphide production rates at exposed plates in different swelling pressures and at different treatments, corresponding to different water saturated bentonite densities. Sulphate reducing bacteria (SRB) in filtered and unfiltered groundwater (G) and in bentonite (B) after two different heat treatments were studied. Error bars represent 95% confidence limits. Straight lines represent exponential trend lines defined by* $y=a \cdot x^b$*. The swelling pressure is valid for MX-80 Wyoming bentonite exposed to 0.1 M NaCl solution.* $SRB\text{-}G_{unfiltered}$ —◇—; $SRB\text{-}G_{filtered}$ - - △ - -; $SRB\text{-}B_{25°C}$ – – ○ – –; $SRB\text{-}B_{120°C}$ - –□ –. *The mean values for SRB-G are based on a sample number of n=12 (except for 1.8 g/cm³ where n=6). For SRB-B the mean values are based on a sample number of n=8 (except for 2.0 g/cm³ treated in 120°C where n=4). The* $Cu^{35}S$ *was produced during 68 days. Error bars show the 95% confidence interval.*

4.7 Matrix Fluid Chemistry

4.7.1 Background

The first phase of the Matrix Fluid Chemistry experiment (1998–2003) increased knowledge of matrix pore space fluids/groundwaters from crystalline rocks of low hydraulic conductivity ($K < 10^{-10}$ ms^{-1}), and complemented the hydrogeochemical studies already conducted at Äspö. The results of this phase were published in early 2004 /Smellie et al. 2003/.

The continuation phase (2004–2006) focuses on areas of uncertainty which remain to be addressed. These are the:

- Nature and extent of the connected pore waters in the Äspö bedrock (chemical, hydraulic and transport properties).
- 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.
- Confirmation or otherwise of laboratory-derived matrix fluid compositions (i.e. crush/leach and diffusion extractions) by conducting a long-term in situ out-diffusion pore water experiment in the matrix borehole.
- Confirmation of rock porosity values previously measured in the earlier studies.

This continuation phase, however, requires an initial "Feasibility Study" to assess the potential for further characterising the matrix borehole. This is necessary because of the untimely excavation of a new tunnel close to the matrix borehole for the Äspö Pillar Stability Experiment in April/May, 2003. Repercussions from the excavation may have influenced the hydraulic (and therefore the hydrochemical) character of the matrix borehole and the host rock vicinity. Prior to any further studies, therefore, these repercussions require to be quantified.

4.7.2 Objectives

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

- To establish the impact of tunnel construction on the matrix borehole by evaluating the monitored pressure profiles (Äspö 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.
- Furthermore, on the same basis, in situ out-diffusion experiments will be conducted in the same isolated fracture-free borehole sections.
- To carry out additional porosity measurements on drillcore samples to confirm or otherwise those values already measured.

4.7.3 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:

- Rock type.
- Mineral and geochemical homogeneity.
- Major rock foliation.
- Depth in the tunnel.
- Presence and absence of fractures.
- Existing groundwater data from other completed and on-going experiments at Äspö HRL.

Special downhole equipment, see Figure 4-23, was constructed ensuring:

- An anaerobic environment.
- Minimal contamination from the installation.
- Minimal dead space in the sample section.
- The possibility to control the hydraulic head differential between the sampling section and the surrounding bedrock.

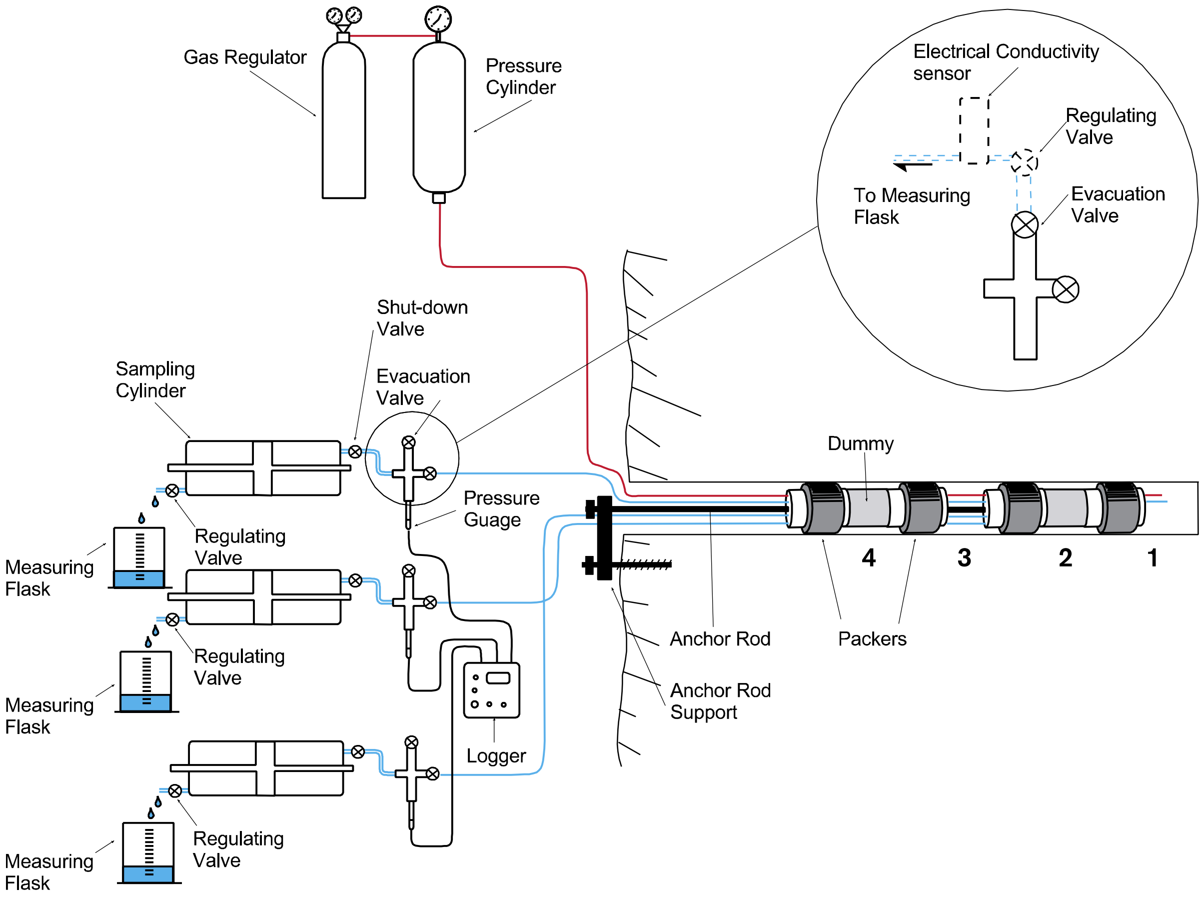


Figure 4-23. *Matrix Fluid Chemistry experimental set-up. Borehole sections 2 and 4 were selected to collect matrix fluid; sections 1–4 are continuously monitored for pressure.*

- In-line monitoring of electrical conductivity and drilling water content.
- The collection of pore waters (and gases) under pressure.
- Convenient sample holder to facilitate rapid transport to the laboratory for analysis.

This experimental equipment, with some modifications, will be used in the continuation phase to sample groundwaters from the microfractures, to measure the hydraulic parameters of the microfractures and the rock matrix, and finally to conduct the long term in situ diffusion experiment.

4.7.4 Results

The Feasibility Study to evaluate the impact of tunnel construction (i.e. Äspö Pillar Stability Experiment) on the hydrogeology and hydrochemistry in the vicinity of the experimental matrix borehole KF0051A01 was delayed due to difficulties accessing the relevant long-term monitoring hydraulic data from the Äspö HMS system. This situation was resolved finally in November 2004. Since then the situation has been addressed and initial results suggest that the integrity of the matrix borehole and its immediate surroundings has not been jeopardised. The evaluation is continuing.

The delay in executing the Feasibility Study did not influence carrying out additional porosity measurements on drillcore samples to confirm or otherwise those values already measured and reported in the Matrix Fluid Chemistry Experiment /Smellie et al. 2003/. However, not only has this present study provided additional porosity data, but it also addressed wider important issues such as the optimum sample size for measurement and the influence of external parameters (e.g. stress-release factors) on the validity of the data obtained.

Porosity measurements were carried out on fresh and unfractured Äspö quartz monzodiorite (Äspö diorite), which was selected from a vertical borehole (KA2599G01) close to the Matrix Fluid Chemistry borehole. Both connected porosity and bulk and grain densities were measured and from these the total porosity was calculated.

Results showed that the total porosity in the Äspö quartz monzodiorite ranges from 0.89 to 1.51 vol% (in fact 70% of the measurements are within the range of 0.98 to 1.23 vol%), and that the connected porosity (by water saturation of 60 mm long drillcore pieces) ranges between 0.32 to 0.44 vol%. The connected porosity measured in the thinner samples (< 20 mm long) is higher and is explained by a relatively high contribution of microfractures formed at the cutting ends of the drillcores. Figure 4-24 shows the relationship between sample thickness and the total and connected porosities. The thicker samples (> 20 mm long) show the lowest connected porosity values, and these probably better represent the bulk rock. The unconnected porosity constitutes the major part (~ 2/3) of the total porosity.

Based on petrofabric studies of the Äspö quartz monzodiorite, the connected pores were found to be preferentially aligned parallel to the foliation such that flow and diffusion in such rocks is likely to be dependent on the orientation of the foliation.

Generally, porosity calculated from laboratory measurements will be higher than the in situ porosity due to secondary effects such as physical disturbance of samples including stress release. These differences may be even more pronounced when using small samples in laboratory measurements.

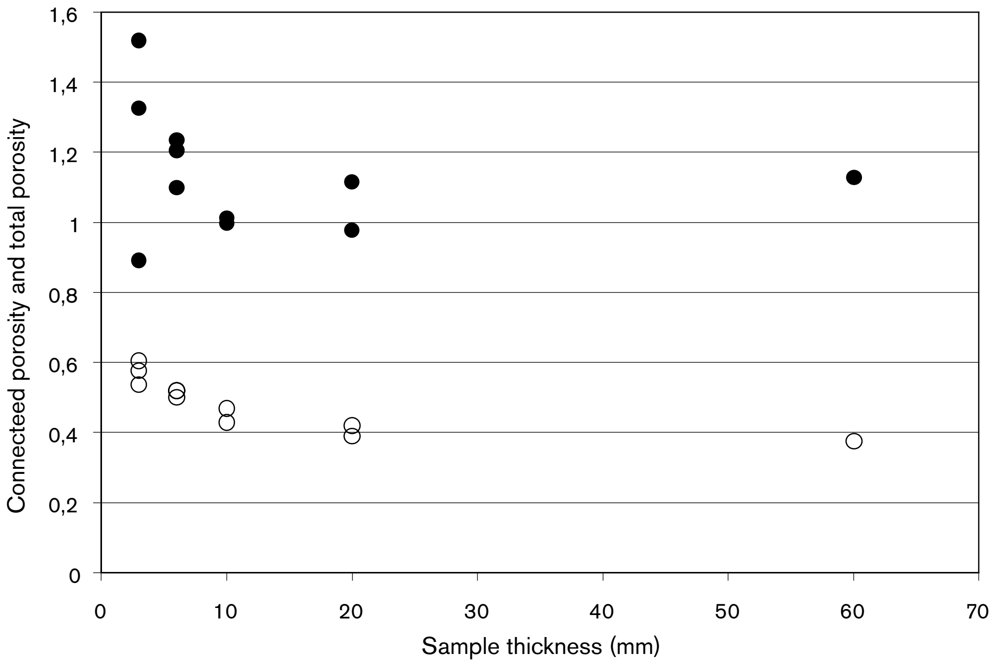


Figure 4-24. *Connected porosity (open circles) and total porosity (filled circles) calculated from bulk and grain density measurements plotted versus sample thicknesses.*

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

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

Task 1 Long term pumping and tracer experiments (completed).

Task 2 Scooping cal culations 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 Understanding Experiment (True), 1st stage (completed).

Task 5 Coupling between hydrochemistry and hydrogeology (completed).

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

4.8.2 Objectives

The Äspö Task Force is a forum for the organisations supporting the Äspö HRL project to interact in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock. In particular, the Task Force shall propose, review, evaluate and contribute to such work in the project. The Task Force 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.

In the Task Force on groundwater flow and transport of solutes, work has been in progress mainly in Task 6 − Performance Assessment Modelling Using Site Characterisation Data. Task 6 tries to bridge the gap between Performance Assessment (PA) and Site Characterisation (SC) models by applying both approaches for the same tracer experiment. It is hoped that this will help to identify the relevant conceptualisations (in processes/ structures) for long term PA predictions and identify site characterisation data requirements to support PA calculations. Task 6 was initiated year 2001. An external review process for Task 6 is on-going. The objectives of this task are to:

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

Six sub-tasks have been defined within Task 6:

Sub-task 6A	Model and reproduce selected True-1 tests with a PA model and/or a SC model to provide a common reference.
Sub-task 6B	Model selected PA cases at the True-1 site with new PA relevant (long term/base case) boundary conditions and temporal scales to understand the differences between the use of PA and SC models. In a variant denoted task 6B2, a line source was used instead of a point source for the injection of solutes.
Sub-task 6C	Develop semi-synthetic, fractured granite hydrostructural models.
Sub-task 6D	Use of the semi-synthetic structural model in addition to a 50 to 100 m scale True-Block Scale tracer experiment in a similar way as sub-task 6A.
Sub-task 6E	Extend the sub-task 6D transport calculations to a reference set of PA time scales and boundary conditions.
Sub-task 6F	Perform a sensitivity study, which is proposed to address simple test cases, individual tasks to explore processes, and to test model functionality.

4.8.3 Results

The modelling work is completed for sub-tasks 6A and 6B. Modelling reports for sub-tasks 6A, 6B, and 6B2 have been made by the modelling groups and most of the reports are printed. A draft of the external review report was produced. Also, the external review of sub-task 6C has resulted in a draft report.

Modelling work for sub-task 6D and 6E have been performed and presented at two Task Force meetings during 2004. In addition, the results are available in draft reports by the modelling teams. The work with sub-task 6F has been initiated.

The 18th International Task Force meeting, hosted by SKB was held January 13–15, 2004 at Äspö HRL. 28 attendees from seven countries participated in the meeting. The modelling groups presented final results of sub-task 6D and preliminary results for sub-task 6E. Later on the same year, the 19th International Task Force meeting, hosted by Posiva was held September 21–23 in Naantali, Finland. This time, 26 attendees from seven countries participated in the meeting. The modelling groups presented final results of sub-task 6E and preliminary results for sub-task 6F. At the meeting, the external review reports of sub-task 6A, 6B, 6B2, and 6C were presented. At this meeting it was also decided to initiate an additional task, Task 7, which concerns a long-term pumping test in Onkalo, Finland. Minutes and proceedings of the International Task Force meetings are published on the Task Force web.

4.9 Padamot

4.9.1 Background

Palaeohydrogeology is a relatively new term used as a common name for information from fracture minerals that is used for interpretations of past hydrogeochemical and hydrogeological systems. The need for such interpretations has become evident in the geological/hydrogeological modelling of sites within the radwaste programmes of several countries and therefore an EC founded 3 year project with the name Equip (Evidences from Quaternary Infills for Palaeohydrogeology) was started in 1997. The Equip project was concentrated on the formulation of a methodology for how to conduct a palaeohydrogeological study; what minerals to use, what analyses to perform, and also the preferred sequence in which the different analyses should be carried out. Each participating country also carried out analyses within their selected sites. Within the Swedish study the selected site is Äspö and the drill cores used was from the pre-investigation boreholes KAS02, KAS03 and KAS04. Some samples from the 1,700 m deep borehole KLX02 from the nearby mainland Laxemar were also included. The study was concentrated on calcite as this mineral relatively quickly responds to changes in groundwater chemistry. However, information from Fe-oxides and sulphides has also been included when possible.

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

4.9.2 Objectives

The objectives for the Padamot project include:

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

The Swedish part of the Padamot study concentrates on the two work packages WP2 (Palaeohydrogeological characterisation of sites) involving applications of several analytical techniques on fracture filling calcites dominantly from KLX01, and WP 5, which deals with Performance Assessment applications of palaeohydrogeological data and modelling.

4.9.3 Results

The EC part of the project will be reported in the beginning of 2005. Major achievements are especially the methodology for selecting calcite samples that represent the possible youngest calcite and also the use of calcite morphology of these calcites in order to sort out different palaeohydrogeological imprints. In addition to morphology detailed scale laser technique and traditional bulk analyses (on very small samples) have been used for trace elements and stable isotopes. The small sample volumes together with the very fine zoning of the samples cause serious limitations in the analyses possible to be applied. The overall pattern obtained from the different analytical techniques shows, however, a past scenario with large variations in salinities in the upper 900 m in borehole KLX01. For example are fresh water carbonates found as deep as 900 m. On the other hand calcites typical for brackish water are found from 20 m depth and saline water precipitates from 100 m. The calcites with stable isotope composition typical for precipitates from Baltic Sea water seems to be less significant at Laxemar compared with Äspö. Decreasing influence of interaction with the surface is recorded although the contribution of e.g. trace elements and organic material seems to reach larger depth at Laxemar compared with Äspö. This is also in agreement with the hydrogeological situation.

4.10 Fe-oxides in fractures

4.10.1 Background

Uptake of radioactive elements in solid phases can lead to immobilisation, thus minimising the escape risk. Uptake extent depends on solution conditions such as concentration, pH, Eh, temperature, pressure and the presence of other components. 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, presence of trace components in minerals can provide information about a mineral's genesis conditions and history. Fe-oxides line fractures 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 components 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 radionuclides or other toxicants from solution and hold them, even during transformation to more stable phases?
- What capacity does 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+}, be provide as a model for actinide behaviour, or such as 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 refuse the hypothesis that, at the time of glacier retreat, oxidising water might have penetrated to depths at or below the level of planned canister burial?
- How might secondary Fe-minerals affect the migration of radionuclides accidentally released from a repository?

4.10.2 Objectives

The basic idea of the project is to examine Fe-oxide fracture linings, in order to explore for suitable palaeo-indicators for their formation conditions, while at the same time learning about the behaviour of trace component uptake in general, both from the natural material as well as through testing of behaviour in controlled parametric studies in the laboratory**.** The approach of the study is to apply solution, surface-sensitive and bulk analytical techniques.

4.10.3 Experimental concept

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 spectroscopy (EDS) will be examined.

4.10.4 Results

One possible suggestion to separate low temperature Fe(III) oxyhydroxides, hydrothermal hematite, and drilling induced Fe(III) precipitates is the use of combined Fe-isotope studies and Mössbauer analyses. This looks very promising and the first study will be reported soon.

Green rust (GR) has been studied in laboratory and the structural of $GRSO_4$ have been determined. It has been shown that the structure changes depending on cation introduced.

5 Äspö facility

5.1 General

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

5.2 Facility operation

5.2.1 Background

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

5.2.2 Results

The operation has worked smoothly and the plant supervision system has considerably increased the possibility to run the facility in a safe and economic way. The availability in the underground-related systems (ventilation, hoist, lightning, pumps etc) has been more than 99% during 2004.

A feasibility study regarding new hard- and software for an automatic registration and object-monitoring system has been carried out through the year. The benefit with the system is to increase personnel safety underground. The results from the functional tests of the system look promising and a decision will be taken in the beginning of next year.

The energy consumption at the facility has decreased with approximately 2% compared to 2003. The slightly lower energy consumption is marginal and can not be ascribed to any particular action.

The long term rock control and reinforcement programme has been continued to ensure safe and reliable rock conditions. As a result of the thorough rock inspection performed during the fall a programme for complementing rock reinforcements, e.g. rock bolts and shotcrete during 2005 has been defined.

A project to decrease wear and movements in the drainage system was initiated in 2003 and finalised in 2004. A steering and control system for soft starts and stops of the pumps has been installed in the underground drainage system and is now in operation. The installation has decreased both the electric current needed at starts and the pressure pulse in the water pipes at stops.

The ventilation system for the underground facility has been mapped and a package of measures to increase the air flow in Äspö HRL was identified. The ventilation system has been rebuilt and the prognosis is 30% increase in airflow without increase in energy consumption.

Work on increased fire safety was also of concern during 2004 and safety-related education and fire fighting training was held in co-operation with the local fire brigade. The work with the water pipe in the ramp underground was completed. The water pipe ranges from the –340 to the –440 m level with the aim to supply the ramp with water for fire protection but also to supply the experiments with water.

In order to improve the quality of the maintenance and to make it more systematic, a PC-based system of maintenance has been installed during the past year. The staff has been educated and the system is partly put into operation. The intention is that all technical systems and vehicles/machines should be included in the system, which will improve among others the follow-up and the documentation of the maintenance. In addition, a machine technician has been recruited to the group and the electronic workshop has been put in good order with new measuring equipments and calibration tools for pressure and temperature sensors.

5.3 Hydro Monitoring System

5.3.1 Background

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

The Hydro Monitoring System (HMS) collects data on-line of groundwater head, salinity, electrical conductivity, Eh, and pH. The data are recorded by numerous transducers installed in boreholes. The system was introduced in 1992 and has evolved through time, expanding in purpose and ambition. The number of boreholes included in the network has gradually increased and comprise boreholes in the tunnel and in Äspö HRL as well as surface boreholes on the islands of Äspö, Ävrö, Mjälen, Bockholmen and some boreholes on the mainland at Laxemar. Weekly quality controls of preliminary groundwater head data are performed. Absolute calibration of data is performed three to four times every year. This work involves comparison with groundwater levels checked manually in percussion drilled boreholes and in core drilled boreholes, in connection with the calibration work.

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

5.3.2 Results

Improvements, new installations and other measures carried out during 2004 are:

- The weirs and the sensors measuring electrical conductivity in the tunnel have been calibrated.

- Maintenance of the hydraulic multiplexer at 1,645 m (–220 m level) in the tunnel.
- Instrumentation of and start registration in new boreholes in the outer part of the Prototype Repository tunnel.
- Four data acquisition units (Borrelogger) have been replaced with modern types (Datataker).
- Three radio modems have been replaced with equivalent equipment.

5.4 Programme for monitoring of groundwater head and flow

5.4.1 Background

The monitoring programme is a support to the experiments undertaken in the Äspö HRL and meets the requirements stipulated by the water rights court. The HMS implemented in the Äspö HRL and on the nearby islands is used to supply data to the programme for monitoring of groundwater head and flow. The monitoring of water level in surface boreholes started in 1987 while the computerised HMS was introduced in 1992. The number of boreholes included in the network has gradually increased. The tunnel construction started in October 1990 and the first pressure measurements from tunnel drilled boreholes were included in the HMS in March 1992. The tunnel excavation began to affect the groundwater level in many surface boreholes during the spring 1991.

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

5.4.2 Objectives

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

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

5.4.3 Results

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

The HMS data was put to use in different ways, in addition to complying with the water rights court it provided the means to continuously control the groundwater head in a rock volume where tracer experiments are conducted. The head distribution in the block should remain constant throughout the experiment since it forms an initial condition to the problem. Alteration in head gradients during the experiment might complicate the analysis. It is always supporting, and indeed is a necessary requirement during the rock characterisation stage preceding the experiments. The number of information points in the end of 2004 is compiled in Table 5-1.

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

Type of measurement	Number of measurement points
Groundwater pressure in tunnel boreholes	263
Groundwater level in surface boreholes	77
Flow of tunnel water	22
Electric conductivity of tunnel water	11

5.5 Programme for monitoring of groundwater chemistry

5.5.1 Background

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

At the beginning of the operational phase, sampling was replaced by a groundwater chemistry monitoring programme, aiming at a sufficient cover of the hydrochemical conditions with respect to time and space within the Äspö HRL.

5.5.2 Objectives

This 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.

5.5.3 Results

The yearly monitoring campaign took place as planned in September. The results presented here are a selection of some of the boreholes sampled during the latest water chemistry campaign. In addition, the results are compared with sampling results from previous years. The boreholes are mainly chosen due to their rather complete time series (data from only some boreholes is presented here).

A selection of boreholes and the elevation of the packed off sections are listed in Table 5-2 (Reference in RT90 system). Upper packer level (secup) and lower packer level (seclow) may vary from year to year since the packer may be moved to other more or less water conducting parts in the borehole.

The results represent water composition from the lowest level and corresponding elevation (from sea level), see table, up to the upper section which level may vary in some cases. The KAS-borehole is drilled from the surface whereas all the other boreholes are located in the tunnel.

The results from the latest monitoring campaign reflect the groundwater composition in the tunnel and are within the range of groundwater compositions from previous years. Chloride concentrations are thought to vary with depth due to mixing of different groundwater types with different composition and salinity although minor changes may reflect ongoing project activities in the tunnel. Groundwater fluctuations are normal due to different project activities such as drilling of new boreholes, hydraulic tests, grouting, injection of resins etc, which may cause temporary changes in groundwater pressure, flow and thus indirectly affecting groundwater chemistry.

At depths less than 200–300 m (below sea level) the chloride concentrations vary from 500 to 4,000 mg/l. Elevated chloride concentrations in groundwater have been monitored for several years and are found only in some sections of the tunnel. In these sections (situated at elevation about 370–380 under sea level) the chloride concentrations may vary between 1,300 to 16,000 mg/l. No project activities are found to explain this effect but it is possible this could be caused by a so called "up-coning" effect present in this part of the tunnel. This means that water with higher salinity derived from deeper groundwaters of brine composition is drawn up due to the tunnel construction. Another explanation may be that there are pockets of higher salinity possibly being trapped in these areas. Further down to repository depths lower concentrations of chloride are found again, which may vary between 3,000 mg/l to around 7,000 mg/l, see Figure 5-1.

Sulphate concentrations, see Figure 5-2, does not follow the same trend as the chloride concentration. This may be due to biogeochemical processes (sulphate reduction). However, through time, the elevated sulphate concentrations are in agreement with the elevated chloride concentrations at intermediate depth (370–380 m). This may also support a possible up-coning effect which needs to be further studied.

Table 5-2. Borehole identification and lower packer level (seclow) given as corresponding elevation (above sea level).

Borehole ID	Elevation seclow (m)	Borehole ID	Elevation seclow (m)
KR0013B	–69.328	SA2600A	–346.201
KR0015B	–69.601	SA2783A	–372.919
KA1061A	–142.984	KA2862A	–381.759
SA1229A	–172.522	SA3045A	–409.156
SA1420	–204.384	KA3385A	–448.879
SA1730A	–238.111	KA3573A	–446.663
KAS03	–241.403	KA3600F	–446.186
SA2074A	–284.206	KAS03	–612.352
SA2273A	–307.051		

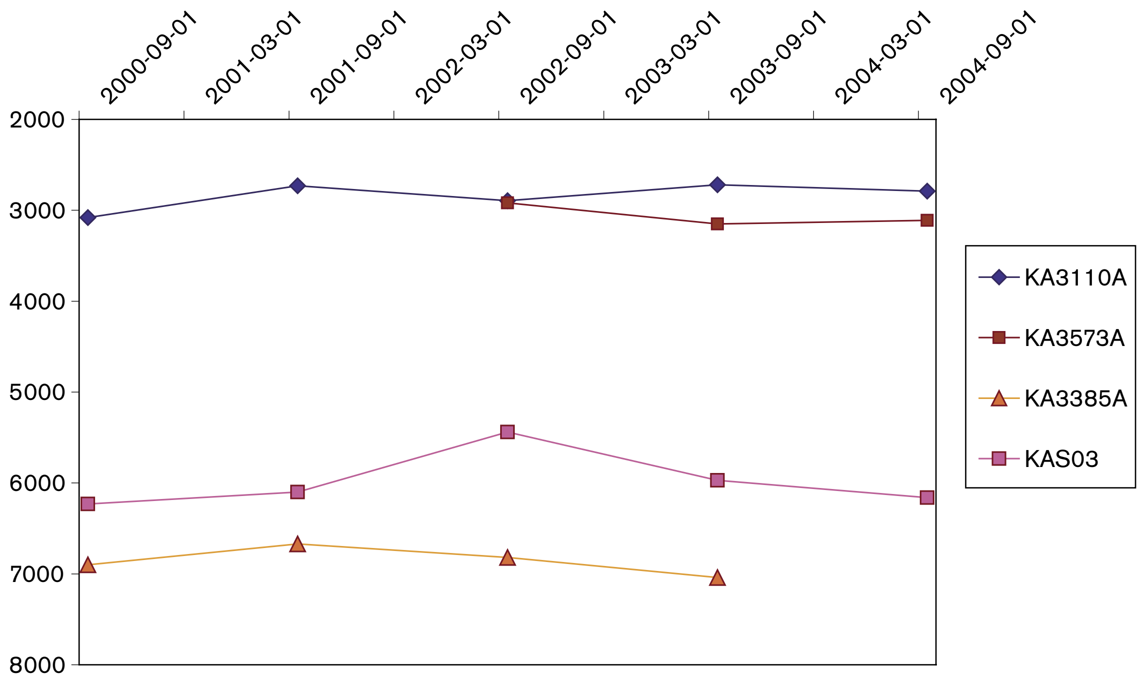


Figure 5-1. Chloride concentrations (mg/l) in selected boreholes in Äspö (tunnel and surface). KA3110A have a seclow elevation at about –416 m (above sea level) and KA3385 reaches a seclow to about –449 m (RT90). KAS03 sample which is a borehole at surface have a packed section at about –612 m.

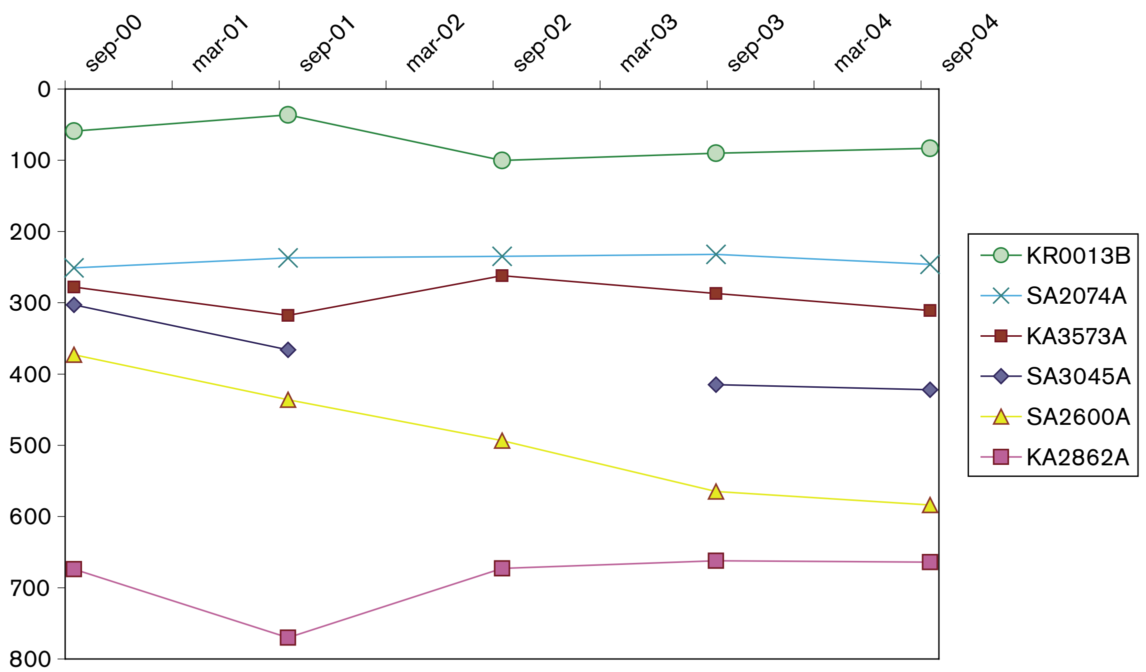


Figure 5-2. Sulphate concentrations (mg/l) in selected boreholes in the Äspö tunnel. KR0013B is the shallowest with elevations about –69 m (above sea level) to KA4573 at –446 m.

6 International co-operation

6.1 General

Seven organisations from six countries have participated in the co-operation at Äspö HRL during 2004. One organisation, Ontario Power Generation of Canada, became a new participant from January 1, 2004, and one, Nagra, have left the central and active core of participants. The co-operation is based on separate agreements between SKB and the organisations in question. The participation by JNC and CRIEPI is regulated by one agreement.

Most of the participating organisations are interested in groundwater flow, radionuclide transport and rock characterisation. Several organisations are participating in the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes, which is a forum for co-operation in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock.

The international organisations have taken part in the projects and experiments described in Chapters 2, 3 and 4 (Technology, Geo-science, and Natural barriers). The participation of each organisation is given in Table 6-1. A description of the main activities performed by the different organisations during 2004 is given in the following sections.

Table 6-1. International participation in the Äspö HRL projects during 2004.

Projects	Andra	BMWA	Enresa	CRIEPI	JNC	OPG	Posiva
Technology							
Prototype Repository	X	X	X	X	X		X
Backfill and Plug Test			X				
Long Term Test of Buffer Material							X
Cleaning and sealing of investigation boreholes							X
Injection grout for deep repositories							X
KBS-3 method with horizontal emplacement						X	X
Large Scale Gas Injection Test		X					X
Temperature Buffer Test	X		X				
Geo-science							
Äspö Pillar Stability Experiment						X	X
Natural barriers							
Tracer Retention Understanding Experiments	X				X		X
Long Term Diffusion Experiment						X	
Radionuclide Retention Project		X					
Colloid Project		X					X
Microbe Project		X					
Matrix Fluid Chemistry							
Task Force on Modelling of Groundwater Flow and Transport of Solutes	X			X	X		X

6.2 Andra

Within the framework of the co-operation agreement with SKB, Andra has in 2004 continued work on projects linked to the natural and engineered barriers. The work with the natural barriers included the True Continuation and Task Force on groundwater flow and transport of solutes. The work with engineered barriers consisted of the Prototype Repository and Temperature Buffer Test.

The results of these projects are described in their respective sections in Chapters 2 and 4 of the present report. However some additional work by Andra has been devoted to the Temperature Buffer Test, which is presented below.

6.2.1 Temperature Buffer Test

Modelling, mock-up testing and rereading of early field data, were complementary approaches followed during 2004 to better understand observed THM behaviour of the two different buffer-heater configurations tested in situ since the end of March 2003. The lower section of the Temperature Buffer Test (TBT) has the bentonite in direct contact with the heater and the upper section has a sand-filled annulus (a sand shield) between the heater and the bentonite.

The TBT evaluation modelling programme was carried out in two steps. Results of the evaluation are given in Section 2.10, and have been reported at the Tours Conference /Hökmark et al. 2005/.

UPC and Clay Technology notably pointed out that changes in the hydraulic boundary condition, temporary lack of water in the external sand filter, were the actual causes of the observed decrease in total pressure and increase in suctions in the sand/bentonite composite buffer at Rings 9 and 10 (mid height of the upper canister), between day 225 and 370, see Figure 6-1. The shortage of water supply to the upper part of the sand filter which occurred

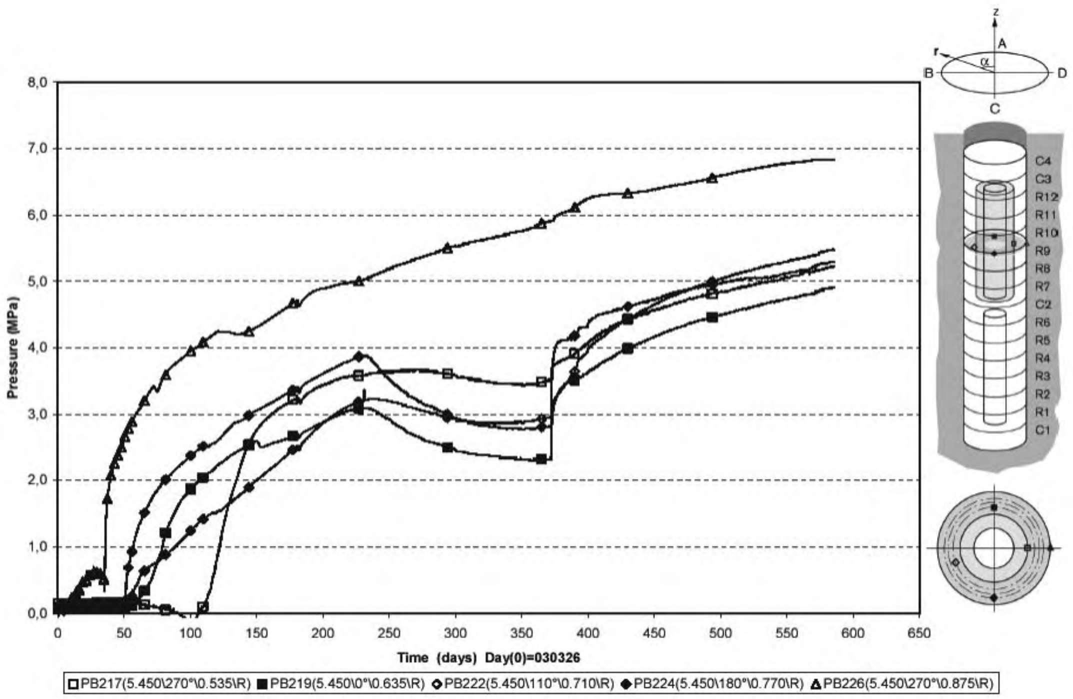
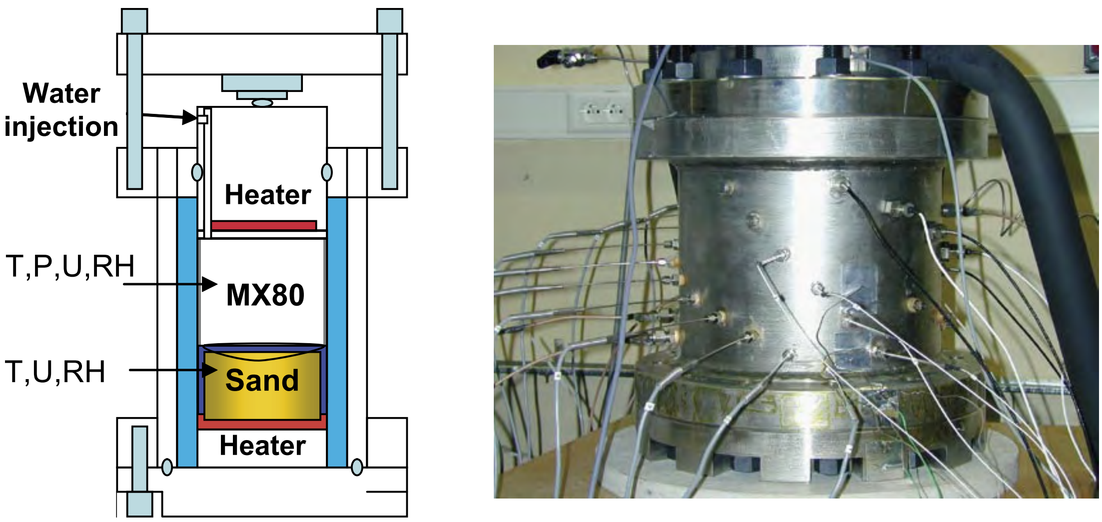


Figure 6-1. Evolution of radial total pressure in Ring 9 of the in situ test (2003-03-26 to 2004-11-01). Most pressures decrease between days 225 and 370.

during November 2003 was unexpected, but inflow resumed on April 1, 2004 following modification of the injection system. Other tentative explanations relying on sand shield mechanical compression under bentonite swelling pressure were considered and determined to be unlikely.

A CEA mock-up cell was used to mimic the composite buffer. When water injection to the hydraulic boundary was cut off, the 1D mock-up test generated pressure decreases similar to those observed in the in situ test, see Figure 6-2. These observations support the explanation developed around the field test. The CEA mock-up will be used during 2005 to further investigate the hydraulic behaviour of unsaturated bentonite submitted to temperature and temperature gradient.

Due to acquisition system malfunction, early temperature data from TBT were noisy. An attempt to reassess them after filtering was successful and permitted to establish a clear picture of the conditions, notably thermal gradients, when water movement has occurred in the unsaturated bentonite.



T = temperature, P =total pressure, U = pore pressure, RH = relative humidity

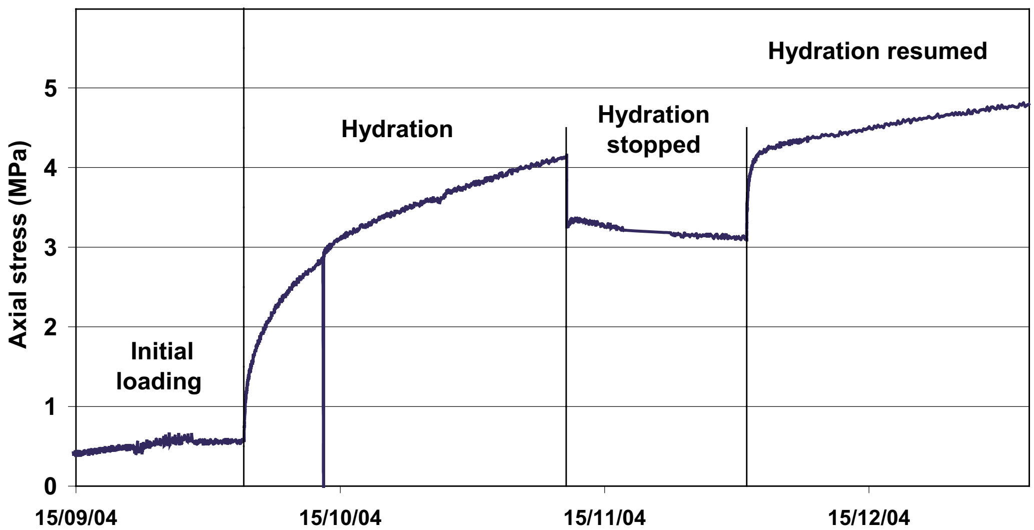


Figure 6-2. *Layout and view of the CEA 1-D mock-up cell (above). Evolution of axial pressure during water hydration and hydration shortage (below).*

The key observation made thus far in the composite buffer at Ring 10, is that no significant water displacement has apparently occurred. This is evidenced by the observations that the thermal gradients within the bentonite remained below 2°C/cm, while higher gradients persisted within the dry sand shield, see Figure 6-3.

In contrast to the composite buffer, the bentonite buffer at Ring 4 (mid height of lower canister) shows thermal gradients above 3°C/cm established around day 10, when desaturation begins, see Figure 6-4. From the figures it can be concluded that high temperature gradients in sand and low ones in bentonite cause no desaturation and high temperature gradients within unsaturated bentonite cause desaturation.

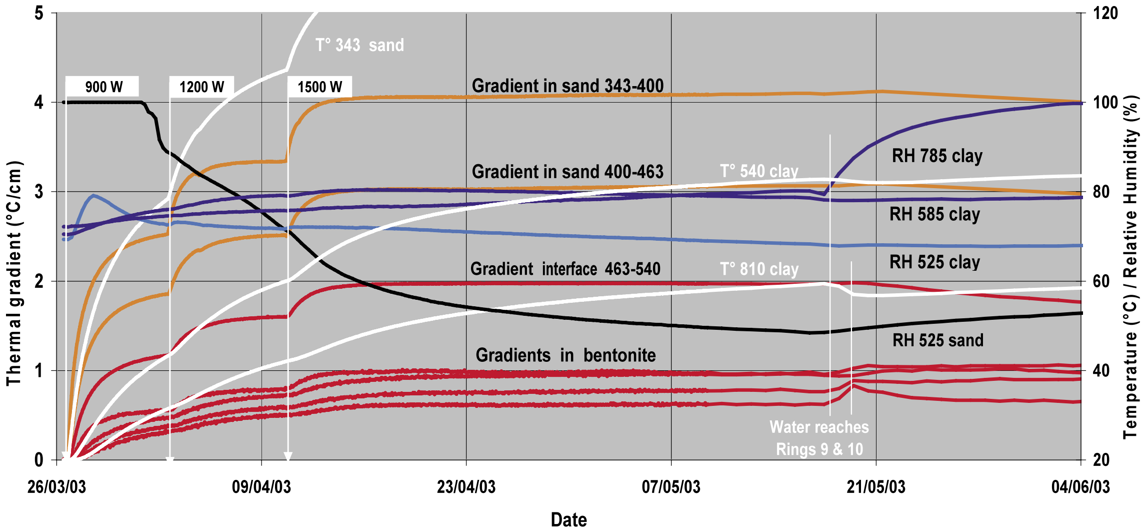


Figure 6-3. *Evolution of thermal gradient, temperature and relative humidity during the first ten weeks of the field test in the sand/composite buffer (Ring 10). Numbers following sensor symbols give radial distance to canister axis (in mm).*

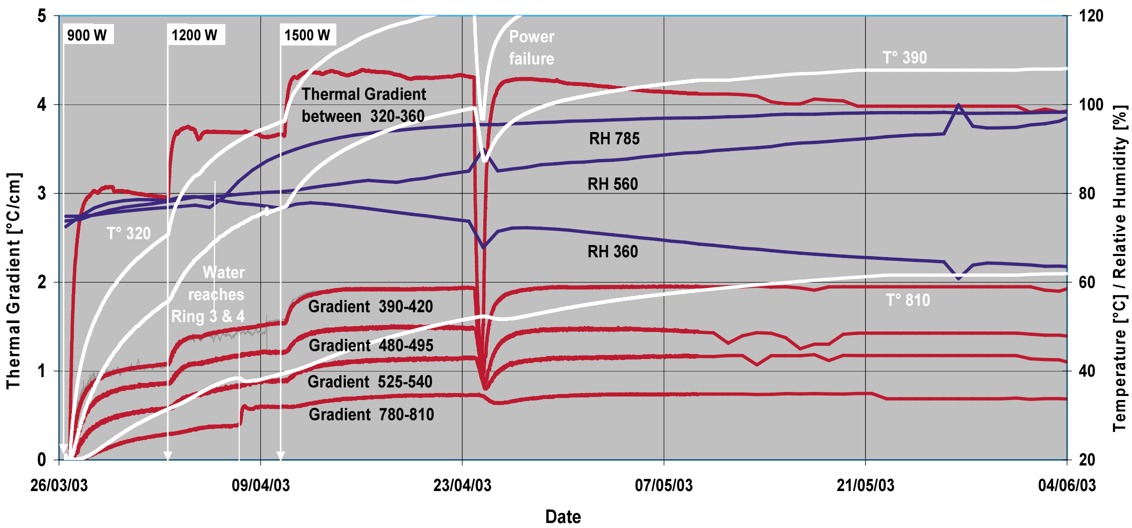


Figure 6-4. *Evolution of thermal gradient, temperature and relative humidity during the first ten weeks of the field test in the bentonite buffer (Ring 4).*

6.3 BMWA

In 1995 SKB and BMWA (Bundesministerium für Wirtschaft und Arbeit) signed the co-operation agreement being the frame for participating in the activities in Äspö HRL. The agreement was extended for a period of six years in 2003. On behalf of and funded by BMWA, five research institutions are currently performing the work in the HRL co-operation: BGR, DBE Technology, FZK, FZR, and GRS.

The general purpose of the Äspö HRL co-operation is to complement knowledge about potential host rocks for high level waste repositories in Germany and to broaden the knowledge of the behaviour of the engineered barrier system. The items of special interest are:

- In situ investigation of water flow in fractured rock, in the rock matrix, and in the engineered barrier system.
- Investigation of buffer material behaviour and the related basic processes by experiments and modelling.
- Geochemical investigations of the migration behaviour of radionuclides, especially actinides, under near field and far field conditions.
- Geochemical modelling of individual processes controlling migration.
- To study microbial activity with regard to the interaction with radionuclides.
- Thermodynamic data bases for radionuclides relevant for long-term safety.

The main work carried out by BMWA in 2004 is described below.

6.3.1 Prototype Repository

Geoelectric monitoring

In the Prototype Repository Project electrical resistivity measurements are being conducted in boreholes and backfilled tunnel sections in order to investigate time-dependent changes of water content in the buffer, the backfill, and in the EDZ (excavation disturbed zone). 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 by GRS in the geotechnical laboratory 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 holes 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 6-5.

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

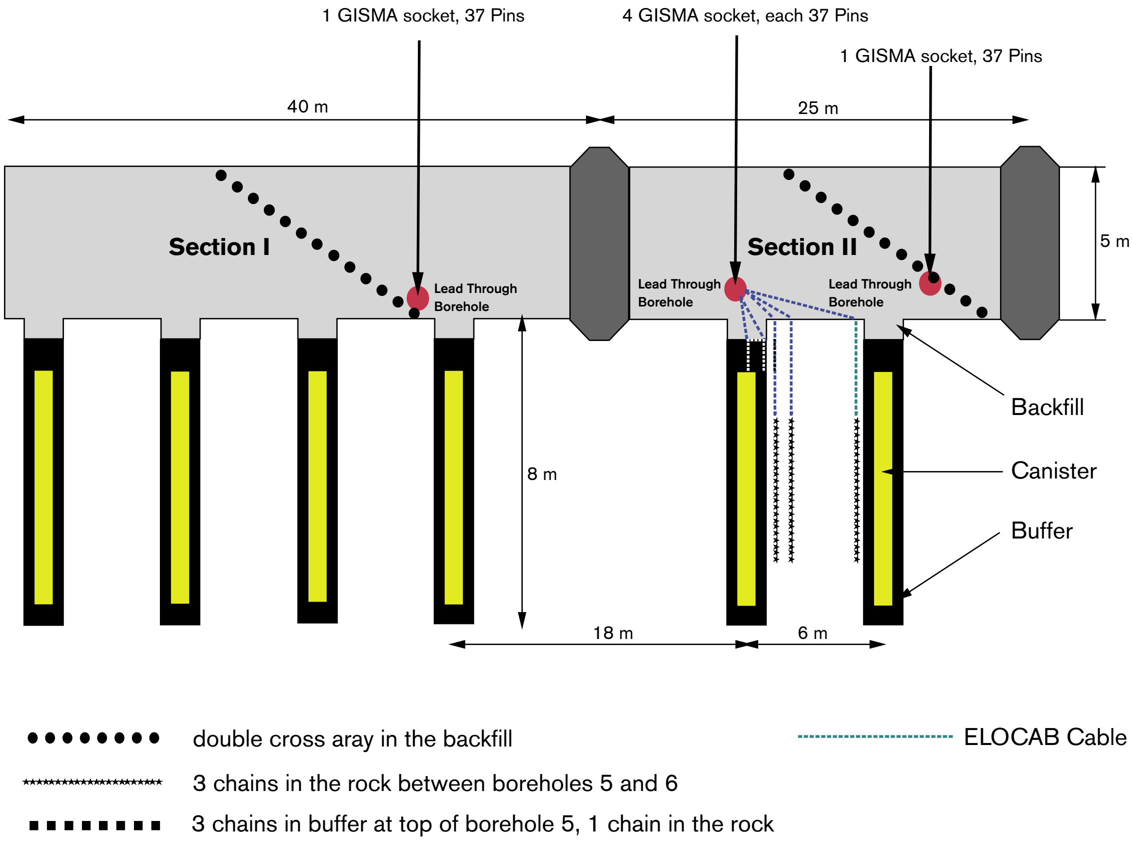


***Figure 6-5.** Arrangement of electrode arrays in the Prototype Repository.*

Results and interpretation

The array in the backfill in Section I was the first one to be installed. The measurements started in October 2001. Figure 6-6 (left side) shows the resulting resistivity distribution of the first measurement. The initial resistivity of the backfill ranges around 10 Ωm to 14 Ωm, corresponding to an initial water content of 13 to 14%. In the lower part of the backfill the resistivity is somewhat higher, which is due to a lower density of the backfill near the floor, which is a consequence of the installation and compaction procedure.

Since the first measurement the resistivity of the backfill has been steadily decreasing, starting near the walls of the tunnel and continuing to the centre. The right side of Figure 6-6 shows the resistivity distribution in December 2004. A very homogeneous resistivity distribution has been reached; with a value around 3 Ωm corresponding to a water content around 22%, which indicates that the backfill is not far from full saturation.

The array in the backfill in Section II was installed in June 2003. The results of the first measurement (Figure 6-7, left) show a much lower resistivity than the early measurements in Section I, especially close to the walls. Obviously, the backfill had considerably higher water content already during installation. This observation was also made during instrumentation. This effect is probably a result of higher water inflow rates in Section II. Resistivity is decreasing further from the drift walls (Figure 6-7, right). Close to the walls it ranges below 3 Ωm; the backfill is therefore more or less fully saturated. In the centre resistivity has decreased to values between 4 and 7 Ωm corresponding to a water content of about 15 to 20%.

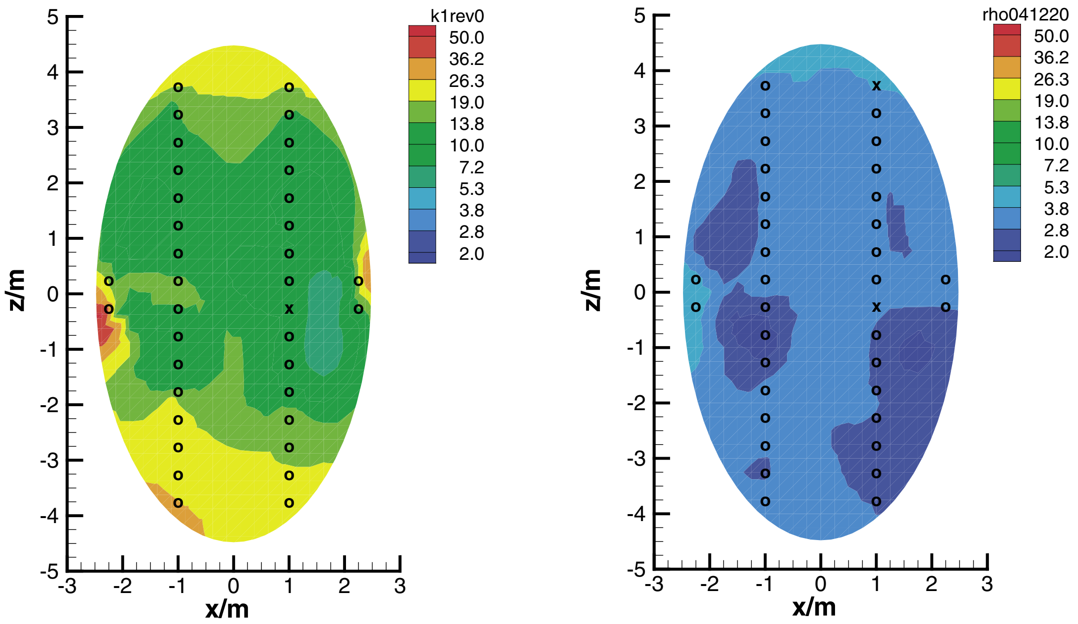


Figure 6-6. *Resistivity distribution in backfill, Section I, October 2001 (left) and December 2004 (right).*

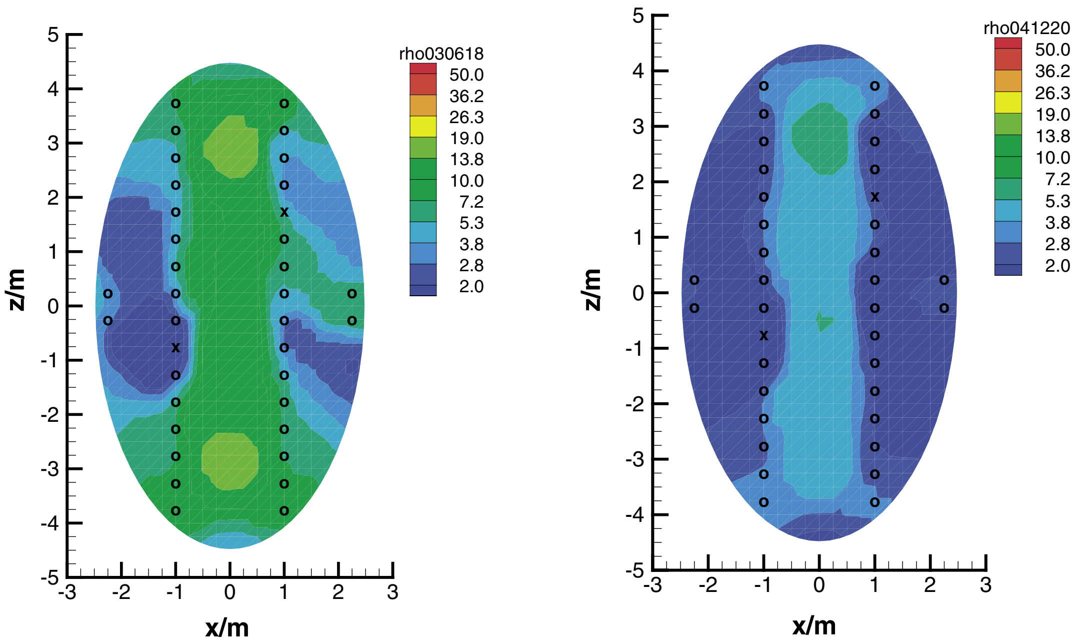


Figure 6-7. *Resistivity distribution in backfill, Section II, June 2003 (left) and December 2004 (right).*

The results of the first measurement in the buffer taken in May 2003 (Figure 6-8, left) show a high resistivity (above 1,000 Ωm) of the rock on the right side and a low resistivity of the buffer (below 80 Ωm) on the left. The picture is somewhat distorted by the fact that along the electrode chains the resistivity is increased compared to the undisturbed buffer. The increased resistivity along the electrode chains can be attributed to the refilling of the electrode boreholes with bentonite powder produced during borehole drilling. As expected, the difference has diminished with time as the buffer has taken up water. This becomes particularly clear in the tomogram from December 2004 (Figure 6-8, right). It can be seen that the resistivity near the electrode chains is no longer higher than in the surrounding buffer. While the overall behaviour is rather clear, it is difficult to interpret the buffer resistivity in terms of water con-tent. In nearly all the monitored buffer arrays the resistivities have decreased to values below 24 Ωm by December 2004.

Along the three electrode chains installed in the rock the resistivity distributions are quite similar to each other. Close to the electrodes the resistivity ranges around 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 typical for saturated granite. Figure 6-9 shows the resistivity distribution around the three chains in November 2004.

Modelling the resaturation of bentonite

In 2004 theoretical studies were carried out using the results of the project that aimed at investigating the resaturation behaviour of compacted MX-80 bentonite /Kröhn, 2004a/. Main objectives of this project were to study this process in the laboratory by testing the water uptake and to develop new conceptual models as well as the appropriate computer codes. The results of the project indicated that vapour diffusion could be the dominant water transport process in the pore space during resaturation. Moreover, there were also some doubts raised if it is appropriate to use the two-phase flow approach in the existing THM-codes.

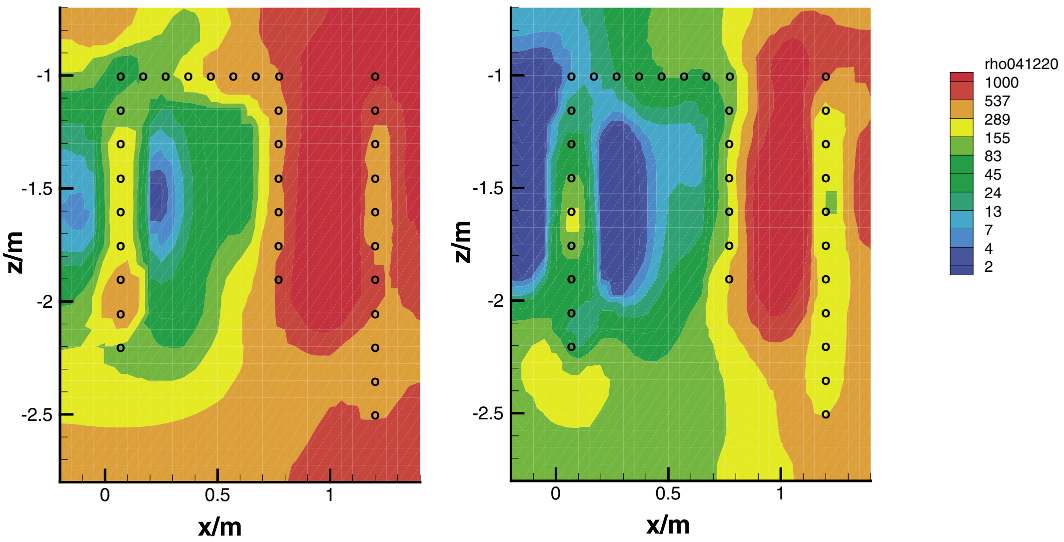


Figure 6-8. *Resistivity distribution in the buffer at the top of deposition hole 5, May 2003 (left) and December 2004 (right).*

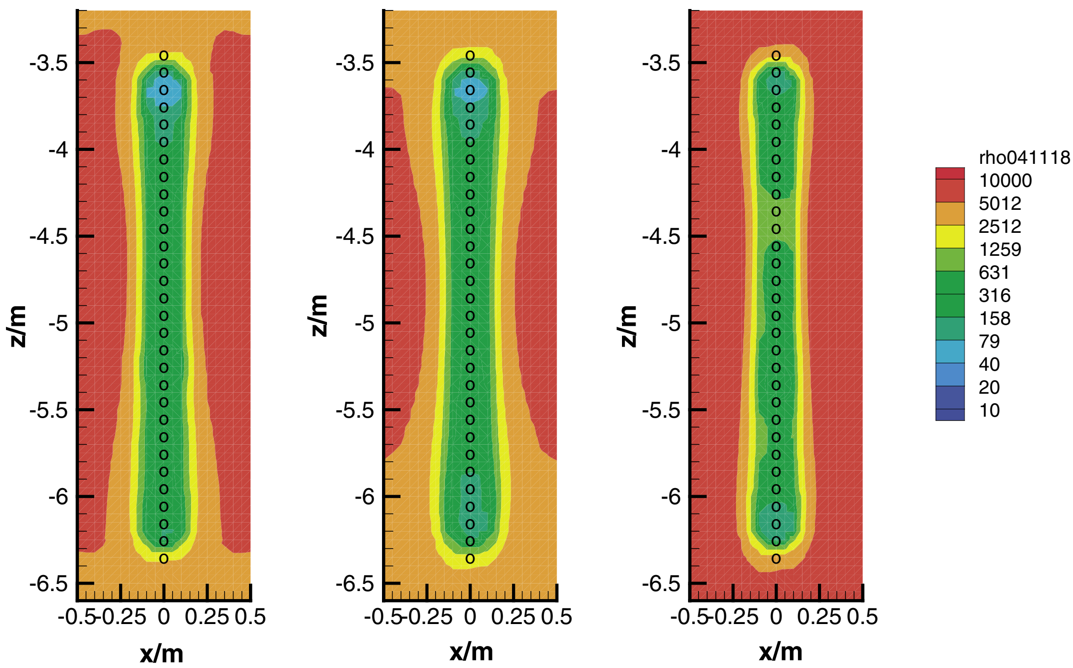


Figure 6-9. *Resistivity distribution along the three electrode chains in the rock, November 2004.*

Problems are caused by comparing the macroscopic two-phase flow concept and the microscopic processes actually taking place during resaturation. The main objection is that the THM-models describe the water content with just one variable, namely, the degree of saturation (or an equivalent measure). However, only part of the water is "freely" moving in the pore space, whereas the rest is immobilised in the interlamellar space of the clay particles. If kinetics of the hydration process is considered, then the mobile and the immobile water are to be taken into account in the balance equations. If kinetics is negligible just one variable is sufficient. But this implies (nearly) equilibrium conditions which leads to the conclusion that flow of liquid water in a partially saturated pore space is not possible /Kröhn, 2003/. Therefore, either the balance equations of the THM-models are incomplete or the equations are not consistent with the actual hydraulic processes.

To tackle this problem, a new conceptual model to describe the resaturation of compacted bentonite has been suggested /Kröhn, 2004b/. It takes into account both experimental observations and theoretical considerations. In this model the process comprises three phases (Figure 6-10).

The preliminary phase begins with the contact of water with the bentonite. In a short period of time water is sucked into the pore space mainly by capillary forces. Hydration starts when liquid water is present in the pore space. The reduction of pore space caused by the swelling of the minerals is accompanied by a remarkable reduction of permeability. Because the uptake of liquid water by clay minerals is a fast process /Pusch and Yong, 2003/, water accesses scarcely into the bentonite before further water inflow is hindered very effectively due to the low permeability. This view is supported by other experimental results /Kröhn, 2004a/ which showed relatively high water content and a particularly low dry density only in a very narrow zone at the wetted surface of the bentonite.

Simultaneously to the uptake of liquid water evaporation occurs in the pore space at the interface between the fluid and the gas phase. Evaporation becomes significant when the inflow of liquid water is low after completing the preliminary phase because the advancement of the water/air interface into the pore space is slowed down by this process.

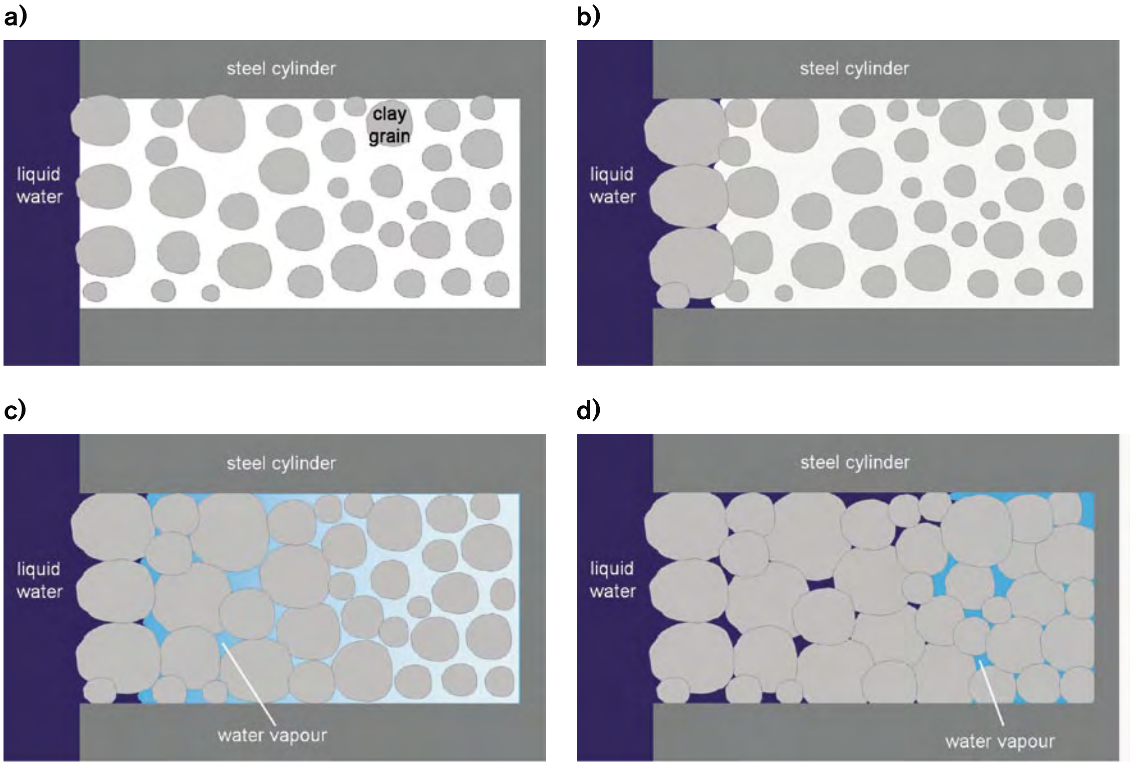


Figure 6-10. *Resaturation of compacted bentonite (experiments of /Kröhn, 2004a/) a) initial state b) preliminary phase c) main phase d) final phase.*

A rough estimate of the flux densities at the end of the preliminary phase shows that the quantity of liquid water moving through the narrow already saturated zone is equal to the quantity of produced vapour flowing into the bentonite /Kröhn, 2004a/. Thus, the saturation with liquid water is temporarily limited to the narrow zone at the wetted bentonite surface. Measurements /Pusch and Kasbohm, 2001/ indicate that the phase of capillary water uptake takes time in the order of minutes.

In the main phase no two-phase flow occurs. All the liquid water entering the bentonite evaporates at the interface between liquid water and air. A further water transport into the bentonite occurs only by vapour diffusion in the gas phase. The low density of the vapour is compensated by the high velocity of the gas diffusion process. The effectiveness of this process has been demonstrated by the vapour diffusion model /Kröhn, 2004a/.

During the main phase the vapour flux at the water/air-interface decreases as the gradient of the relative humidity decreases. Concurrently, the water vapour increases the amount of hydrated water next to the interface. This reduces the suction and thus the liquid water flow through the narrow saturated zone at the inlet. Therefore, it is quite probable that the water/air-interface movement is delayed for some time.

In the final phase two-phase flow commences again when the vapour flux eventually drops below the likewise decreasing liquid water flux. The suction forces are reduced considerably at this stage due to the resaturation via water vapour. Additionally, the permeability is very low in an advanced stage of resaturation. The significance of this third phase is not still clear.

6.3.2 Large Scale Injection Gas Test

Hydraulic characterisation of the deposition hole

The Large Scale Gas Injection Test (Lasgit) will be performed in the deposition hole DA3147G01. For the characterisation of this borehole SwedPower AB has done geological mapping and has conducted hydraulic tests in surrounding boreholes that are going to be used as anchor bore-holes for fixation of the lid on the top of the experiment. In the 4th Lasgit meeting in August 2004, BGR was asked to analyse the hydraulic tests. The results are published in an SKB-report /Hardenby, 2004/.

Figure 6-11 shows one of the measured pressure evolutions (HA3147G01) together with calculated pressure evolutions for different permeability values ($5 \cdot 10^{-19}$, $1 \cdot 10^{-18}$, and $2 \cdot 10^{-18}$ m^2) a porosity of 0.7% was assumed in the pressure evolutions. The permeability values received from the pulse tests analyses are in the lower range of other comparable fractured areas.

Hydraulic characterisation of the excavation damaged zone

For the hydraulic characterisation of the excavation disturbed zone BGR has developed the principle of surface packer tests. This packer type is fixed directly on the gallery wall, for this reason it is very qualified as a tool to characterise the area that is most damaged by excavation where borehole packers are not applicable /Nowak and Liedtke, 2004/. In February and September 2004 measuring campaigns took place in the Äspö HRL. In Figure 6-12 the scheme of the equipment is shown.

The measuring campaign in September 2004 took place in a drill and blast gallery (so called Q-tunnel). In order to characterise the induced damage by excavation there are slots cut in the gallery wall to see the blast induced cracking. Three of the test locations were arranged in one of these slots (Figure 6-13) near to the gallery wall. Figure 6-14 shows the normalised pressure pulses for the tests.

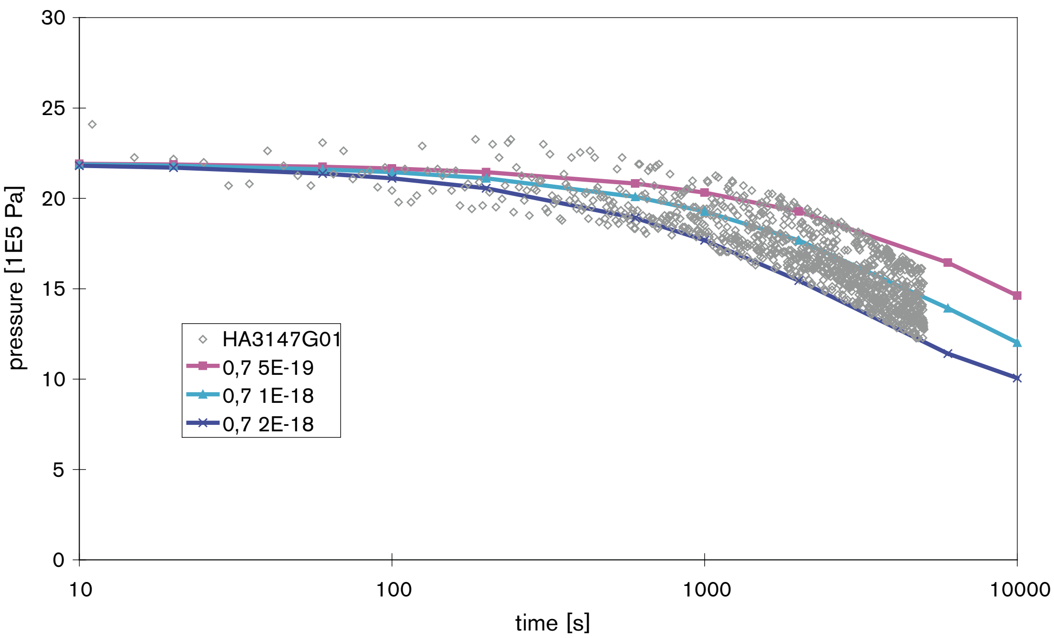


Figure 6-11. *Measured and calculated pressure evolutions for pulse test in one of the anchor boreholes (G01).*

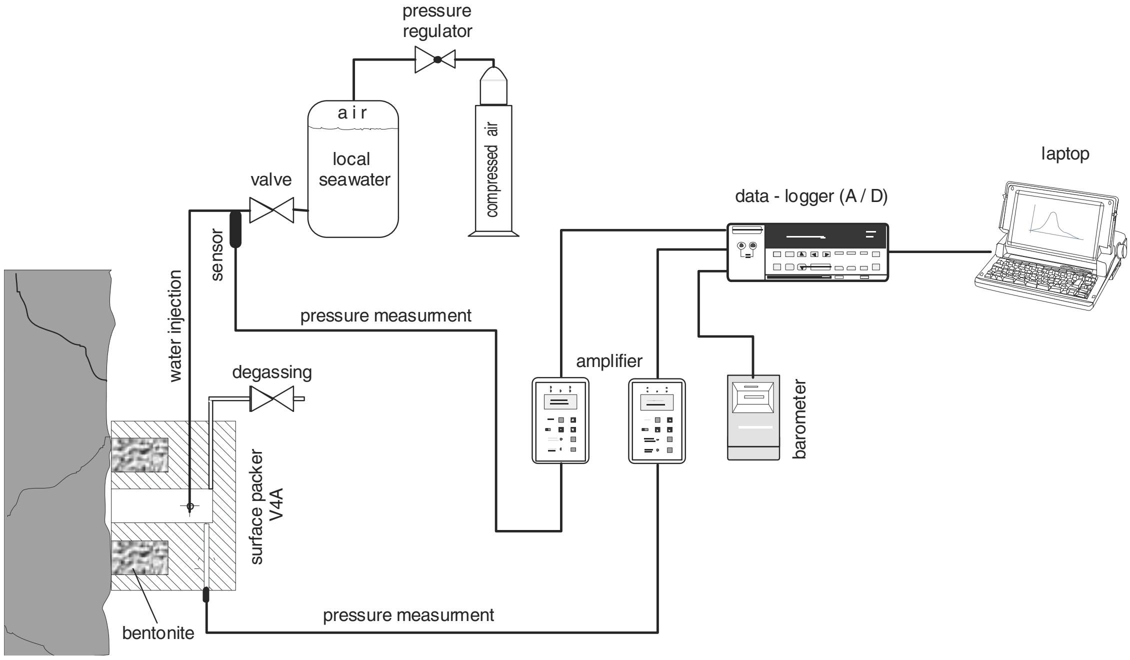


Figure 6-12. *Scheme of the surface packer equipment.*

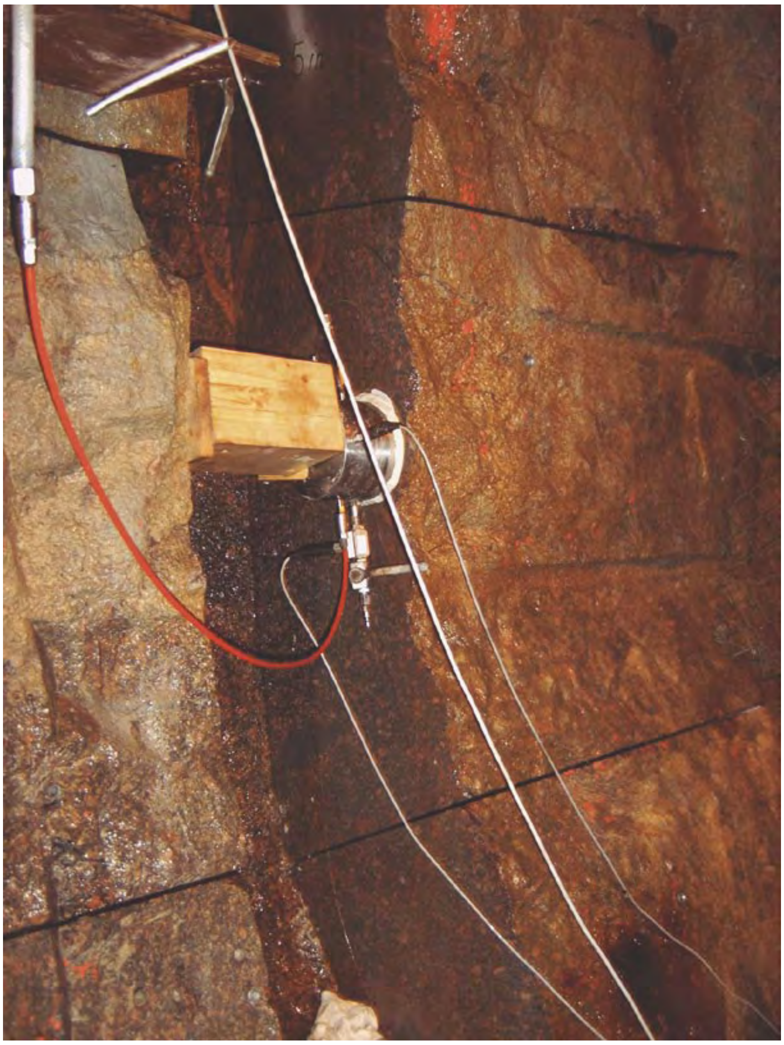


Figure 6-13. *Test location of the surface packer in a slot (Q-Tunnel).*

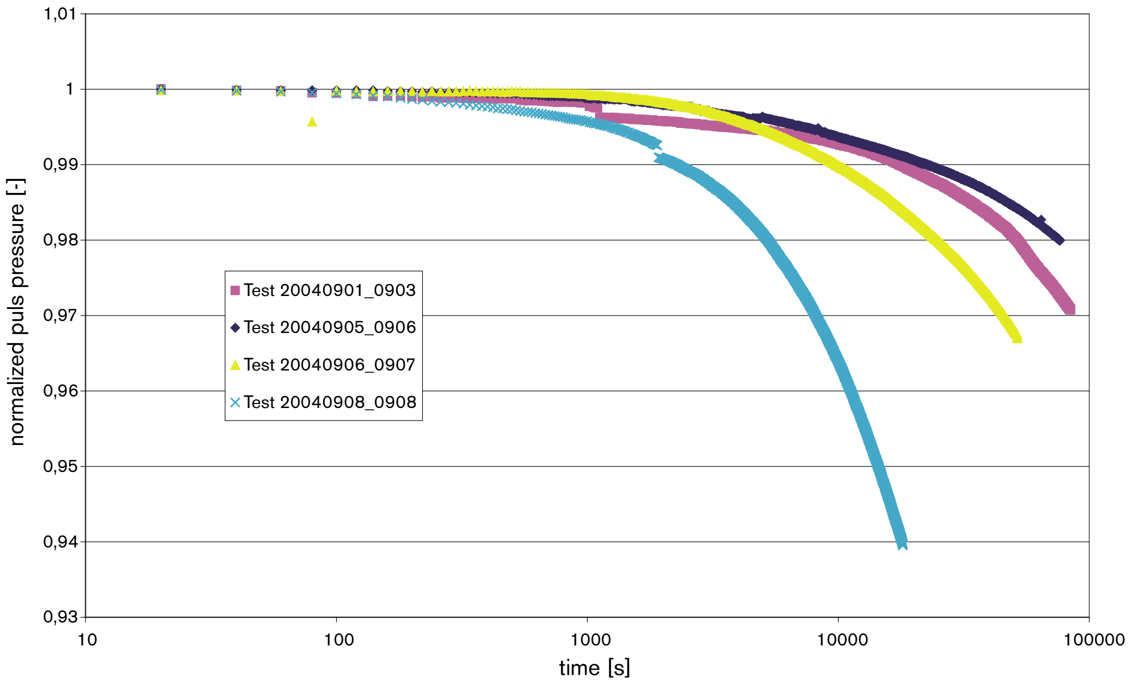


Figure 6-14. *Normalised pressure pulses from the measuring campaign in September 2004.*

Preliminary modelling of the saturation phase

In Lasgit it is planned to accelerate the saturation of the bentonite by injection of water via filter mats additionally to the natural inflow of water from the host rock. In order to predict the time that is necessary until full saturation is reached some preliminary two-phase-flow calculations have been performed with the FE-code Rockflow /Nowak and Shao, 2003/, see Figure 6-15. Additionally the capabilities of the mesh generation tool Gina developed by BGR have been enhanced with respect to intersecting fractures, see Figure 6-16.

6.3.3 Temperature Buffer Test

Two canisters placed in a deposition borehole are equipped with heating elements. Thermo-couples are placed inside the canisters and on the surface for continuous temperature measurement. The lower canister is surrounded by a bentonite buffer and the upper canister is surrounded by sand and a bentonite buffer. A more detailed description is given in Section 2.10

The slot between the wall of the deposition hole and the buffer is filled with compacted sand and functions as a filter. An artificial water pressure is applied in this slot.

The buffer material is instrumented with pressure cells (total and water pressure), thermocouples and moisture gauges. By this instrumentation the temperature distribution, the progress of water saturation and the build-up of swelling pressure in the bentonite can be measured. Thermocouples are also installed in the rock.

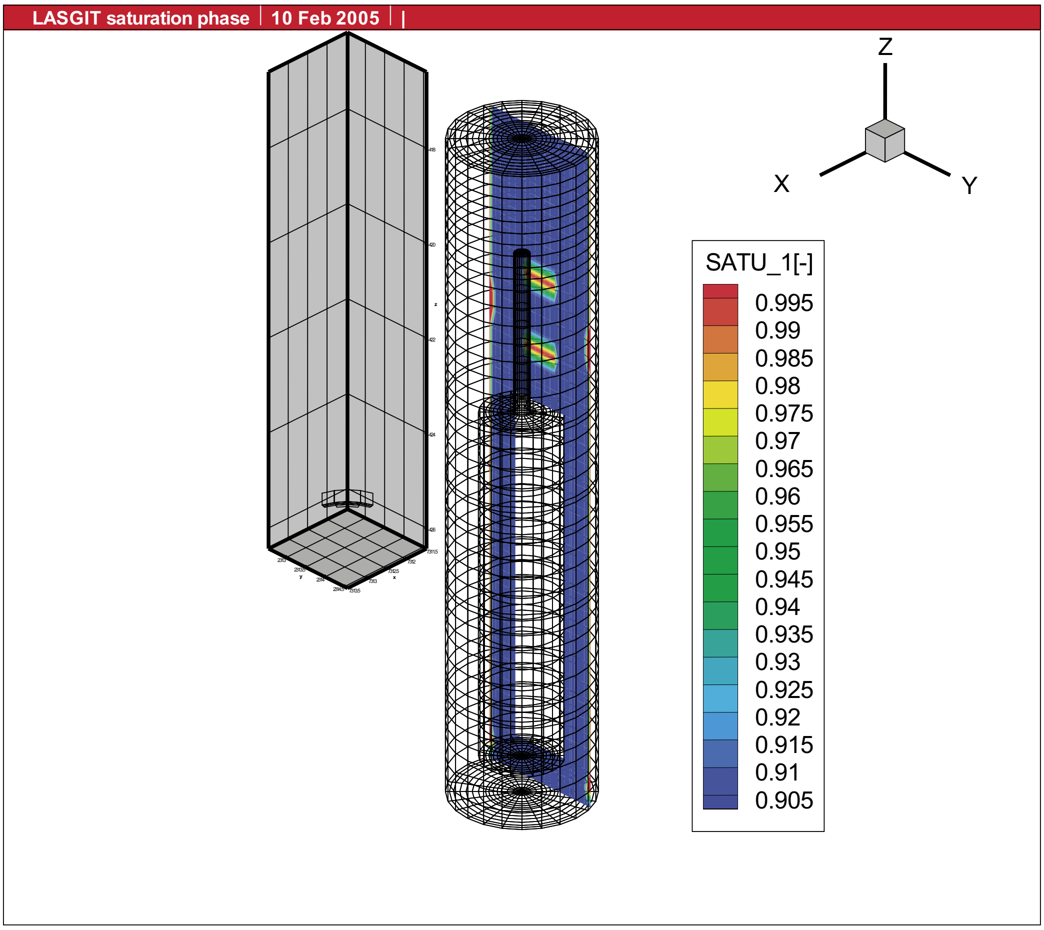


Figure 6-15. *Preliminary modelling of the saturation phase for Lasgit.*

Measurement data are available for total pressure, pore pressure and temperature at different points around the upper and the lower canister in the buffer and the host rock. An example is given in Figure 6-17 showing the development of temperature and pore pressure at Ring 3.

Several laboratory tests have been performed on bentonite samples from Äspö HRL to determine the following thermo-physical properties: thermal conductivity, thermal diffusivity, specific heat capacity, and thermal expansion. These properties were determined on samples with different water content /Buntebarth, 2004/.

The thermal conductivity and thermal diffusivity was measured at temperatures between 35°C and 200°C and at a uniaxial pressure of 2 MPa. The specific heat capacity was measured with a heat flow difference calorimeter, developed for a temperature range from ambient temperature to a temperature of 250°C. The measurement readings of the heat expansion were recorded dynamically at a heating rate of 2 K/min from ambient temperature to a temperature of 210°C.

For the thermal conductivity (Figure 6-18) and the thermal diffusivity one function with the temperature as the only parameter has been proposed for all considered water contents.

For the specific heat capacity (Figure 6-19) and the heat expansion an obvious dependency from the water content of the samples was observed.

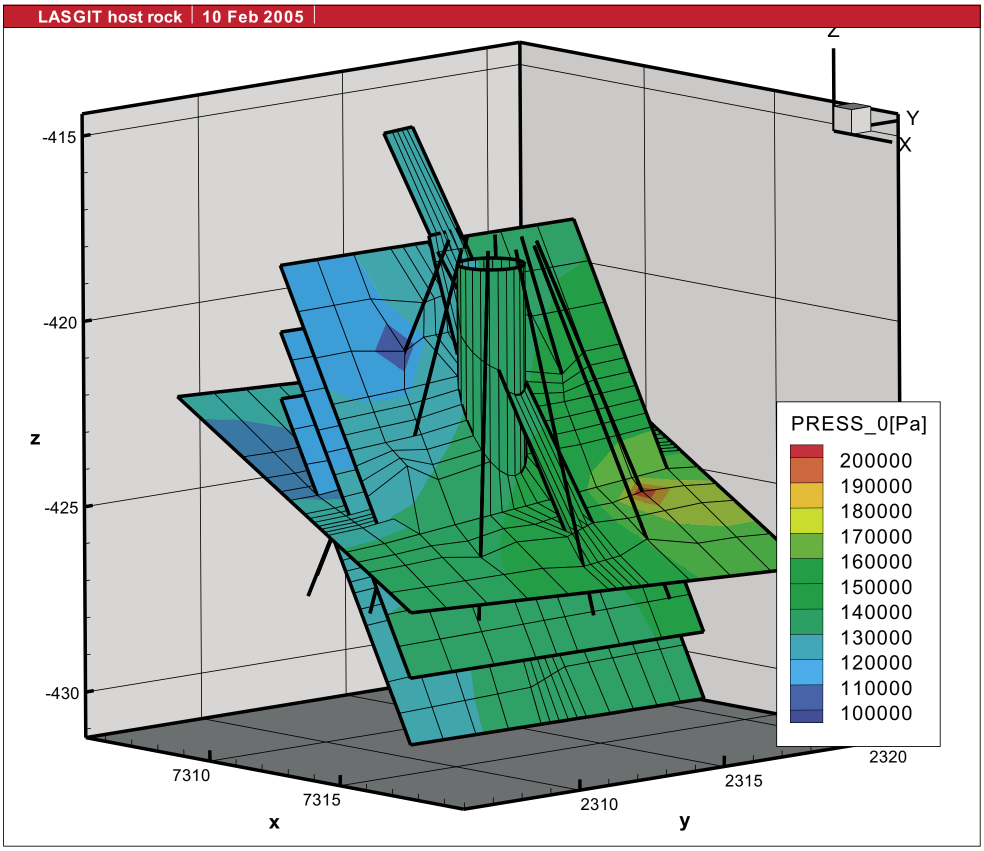


Figure 6-16. *Preliminary modelling of the host rock (intersecting fractures) around the Lasgit deposition hole.*

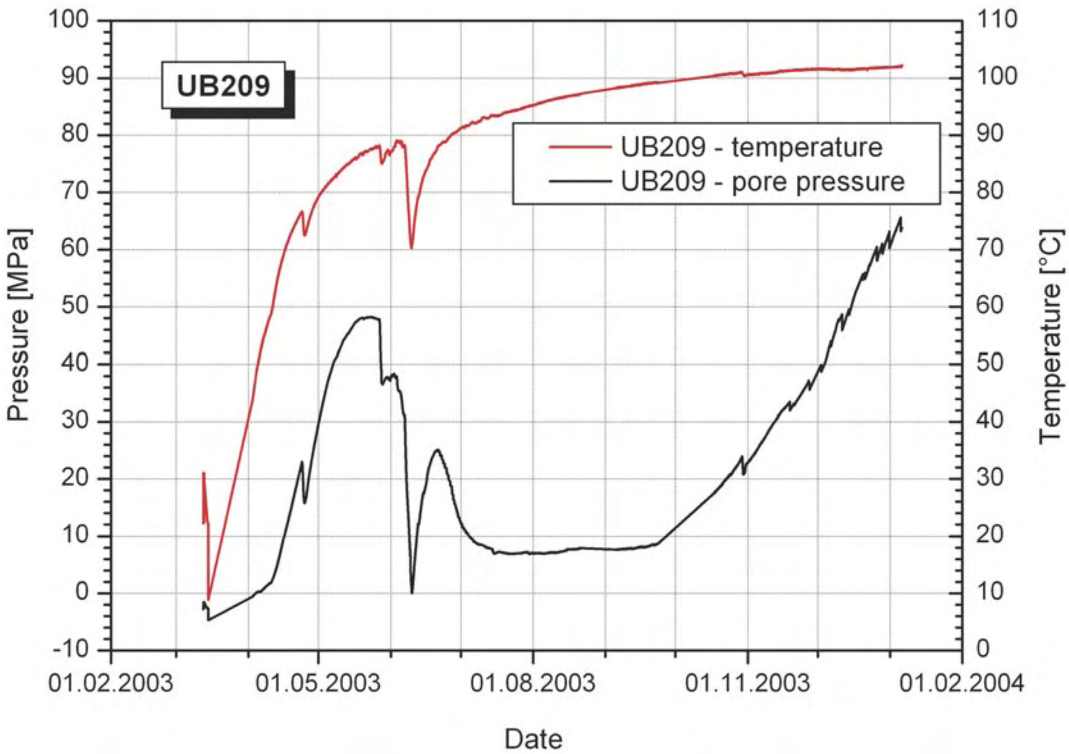


Figure 6-17. *Gauge UB209 at Ring 3, measuring section 2.*

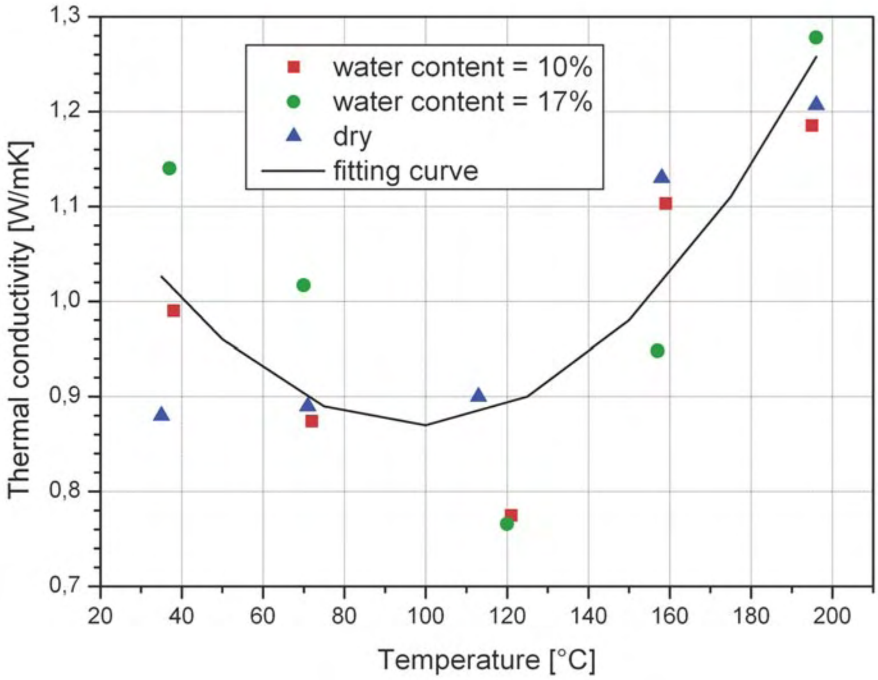


Figure 6-18. *Thermal conductivity as a function of temperature.*

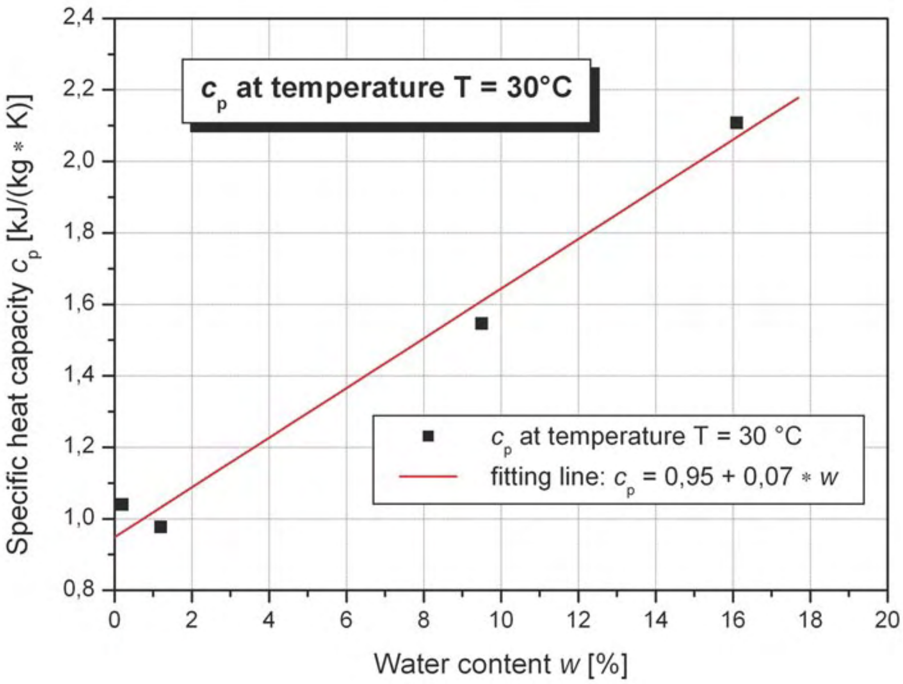


Figure 6-19. *Dependence of specific heat capacity on water content.*

For modelling of the Temperature Buffer Test a back analysis with a stepwise solution has been applied. Due to the fact that the temperature is the driving force for a thermo-hydro-mechanical (THM) behaviour only the temperature evolution was modelled first. This is to achieve a most realistic temperature field prior to any hydro-mechanical simulation. Different sets of thermal parameters within a range given by literature values or accompanying laboratory investigations were used to achieve the best fit of measured and calculated temperatures.

The temperature development in the area of the lower canister, where the canister is surrounded directly by the bentonite, has been analysed. The mathematical calculations were performed with FLAC 3D which is a 3D continuum code based on the finite difference method. It uses an explicit or implicit solution scheme and can be used for thermal, fluid, creep and dynamic analysis. Coupled THM-problems can also be handled (Figure 6-20). For this calculation the density, specific heat capacity and the thermal conductivity of the modelled materials are needed.

The calculations have been performed with a model consisting of about 12,000 elements and 14,200 nodes. The volumetric extension of the model has been chosen to be large enough to avoid a temperature increase at the model boundaries during the experiment. The smallest discretisation has been realised in the direct vicinity of the heaters with respect to the high temperature gradient as well as in the vicinity of the gauges to get a degree of accuracy as high as possible in the area of the considered gauges.

Only thermal calculations have been performed, that means only parameters which are necessary for the thermal calculations were considered. The parameters of the bentonite are given by laboratory investigations and the host rock parameters have been obtained from literature. The thermal conductivity is assumed to be constant over the whole temperature range. This is confirmed by two separate studies at Äspö HRL, which show no significant trend for the thermal conductivity with respect to temperature for different rock types. The exception is altered Äspö diorite. The thermal conductivity of Äspö diorite increased about 7% in the interval 25–80°C.The maximum measured temperatures in the host rock are lower than about 70°C (area of the lower canister). For this reason and because of the lack of more detailed material data the thermal conductivity of the host rock was assumed to be constant.

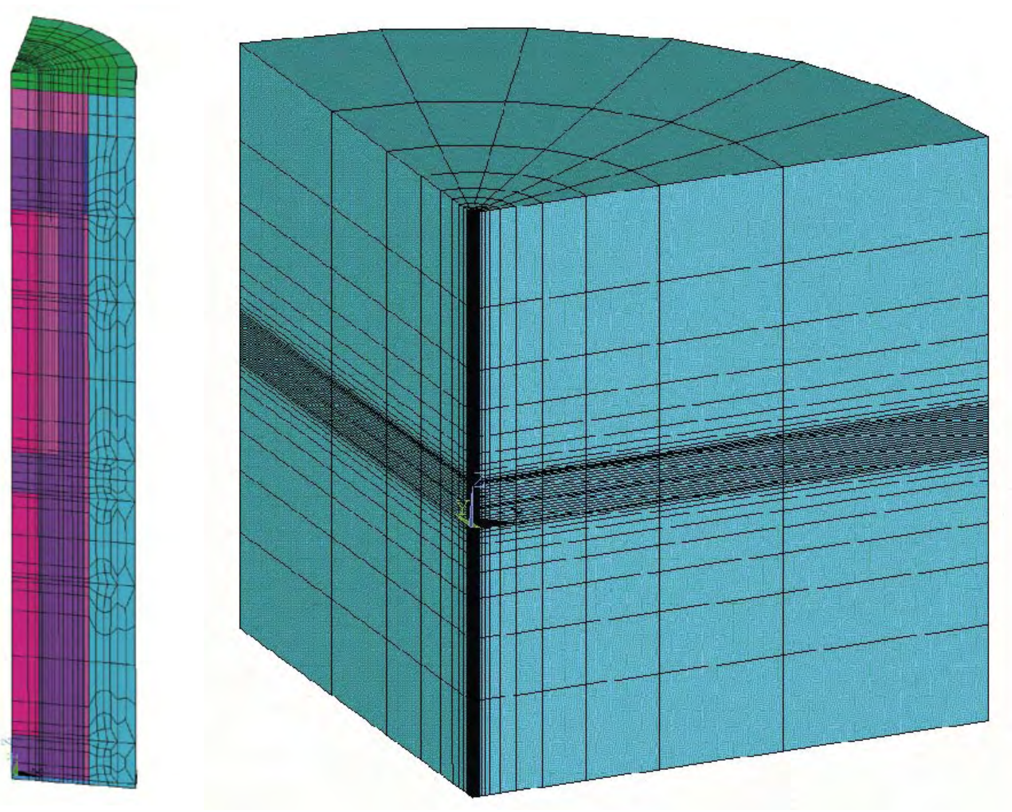


__Figure 6-20.__ Numerical model, overview and detailed view of the experiment area.

The densities of all materials are well known. The specific heat capacity has minor influence on temperatures because steady state heat flow is established in the bentonite and the host rock within a short time after starting the heating. Therefore, one value out of a given range was taken, if no exact value is known. The thermal conductivity of all considered materials is known with the exception of the bentonite and the host rock. Because of the great influence of these two parameters on the temperatures different parameter variations were performed.

Several calculations for different thermal conductivities of the host rock show that a higher thermal conductivity leads to lower temperatures in the bentonite.

When steady state heat flow conditions are reached the difference between temperature curves considering different constant values for the thermal conductivity is nearly constant. The influence on the temperature in the bentonite is the same at all measurement points.

In contrast the influence of the thermal conductivity of the bentonite on the temperature decreases with greater distance to the canister. A comparison between the proposed fitting curves for all considered water contents of the laboratory investigations with the fitting curves for each water content show that the influence is negligible. Therefore, the fitting curve for all samples will be used for further calculations.

To get the best fit of measured and calculated temperatures several combinations of the thermal conductivity of the host rock and the bentonite were investigated. For the proposed fitting curve of all considered water contents and a constant thermal conductivity of $\lambda_{Host\ Rock} = 2.20\ Wm^{-1}K^{-1}$ the calculated temperature are quite concordant with the measured temperatures, see Figure 6-21. These values will be used for further coupled calculations.

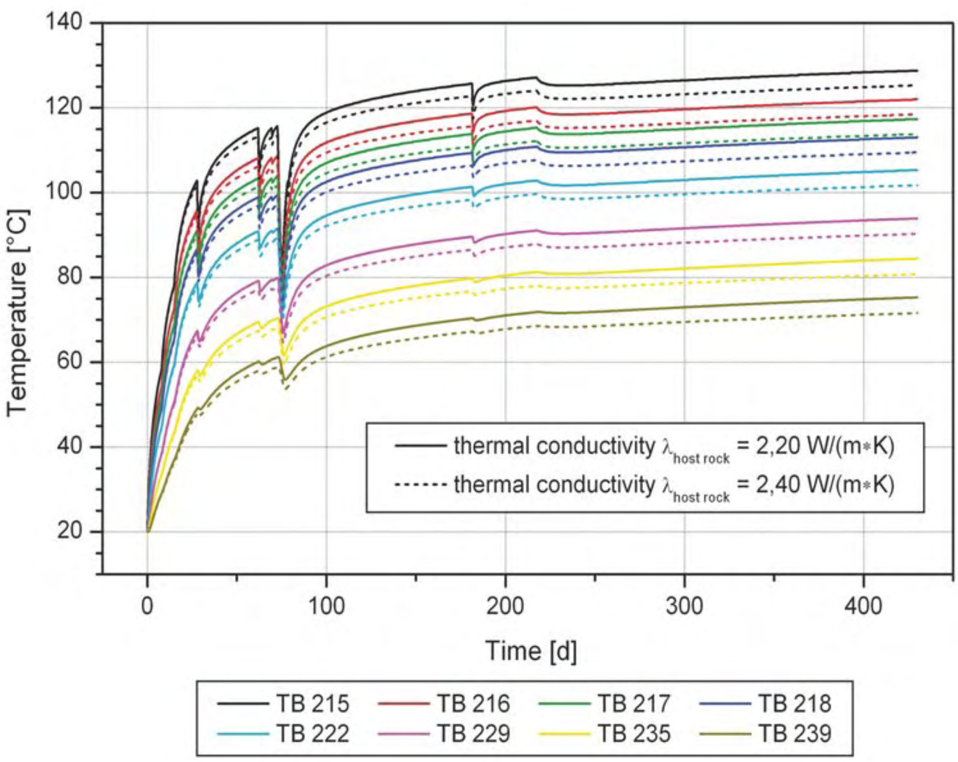


***Figure 6-21.** Influence of the thermal conductivity of the host rock on the calculated temperatures. (The coloured lines are calculated temperatures taken from nodes of the numerical mesh that are comparable to the location of the assigned sensors in the experiment).*

6.3.4 Radionuclide Retention Experiments

Objectives

The objectives of the FZK/INE investigations are focusing on the quantification of the retention of different actinide elements in single fractures of a granite host rock and the investigation of the sorption mechanisms. To guarantee undisturbed groundwater conditions, the experiments are designed to be compatible with the Chemlab 2 probe. It is expected, that the results will show whether radionuclide retention coefficients measured in laboratory batch experiments can be applied to in situ conditions and whether they will reduce the uncertainties in the retardation properties of americium, neptunium and plutonium, uranium and technetium.

Experiments and Results

An in situ migration experiment was started with the Chemlab 2 probe in May 2004. A core (Core #7) was prepared as in previous experiments. The flow path properties and the breakthrough of inert HTO tracer were investigated in laboratory. In this in situ experiment, HTO, ^{233}U and ^{99}Tc are used as tracers. Similar flow rates are applied as in the previous experiment (0.03–0.05 ml h^{-1}). The experiment will be terminated in mid 2005, and therefore only breakthrough curves are available from this test. Before starting the experiment, sorption data onto granite and weathered material from the fracture were investigated in laboratory, see Table 6-2.

The table shows the highest sorption coefficient onto granite and on weathered fracture surfaces for Pu, one order of magnitude lower for Np and Tc and again a factor of 10 lower for U. For this reason, a significantly higher recovery of U is expected in comparison to Np and Tc.

The following figures show the breakthrough of the tracer elements until end of October 2004. At this time, the eluted groundwater has accumulated to about 130 ml. In Figure 6-22 the HTO breakthrough shows the maximum after ~ 20 days (left axis), ^{233}U reveals the peak maximum after the same time (right axis). After this initial decrease of U, a certain increase of the concentration is observed until summer vacations. During vacations, the experiment was stopped. After restart of the experiment in September 2004, a significant short term release of U is observed. By ICP-MS analysis of the water samples, the natural U isotopes (238, 235 and 234) follow the ^{233}U tracer concentration. This finding indicates an externally forced U mobilisation process. Such a process may be the result of an increase of the redox potential as a result of desorption of oxygen from inner surfaces of the core. After this peak, the U concentration is found in the expected range. The assumption of O_2 diffusion from the matrix is supported by the slight HTO peak at the same time which is certainly a result of diffusion out of the rock sample (matrix).

Table 6-2. Surface related retention coefficient of radionuclides onto granite slices and fracture surfaces after 14 days of exposure.

Nuclide	Surface related retention coefficient, K_s (cm)	
	Freshly broken granite	Altered material
^{243}Am	Not available	9.5
^{238}Pu	2.50	1.30
^{237}Np	0.16	0.16
^{233}U	0.026	0.018
^{99}Tc	0.210 ± 0.013	Not available

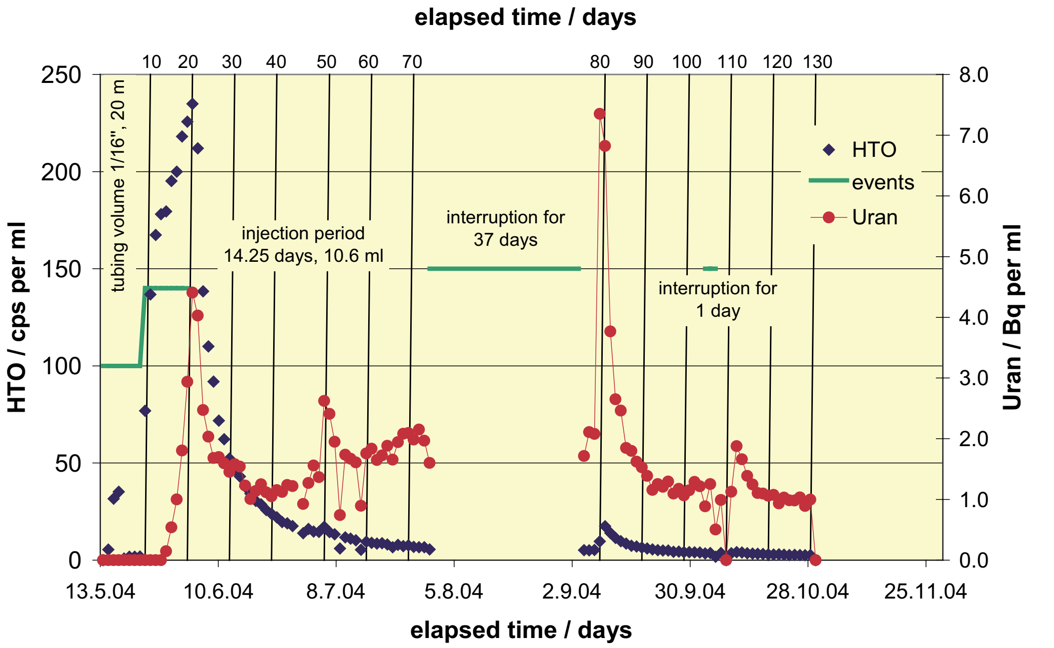


Figure 6-22. *Breakthrough curves of ^{233}U (right axis) and HTO (left axis) as function of time.*

In Figure 6-23 the maximum ^{99}Tc concentrations in the eluted samples are found significantly before (~ 12 days) the maximum concentrations of HTO (~ 20 days). After the initial peak, Tc concentrations drop.

Investigations of the eluted samples will be continued. In March 2005, the experiment will be terminated and Core #7 analysed with respect to sorbed U and Tc.

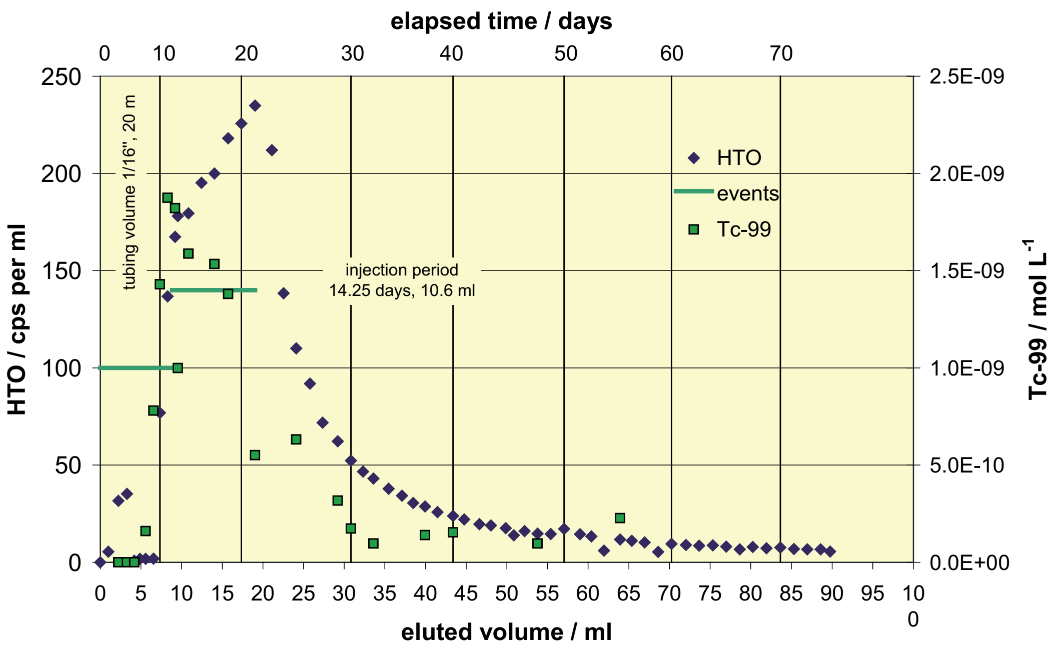


Figure 6-23. *Breakthrough curves of ^{99}Tc (right axis) and HTO (left axis) as function of the eluted volume.*

6.3.5 Colloid Project

In safety assessment for a radioactive waste repository, aquatic colloids existing in natural groundwater play a role as carrier for the migration of radionuclides, mainly actinide ions from the waste to the biosphere. Apart from actinide oxide/hydroxide colloids, colloids released from bentonite buffer and backfill and also background colloids present in natural groundwater can contribute to the migration of radionuclides. Therefore, a study is being performed to investigate the amount of background colloids in natural granite groundwater.

Starting in 2001, the Laser-induced Breakdown Detection (LIBD) method has been applied to detect in situ the amount of colloids in a series of groundwaters from different boreholes along the access tunnel of the Äspö HRL. From these investigations a decrease of the background colloid concentration with increasing groundwater salinity may be assumed. The experiments also demonstrated the perturbing influence of artefacts on the colloid detection. This was an erosion of additional colloids from fracture filling material with increasing groundwater flow rate. Additionally, diffusion of atmospheric oxygen through the groundwater tubing or intrusion through the fractured rock of the excavation disturbed zone (EDZ) caused a significantly higher amount of colloids by precipitation of Fe(III) oxide/hydroxide colloids.

Therefore, a new sampling campaign was initiated in 2004. Colloids from boreholes KXTT3/3, KXTT4/4, KA1755A, and HA2780A with a Cl^- content > 4 g/l in the groundwater have been detected at site under unperturbed in situ conditions without any interference by sampling.

Experimental work

The mobile system of the LIBD combined with a geo-monitoring unit for detection of pH, Eh, electrical conductivity, oxygen content, and system pressure is applied. The LIBD method has previously been described. The sensors and detection cells of the new geo-monitoring unit can be operated at hydrostatic pressures up to 15 bar. The electrical signals of the transmitters are transformed in an external data logger and stored in a personal computer as a function of detection time. The investigations are completed with groundwater chemical analysis by ICP-MS, ICP-AES, IC and colloid analysis of filtered water samples by scanning electron microscopy and EDX.

Results

Figure 6-24 shows the actual correlation between the detected colloid concentration and the Cl^- concentration of the groundwater. The new LIBD results from in situ investigations at Äspö demonstrate a colloid concentration of ~ 0.06 µg/l for groundwater from boreholes KXTT3/3, and KXTT4/4 from the True-1 site with chloride contents ~ 4 g/l. For groundwater from borehole KA1755A, and HA2780A with chloride > 10 g/l colloid concentrations close to the LIBD detection limit of ~ 0.01 µg/l are detected.

For borehole HA2780A earlier results showed a two orders of magnitude higher colloid concentration. The influence of the EDZ was assumed. Before the 2004 measurements, the packers have been moved outside the EDZ. The detected low colloid concentration proves the influence of the EDZ. The actual investigations demonstrate a significant decrease of the background colloid concentration with increasing salinity.

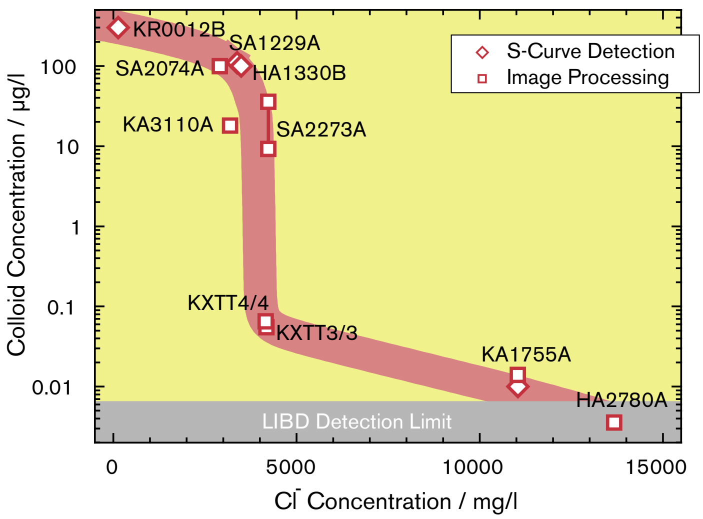


Figure 6-24. *Colloid background concentration as a function of the groundwater chloride concentration.*

6.3.6 Microbe Project

Introduction

The investigations of FZR/IRC were focused on the description of the interaction processes of selected actinides with indigenous bacteria in the Äspö aquifer. In the last three years, a project was performed investigating: (i) the interaction of U, Cm, Np and Pu with the sulphate-reducing bacterial (SRB) strain *Desulfovibrio äspöensis* found in Äspö groundwater /Motamedi and Pedersen, 1998/, (ii) quantification of the actinides bonding on the bacteria in dependence of the chemical conditions in the groundwater, and (iii) spectroscopic characterisation of the actinide complexes/compounds formed by interaction with microbes. Before the present project, it was unknown in which way cells of *D äspöensis* are interacting with the selected actinides. The main outcome of this project is summarised in this report.

Cultivation and characterisation of the biomass

The Swedish partners investigated the microbial diversity of the Äspö site and could show that SRB are frequently occurring, 10^1 to $2{\cdot}10^4$ cells ml^{-1}, in the deep granitic aquifer system at the Äspö hard rock laboratory /Pedersen et al. 1996; Pedersen, 1999; Kotelnikova and Pedersen, 1998/.

The cells of *D äspöensis* were successfully cultivated under anaerobic conditions in liquid and on solid medium. Under the given experimental conditions, the cells reached the stationary phase of the growth curve after 8 to 9 days after inoculation at 22°C. The purity of the cultures was verified using light microscopy and by applying the molecular microbiological method Amplified Ribosomal DNA Restriction Enzyme Analysis (Ardrea) as described in /Moll et al. 2004a/. Figure 6-25 (right) summarises the results of the molecular analysis. The predicted pattern for each endonuclease is drawn in A and the experimentally determined pattern is presented in B. Both are in agreement and show the purity of the used bacterial cultures. To study the interaction of *D äspöensis* with the selected actinides the cells were grown to the mid-exponential phase (4 days). The biomass was collected by centrifugation and washed three times with 0.9% NaCl. The collected biomass was 1.0 ± 0.2 $g_{dry\ weight}$/l.

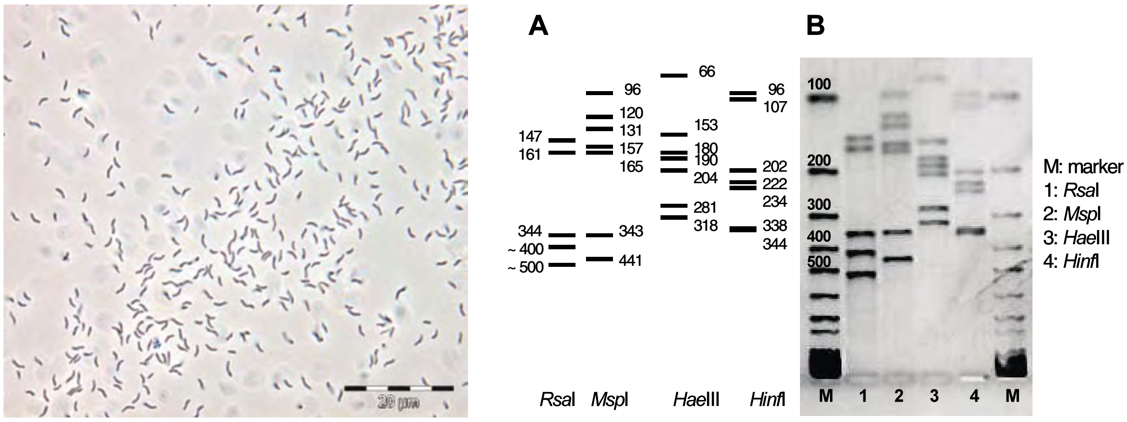


Figure 6-25. *Left: Visualisation of D äspöensis DSMZ 10631T bacteria by light mi-croscopy; Right: Identification of D äspöensis based on 16S-Ardrea. A) Scheme of the endonuclease-specific Ardreaprofiles of D äspöensis drawn on the basis of the sequence analysis of the 16S rRNA gene. B) Experimentally derived 16S Ardreapat-terns of D äspöensis.*

Investigation of the interaction of D äspöensis with U(VI), Np(V), and Cm

For the first time it could be demonstrated the removal of U(VI) from solution due to the activity of the cells of *D äspöensis* /Moll et al. 2003a;b; 2004a;b; Merroun et al. 2004/. Three parameters are influencing the removal efficiency of U(VI): a) the interaction time, b) the pH, and c) the initial uranium concentration, $[U]_{initial}$, present in the test solutions. The amount of U bound to the biomass increased with increasing pH from 3 to 6. However, at pH 8 a strong decrease of the amount of accumulated uranium was observed. The cells of *D äspöensis* removed 55% of the U(VI), 10.1 $mg/g_{dry\ weight}$, from an aqueous solution of 14.6 mg/l U(VI), supplemented with 10 mM lactate, after 72 h of incubation at pH 5. Within this investigation the first direct spectroscopic proof for a reduction of U(VI) to U(IV) most likely by an enzymatic reaction due to the activity of the cells was obtained. The toxicity of U(VI) towards *D äspöensis* could by proved using microbiological methods. As a consequence, the membrane system gets damaged and uranium can penetrate inside the bacterial cells (see Figure 6-26).

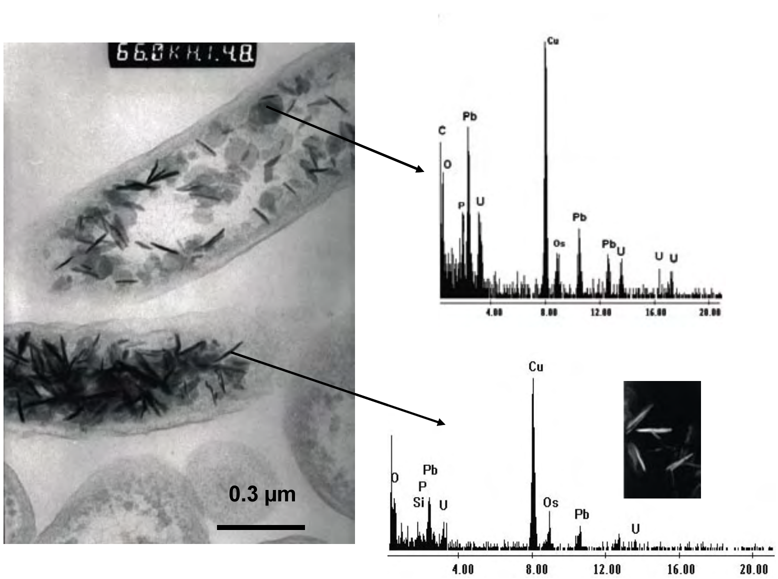


Figure 6-26. *Transmission Electron Microscopy (TEM) and Energy-Dispersive X-Ray Spectroscopy (EDX) analysis of the cellular localisation of uranium accumulated by the cells of D äspöensis.*

The EDX spectrum derived from the U deposits indicated that they are composed of oxygen (O), phosphorus (P) and uranium (U). The high copper (Cu) peak is from the grid used to support the specimen. The lead (Pb) peak originated from the lead citrate solution which was used in order to improve the visualisation of the uranium-treated cell thin sections.

The results are indicating a complex interaction mechanism consisting of biosorption, bioreduction, and bioaccumulation.

Furthermore, it could be shown for the first time the removal of Np(V) from the solution by cells of *D äspöensis* /Moll et al. 2005a/. The cells of *D äspöenis* removed only 2.5% of the Np(V), 0.69 $mg/g_{dry\ weight}$, from an aqueous solution of 23.7 mg/l Np(V) under steady state conditions at pH 5. Similar to U(VI), the interaction time, the pH, and the initial neptunium concentration, $[Np]_{initial}$, present in the test solutions are influencing the amount of bound Np(V) to the cells. The time dependent decrease of the Np concentration in solution shows slightly slower kinetics compared to uranium. Furthermore, Np(V) exhibits a weaker tendency to interact with the biomass than U(VI). Interestingly, no difference was detected in the amount of accumulated Np by the biomass in the presence or the absence of U in the test solutions. This might indicate the occurrence of different binding places and/or binding modes for Np and U on the cell envelope of *D äspöensis*.

The ^{242}Pu was provided as a mixture of c 46% Pu(VI) and c 34% Pu(IV)-polymer. Interactions between bacteria and plutonium in mixed oxidation states were not yet intensively investigated.

In this study, accumulation experiments were performed in order to obtain information about the amount of the Pu bound by bacteria in dependence on the contact time and the [^{242}Pu] initial at pH 5. The cells of *D äspöensis* removed 30% of ^{242}Pu, 4.70 mg/g dry weight, from an aqueous solution of 15.7 mg/l ^{242}Pu after 72 h of incubation at pH 5. Liquid-liquid-extractions and absorption spectroscopy were used to determine the Pu speciation. In agreement with the results obtained with U(VI) and Np(V) a strong dependence of the amount of accumulated Pu with $[^{242}Pu]_{initial}$ was found.

Based on our results and taking into consideration the findings of /Panak and Nitsche, 2001/, a model describing the interaction of Pu(VI) and Pu(IV)-polymers with *D äspöensis* was developed. In a first step, the Pu(VI) and Pu(IV)-polymers are bound to the biomass. The Pu(VI) is reduced to Pu(V) due to the activity of the cells within the first 24 h of contact time. Most of the formed Pu(V) dissolves due to the weak complexation properties. The dissolved Pu(V) disproportionates to Pu(IV) and Pu(VI) which are then interacting with functional groups of the cell surface structure. Indications were also found for a penetration of Pu species inside the bacterial cells. Similarly to U(VI) and Np(V), the interaction of Pu with *D äspöensis* is a complex mechanism which consists of sub-processes (Figure 6-27).

For Cm(III) at a trace concentration level of $3 \cdot 10^{-7}$ M, the pH dependence of the fluorescence emission spectra with a pure biosorption forming an inner-sphere surface complex of Cm(III) onto the *D äspöensis* cell envelope was interpreted /Moll et al. 2004a;b/. It seems that there are no spectrophotometric data available for interactions of Cm(III) with bacteria and especially with sulphate-reducers of the *Desulfovibrio* genus. The Cm(III)-*D äspöensis*-surface complex is characterised by its emission spectrum (peak maximum at 600.1 nm, see Figure 6-28) and its fluorescence lifetime (162 ± 5 µs).

From other investigations of biological systems and from a spectroscopic study of the complexation of Cm(III) with adenosine 5’-triphosphate /Moll et al. 2005b/, it was concluded that mainly organic phosphate groups of the cell surface are involved in the bonding of Cm(III) to *D äspöensis*. A reversible biosorption reaction was observed.

Process A and E:
Simultaneous complexation of Pu(VI) and Pu(IV)-polymers by functional groups of the cell surface (e.g., phosphate groups)

Process B:
Fast reduction of Pu(VI) to Pu(V) and dissolution of Pu(V)

Process C:
Disproportionation of Pu(V) to Pu(IV) and Pu(VI) and complexation with the biomass

Process D:
Slow reduction of Pu(V) and Pu(VI) to Pu(IV) followed by the formation of Pu(IV)-polymers

Process F:
Penetration of Pu inside the cells

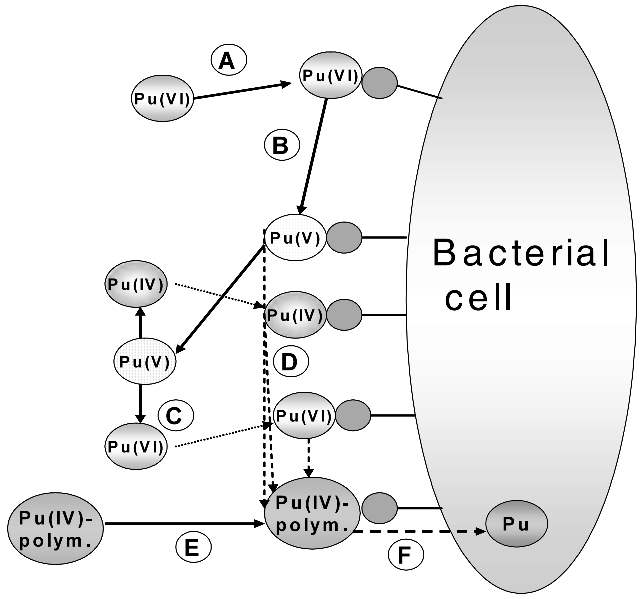


Figure 6-27. *Illustration of the different processes of the interaction of* ^{242}*Pu with D äspöensis based in the schema developed by /Panak and Nitsche, 2001/.*

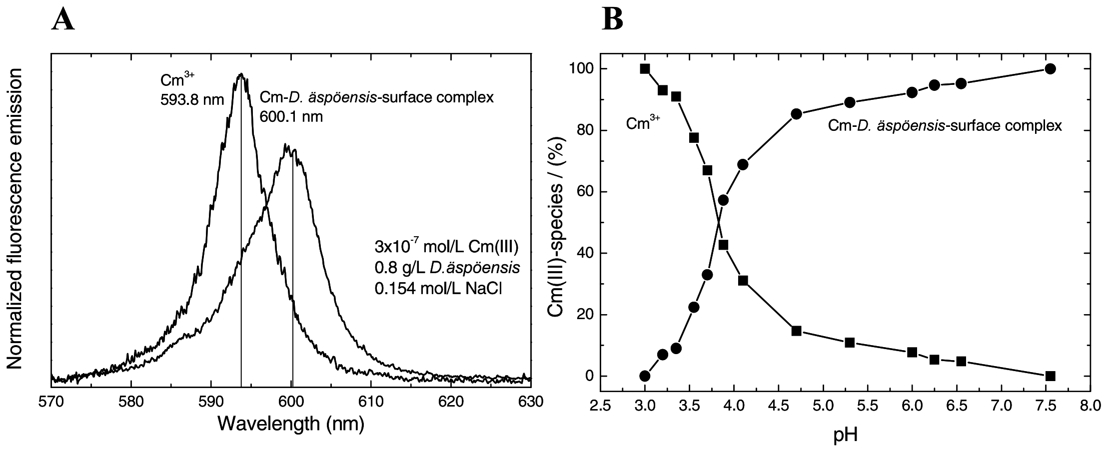


Figure 6-28. *(A) Time-resolved Laser Fluorescence spectroscopy (TRFLS) spectra of component 1: Cm^{3+} and component 2: Cm-D äspöensis-surface complex as derived by peak deconvolution; the spectra are scaled to the same peak area. (B) Experimental specie distribution of the Cm(III)-D äspöensis system as a function of pH.*

Under the given experimental conditions, 84% of the Cm, 0.078 mg/$g_{dry\ weight}$, is bound to the bacteria at pH 5 after 72 h of incubation. No evidence was found for an incorporation of Cm(III) into the bacterial cells at this low initial actinide concentration.

In summary it can be said, that the study demonstrates that the interactions of uranium, plutonium and possibly neptunium with *D äspöensis* cause changes of the oxidation state of the actinides which have an impact on their migration behaviour. Furthermore, important results were obtained about the cultivation and characterisation of the biomass, their potential to remove the selected actinides from the surrounding solution and about the different interaction mechanisms dependent on the nature of the actinide element.

Assuming attached cells of *D äspöensis* to the granitic rock of the Äspö HRL, released Cm(III) in the aquifer gets immobilised due to a biosorption on the bacterial cells in the neutral pH range.

In the case of the other actinides, the interaction mechanism is more complex and consists of sub-processes. To summarise, the strength of the interaction of *D äspöensis* with the selected actinides at pH 5 and actinide concentrations ≥ 10 mg/l ([Cm] 0.07 mg/l) follows the pattern: Cm > U > Pu >> Np.

The results lead to a more realistic description of the influence of microbial actions on the migration behaviour of actinides.

6.4 Enresa

Within the frame of the collaboration agreement signed with SKB, Enresa has continued working with three of the Äspö HRL projects related to the performance of the engineered barrier system during 2004: Prototype Repository, Backfill and Plug Test, and Temperature Buffer Test. The work performed mainly comprises data monitoring, as well as interpretation and modelling of the experimental results.

6.4.1 Prototype Repository

Instrumentation and monitoring work

The maintenance and remote monitoring of the system installed by Aitemin in deposition holes 3 and 6 for tracking potential movements in the canisters continued during 2004. One of the 12 sensors installed has failed. The data generated was handled to Clay Technology on a quarterly basis.

THM analyses

Year 2004 was the end of the EC Project supporting the experiment and most of the work was devoted to the final compilation of the simulations performed in holes 1 and 3 in Section I. The numerical code Code Bright, described in detail in previous reports, was used in all the analyses.

In the analyses data from measurements performed up to September 2004 was used for comparison /Goudarzi and Johannesson, 2004/. The modelling results are based on Quasi3D_THM analysis. In previous works, six different geometric models were compared in order to check their effect on some fundamental variables of the problem (i.e. temperature on the canister surface). It was concluded that an axisymmetric model considering one heater was a compromise between simplicity and quality of the results. In particular, differences in terms of temperature with respect to the full 3D analyses were always less than 5°C. Therefore a "Quasi-3D" geometry (or 2D axisymmetric) was finally adopted. Some basic assumptions were made in these Quasi3D_THM simulations:

- The 10 mm gap between heater and bentonite is considered in the analyses by means of elements with a small stiffness and high hydraulic conductivity before the gap closes, but with the same modulus as the heater after the closing of the gap.

- Barcelona Basic Model (BBM) is used for bentonite and pellets, and the main values of the parameters are based on laboratory tests performed by Ciemat.
- Different hydraulic conductivity is used for the host rock around hole 1 and 3, respectively, based on the in situ investigation, i.e. $k_0 = 3{\cdot}10^{-19}\ m^2$ (hole 1), $k_0 = 5{\cdot}10^{-22}\ m^2$ (hole 3).
- The initial conditions of saturation degree of the 10 mm gap and pellets are different for hole 1 and 3. This due to the fact that hole 3 was dry before installation, whereas hole 1 was wet and had a much larger inflow of water due to the fractured nature of the rock around the hole.
- Hole 1 and 3 were selected for analysis because they are well instrumented, one is "dry" (hole 3 is saturating very slowly) and the other is "wet" (hole 1 is saturating at a very fast rate).

The comparison between temperature and degree of saturation measured and computed at different radius, during more than three years are shown in Figure 6-29 to Figure 6-32.

It can be concluded from the analysis that, despite the large amount of parameters and the difficulties in characterising those materials, the simulation can reproduce the main aspects of the processes involved, as for instance, the wetting-drying cycles of the bentonite. This effect has been simulated thanks to the consideration of the vapour flow in the system. The result is also consistent with other THM simulations performed in similar context of EBS performance. Therefore the work developed within the frame of this large scale experiment has shown the good capability of the Code Bright code for simulating THM processes. Some specific aspects of the Prototype test, as the effect of gaps, the spatial variability of the rock properties and the material properties of the MX-80 bentonite have been handled successfully during the development of the project.

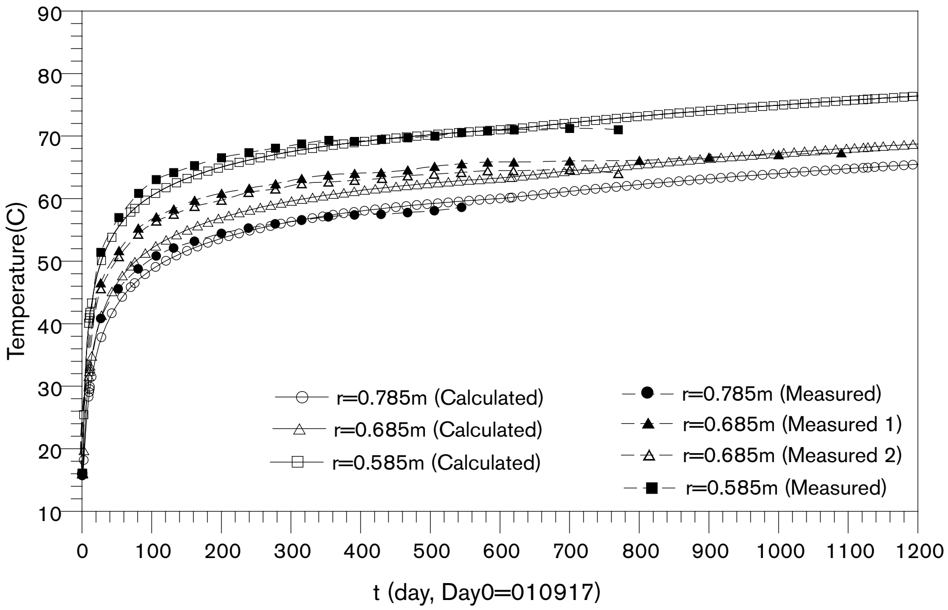


Figure 6-29. *Evolution of temperature in Ring 5 of hole 1 at z=2.87m. Data measured versus computed results.*

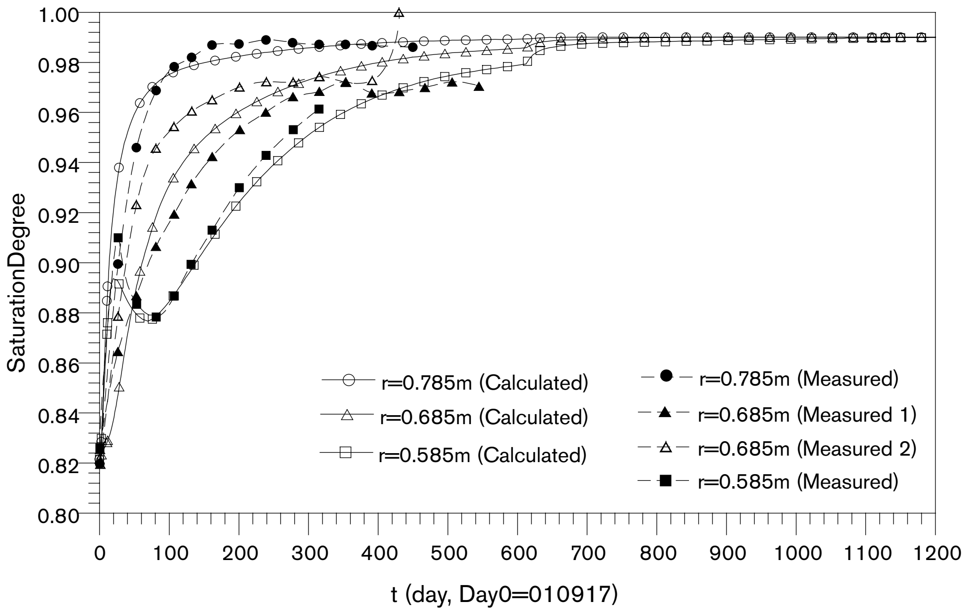


Figure 6-30. *Evolution of the degree of saturation in Ring 5 of hole 1 at z=2.87m. Data measured versus computed results.*

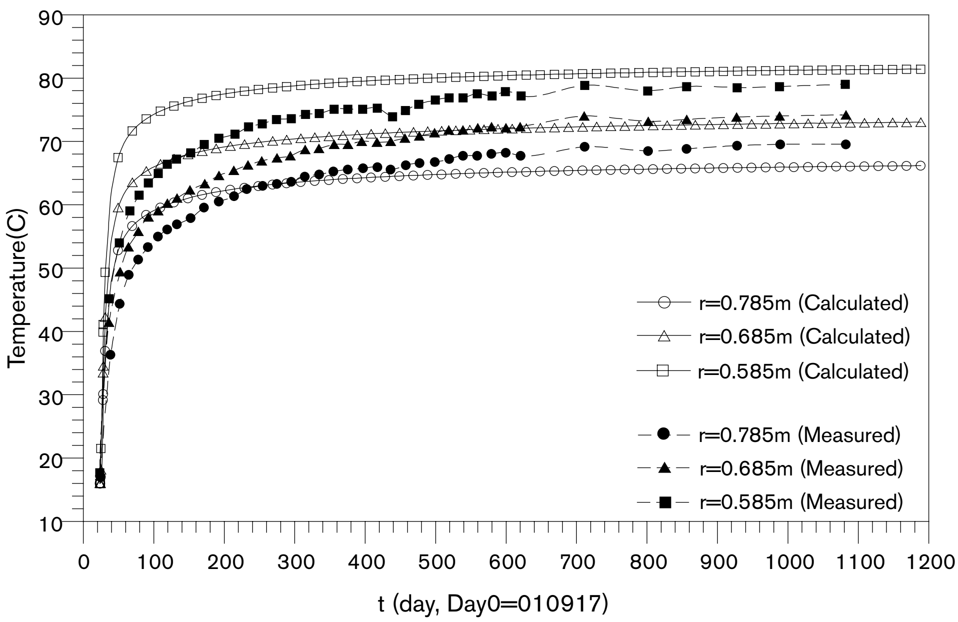


Figure 6-31. *Evolution of temperature in Ring 5 of hole 3 at z=2.84m. Data measured versus computed results.*

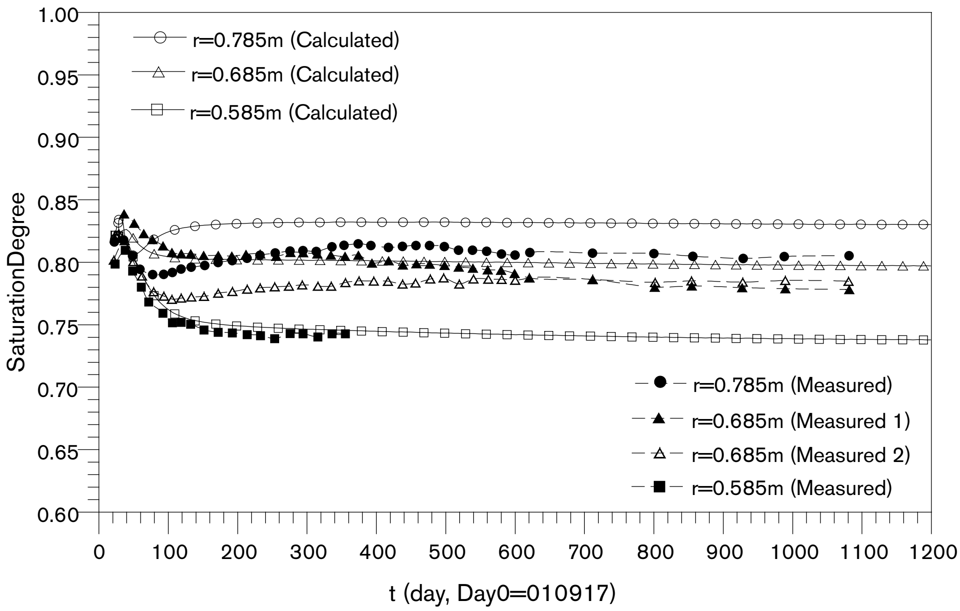


Figure 6-32. *Evolution of the degree of saturation in Ring 5 of hole 3 at z=2.84m. Data measured versus computed results.*

6.4.2 Backfill and Plug Test

Testing and monitoring work

As foreseen in the Äspö HRL Planning Report 2004, maintenance and remote monitoring were carried out until March 2004. The system is working properly and the data from the sensors in operation is continuously and automatically recorded.

Modelling work and pulse test interpretation

A comprehensive study of the backfill response to pore water pressure pulses allows an estimation of the hydraulic conductivity and the elastic modulus of the material at local scale. With this perspective, the participation of ENRESA in the project since the beginning of the experiment has been devoted to the development of a procedure to obtain a map of local properties in the backfill (i.e. hydraulic conductivity). After the design and installation of the sensors and equipments at the beginning of the project, most of the pulses were performed during 2003. Finally, during 2004 the analysis of those measurements was carried out by considering several approaches. In particular, Gibson's analytical theory (based on the consolidation of a spherical domain) and the finite element method were considered. The code Code Bright was used in the latter case. In general both simulations provided similar results in terms of local permeabilities in the backfill.

The input data available corresponds to the pulses from 7 sensors that worked properly during 2003 and 2004. A typical plot regarding pore water pressure evolution of sensor DPP9 after two pulses performed in august 2003 and interpreted during 2004 is shown in Figure 6-33. In Figure 6-34 the interpretation of the first pulse using a finite element model is shown. Note that the prediction with the model has been performed selecting a set of parameters that minimise the difference between measured and computed pressures.

That is, an optimisation procedure was adopted, in order to obtain the parameters that best reproduce the measured values. The differences between measurements and the model results at the beginning of the pulse (around 10 to 1,000 seconds) appear in most of the simulations. It is partly related to the parameters selected by the optimisation procedure, which gives more weight to the measurements obtained after longer times.

The dissipation of pore water pressure depends not only on the hydraulic properties of the backfill, but also on its compressibility. The optimisation procedure indicated that the reliability of the mechanical parameters estimated from pulses was low. Therefore, the information obtained in oedometer tests of the backfill carried out during the period 2001–2003 was used as a complement for interpreting the pulse tests properly.

In Figure 6-35 the local permeability values obtained after this identification process in the sensors that were considered more reliable are shown. Note that close to the rock walls the hydraulic conductivity is close to 10^{-10} m/s, whereas in the central part of the backfill values are smaller and close to 10^{-11} m/s. That may be explained in terms of the difference in density obtained by compaction of the backfill close to the rock walls or in the central zone. Figure 6-36 shows the corresponding values of compressibility (inverse of confined Young's modulus) obtained for the same points. It can be observed that points close to the rock walls exhibit higher values of compressibility, which is also consistent with the lower density obtained in the compaction process on those areas.

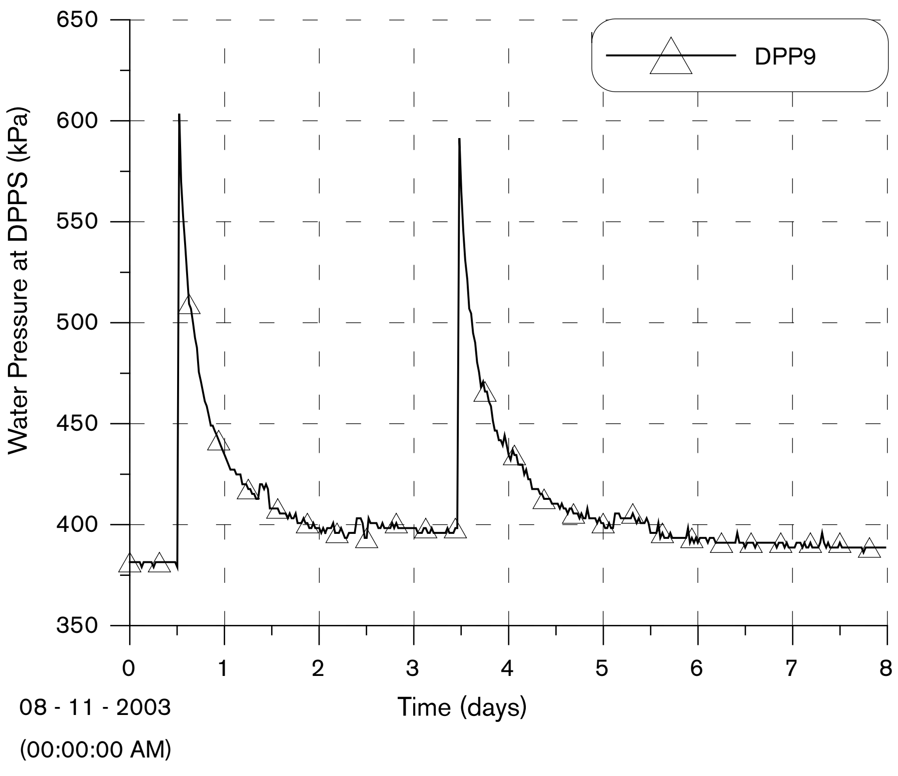


Figure 6-33. Evolution of water pressure at sensor DPP9 during two pulses.

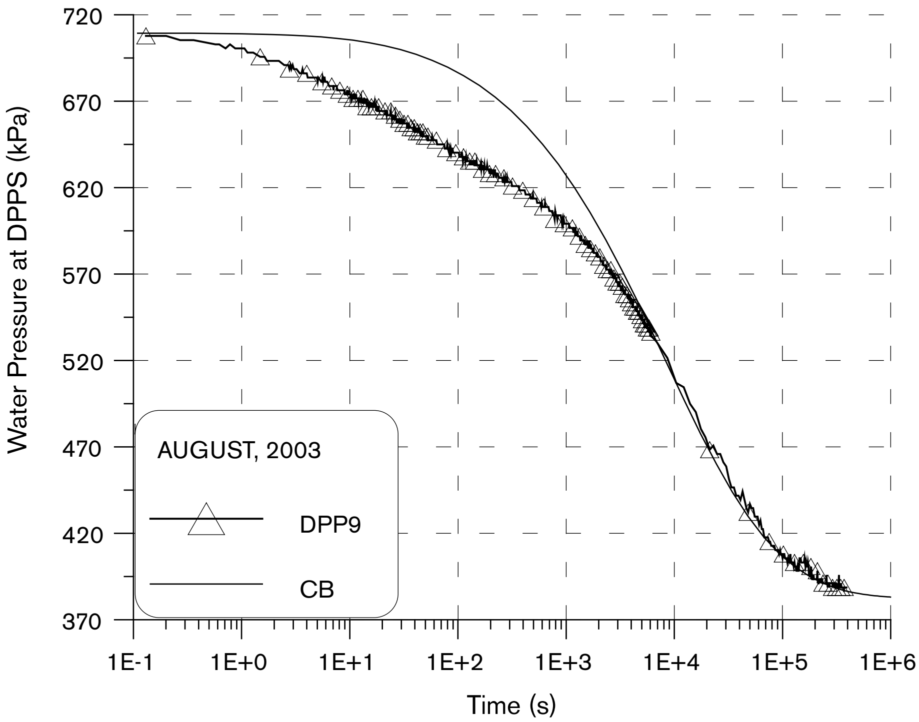


Figure 6-34. *Comparison between the computed dissipation process and the measured water pressure at sensor DPP9.*

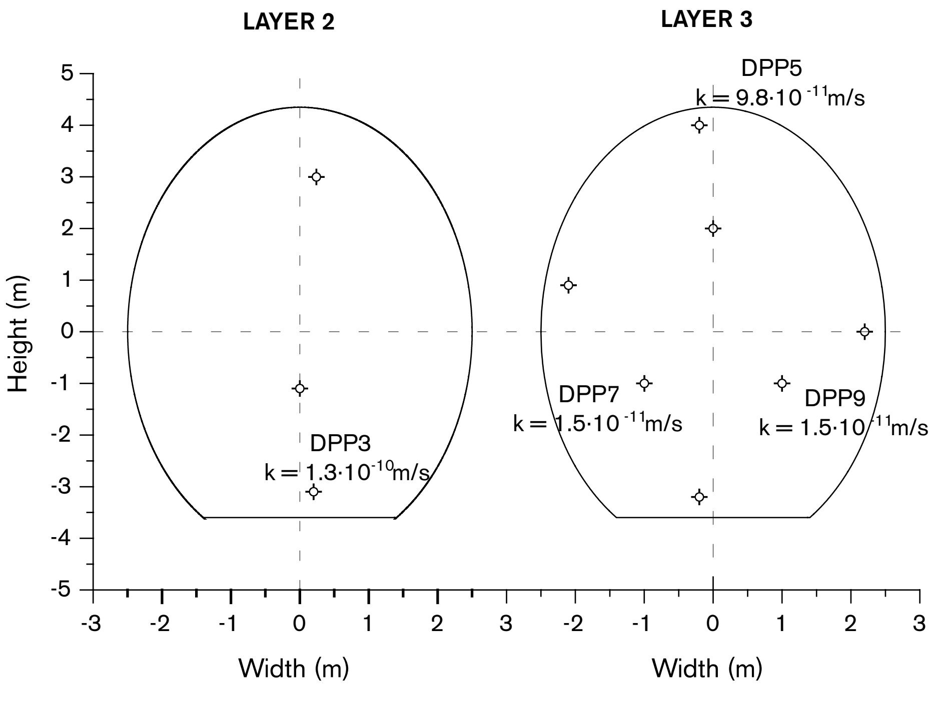


Figure 6-35. *Map of backfill local hydraulic conductivity computed after the final analyses of the in situ pulse tests.*

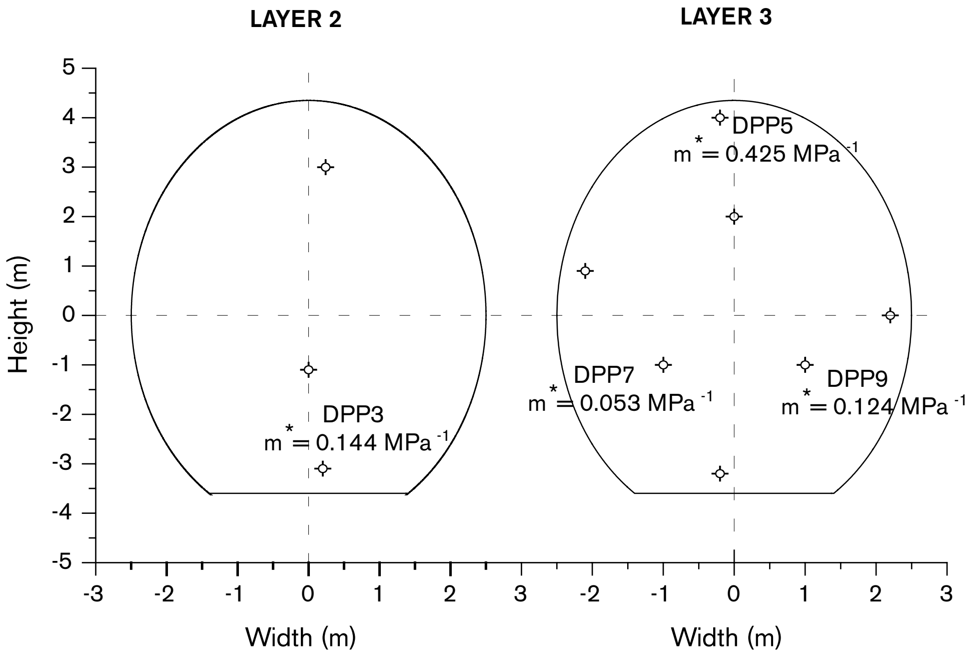


Figure 6-36. Map of backfill compressibility (inverse of confined elastic modulus) computed after the final analyses of the in situ pulse tests.

6.4.3 Temperature Buffer Test

The participation of ENRESA in this project during 2004 was focussed mainly on the THM operational analysis of the experiment. Additionally some laboratory tests were initiated in order to improve the knowledge on the parameters needed for the models.

THM analyses

The measurements of the THM variables in the experiment showed an unexpected behaviour in the bentonite rings 9 and 10 corresponding to the upper heater. The main concern was a cycle of suction and stresses that was measured in some points of those bentonite blocks. Previous simulations did not present any cycle of that type because the hydration was assumed to work properly and continuously from the outer boundary of the deposition hole. During 2004 most of the THM analyses were devoted to the study of such a cycle which was difficult to explain with the information available.

Two main hypotheses have been considered for explaining that behaviour:

- The cycles of stresses may be due to a mechanical effect of the system sand/bentonite included in the upper heater. Bentonite swells and generates compression everywhere, including the sand filter and the sand shield. A sudden deformation of the sand (i.e. a collapse created by wetting an initial unsaturated state under loading) may release stresses in the bentonite for a period of time. The further hydration of the bentonite would again increase the stresses everywhere. Expansion of the bentonite due to a stress release would increase void ratio and suction for a while and that would explain the measured suction cycle.
- The cycle of suction may be due to a lack of water available for hydrating the bentonite. The reason could be of a practical nature (i.e. a problem in the water supplying system, etc). Bentonite stops swelling and even may shrink a bit when water is taken out. That would explain the cycle in stresses as well.

Both explanations were analysed in detail by considering different numerical approaches. Code Bright was used in all cases. The analyses performed suggested that, most probably, the cycle of suction and stresses at rings 9 and 10 was due to the lack of water available to saturate the bentonite after approximately day 100. However, some mechanical effects of the interaction sand/bentonite could also play a role, although they might not be the main reason for the unexpected behaviour.

The most convincing simulation for explaining the unexpected behaviour was done using the total volume of water injected into the system as input data, instead of the water pressure in the injecting pipes. Indeed the records of volume of water seem to be more reliable than the measurements of the pore water sensors that have had many disruptions during the development of the experiment. If that total volume is used, the finite element simulations suggest that after day 100 the water injected was not enough and the bentonite soaked more water than the water available in the sand filter. In Figure 6-37 the profiles of saturation degree for different times at the sand filter are shown. Note that the sand de-saturates in some areas after day 72 and day 100. Therefore malfunction of the system supplying water to the test seems to be the most reasonable hypothesis for that unexpected behaviour.

The measured cycle of suction at bentonite Ring 10 and the corresponding computed results are shown in Figure 6-38. It becomes evident that the cycle is well reproduced when using this approach. Finally, Figure 6-39 shows the cycle of radial stresses measured and computed in the test at Ring 9. In this case the computed cycle is less pronounced than the measured one, but that could be related to the values of the mechanical parameters used in the analysis. In addition to that, the mechanical effect of the sand, not considered in detail here, could be responsible for the bigger amplitude of the cycle in terms of stresses.

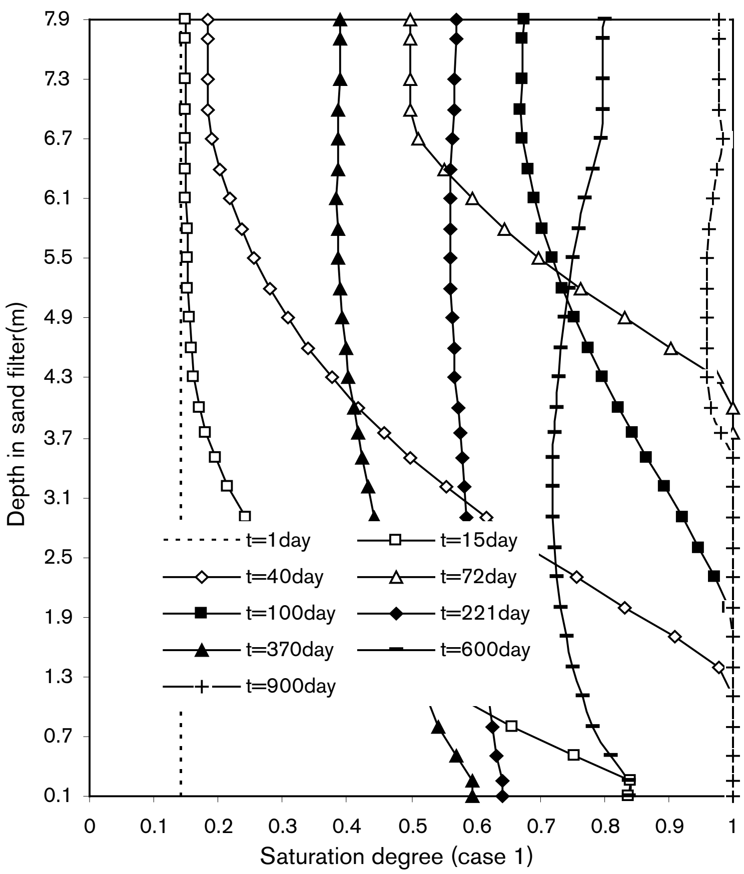


Figure 6-37. *Profiles of the degree of saturation in the sand filter at different times.*

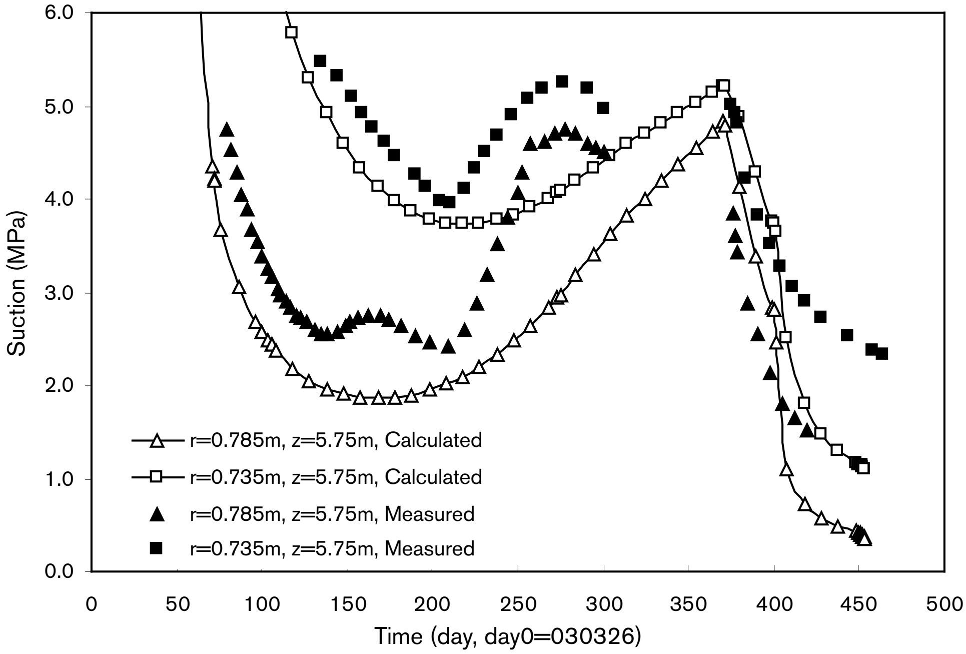


Figure 6-38. *Comparison between measured and computed suction at Ring 10.*

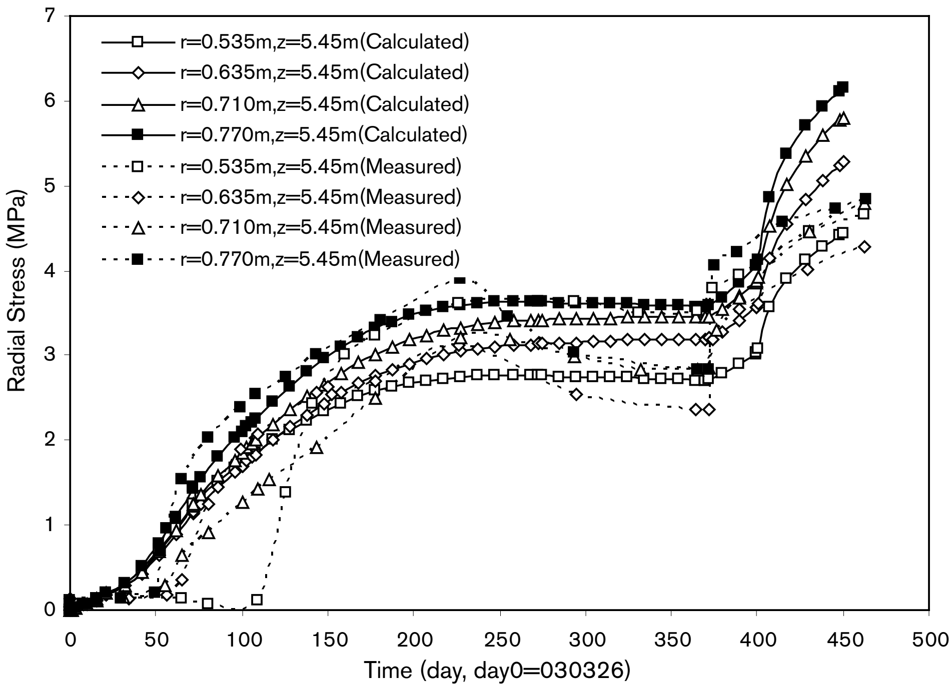


Figure 6-39. *Comparison between computed and measured radial stresses at Ring 9.*

In conclusion the THM analyses performed during 2004 were able to reproduce the general trends of the variables measured, even taking into account the unexpected behaviour of the bentonite rings surrounding the upper heater, and the difficulties when considering the injected water as input data.

6.5 CRIEPI

The Central Research Institute of the Electric Power Industry (CRIEPI) joined the Äspö HRL project and participated mainly in modelling activities. CRIEPI has been developing a numerical code for simulating coupled phenomena in the engineered barrier system and decided to participate in the Task Force on Engineered Barrier Systems. CRIEPI has participated also in the Task Force on Modelling Groundwater Flow and Transport of Solutes. CRIEPI has reported the results of its calculations on sub-tasks 6A, 6B and 6B2 in an International Progress Report and has performed modelling under sub-task 6F. In addition, CRIEPI has started its voluntary project on the impact of microbes on radionuclide retention.

6.5.1 Task Force on Engineered Barrier Systems

CRIEPI has been developing the thermal-hydrological-mechanical (THM) coupling code for evaluating the phenomena that will occur around the engineered barrier system. In 2004, the function for analysing HM coupled geotechnical phenomena was incorporated into the THM coupled analysis code. CRIEPI attended the kick-off meeting of Task Force on EBS, and decided to participate in THM benchmark. Thereafter, the preparation for the analysis of benchmark 1 began.

6.5.2 Task Force on Modelling Groundwater Flow and Transport of Solutes

The results of CRIEPI's calculations for sub-tasks 6A, 6B and 6B2 have already been published /Tanaka, 2004/.

In addition, CRIEPI performed a numerical analysis for sub-task 6F. In this task, groundwater flow and tracer transport were simulated in each feature of two basic Geologic Structure Types. Figure 6-40 shows the conceptual models for the features of the Geologic Structure Types. Each feature was assumed to contain a single conductive fracture. In case of Geological Structure Type 1 (Fault) a single fracture was surrounded by intact unaltered granite, altered zone, cataclasite, fault gouge and fracture coating. On the other hand, in case of Geological Structure Type 2 (Non-fault) a single fracture was surrounded only by intact unaltered granite, altered zone and fracture coating. Figure 6-41 shows the finite element mesh used for the numerical analysis. A numerical code developed by CRIEPI for groundwater flow and solute transport in rock formations, FEGM, was used for the analysis. In Case A, Case B and Case C, the hydraulic heads at the model boundaries were set as to have an estimated groundwater travel time of 0.1, 1 and 10 years, respectively. Simulations were requested for a Dirac pulse input of three tracers, ^{129}I, ^{137}Cs and ^{241}Am.

Figure 6-42 shows an example of calculated results for changes of tracer distribution with time and Figure 6-43 to Figure 6-45 show the calculated breakthrough curves at the recovery section for each tracer. As the groundwater travel time was larger, the peak of breakthrough curve and the mass recovery rate became smaller due to the influence of matrix diffusion. The breakthrough curves of the feature of Geological Type 2 reached their peaks earlier than the feature of Type 1 except for the Case C for Am.

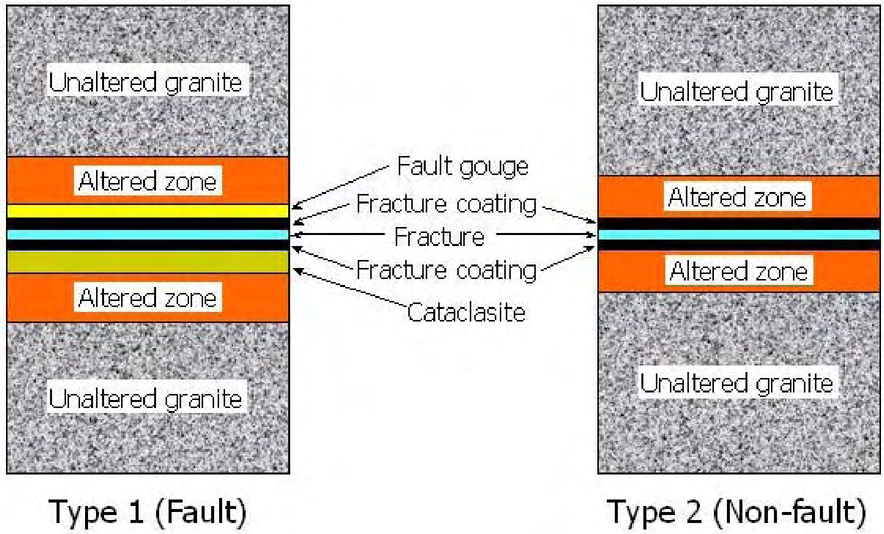


Figure 6-40. *Conceptual models for features of basic Geologic Structure Types.*

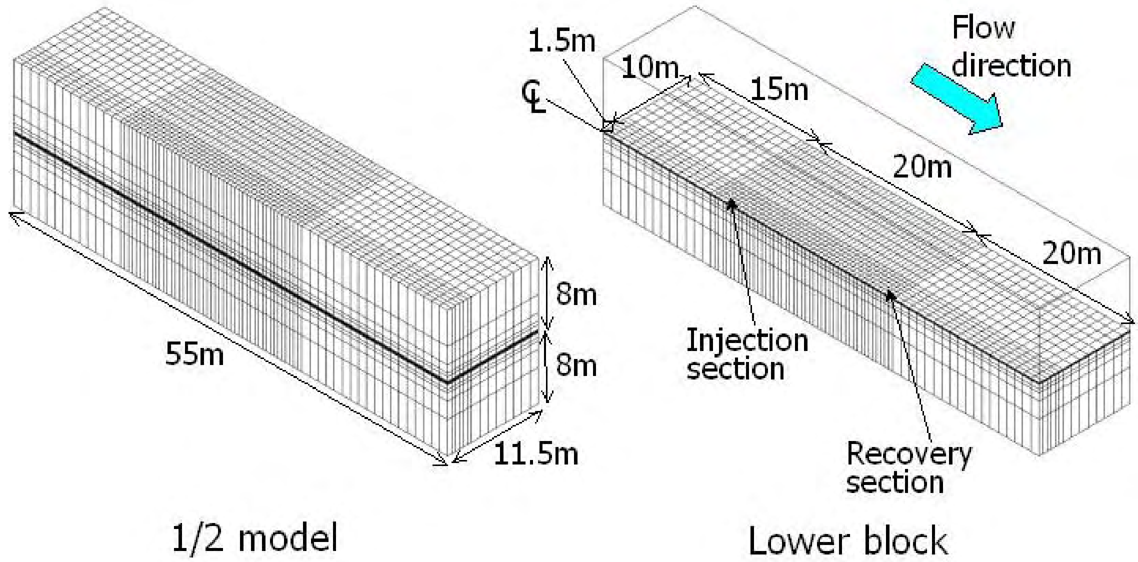


Figure 6-41. *Finite element mesh used for numerical analysis of sub-task 6F.*

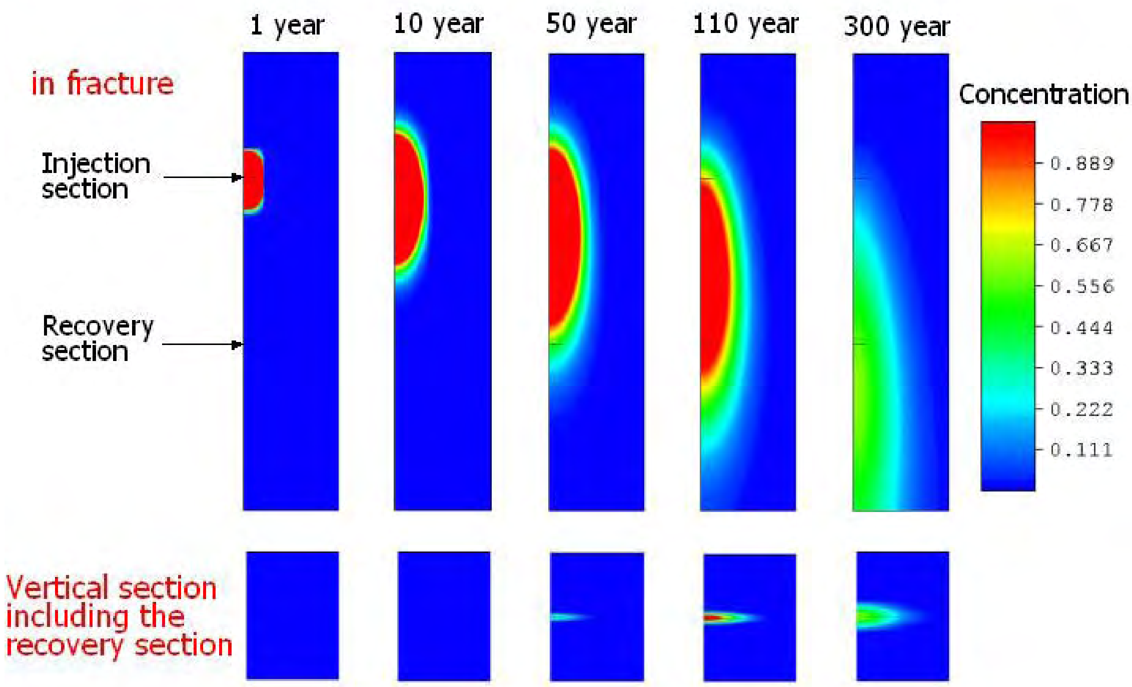


Figure 6-42. *Calculated results for change of distribution of* ^{129}I *with time.*

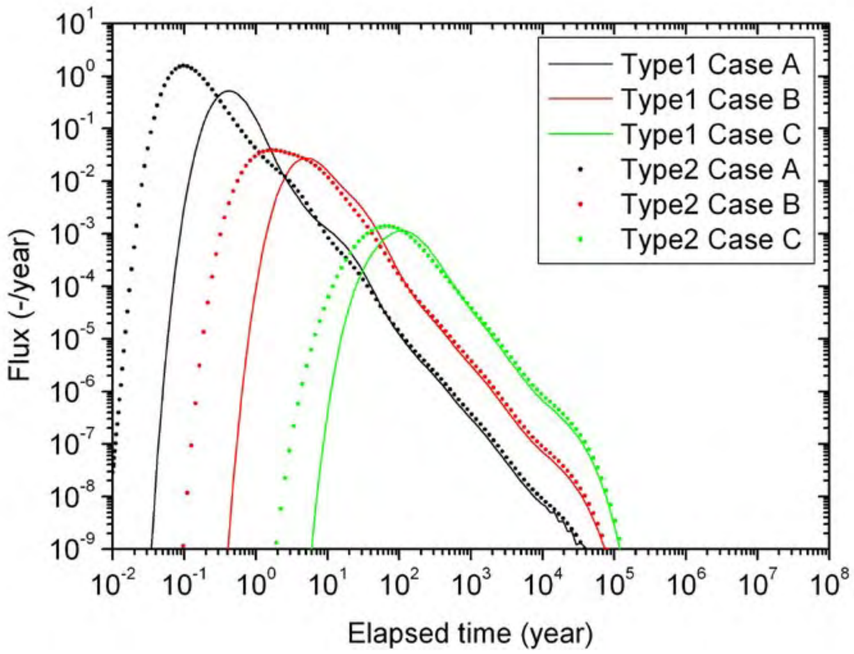


Figure 6-43. *Calculated breakthrough curves at recovery section for* ^{129}I*.*

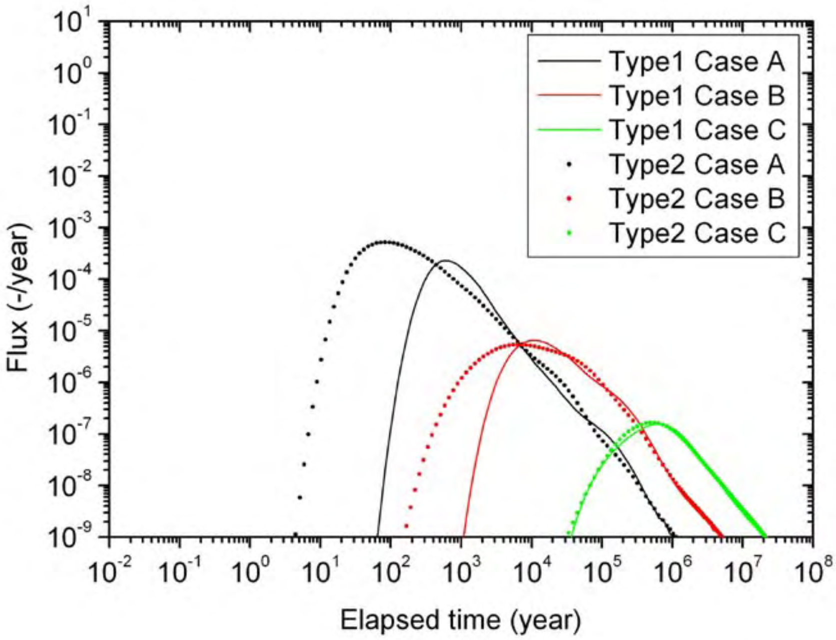


Figure 6-44. *Calculated breakthrough curves at recovery section for* ^{137}*Cs.*

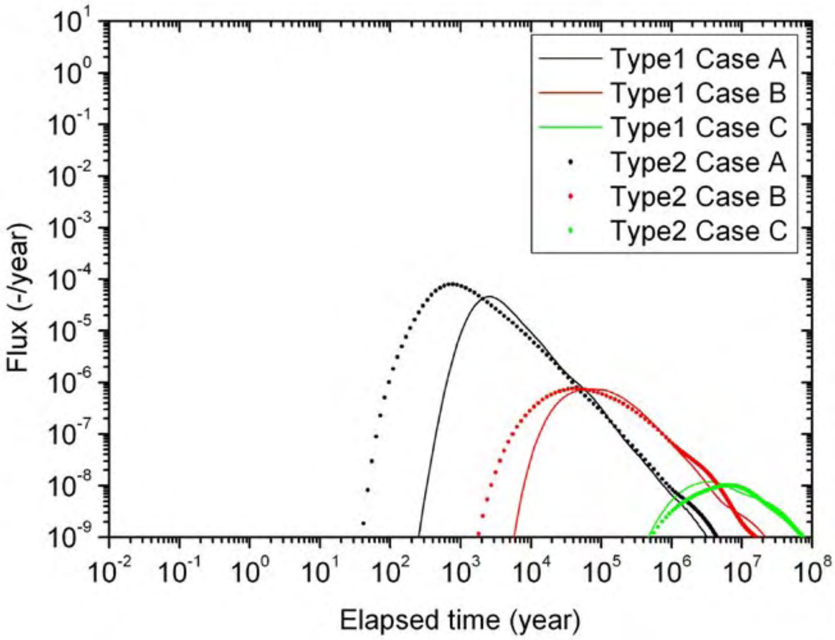


Figure 6-45. *Calculated breakthrough curves at recovery section for* ^{241}*Am.*

6.5.3 Voluntary project on impact of microbes on radionuclide retention

The metabolic activities of microbes have an influence on the geochemical conditions of groundwater, such as pH and redox potential. Thus, microbes can affect the solubility and migration of radionuclides. In order to evaluate the microbial impact on the geochemistry of groundwater, a groundwater circulation system in the experimental laboratory of CRIEPI, Abiko, Japan, has been developed. The circulation system consists of a rock-packed column, a dual-plunger pump with pressure gauge and flow rate controller (GL Science), an in-line electric conductivity monitor (Amasham Bioscience), and a groundwater reservoir, which is installed in the temperature-controlled chamber as shown in Figure 6-46. The PEEK (polyether-ether-ketone) and Teflon tubing are used to connect these equipments, and the circulation system can withstand at the pressure of 3 MPa and more. The groundwater can be sampled into serum bottles via a switching valve, and pH and redox potential can be measured with needle-type electrodes (Unisense) penetrating through the butyl rubber stopper of the bottles. The inhibitor of microbial activities (i.e. sodium azide) can be added to the circulating groundwater by the use of a sample injector.

In 2005, the pump for the circulation system will be replaced by a gear pump to reduce the pulse flow which causes bubble cavitations. Also, the groundwater reservoir will be replaced by the piston-type reservoir which was invented by Professor Karsten Pedersen, Göteborg University, Sweden. The reservoir plays an important role to maintain the in situ pressure condition of the circulation system when sampling even small amount of circulating groundwater, by pushing the piston with the compressed nitrogen gases. Furthermore, the piston-type groundwater reservoir can be used as a sampler for in situ condition groundwater. The project will be carried out in cooperation with Prof. Pedersen and sampling of groundwater will be carried out at Microbe-450 site from KJ0052F01.

Figure 6-46. *Groundwater circulation system in experimental laboratory.*

6.6 JNC

JNC is currently constructing underground research laboratories at Horonobe and Mizunami, Japan. JNC is also preparing a major progress report to provide the technical basis for Numo, the Japanese implementing body and for regulations. As a result, JNC continues to be active in research at Äspö HRL, which is directly applicable to the Japanese programme.

The main objectives of JNC's participation related to the research at Äspö HRL during 2004 were to:

- Develop technologies applicable for site characterisation.
- Improve understanding of flow and transport in fractured rock.
- Improve understanding of the behaviour of engineered barriers and surrounding host rock.
- Improve techniques for safety assessment by integration of site characterisation information.
- Improve understanding of underground research laboratory experiments and priorities.

These objectives are designed to support high level waste repository siting, regulation, and safety assessment.

6.6.1 Prototype Repository Project

JNC has participated in the Prototype Repository Project since 2000. JNC participated in Work packages of THM modelling of buffer, backfill and interaction with near-field rock, and C modelling of buffer, backfill and groundwater.

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

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

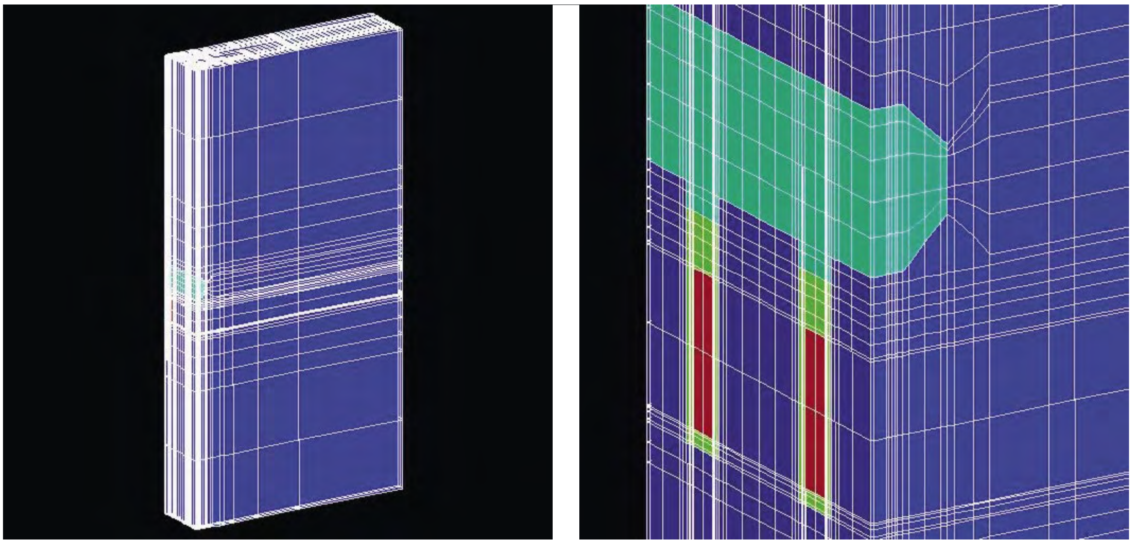
The main objective is to predict THM processes in and around the EBS by applying existing models, and to compare the prediction with the obtained data. This will demonstrate the validity of the existing model and the capacity of numerical modelling of the performance of the bentonite buffer and the backfill.

Results

JNC has carried out prediction analysis A (2D analysis) /Sugita et al. 2002/ and the prediction analysis B (3D analysis) /SKB, 2003/ for the Prototype Repository. The results of an additional analysis, with the aim to examine the effect of permeability of rock mass, are described below.

Figure 6-47 shows the finite element mesh describing the tunnel and two deposition holes. The input data of each material and other conditions are the same as those used in the prediction analysis B (3D analysis) /SKB, 2003/. Figure 6-48 to Figure 6-50 show the analysis results when the hydraulic conductivity of the rock mass is 10^{-10} m/s. Figure 6-48 shows the measured and calculated time history of temperature in deposition hole 3. The calculated temperatures at all points are higher than those measured. In Figure 6-49 the time history of measured and calculated relative humidity in deposition hole 3 is shown. The tendency for the measured relative humidity near the heater (PXPWBU313 and PXPWBU319) is to decrease with time, however, the results from the calculations indicate an increase. This may be caused by the relatively high rock permeability assumed around the deposition holes in the calculations. The initial condition for the relative humidity is a translation of a calculated water head, this caused the discrepancy between measured and calculated initial relative humidity. In Figure 6-50 the calculated and measured stress in deposition hole 3 are shown. Though the calculations indicate a stress of 5–7 MPa after 500 days, the measurements are barely indicated.

Figure 6-51 to Figure 6-53 show results from analysis of a rock mass with a hydraulic conductivity of 10^{-13} m/s. The calculated relative humidity in the buffer increase slower when the hydraulic conductivity of rock mass is 10^{-13} m/s compared 10^{-10} m/s. As expected, the model results indicate a slower increase of the saturation degree in the buffer, when the water supply decreased due to a lower hydraulic conductivity in the surrounding rock. In a similar manner the stress in the buffer increases slower, see Figure 6-53, when the infiltration to the buffer is lower. On the other hand, the temperature in the buffer is higher if the rock has a lower hydraulic conductivity, see Figure 6-51.



(a) Full scale mesh. (b) Mesh around the deposition holes.

Figure 6-47. *Finite element mesh for analysis of Prototype Repository.*

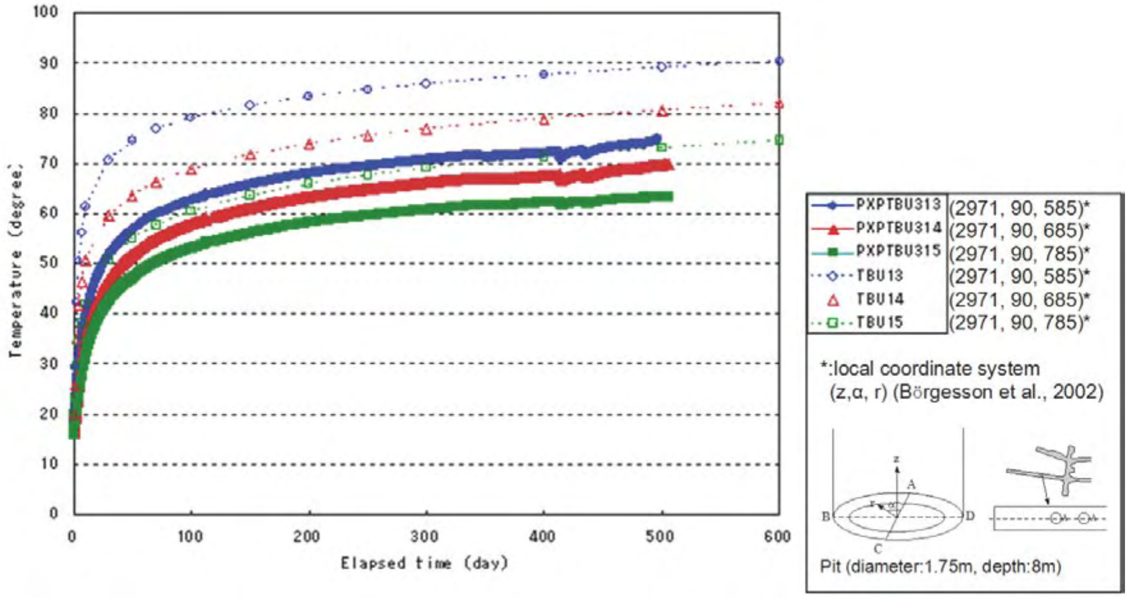


Figure 6-48. *Time history of measured and calculated temperature in deposition hole 3 (hydraulic conductivity in rock mass:* 10^{-10} *m/s).*

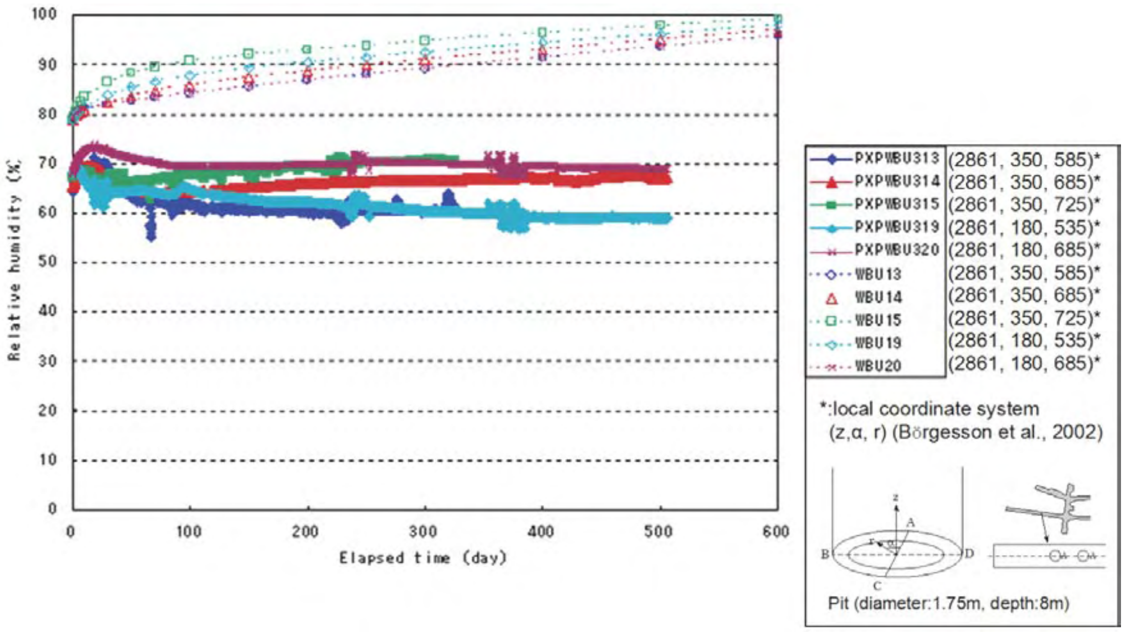


Figure 6-49. *Time history of measured and calculated relative humidity in deposition hole 3 (hydraulic conductivity in rock mass:* 10^{-10} *m/s).*

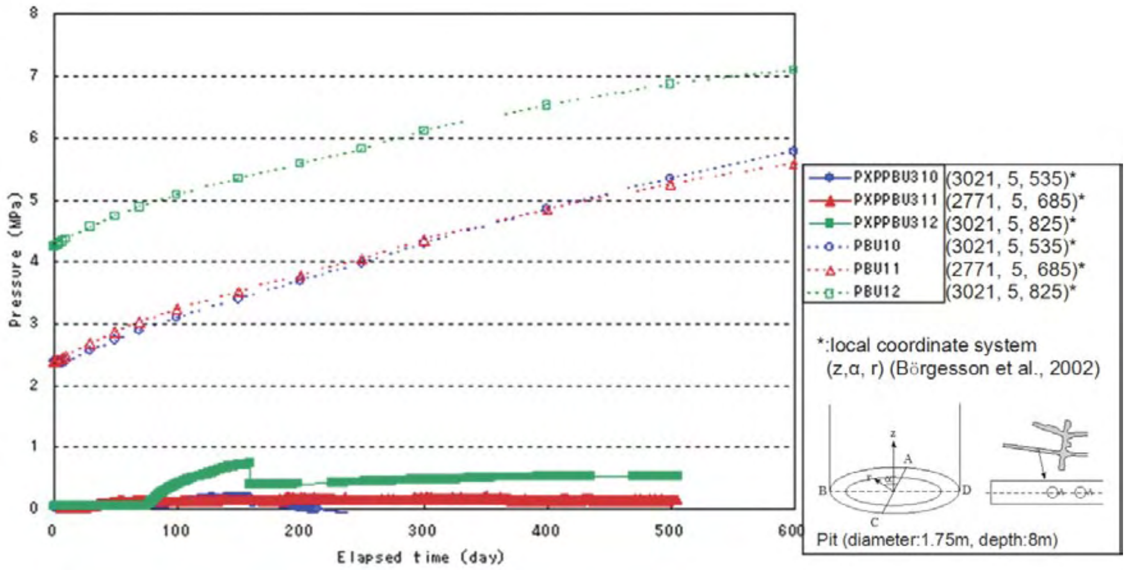


Figure 6-50. *Time history of measured and calculated stress in deposition hole 3 (hydraulic conductivity in rock mass: 10^{-10} m/s).*

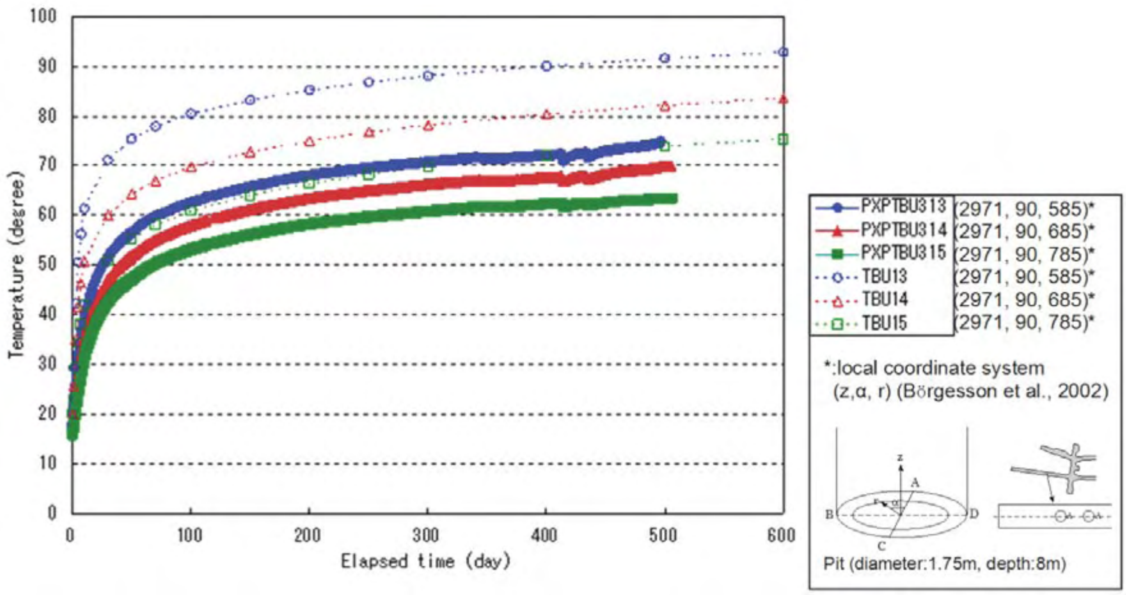


Figure 6-51. *Time history of measured and calculated temperature in deposition hole 3 (hydraulic conductivity in rock mass: 10^{-13} m/s).*

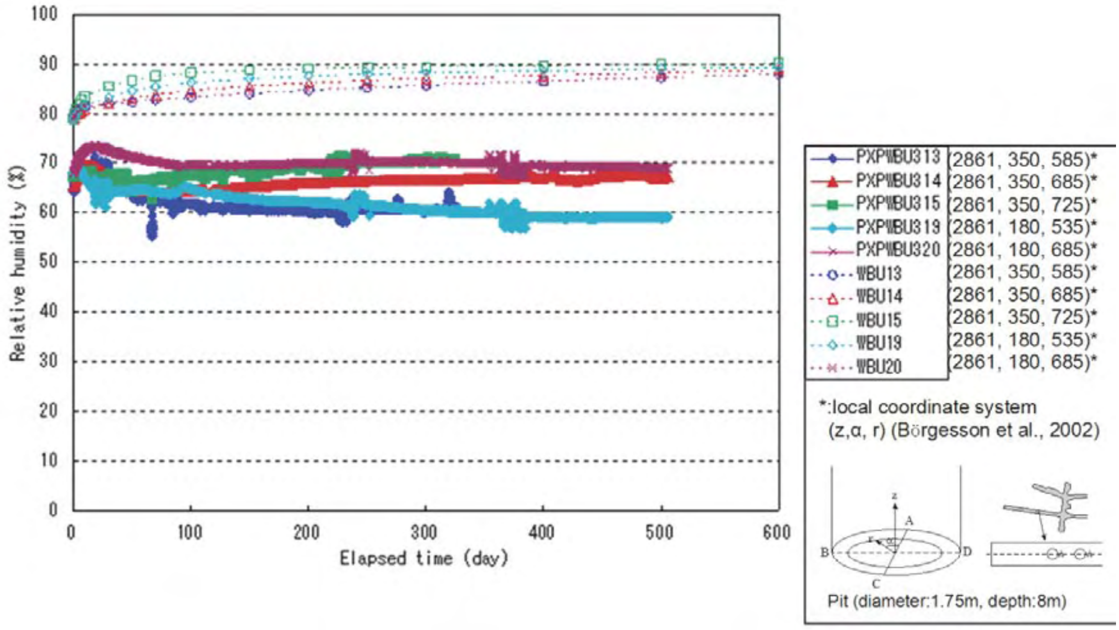


Figure 6-52. *Time history of measured and calculated relative humidity in deposition hole 3 (hydraulic conductivity in rock mass: 10^{-13} m/s).*

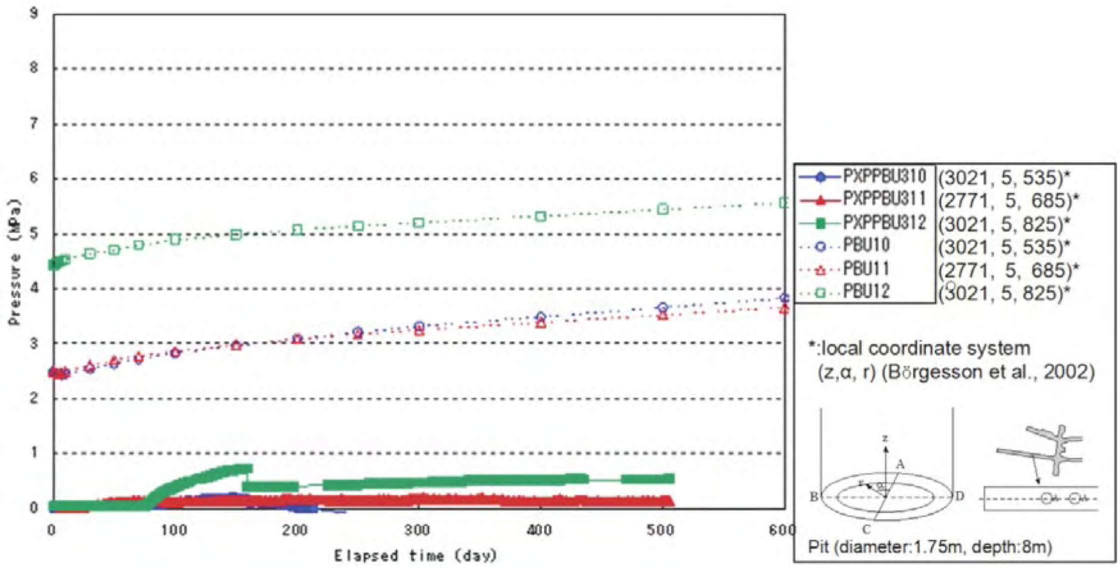


Figure 6-53. *Time history of measured and calculated stress in deposition hole 3 (hydraulic conductivity in rock mass: 10^{-13} m/s).*

C modelling of buffer, backfill and groundwater

In the near-field of a high-level radioactive waste (HLW) repository, the coupled thermo-hydro-mechanical and chemical (THMC) processes will occur, involving the interactive processes among radioactive decay heat from vitrified waste, infiltration of groundwater into buffer material, swelling pressure of buffer material due to saturation and chemical reaction between EBS material and porewater. Since observation periods by laboratory and in situ experiments are very short and information by natural analogue studies is very limited, numerical experiments are the only available approach to predict the near-field long-term evolution.

To understand and assess the long-term performance of the near-field of a HLW repository, relevant predictions of the coupled THMC processes are required. The near-field chemistry, which is one of the most important factors for radionuclides migration and overpack corrosion, should be predicted under consideration of initial transient state, because the chemical process is strongly dependent on temperature, water movement and stress after the emplacement of engineered barriers. From a long-term viewpoint, the chemical process can lead to the changes in porosity, permeability and swelling pressure, and can affect the integrity of the near-field. In order to predict the near-field long-term evolution, JNC has initiated a research on the coupled THMC processes. The main objectives of the chemistry modelling are to predict near-field chemistry for overpack corrosion and radionuclide migration as well as near-field long-term integrity by understanding of chemical degradation.

The interaction between liquid and vapour phases in the buffer occurs under unsaturated condition at EBS emplacement. The oxygen and carbon dioxide in the buffer affect porewater chemistry in the buffer, because they dissolve and are consumed by dissolution or precipitation of minerals. So it is essential for the evaluation of chemical phenomena during the resaturation period to be able to model gas behaviour contributing to evolution of geochemistry conditions. Therefore, governing equations of chemical phenomena are developed, e.g. degassing, dissolution, and diffusion of gas influencing geochemistry reactions during the resaturation period.

There are great hopes that buffer property has long-term stability. Swelling and hydraulic properties of buffer depend on physicochemistry characteristics of smectite. Therefore, an approach considering dissolution and precipitation of smectite based on kinetics was developed to predict long-term stability of buffer with alteration under alkaline environment.

6.6.2 True Block Scale Continuation

JNC has participated in the True-Block Scale Project since 1997. During 2004, JNC's participation in the project, focused on analyses and modelling of the pre-tests (CPT) and BS2b tracer experiments. The experiments were carried out on the 50 to 100 m scale, involving fracture networks related to the 200 m scale Structure #19. These simulations were all run as predictive modelling, implementing the derived hydrostructural and microstructural models, rather than as inverse modelling calibrated to tracer experiments.

The CPT and BS2b tracer simulations were carried out using a Discrete Fracture Network (DFN) implementation of the project hydrostructural model, see Figure 6-54. These forward models provided excellent matches to the CPT4 preliminary tracer tests for the fracture pathway within the deterministic hydrostructural Structure #19, see Figure 6-55, using the microstructural model parameters defined in the reference model. However, these microstructural model parameters did not produce an acceptable match for the pathway involving the background fracture BG#1. For this pathway, it was necessary to increase the aperture to 4 mm to obtain an acceptable match, see Figure 6-56. Although the Cartesian distance for the BG#1 background fracture pathway and the Structure #19 pathway were almost identical (approximately 50 m), the travel time for the conservative tracer was four times larger for the background fracture BG#1 pathway.

This could only be explained by the:

a) Applied unreasonably large apertures to BG#1 to slow solute transport (Figure 6-56).

b) Modification of the hydrostructural model to force a longer path length from BG#1 to the pumping well in Structure #19.

Three simulations were carried out for the BS2b transport pathway involving the background fracture BG#1. These simulations implemented the two options listed above (a and b), and also implemented the project hydrostructural model directly. However, the unreasonably large aperture used in this simulation reduced the solute retention for sorbing tracers on the BG#1 background fracture pathway. The simulation a) was used as the predictive modelling for BS2b, since it provide a good match to the CPT4 pre-test, without requiring a modification to the underlying hydrostructural model. Examples of predictive simulations are compared to the in situ tracer test experiment results in Figure 6-57 and Figure 6-58.

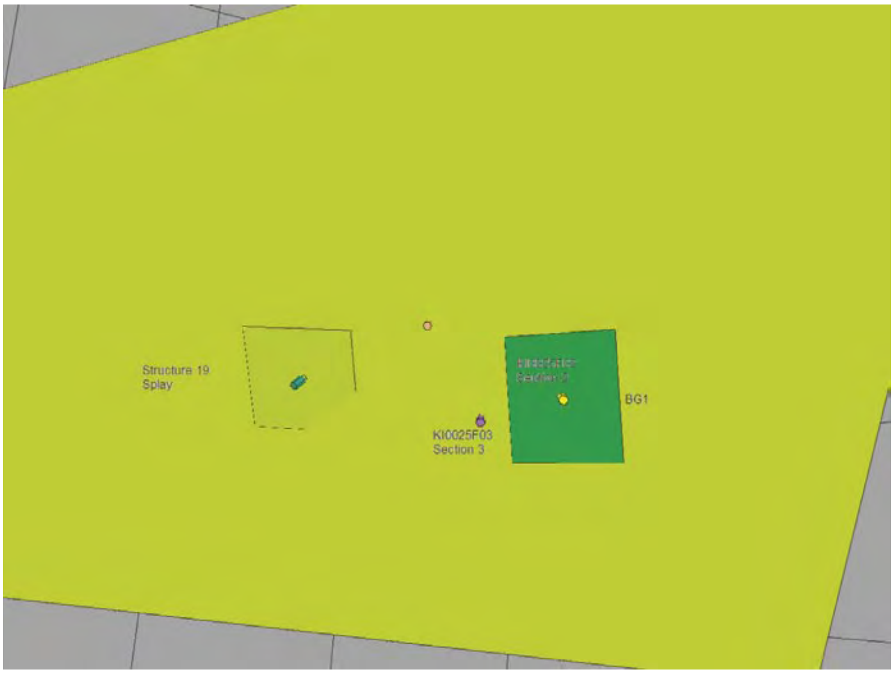


Figure 6-54. *True-BSC hydrostructural conceptual model structures #19, #19 splay, and BG1, as implemented in the JNC/Golder BS2b model.*

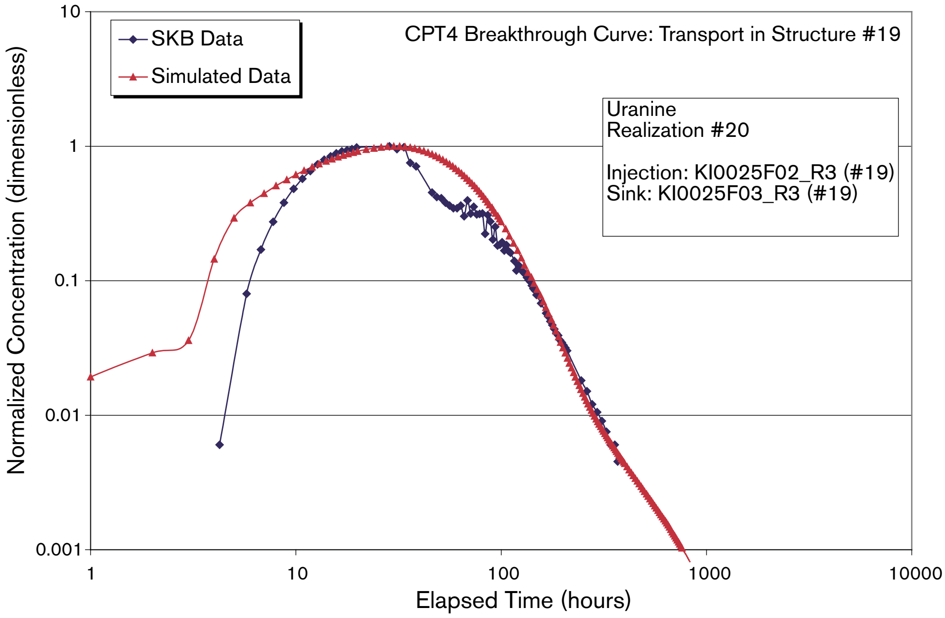


Figure 6-55. *Simulation of CPT-4 tracer test in structure #19, directly applying hydrostructural and microstructural models.*

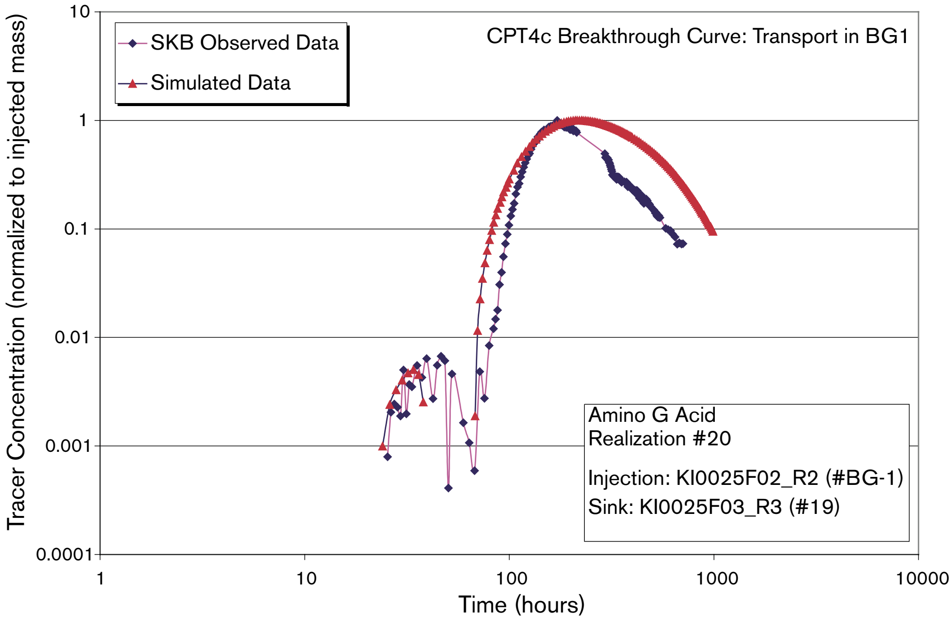


Figure 6-56. *Simulation of CPT-4c tracer test in background fracture BG1. Required BG1 transport aperture values of 4 mm, much larger than is physically reasonable.*

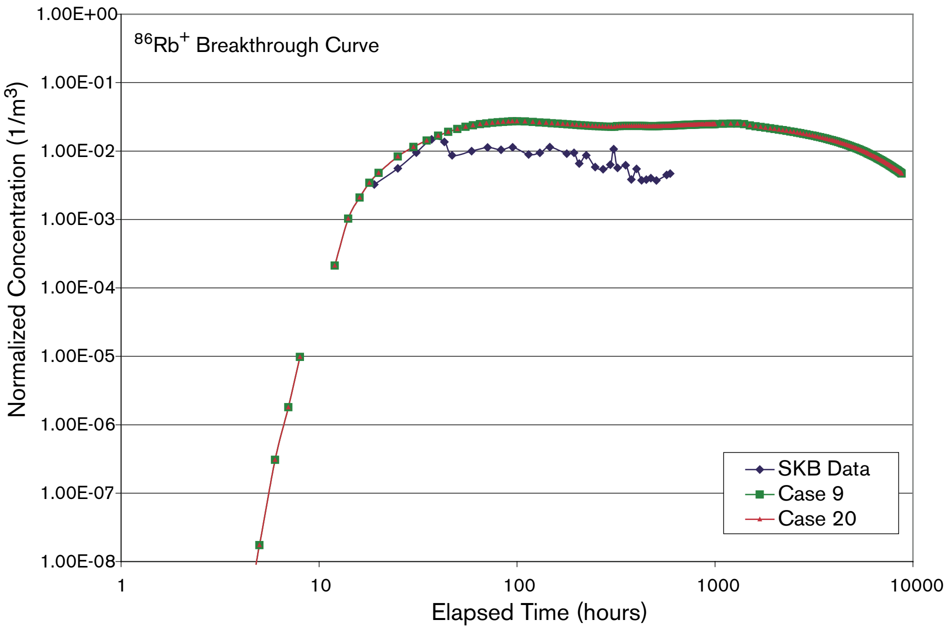


Figure 6-57. *Predictive sorbing tracer simulation of BS2b pathway in Structure #19. Comparison of two FracMan simulations against SKB in situ measurements.*

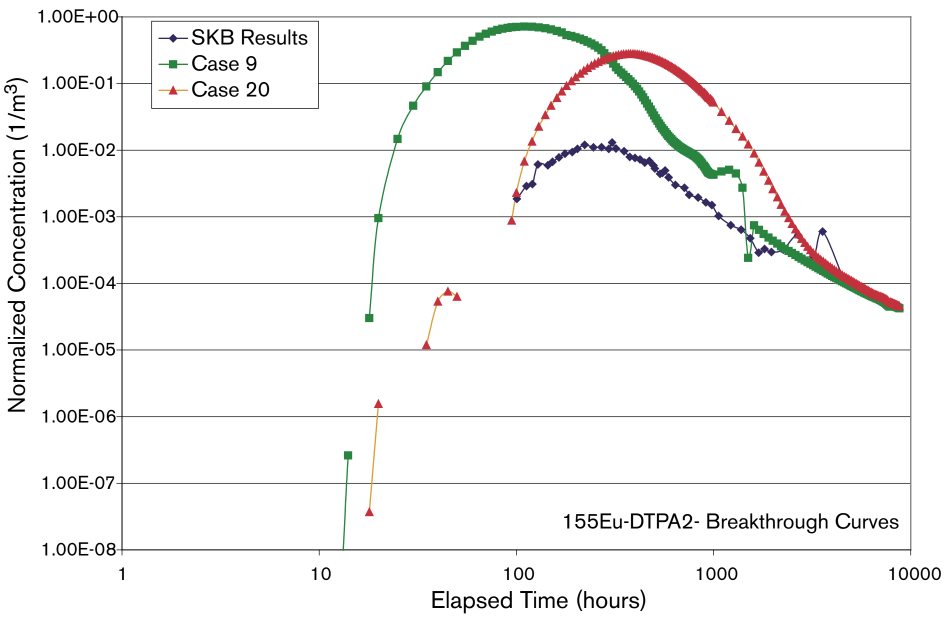


Figure 6-58. *Predictive tracer simulation of BS2b pathway in background fracture BG1. Comparison of two model calculations with FracMan against SKB in situ measurements.*

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

JNC participation in the Äspö Task Force on Groundwater Flow and Transport of Solutes during 2004, focused on the Task 6 Project, "Performance Assessment Modelling Using Site Characterisation Data (PASC)". The objective of JNC's participation in this task is to provide theoretical and experimental support for integration of site characterisation and performance assessment activities and techniques. During 2004, JNC's participation in the PASC project included:

- Simulations for sub-tasks 6A and 6B to identify circumstances under which site characterisation activities can significantly constrain solute transport behaviour for safety assessment.
- Simulations for sub-tasks 6A and 6B to study the role of gouge in solute retention at safety assessment time scales.
- Participation in technical review of the sub-tasks 6C Hydrostructural Model.
- Reporting for sub-task 6D, fracture network transport at site characterisation time scales.
- Simulations for sub-task 6E, fracture network transport under performance assessment boundary conditions.

Sub-tasks 6A and 6B

Task 6AB involves modelling of sorbing and conservative solute transport in a single fracture at the 10 m scale, based on the True-1 tracer experiments. Sub-tasks 6A and 6B simulations are carried out under both experimental and safety assessment time scales. During 2002 and 2003, an attempt was made to characterise the ability of tracer experiments to constrain safety assessment time scale experiments. During 2004, JNC determined that the 2002 and 2003 simulations were not successful primarily due to the large number of parameters which were assumed to be unconstrained.

During 2004, JNC carried out an extensive series of simulations which utilised tracer experiments to constrain only key parameters such as flow wetted surface and transport channel geometry, based on the assumption that physical parameters such as porosity could be constrained through direct measurements. The conceptual model for these studies is shown in Figure 6-59. The simulations during 2004 were successful in identifying and characterising significant improvements in safety assessment from site characterisation experiments (Figure 6-60).

Another major sub-tasks 6A and 6B study carried out by JNC during 2004 addressed the importance of gouge materials for transport at safety assessment time scales. The standard assumption for repository safety assessment is that fracture gouge materials have too small a volume to provide significant retention over time scales of thousands of years. Using the sub-tasks 6A and 6B conceptual model (Figure 6-59), JNC carried out simulations which showed that even where the gouge itself does not provide long term retention, the gouge can significantly improve the access of solutes to the rock mass porosity, effectively increasing the "flow wetted surface" for retention. This is illustrated in Figure 6-61.

Sub-task 6C

During 2004, JNC assisted the Äspö Modelling Task Force in technical review and application of the sub-task 6C hydrostructural model. In particular, JNC revisited the assumptions made in developing that model, and provided additional hydrostructural and microstructural model implementation files for Task Force members.

Sub-task 6D

JNC carried out sub-task 6D, conservative and sorbing solute transport simulations at the site characterisation time scale, during 2003. During 2004, JNC prepared and submitted reports describing these simulations.

Sub-task 6E

During 2004, JNC simulated the sub-task 6E "Base Case" model under performance assessment boundary conditions, to provide a basis for comparison between different modelling groups of the Task Force. In addition, JNC carried out simulations under a range of alternative boundary conditions, geometry, and material property boundary conditions to assist the Task Force in defining the scope for sensitivity studies of sub-task 6F.

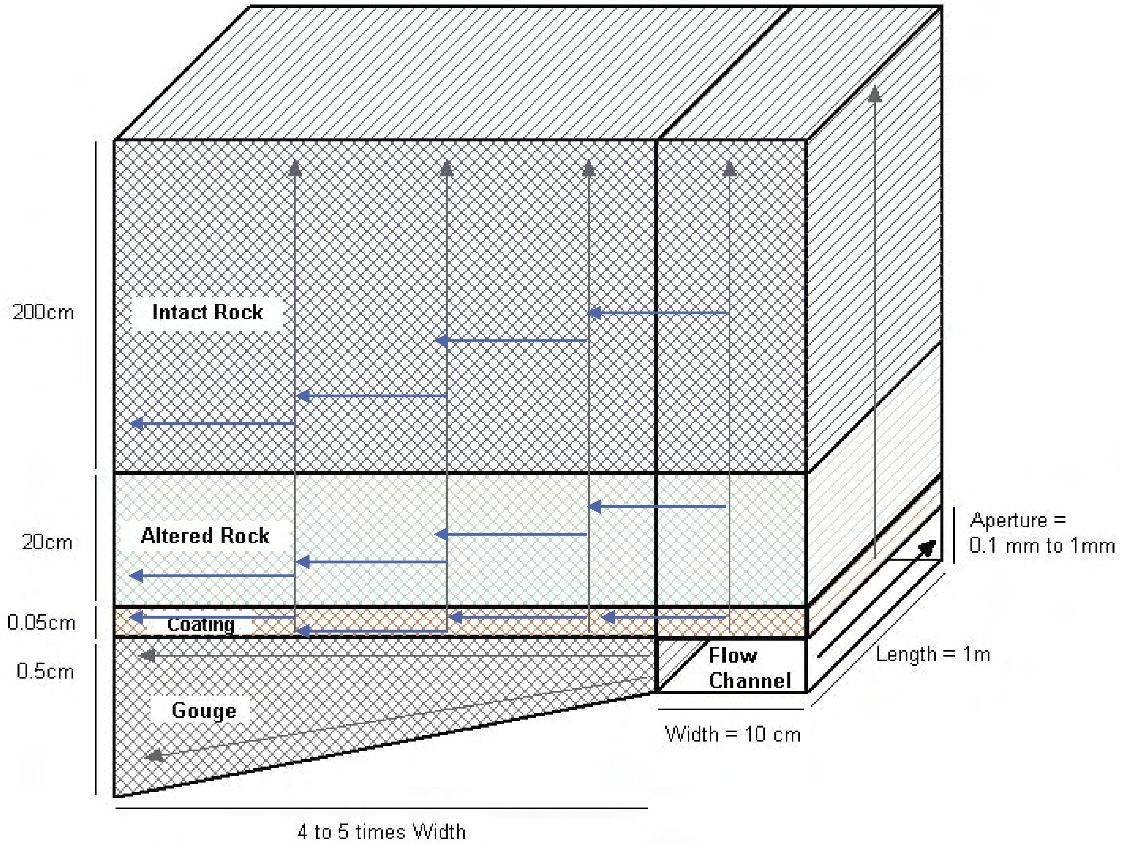


__Figure 6-59.__ JNC/Golder microstructure/pathway conceptual model for sub-tasks 6A and 6B.

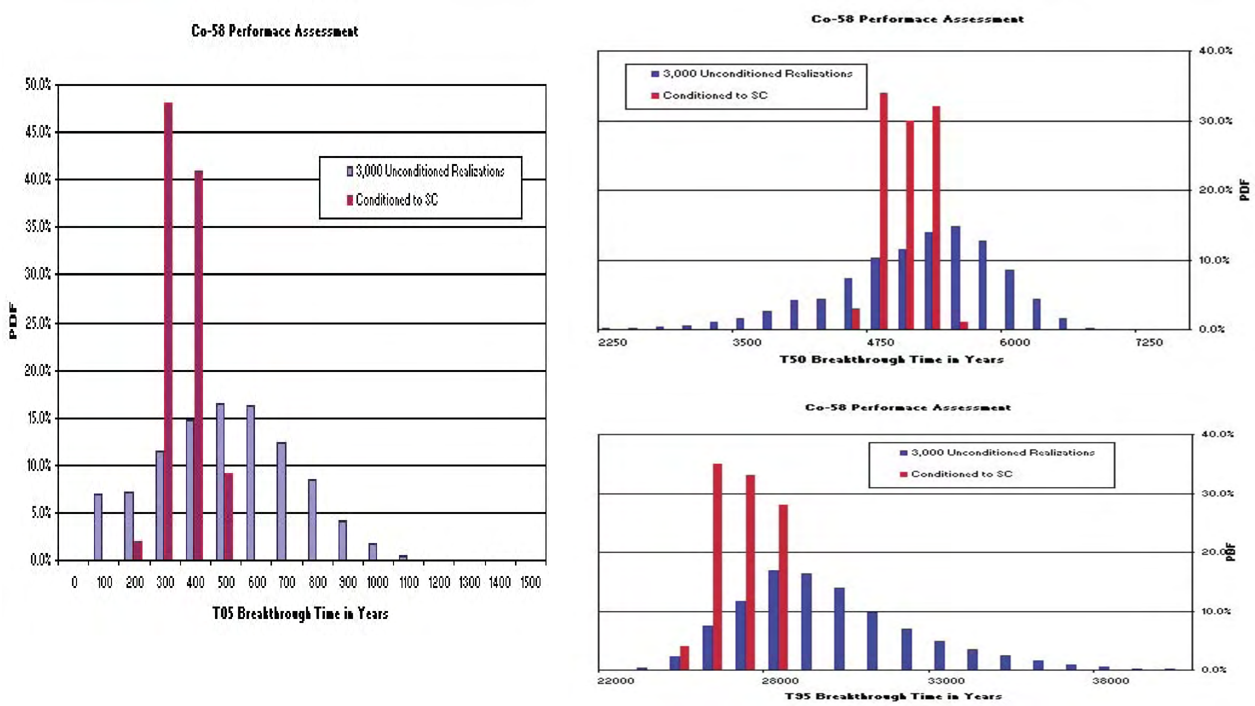


Figure 6-60. *Sub-tasks 6A and 6B Conditioned and unconditioned breakthrough statistics for sorbing solute ^{58}Co under PA boundary conditions, using 2004 conditioning approach.*

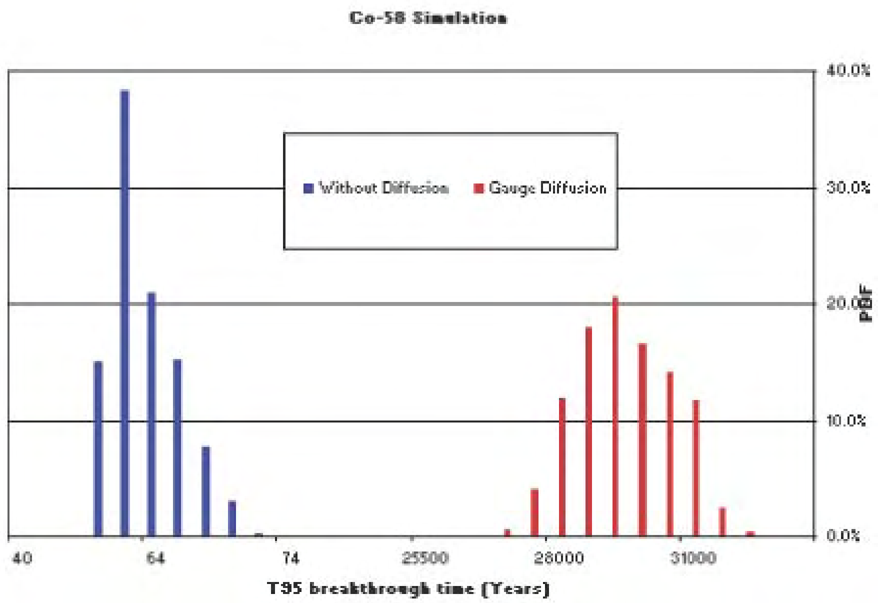


Figure 6-61. *Sub-tasks 6A and 6B Performance assessment results showing long term effect of gouge effects on solute breakthrough of ^{58}Co.*

6.7 OPG

In 2004, Ontario Power Generation Inc. (OPG) started its five-year agreement with SKB for participation in the Äspö HRL. As a new participant in Äspö, OPG's participation is still developing. Tasks in which specific results were obtained in 2004 are described below.

6.7.1 KBS-3 method with horizontal emplacement

Scoping post-closure safety analyses have been carried out for the horizontal borehole emplacement method in the context of a Canadian deep geologic repository in the Canadian Shield. The estimated peak dose rates with horizontal borehole emplacement are similar to those previously calculated using an in-room emplacement method in the Canadian Third Case Study /Gierszewski et al. 2004/.

6.7.2 Äspö Pillar Stability Experiment

OPG contracted Atomic Energy of Canada Limited (AECL) to participate in the Äspö Pillar Stability Experiment. AECL supplied and calibrated 22 Schaevitz GPD-121-250 Linear Variable Differential Transformers (LVDTs) and provided technical advice and equipment for LVDT installation. A total of 18 of the LVDTs supplied were eventually used in the experiment. The LVDTs were installed in one of two 1.8 m diameter and 6.4 m deep boreholes comprising the experiment. The borehole had three steel pillars (Figure 6-62). Flat plates were clamped to the vertical pillars to allow each set of LVDTs to be positioned at the correct depth (Figure 6-63). The LVDT mounting plates were attached by a threaded bolt and could be rotated to orient the LVDTs radially towards the borehole wall. The LVDTs were clamped to their mounting plates using hose clamps.

Two types of LVDTs were used to monitor the borehole wall displacement during the course of the experiment. AECL's LVDTs, having a 12 mm range, were mounted in pairs on the pillars in two arrays, one at 2.5 m downhole and the second at 3.06 m downhole (Figure 6-64). Just above or below each array of AECL LVDTs was a pair of SKB-supplied LVDTs (GeoLVDTs), having a range of 40 mm. Thermocouples and thermistors were used to monitor temperature.

During an AECL staff visit, it was noted that the arrangement of the clamps for the AECL LVDTs was not as expected. The issue was discussed with SKB experiment staff, which modified the clamps to a new design prior to the start of heating. The LVDT measurements before and after the clamp change were comparable so the initial data could be used.

The LVDTs performed well over the course of APSE. After the conclusion of the in situ portion of the APSE, the LVDTs were returned to AECL for re-calibration. The recalibration information has been sent to SKB. The results are expected to be reviewed in 2005.

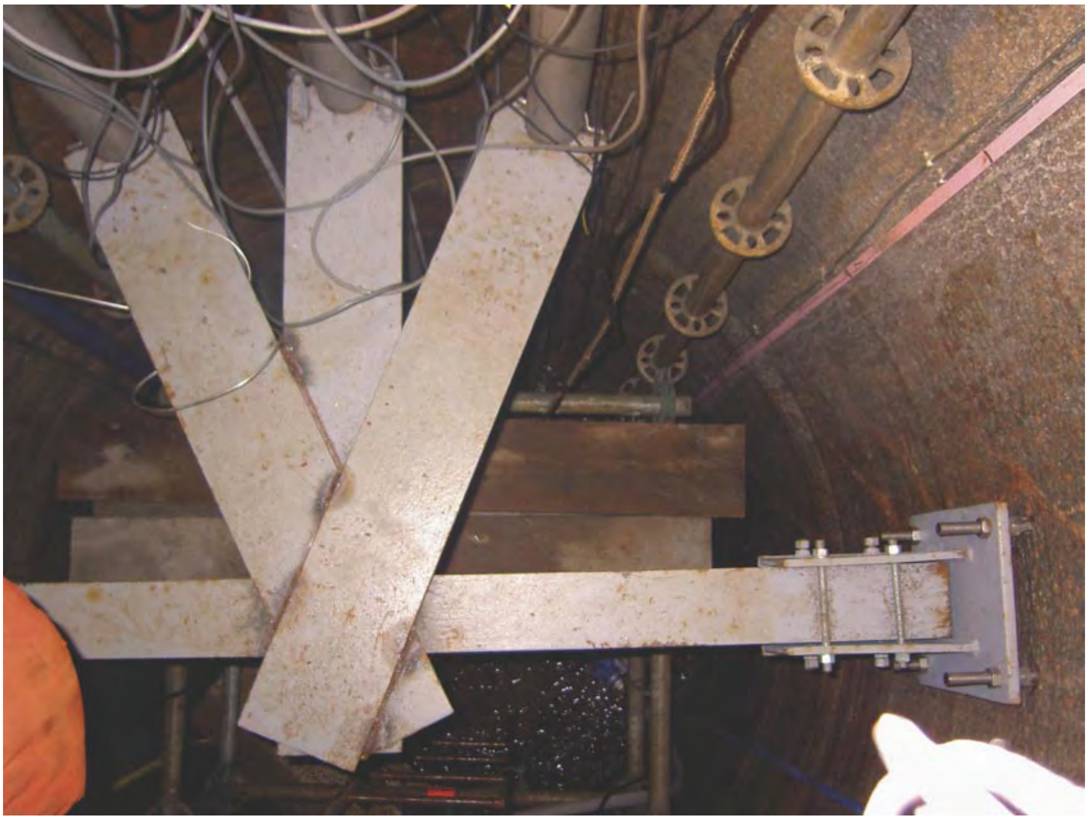


Figure 6-62. *Pillar support arrangement.*

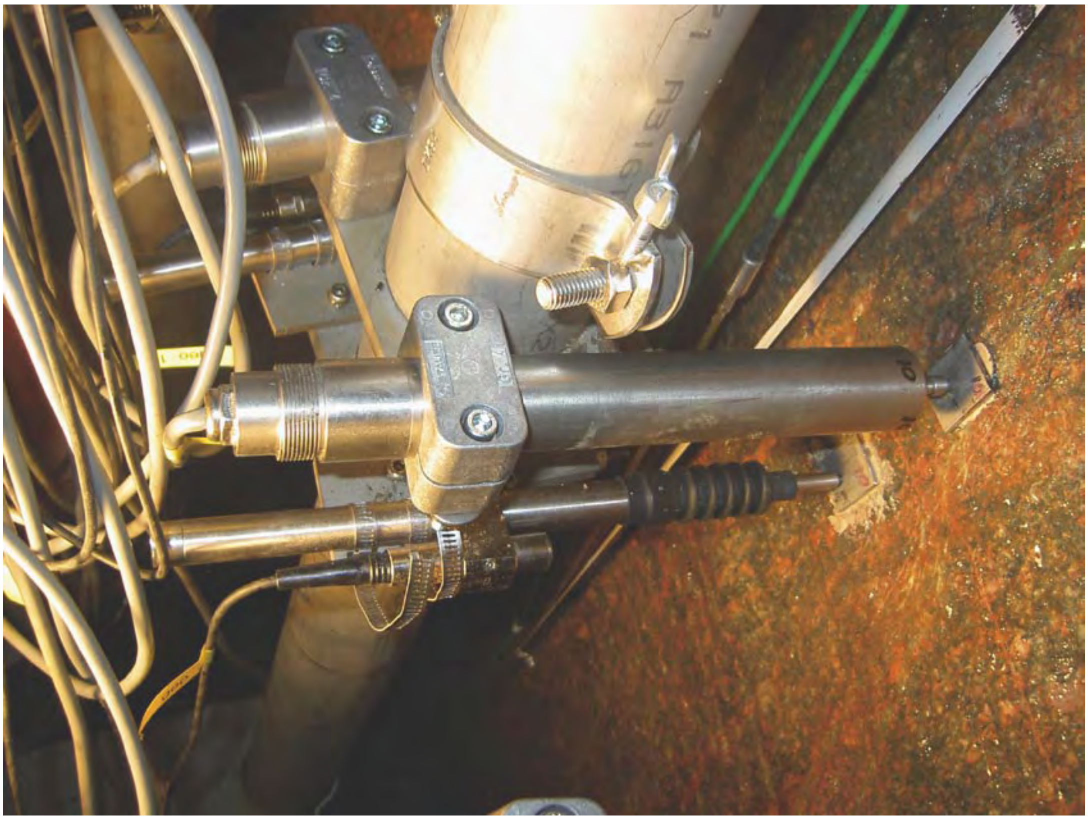


Figure 6-63. *Revised clamping arrangement for AECL Supplied LVDTs.*

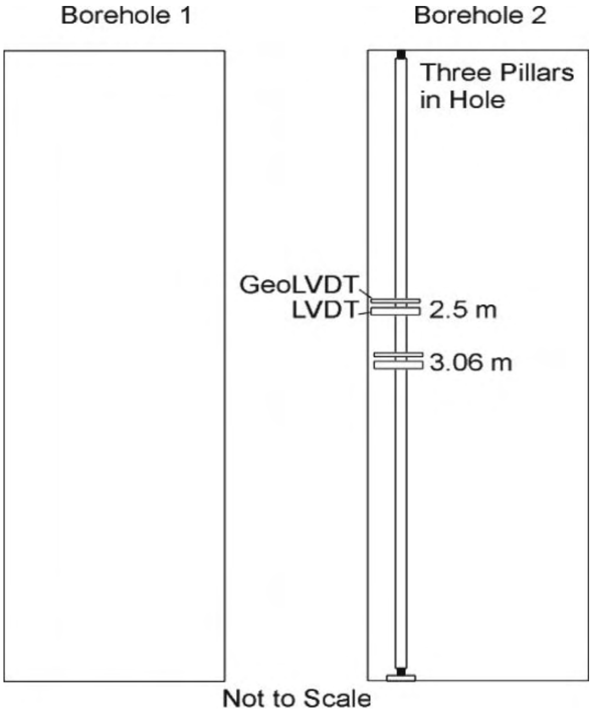


Figure 6-64. *LVDT Placement in Borehole 2. Only one of three pillars shown for illustration purposes.*

6.7.3 Long Term Diffusion Experiment

A programme of supporting laboratory experiments has been initiated at AECL's Whiteshell Laboratories. The purpose of this work is to provide a means for comparing laboratory-derived diffusion coefficients to the Äspö in situ derived values and thereby address the applicability of laboratory values in simulating larger-scale in situ processes.

One of the activities of the experimental programme consists of a radial diffusion experiment using a large diameter core from the LTDE borehole (KA3065A03) with a "slim" borehole drilled through the centre, which will serve as a tracer reservoir. The purpose of this experiment is to derive effective diffusion coefficients by through-diffusion using a radial geometry and obtain diffusion profiles that can be compared to those from the in situ "slim" borehole.

The other experimental activity consists of diffusion cell experiments using small core sub-samples obtained from the vicinity of a fracture in the LTDE borehole. The purpose of these experiments is to determine variations in porosity, diffusivity and permeability as a function of distance from the fracture surface and to determine the nature of rock property anisotropy in the region next to fractures containing alteration minerals.

Rock core samples from KA3065A03 were cut at the Äspö HRL and shipped to Whiteshell Laboratories in October 2004 for characterisation and testing. The radial diffusion experiment and porosity measurements were initiated in December (Figure 6-65) /Vilks and Miller, 2005/. Measurements of porosity, diffusivity and permeability, as well as diffusion modelling by MOTIF are anticipated to be completed in 2005.

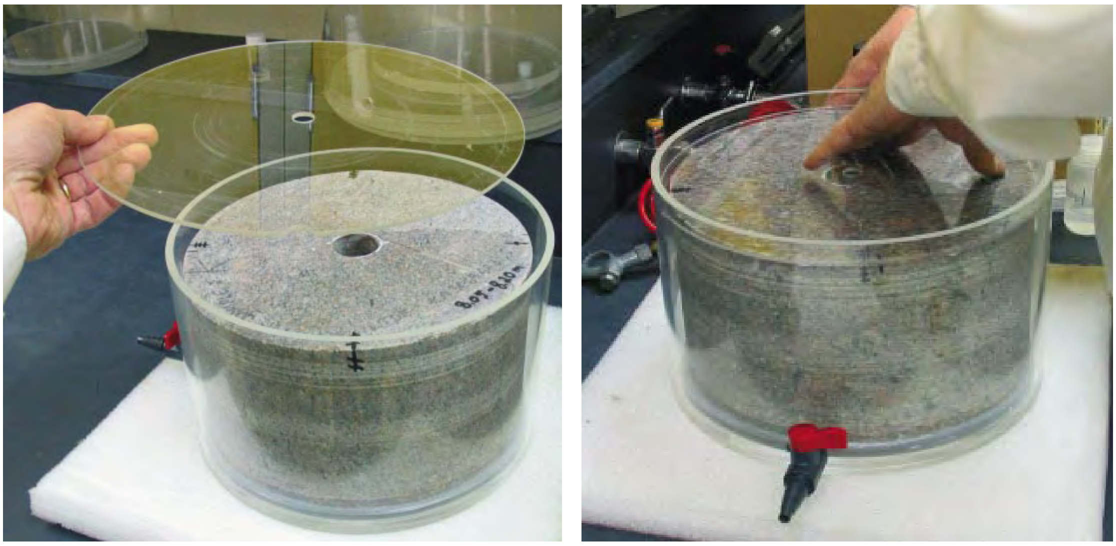


Figure 6-65. *Assembly of radial diffusion experiment at AECL's Whiteshell Laboratory.*

6.8 Posiva

Posiva's participation in the work at Äspö HRL was mainly in the areas of research and development of disposal technology and site evaluation. The following text summarises the work done during 2004 as part of the joint projects with SKB and the multilateral projects at Äspö HRL.

6.8.1 Prototype Repository

Posiva-VTT team has concentrated on the geochemical modelling calculations in the engineered barrier system (EBS) of the Prototype repository. The approach deals with the concentrations of the major species in pore waters, and the contemporary changes in solid phases. Calculations predict geochemical changes at the EBS boundaries, and changes that occur during wetting within the EBS.

The material properties given for the EBS (physical and mineralogical) are based on literature values. The chemical processes considered to be likely at repository depth are dissolution/precipitation of certain minerals, cation exchange within clays, and surface complexation (diffuse double layer approach).

Results

Examples of results are shown in Figure 6-66 and Figure 6-67. Repeated parcels of altered seawater enter into a reaction cell at the tunnel backfill boundary. The evolution in material properties, resulting porewater, and changes within the clay surfaces are modelled as a function of batch reaction cycles. Initially the boundary cell contains air in pore volume. During the first fill-up, all gaseous oxygen is consumed by pyrite dissolution and simultaneous goethite precipitation. The first cycles dissolve all gypsum from the boundary cell. In the course of time, the model predicts small amounts of calcite precipitation at the boundaries of the repository tunnel. Quartz is dissolved from the boundaries due to the temperature gradient effect. However, quartz will precipitate if the temperature of the porewater drops. The resulting porewater compositions evolve as a function of batch reaction cycles because of mineral reactions, and because of significant cation exchange processes. The modelling results have been reported in more detail by /Luukkonen, 2004/.

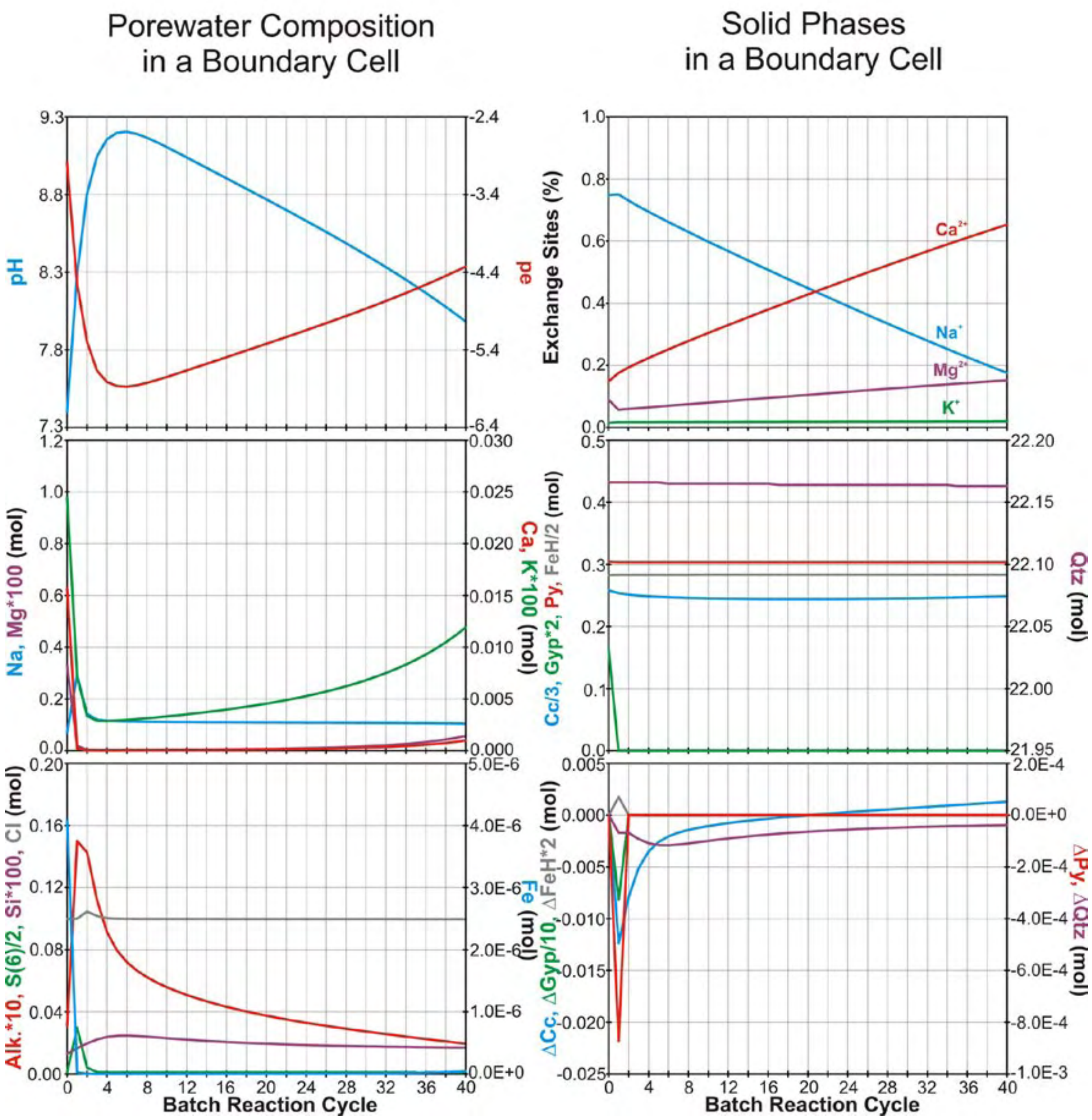


Figure 6-66. *Geochemical evolution among solid phases and resulting "free" porewater compositions in an EBS cell volume at the backfill boundary. The cell volume is refilled 40 times with altered seawater. The equilibrium temperature assumption is 40°C. Alk. = alkalinity, Cc = calcite, Gyp = gypsum, Py = pyrite, FeH = goethite.*

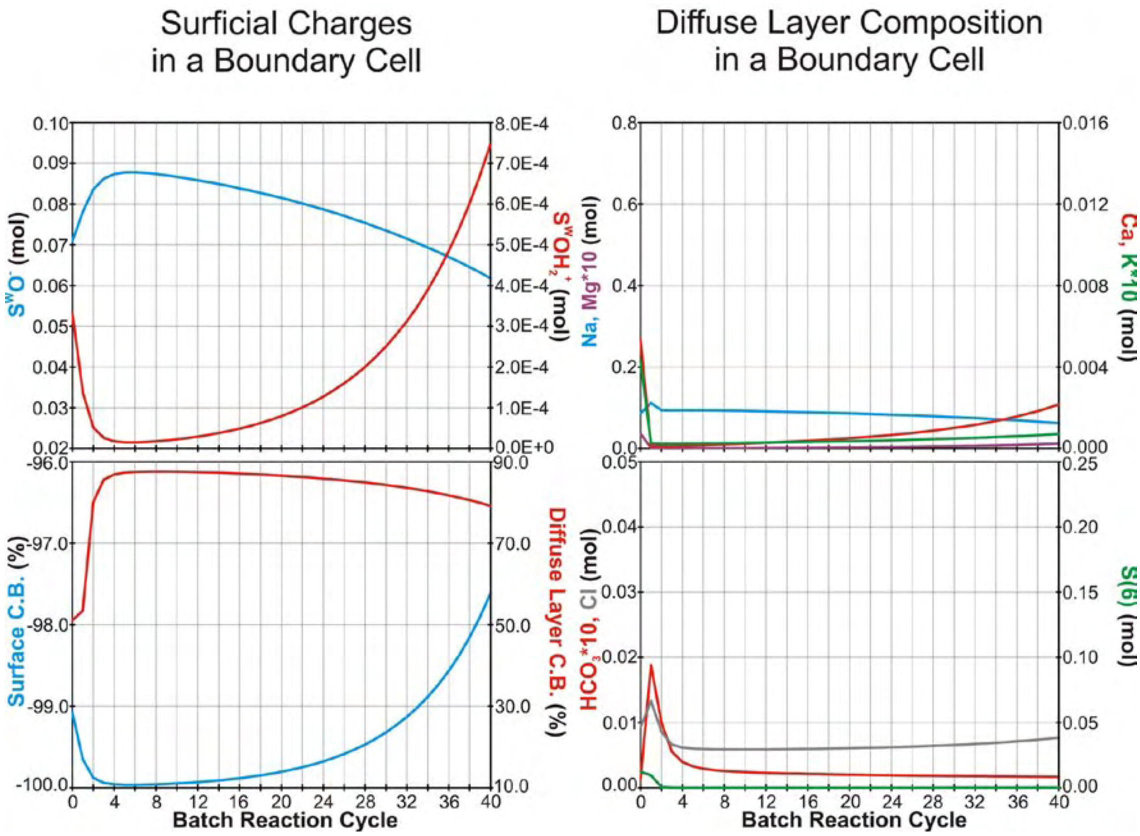


Figure 6-67. *Bulk geochemical conditions within charged surfaces of clay platelets and diffuse layer in an EBS cell volume at the backfill boundary. The cell volume is refilled 40 times with altered seawater.*

6.8.2 Long Term Test of Buffer Material

Posiva's task in the Long Term Test of Buffer Material 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. Planning of the uplift and research of the next parcel was started in the year 2004. The uplift is scheduled to occur in the year 2005.

6.8.3 Cleaning and sealing of boreholes

Phase 2 of the project started in 2003 and was preceded by a pre-study. Posiva joined the project during 2004. The project addresses issues that are part of the sealing process i.e. cleaning and stabilising boreholes, plugging material, construction and installation of plugs, performance assessment etc.

The primary goal of the work is to develop a concept for sealing of investigation boreholes, which have been drilled in the vicinity of the deep repository. The sealing aims at preventing the boreholes from becoming potential transport pathways for groundwater flow in the host rock. There is a need for this to ensure the long-term safety of the repository.

The specific goal for Phase 2 of the work was to develop a method, which is potentially capable to fulfil the intended purpose, and to make recommendation for the full scale testing of the method. A report describing the sealing concept is now being reviewed before printing.

In addition, to the participation in the work within the project has a report on “Cleaning of Boreholes” been compiled by Suomen Malmi Oy as an assignment from Posiva. This report was used as background material for the above-mentioned report describing the sealing concept.

6.8.4 Injection grout for deep repositories

Work packages SP1 and SP3 have been managed by Posiva. These work packages includes development work to find a suitable low pH cementitious injection grout for larger fractures (> 100 μm). The development of the technical properties of the grout has been made in the laboratory and was carried out mainly by VTT Building and Construction. The analyses of leaching properties of developed recipes and the pH in leachates were made by VTT Processes. The work has been reported as Posiva working reports /Kronlöf, 2004; Vuorinen et al. 2004/. The most promising mixes (one slag based and two silica-cement mixes with and without superplastisiser) have been tested in the field in pilot tests. The results will be reported during spring 2005.

6.8.5 KBS-3 method with horizontal emplacement

Posiva participates in the planning and the co-ordination of the project. Posiva is also responsible for the long-term safety studies in the development of the KBS-3H concept. The overall goal is a safety assessment of the KBS-3H concept in 2007, using Olkiluoto as a reference site. The aim is to perform a safety assessment of the same type as SKB’s safety assessment SR-Can for KBS-3V.

6.8.6 Large Scale Gas Injection Test

Posiva is taking part in Lasgit and has followed the test programme planning, the design and manufacturing of equipment, and the installation. VTT has been a reviewer of the project documentation; reports and activity plans. The project is currently changing from installation phase to hydration phase and later to gas injection phase.

6.8.7 Äspö Pillar Stability Experiment

The large-scale pillar stability experiment called Apse is focused on understanding and controlling the progressive rock failure in a pillar and damages caused by high stresses. The heating experiment took place in summer 2004. The heating increased, as expected, the spalling process in the boreholes. After about two months of additional thermal loading the spalling had progressed to 5 m depth in the hole and the experiment was then terminated. The confinement pressure of 150 to 200 kPa seemed sufficient to suppress the spalling. An extensive monitoring programme including temperature, displacement and acoustic emission monitoring was made during the experiment. The analysis of the experiment data has recently started.

The experiment was prior to the test execution modelled by different research groups using different analysis approaches. Posiva's contribution in 2004 was to participate in the project follow-up, in planning the monitoring programme and in finalising the report on the final three dimensional thermo-mechanical analyses and preliminary two dimensional particle-mechanical analyses. The work was carried out by Saanio and Riekkola Oy. The modelling of the experiment was performed using the three dimensional element code FLAC3D and a novel coupled FLAC/PFC2D code /Magnor, 2004/. The modelling results indicated rock damages to about two metres depth down in the hole, but the experiment showed clearly larger damages in the holes. Comparisons or detailed interpretations between the modelling results and measurements have not yet been performed.

6.8.8 True Block Scale Continuation

The True Block Scale Continuation (BS2) project is a continuation of the True Block Scale experiment and it utilises the same rock volume in the Äspö laboratory as it's forerunner. BS2 comprises continued monitoring of the tailings of True Block Scale tracer experiments (BS2a) and a new set of tracer experiments (BS2b).

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

The experiment is designed to study transport of tracers through a network of fractures. The target volume is a cube with size about 50 m. During years 2003 and 2004 a set of different tracer tests were carried out. These include pre-testing phase for the characterisation of the flow paths (CPT-tests) and migration of both non-sorbing and sorbing tracer tests were predicted. Evaluation of the BS2B-tests by the modelling groups will be carried out during spring 2005.

During year 2004 sorbing tracer tests (BS2B-tests) were predicted by modelling groups. Posiva's contribution to the BS2B-modelling included also definition of the performance measures for the predictions.

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

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

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

Task 6 does not contain experimental work but it uses experimental results of the former Task 4 and True Block Scale project. Task 4 was a series of tracer tests performed in single feature over transport distance of about 5 m using simple flow geometry and both conservative and sorbing tracers. True Block Scale was a series tracer tests that were performed in fracture network over tens of metre distances.

During year 2004, modelling of the sub-task 6D was finalised and a draft report of the modelling was written. Preliminary sub-task 6E modelling results were presented at the 19th Task Force meeting. Modelling of the sub-tasks 6D and 6E showed that the link between the site characterisation models and PA models need to be evaluated carefully. Some of the geological materials, like fault gouge, are very efficient sources of retention but their volume is also significantly limited. This means that extrapolation of the retention properties from SC scale to the PA scale is not only a straightforward scaling of flow conditions.

6.9 EC projects

SKB has taken part in several EC projects of which the representation was channelled through Repository Technology. The projects are briefly described in the following sections. All projects are either finalised during 2004, or are in the stage of being finalised.

6.9.1 Prototype Repository

Prototype Repository – Full scale testing of the KBS-3 concept for high-level radioactive waste	
Start Date: 2000-09-01	**End Date:** 2004-02-29
Co-ordinator: Swedish Nuclear Fuel and Waste Management Co, Sweden	**Participating countries:** Finland, Germany, Japan, Spain, Sweden and United Kingdom

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

6.9.2 Crop

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

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

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

6.9.3 Febex II

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

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

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

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

6.9.4 Benchpar

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

Start Date: 2000-10-01

End Date: 2003-09-30

Co-ordinator: Royal Institute of Technology (Dep of Civil and Environmental Engineering), Sweden

Participating countries: Finland, France, Spain, Sweden and United Kingdom

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

6.9.5 Ecoclay II

Ecoclay II – Effects of cement on clay barrier performance, phase II

Start Date: 2000-10-01

End Date: 2003-09-30

Co-ordinator: National Radioactive Waste Management Agency of France

Participating countries: Belgium, Finland, France, Germany, Spain, Sweden, Switzerland and United Kingdom

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

6.9.6 Safeti

Safeti – Seismic validation of 3D thermo-mechanical models for the prediction of the rock damage around radioactive spent fuel waste

Start Date: 2001-09-01	**End Date:** 2004-09-01
Co-ordinator: The University of Liverpool (Dep of Earth Sciences), United Kingdom	**Participating countries:** France, Sweden and United Kingdom

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

6.9.7 Padamot

Padamot – Palaeohydrogeological data analysis and model testing

Start Date: 2001-11-01	**End Date:** 2004-11-01
Co-ordinator: Nirex Ltd, United Kingdom	**Participating countries:** Czech Republic, Spain, Sweden and United Kingdom

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

6.9.8 Net.Excel

Net.Excel – Network of excellence in nuclear waste management and disposal	
Start Date: 2002-11-01	**End Date:** 2004-03-31
Co-ordinator: Swedish Nuclear Fuel and Waste Management Co, Sweden	**Participating countries:** Belgium, Finland, France, Germany, Spain, Sweden, Switzerland and United Kingdom

The objectives are a future efficient use of European resources in research and development of safe methods for final disposal of high-level radioactive waste. This calls for close interaction between European end users in planning of national programmes as well as in development of international projects. The proposal concerns the forming of a network of end users for the intended analysis of present status and future requirements in RTD for the three different rock media: salt, clay sediments and crystalline rock. The expected results are common and systematic basis for priorities and co-ordination of future European RTD work for radioactive waste management, and suggested areas and priorities for joint RTD projects. The objective is to develop a common and systematic basis for priorities and co-ordination of future European RTD work for Radioactive Waste Management and suggest areas and priorities for joint RTD projects. This will be accomplished by forming a Network of Excellence with the main European organisations given the national responsibilities to develop systems for safe handling and disposal of long-lived radioactive waste and by jointly working out a document that can serve as an aid for the planning and execution of future co-ordinated RTD activities between European implementers.

7 Environmental research

7.1 General

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

7.2 Äspö Research School

Background

Kalmar University's Research School in Environmental Science at Äspö HRL is called Äspö Research School and started in October, 2002. This School is the result of an agreement between SKB and Kalmar University. It combines two important regional resources, i.e. Äspö HRL and Kalmar University's Environmental Science Section. The activity within the School will lead to: (a) development of new scientific knowledge, (b) increase of geo and environmental scientific competence in the region and (c) utilisation of the Äspö HRL for environmental research.

Results

Currently the scientific team consists of a professor of Environmental geology, three assistant supervisors and six Ph D students. The research activity focuses on biogeochemical systems, in particular in the identification and quantification of dispersion and transport mechanisms of contaminants (mainly metals) in and between soils, sediments, water, biota and upper crystalline bedrock. In addition to financial support from SKB and University of Kalmar, the School receives funding from the city of Oskarshamn.

There are currently a variety of research activities at sites outside Äspö HRL. These activities have resulted in several scientific publications, and the first Ph D dissertation will take place in 2005. In the Äspö HRL, however, the activities are as yet minor. A Ph D project focusing on hydrogeology is currently being planned (to be initiated in early 2005). Sampling of ground waters took place in spring, and a strategy for interpreting existing hydrochemical data on transition metals has been made.

8 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, 169–178.

Andersson P, Byegård J, Winberg A, 2002a. Final report of the TRUE Block Scale Project 2. Tracer tests in the block scale. SKB TR-02-14, Svensk Kärnbränslehantering AB.

Andersson P, Byegård J, Dershowitz B, Doe T, Hermanson J, Meier P, Tullborg E-L, Winberg A, 2002b. Final report of the TRUE Block Scale projekt 1. Characterisation and model development. SKB TR-02-13, Svensk Kärnbränslehantering AB.

Andersson P, Gröhn S, Nordqvist R, Wass E, 2004. TRUE Block Scale continuation project. BS2B pretests. Crosshole interference, dilution and tracer tests CTP-1–CTP-4. SKB IPR-04-25, Svensk Kärnbränslehantering AB.

Andersson P, Byegård J, Nordqvist R, Wass E, 2005. TRUE Block Scale continuation project. BS2B tracer tests with sorbing tracers – experimental results and preliminary evaluation. SKB IPR-05-01, 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.

Bono N, Röshoff K, 2003. Prototype Repository. Instrumentation for stress, strain and displacement measurements in rock. SKB IPR-03-19, Svensk Kärnbränslehantering AB.

Buckau G, Wolf M, 2002. Origin, stability and mobility of humic colloids in Äspö groundwater: Feasibility study. Project contribution to the Äspö Colloid Workshop 5:th of March in Stockholm.

Buntebarth G, 2004. Laboratory investigations on bentonite samples, Geophysikalisch-Technisches Büro, Clausthal-Zellerfeld.

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.

Byegård J, 2005 (in prep). Sorption experiments using fault gouge and rim zone materials fronm the Äspö Hard Rock Laboratory. 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.

Collin M, Börgesson L, 2002. Prototype Repository. Instrumentation of buffer and Backfill for measuring THM processes. SKB IPR-02-09, Svensk Kärnbränslehantering AB.

Cvetkovic V, Selroos J O, Cheng H, 1999. Transport of reactive solute in single fractures, J. Fluid Mech. 318, 335–356, 1999.

Degueldre C, 2002. Review comments to the Äspös Colloid Wordkshop 5:th of March 2002. Project contribution to the Äspö Colloid Workshop 5:th of March in Stockholm.

Dershowitz W, Winberg A, Hermanson J, Byegård J, Tullborg E-L, Andersson P, Mazurek M, 2003. A semi synthetic model of block scale conductive structures at the Äspö HRL. SKB IPR-03-13, Svensk Kärnbränslehantering AB.

Ekendahl S, O'Neill A H, Thomsson E, Pedersen K, 2003. Characterisation of yeasts isolated from deep igneous rock aquifers of the Fennoscandian Shield. Microb Ecol 46, 416–428.

Emmelin A, Eriksson M, Fransson Å, 2004. Characterisation, design and execution of two grouting fans at 450 m level, Äspö HRL. SKB R-04-58, Svensk Kärnbränslehantering AB.

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, 181–192.

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, 1035–1042.

Gierszewski P, Avis J, Calder N, D'Andrea A, Garisto F, Kitson C, Melnyk T, Wei K, Wojciechowski L, 2004. Third Case Study – Postclosure Safety Assessment. Ontario Power Generation, Nuclear Waste Management Division Report 06819-REP-01200-10109-R00.

Goudarzi R, Johannesson L-E, 2004. Prototype Repository. Sensors data report (Period: 010917-040901). Report No:11. SKB IPR-04-48, Svensk Kärnbränslehantering AB

Goudarzi R, Börgesson L, Röshoff K, Edelman M, 2004a. Canister Retrieval Test. Sensors data report (Period 001026-040501). Report no 8. SKB IPR-04-28, Svensk Kärnbränslehantering AB.

Goudarzi R, Börgesson L, Röshoff K, Edelman M, 2004b. Canister Retrieval Test. Sensors data report (Period 001026-041101). Report no 9. SKB IPR-04-53, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, Börgesson L, 2004c. Backfill and Plug Test. Sensors data report (Period 990601-040701). Report No:9. SKB IPR-04-47, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, Börgesson L, 2005a. Backfill and Plug Test. Sensors data report (Period 990601-050101). Report No:10. SKB IPR-05-12, Svensk Kärnbränslehantering AB.

Goudarzi R, Åkesson M, Hökmark H, 2005b. Äspö Hard Rock Laboratory. Temperature Buffer Test. Sensors data report (period 030326-050101) Report No:5. SKB IPR-05-06, Svensk Kärnbränslehantering AB.

Gurban I, 2002. Electric conductivity measurements along the Äspö tunnel. Project contribution to the Äspö Colloid Workshop 5:th of March in Stockholm.

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

Hallbeck L, Pedersen K, 1990. Culture parameters regulating stalk formation and growth rate of *Gallionella ferruginea*. J Gen Microbiol 136, 1675–1680.

Hallbeck L, Pedersen K, 1991. Autotrophic and mixotrophic growth of *Gallionella ferruginea*. J Gen Microbiol 137, 2657–2661.

Hallbeck L, Ståhl F, Pedersen K, 1993. Phylogeny and phenotypic characterization of the stalk-forming and iron-oxidizing bacterium *Gallionella ferruginea*. J Gen Microbiol 139, 1531–1535.

Hallbeck L, Pedersen K, 1995. Benefits associated with the stalk of *Gallionella ferruginea*, evaluated by comparison of a stalk-forming and a non-stalk-forming strain and biofilm studies in situ. Microb Ecol 30, 257–268.

Hardenby C, 2004. Äspö Hard Rock Laboratory – Large Scale Gas Injection Test – The LASGIT hole DA3147G01 Hydrogeology. SKB IPR-04-52, Svensk Kärnbränslehantering AB.

Hauser W, Götz R, Geckeis H, Kienzler B, 2002. In situ Colloid Detection in Granite Groundwater along the Äspö Hard Rock Laboratory Access Tunnel. Project contribution to the Äspö Colloid Workshop, 5:th of March in Stockholm.

Haveman S A, Pedersen K, 2002. Microbially mediated redox processes in natural analogues for radioactive waste. J Contam Hydrol 55, 161–174.

Hökmark H, Ledesma A, Lassabatere T, Fälth B, Börgesson L, Robinet J-C, Sellani N, Sémété P, 2005. Modeling heat and moisture transfer in the ANDRA/SKB temperature buffer test. Proceeding Tours 2nd International meeting.

Jansson, M, Eriksen T E, 1998. CHEMLAB – In situ Diffusion Experiments Using Radioactive Tracers, Radiochim. Acta 82, pp 153–156.

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

Jansson M, Eriksen T E, 2004. In situ anion diffusion experiments using radiotracers. J. Cont. Hydr. Vol 68/3–4 (2004) pp 183–192.

Jansson M, Eriksen T E, Moreno L, 2004. 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.

JNC, 2000. Second Progress Report on Research and Development for the Geological Disposal of HLW in Japan; H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, JNC TN1400 2000-001-003.

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.

Kienzler B, Römer J, Vejmelka P, Jansson M, Eriksen T E, Spahiu K, 2003a. Actinide migration in granite fractures: Comparison between in situ and laboratory results Materials Research Societu Symposium Proceedings (2002) Volume Date 2003, 757 (Scientific Basis for Nuclear Waste Management XXVI) 523–538.

Kienzler B, Vejmelka P, Römer J, Fanghänel E, Jansson M, Eriksen T E, Wikberg P, 2003b. Swedish-German actinide migration experiment at ÄSPÖ hard rock laboratory. J. Cont. Hydr. 61, (2003) 219–233.

Kienzler B, Römer J, Schild D, Bernotat W, 2003c. Sorption of actinides onto granite and altered material from Äspö HRL. In Oversby, V.M. (Ed) Scientific Basis for Nuclear Waste Management XXVII : Symp, Kalmar, S, June 15–19, 2003 (Materials Research Society Symposium Proceedings; 807).

Kienzler B, Römer J, Schild D, Bernotat W, 2004. Sorption of actinides onto granite and altered material from Äspö HRL. SOPRO 2004 : Internat.Workshop on Sorption Processes at Oxide and Carbonate Mineral Water Interfaces, Karlsruhe, March 25–26, 2004, Book of extended abstracts S.69–74, Wissenschaftliche Berichte, FZKA-6986 (Juni 2004).

Kotelnikova S, Pedersen K, 1998. Distribution and activity of methanogens and homoacetogens in deep granitic aquifers at Äspö Hard Rock Laboratory, Sweden. FEMS Microbiology Ecology 26, 121–134.

Kronlöf A, 2004 (in print). Injection Grout for Deep Repositories, Low pH Cementitious Grout for Larger Fractures, Testing technical performance of materials. VTT Building and transport. Posiva Working report 2004-45. Posiva Oy, Olkiluoto, Finland.

Kröhn K P, 2003. New conceptual models for the resaturation of bentonite, proceedings of the Workshop on "Clay Microstructure and its Importance to Soil Behaviour" held in Lund, 2002, Applied Clay Science, Vol. 23.

Kröhn K P, 2004a. Modelling the re-saturation of bentonite in final repositories in crystalline rock, final report of BMWA-project no. 02 E 9430, GRS-report GRS-199.

Kröhn K P, 2004b. Proposal of an alternative re-saturation model for bentonite buffers – the conceptual model, the numerical model and the data base. in: Pusch R, Svemar Ch: Proceedings from the TaskForce-related meeting on Buffer & Backfill modelling" in Lund. SKB IPR-04-23, Svensk Kärnbränslehantering AB.

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.

Luukkonen A, 2004. Modelling approach for geochemical changes in the Prototype repository engineered barrier system. Working Report 2004-31. Posiva Oy, Olkiluoto, Finland.

Mærsk Hansen L, Staub I, 2004. TRUE-1 Continuation project. Fault rock zones characterisation. Overcoring (300mm) of impregnated fault rock zones at chainages 2/430, 2/545, 2/163 and 1/600m. SKB IPR-04-10, Svensk Kärnbränslehantering AB.

Magnor B, 2004. Äspö Pillar Stability Experiment. Geological mapping of tunnel TASQ. SKB IPR-04-03, Svensk Kärnbränslehantering AB.

Mattsén C, 2002. Compilation of groundwater chemistry data October 2001. Project contribution to the Äspö Colloid Workshop 5:th of March in Stockholm.

Mazurek M, Jacob A, Bossart P, 2002. Solute transport in crystalline rocks at Äspö – I: Geological basis and model calibration, J. of Cont. Hydrology (61), pp 157–174.

Merroun M, Moll H, Maitz G, Bernhard G, Selenska-Pobell S, 2004. Toxicity of Uranium Towards Desulfovibrio äspöensis DSM 10631: Flow Cytometry and Transmission Electron Microscope Studies FZR, Annual Report 2003, FZR-400, 26.

Moll H et al. 2003a. Interaction of Desulfovibrio äspöensis with Actinides, presented at the 9th International Conference MIGRATION'03, Gyeongju, Korea, 2003; Paper B4-4.

Moll H, Merroun M, Selenska-Pobell S, Bernhard G, 2003b. Interaction of actinides with Desulfovibrio äspöensis (DSM 10631): Part I Uranium, FZR, Annual Report 2002, FZR-373, 31, 32.

Moll H, Stumpf Th, Terroun M, Rossberg A, Selenska-Pobell S, Bernhard G, 2004a. Time-resolved Laser Fluorescence Study on the Interaction of Cm (III) with Desulfovibrio äspöensis DSM 10631**.** Environmental Science &. Technoogy. 38, 1455.

Moll H, Geipel H, Merroun M, Selenska-Pobell S, Bernhard G, 2004b. Desulfovibrio äspöensis (DSM 10631) and Uranium – First LIPAS results, FZR, Annual Report 2003, FZR-400, 27.

Moll H, Merroun M, Selenska-Pobell S, Bernhard G, 2005a. Interaction of actinides with Desulfovibrio äspöensis (DSM 1061): Part III Neptunium, FZR, Annual Report 2004, FZR-419, 36.

Moll H, Geipel G, Berhard G, 2005b. Complexation of Cm(III) by adenosine 5'-triphosphate (ATP): A time resolved laser-induced fluorescence spectroscopy (TRLFS) Inorg. Chim. Acta, 358, 7, 2275.

Motamedi M, Pedersen K, 1998. *Desulfovibrio aespoeensis* sp. nov. a mesophilic sulfate-reducing bacterium from deep groundwater at Äspö hard rock laboratory, Sweden. Int. J. Syst. Bacteriol. 48, 311–315.

Nowak T, Shao H, 2003. Approach for THM-coupled modeling of the FEBEX in situ experiment, Final report of BGR-project no. AP 9Y3211010000, Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover.

Nowak T, Liedtke L, 2004. Final report of BGR-project no. AP 9Y3211020000, Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover.

Ohnishi Y, Shibata H, Kobayashi A, 1985. Development of Finite Element Code for the Analysis of Coupled Thermo-Hydro-Mechanical Behavior of Saturated-Unsaturated Medium, Proc. Of Int. Symp. On Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Berkeley, pp 263–268.

Panak P, Nitsche H, 2001. Interaction of aerobic soli bacteria with plutonium (IV), Radiochim. Acta 89, 499.

Pedersen K, Arlinger J, Ekendahl S, Hallbeck L, 1996. 16S rRNA gene diversity of attached and unattached groundwater bacteria along the access tunnel to the Äspö Hard Rock Laboratory, Sweden. FEMS Microbiol. Ecol. 19, 249–262.

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

Pedersen K, 2000. The microbe site. Drilling, instrumentation and characterisation. SKB IPR-00-36, Svensk Kärnbränslehantering AB.

Pedersen K, Motamedi M, Karnland O, Sandén T, 2000a. Cultivability of microorganisms introduced into a compacted bentonite clay buffer under high-level radioactive waste repository conditions. Engineering Geology 58, 149–161.

Pedersen K, Motamedi M, Karnland O, Sandén T, 2000b. Mixing and sulphate-reducing activity of bacteria in swelling compacted bentonite clay under high-level radioactive waste repository conditions. J Appl Microbiol 89, 1038–1047.

Pedersen K, 2001. Diversity and activity of microorganisms in deep igneous rock aquifers of the Fennoscandian Shield. In Subsurface microbiology and biogeochemistry. Edited by Fredrickson J.K. and Fletcher M. Wiley-Liss Inc, New York. pp 97–139.

Pedersen K, 2002a. 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, 2002b. Total number of microorganisms in groundwater sampled during background colloid measurements along the Äspö HRL-tunnel. Project contribution to the Äspö Colloid Workshop 5:th of March in Stockholm.

Poteri A, Billaux D, Cvetkovic V, Dershowitz B, Gómez-Hernández J-J, Hautojärvi A, Holton D, Medina A, Winberg A, 2002. TRUE Block Scale Project. Final Report – 3. Modelling of flow and transport. SKB TR-02-15, Svensk Kärnbränslehantering AB.

Puigdomenech I, Sandén T, 2001. Prototype Repository. Instrumentation for gas and water sampling in Buffer and Backfill.Sensors data report. Report No:11. SKB IPR-04-48, Svensk Kärnbränslehantering AB.

Pusch R, 2001. Prototype Repository. Selection of THMCB models. SKB IPR-01-66, Svensk Kärnbränslehantering AB.

Pusch R, Kasbohm J, 2001. Can the water content of highly compacted bentonite be increased by applying a high water pressure? SKB TR-01-33, 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.

Pusch R, Svemar C, 2004. EBS Task Force. Proceedings from Task Force-related meeting on Buffer and Backfill modelling. SKB IPR-04-23, Svensk Kärnbränslehantering AB.

Pusch R, Yong R, 2003. Water saturation and retention of hydrophilic clay buffer – microstructural aspects. Proceedings of the Workshop on "Clay Microstructure and its Importance to Soil Behaviour" held in Lund, Applied Clay Science, Vol. 23, 2003.

Rantanen M, Mäntynen M, 2002. Groundwater sampling in Äspö tunnel. Project contribution to the Äspö Colloid Workshop 5:th of March in Stockholm.

Rhén I, Forsmark T, Magnusson, 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.

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.

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

SKB, 2001b. Forsknings-, utvecklings- och demonstrationsprogram för ett KBS-3-förvar med horisontell deponering. SKB R-01-55. Svensk Kärnbränslehantering AB.

SKB, 2003. Äspö Hard Rock Laboratory, Annual Report 2002. SKB TR-03-10, Svensk Kärnbränslehantering AB.

SKB, 2004. Äspö Hard Rock Laboratory. Planning Report for 2004. SKB IPR-04-12, Svensk Kärnbränslehantering AB.

Smellie J, Waberg N, Frape S, 2003. Matrix fluid chemistry experiment. Final report. June 1998–March 2003. SKB TR-03-18, Svensk Kärnbränslehantering AB.

Staub I, Andersson C, Magnor B, 2004. Äspö Pillar Stability Experiment. Geology and mechanical properties of the rock in TASQ. SKB R-04-01, Svensk Kärnbränslehantering AB.

Sugita Y, Ito A, Chijimatsu M, Kurikami H, 2002. Prediction analysis A for the PRP with the numerical code THAMES. SKB IPR-02-24, Svensk Kärnbränslehantering AB.

Sundberg J, 2002. Determination of thermal properties at Äspö HRL, Comparison and evaluation of methods and methodologies for borehole KA 2599 G01. SKB R-02-27, Svensk Kärnbränslehantering AB.

Sundberg J, 2003. Thermal Properties at Äspö HRL, Analysis of Distribution and scale Factors. SKB R-03-17, Svensk Kärnbränslehantering AB.

Tanaka Y, 2004. Äspö Task Force. Application of FEGM and FERM to Task 6A, 6B and 6B2. Performance assessment modelling using site characterisation data. SKB IPR-04-38, Svensk Kärnbränslehantering AB.

Thorsager P, Lindgren E, 2004. KBS-3H. Summary report of work done during Basic Design. SKB R-04-42, Svensk Kärnbränslehantering AB.

Vilks P, Miller N H, 2005. Status report on 2004 supporting work for SKB's long term diffusion experiment. Ontario Power Generation, Nuclear Waste Management Division Report 06819-REP-01300-10098-R00.

Vuorinen U, 2002. Characteristics of natural colloids in two groundwater samples from the Äspö HRL-tunnel. Project contribution to the Äspö Colloid Workshop 5:th of March in Stockholm.

Vuorinen U et al. 2004. Injection Grout for Deep Repositories, Low-pH Cementitious Grout for Larger Fractures, Leach testing of Grout Mixes. VTT Processes. Posiva working report 2004-46, Posiva Oy, Finland.

Winberg A, Andersson P, Hermansson J, Byegård J, Cvetkovic V, Birgersson L, 2000. Äspö Hard Rock Laboratory. Final report of the first stage of the Tracer Retention Understanding Experiments. SKB TR-00-07, Svensk Kärnbränslehantering AB.

Winberg A, Andersson P, Byegård J, Poteri A, Cvetkovic V, Dershowitz W, Doe T, Hermanson J, Gómez-Hernández J J, Hautojärvi A, Billaux D, Tullborg E-L, Holton D, Meier P, Medina A, 2003a. Final report of the TRUE Block Scale project. 4. Synthesis of flow, transport and retention in the block scale. SKB TR-02-16, Svensk Kärnbränslehantering AB.

Winberg A, Hermansson J, Tullborg E-L, Staub I, 2003b. 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, 2002a. Formation of inorganic colloids in solutions in contact with bentonite. Project contribution to the Äspö Colloid Workshop 5:th of March in Stockholm.

Wold S, Eriksen T, 2002b. Background inorganic colloid measurements in different Äspö-waters. Project contribution to the Äspö Colloid Workshop 5:th of March in Stockholm.

List of papers and articles published 2004

Pillar Stability Experiment

Andersson J C, Martin C D, Christiansson R, 2004. SKB's Äspö pillar stability experiment, Sweden. Paper presented at Gulf Rocks 2004 Rock mechanics across borders and disciplines, June 5–10, 2004 Marriot Westchase Houston Hotel – Houston,

Microbe Project

Meetings

Pedersen K, 2004. Exploration of deep intra-terrestrial and sub-sea floor microbial life. Keynote at ISME-10, Tuesday 24 August. International Symposium on Microbial Ecology, Cancun, Mexico, August 22–27, 2004

Pedersen K, 2004. Geobiology – exploring the interface between the biosphere and the geosphere. Keynote at the 74th Jahrestagung der Paläontologischen Gesellschaft, Göttingen, Germany, October 2–8, 2004

Pedersen K, 2004. Explore deep biosphere by deep continental drilling. International Continental Drilling Program (ICDP) Workshop on drilling the Eger rift. Býkov, Czech Republic October 3–7, 2004

Pedersen K, 2004. Exploration of the deep subterranean biosphere. Key Note, Lithosphere 2004. Third symposium on the structure, composition and evolution of the lithosphere in Finland. Åbo Akademi University, Arken Campus, Turku, November 10–11 2004.

Pedersen K, 2004. Microorganisms and their influence on radionuclide migration in igneous rock environments. JAERI-ASR. The fourth International Symposium on Advanced Science Research – Advances in heavy elements microbiology research. ASR 2004, Tokai, Japan, November 15–16, 2004.

Proceedings

Anderson C R, Pedersen K, 2004. Adsorption and retention of U-238 and Th-232 from groundwater using BIOS. In Scientific basis for nuclear waste management XXVII. Edited by Oversby V.M. and Werme L.O. Materials Research Society, Warrendale, Pennsylvania. pp 817–822.

Arlinger J, Oskarsson A, Albinsson T, Anlid T, Pedersen K, 2004. Mobilisation of radionuclides by ligands produced by bacteria from the deep subsurface. In Scientific basis for nuclear waste management XXVII. Edited by Oversby V.M. and Werme L.O. Materials Research Society, Warrendale, Pennsylvania. pp 823–828.

Masurat P, Pedersen K, 2004. Microbial sulphide production in compacted bentonite at the commencement of long-term disposal of high-level radioactive waste. In Scientific basis for nuclear waste management XXVII. Edited by Oversby V.M. and Werme L.O. Materials Research Society, Warrendale, Pennsylvania. pp 805–810.

Publications

Martinez R E, Pedersen K, Ferris G F, 2004. Cadmium complexation by bacteriogenic iron oxides from a subterranean environment. J Colloid Interface Sci 275, 82–89.

Documents published 2004

During 2004 the following reports and documents have been published.

Technical reports

SKB, 2004. Äspö Hard Rock Laboratory. Annual Report 2003. SKB TR-04-10, Svensk Kärnbränslehantering AB.

International Progress Reports

Mengel K, Gerdes A, 2001. U/Th Isotopes as Natural Analogues for the Mobility of Antinides in Granitic Rocks. SKB IPR-02-08, Svensk Kärnbränslehantering AB.

Liedtke L, Engelhardt I, Fiene M, Kröhn K-P, Kull H, Jacobs H, Thorenz C, 2001. Two-phase flow in fractured crystalline rock. Investigations in Niche 2175. SKB IPR-02-09, Svensk Kärnbränslehantering AB.

Dershowits W, Klise K, Fox A, Takeuchi S, Uchida M, 2002. TRUE Block Scale project. Channel network and discrete fracture network analysis of hydraulic interference and transport experiments and prediction of Phase C experiments. SKB IPR-02-29, Svensk Kärnbränslehantering AB.

Gómez-Hernández J-J, Hendricks Fransen H-J, Medina Sierra A, Marcuello A, Carrera J, Sendrós D, 2002. TRUE Block Scale project. Stochastic continuum modelling of flow and transport. SKB IPR-02-31, Svensk Kärnbränslehantering AB.

Dershowitz W, Klise K, 2002. TRUE Block Scale project. Evaluation of fracture network transport pathways and processes using the Channel Network approach. SKB IPR-02-34, Svensk Kärnbränslehantering AB.

Sjöberg J, 2002. Äspö Pillar Stability Experinent. 3D overcoring rock stress measurement in borehole KA3376B01 at the Äspö HRL. SKB IPR-03-16, Svensk Kärnbränslehantering AB.

Bono N, Röshoff K, 2003. Prototype Repository. Instrumentation for stress, strain and displacement measurement in rock. SKB IPR-03-19, Svensk Kärnbränslehantering AB.

Darcel C, 2003. True Block Scale continuation project. Assessment of the feasiblity of tracer tests with injection in "background fractures" using a model based on a power law fracture length distribution. SKB IPR-03-41, Svensk Kärnbränslehantering AB.

Poteri A, 2003. TRUE Block Scale continuation project. Retention processes discrimination for various assumptions of fracture heterogeneity. SKB IPR-03-42, Svensk Kärnbränslehantering AB.

Cvetkovic V, 2003. TRUE Block Scale continuation project. Significance of diffusion limitations and rim zone heterogeneity for tracer transport through fractures at the Äspö site. SKB IPR-03-43, Svensk Kärnbränslehantering AB.

Bono N, Röshoff K, 2003. Prototype Repository. Instrumentation of the outer plug to monitor strains and deformations. SKB IPR-03-44, Svensk Kärnbränslehantering AB.

Goudarzi R, Gunnarsson D, Börgesson L, 2003. Backfill and Plug test. Sensors data Report No: 7. SKB IPR-03-45, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, 2003. Prototype Repository. Sensors data report (Period: 010917-030901). Report No:7. SKB IPR-03-46, Svensk Kärnbränslehantering AB.

Rothfuchs T, Hartwig L, Komischke M, Miehe R, Wieczorek K, 2003. Prototype Repository. Deliverable D10. Instrumentation for resistivity measurements in buffer, backfill and rock in Section ll. SKB IPR-03-48, Svensk Kärnbränslehantering AB.

Stigsson M, Hermansson J, Forssberg O, 2003. TRUE-1 Continuation project. Fault rock zones characterisation. Review of existing structural information and construction of local RVS models of four potential experimental sites. SKB IPR-03-49, Svensk Kärnbränslehantering AB.

Winberg A, Hermansson J, Tullborg E-L, Staub I, 2003. 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.

Goudarzi R, Börgesson L, Röshoff K, Bono N, 2003. Canister Retrieval Test. Sensors data report (Period 001026-031101) Report no: 7. SKB IPR-04-01, Svensk Kärnbränslehantering AB.

Goudarzi R, Börgesson L, Sandén T, Barcena I, 2003. Temperature Buffer Test. Sensors data report (Period: 030326-031001) Report No:1. SKB IPR-04-02, Svensk Kärnbränslehantering AB.

Magnor B, 2004. Äspö Pillar Stability Experiment. Geological mapping of tunnel TASQ. SKB IPR-04-03, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, 2003. Prototype Repository. Sensors data report (Period: 010917-031201). Report No:8. SKB IPR-04-04, Svensk Kärnbränslehantering AB.

Ask D, Cornet F H, Stephansson O, 2002. Analysis of overcoring stress data at the Äspö HRL Sweden. Analysis of overcoring rock stress measurements preformed using the Borre Probe. SKB IPR-04-05, Svensk Kärnbränslehantering AB.

Ask D, 2003. Analysis of overcoring stress data at the Äspö HRL, Sweden. Analysis of overcoring rock stress measurements preformed using the CSIRO HI. SKB IPR-04-06, Svensk Kärnbränslehantering AB.

Barton N, 2003 Äspö Pillar Stability Experiment.Q-logging of the APSE tunnel at Äspö. For rock quality assessment and for development of preliminary model parameters. SKB IPR-04-07, Svensk Kärnbränslehantering AB.

Scherneck H-G, 2001. Using borehole tides to determine fracture parameters. 1 − Theory, pre-study, and literature survey. SKB IPR-04-08, Svensk Kärnbränslehantering AB.

Scherneck H-G, 2003. Using borehole tides to determine fracture parameters. 2 − Data analysis. SKB IPR-04-09, Svensk Kärnbränslehantering AB.

Mæresk Hansen L, Staub I, 2004. TRUE-1 Continuation project. Fault rock zones characterisation. Overcoring (300mm) of impregnated fault rock zones at chainages 2/430, 2/545, 2/163 and 1/600m. SKB IPR-04-10, Svensk Kärnbränslehantering AB.

Äspö Hard Rock Laboratory, 2004. Planning Report for 2004. SKB IPR-04-12, Svensk Kärnbränslehantering AB.

Johannesson L-E, Gunnarsson D, Sandén T, Börgesson L, 2004. Prototype Repository. Installation of buffer, canisters, backfill, plug and instruments in Section II. D15 and D17. SKB IPR-04-13, Svensk Kärnbränslehantering AB.

Goudarzi R, Börgesson L, Sandén T, Barcena I, 2004. Temperature Buffer Test. Sensors data report (Period: 030326-040101) Report No:2. SKB IPR-04-14, Svensk Kärnbränslehantering AB.

Forsmark T, Forsman I, Rhén I, 2004. Prototype Repository. Hydraulic tests and deformation measurements during operation phase, test campaign 1, interference test. SKB IPR-04-16, Svensk Kärnbränslehantering AB.

Forsmark T, Rhén I, 2004. Prototype Repository. Hydraulic tests and deformation measurements during operation phase test campaign 1, single hole tests. SKB IPR-04-17, Svensk Kärnbränslehantering AB.

Forsmark T, Rhén I, 2004. Prototype Repository. Hydraulic tests and deformation measurements during operation phase, test campaign 2, single hole tests. SKB IPR-04-18, Svensk Kärnbränslehantering AB.

Forsmark T, Rhén I, 2004. Prototype Repository. Hydraulic tests and deformation measurements during operation phase test campaign 3, single hole tests. SKB IPR-04-19, Svensk Kärnbränslehantering AB.

Äspö Hard Rock Laboratory, 2004. Status Report. October–December 2003. SKB IPR-04-20, Svensk Kärnbränslehantering AB.

Pusch R, Andersson C, 2004. Prototype Repository. Preparation of deposition holes prior to emplacement of buffer and canisters in Section ll D13. SKB IPR-04-21, Svensk Kärnbränslehantering AB.

Rhén I, Forsmark T, 2004. Prototype Repository. Hydro-Mechanical behaviour of fractures due to excavation and thermal load. SKB IPR-04-22, Svensk Kärnbränslehantering AB.

Pusch R, Svemar C, 2004. EBS Task Force. Proceedings from Task Force-related meeting on Buffer and Backfill modelling. SKB IPR-04-23, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, 2004. Prototype Repository. Sensors data report (Period: 010917-040301). Report No:9. SKB IPR-04-24, Svensk Kärnbränslehantering AB.

Pedersen K, Kennedy C, Nederfeldt K-G, Bergelin A, 2004. Prototype Repository. Chemical measurements in buffer and backfill; sampling and analyses of gases. SKB PR-04-26, Svensk Kärnbränslehantering AB.

Goudarzi R, Börgesson L, Röshoff K, Edelman M, 2004. Canister Retrieval Test. Sensors data report (Period 001026-040501) Report No:8. SKB IPR-04-28, Svensk Kärnbränslehantering AB.

Goudarzi R, Börgesson L, Hökmark H, 2004. Temperature Buffer Test. Sensors data report (Period: 030326-040401) Report No:3. SKB IPR-04-29, Svensk Kärnbränslehantering AB.

Cheng H, Cvetkovic V, 2003. Äspö Task Force. Tasks 6A, 6B and 6B2. Modelling of sorbing tracer breakthrough for Tasks 6A, 6B and 6B2. SKB IPR-04-30, Svensk Kärnbränslehantering AB.

Crawford J, Moreno L, 2003. Äspö Task Force. Task 6A and 6B/6B2. Modelling of the STT1b, detailed scale tracer tests at Äspö using the channel network model. SKB IPR-04-31, Svensk Kärnbränslehantering AB.

Dershowitz W, Uchida M, Shuttle D, 2003. Äspö Task Force. Task 6A, 6B and 6B2. GoldSim and FracMan/LTG Modelling. Performance assessment modelling using site characterisation data (PASC). SKB IPR-04-32, Svensk Kärnbränslehantering AB.

Doughty C, Uchida M, 2003. Äspö Task Force. PA calculations for feature A with third-dimension structure based on tracer test calibration. SKB IPR-04-33, Svensk Kärnbränslehantering AB.

Äspö HRL, 2004. Äspö Hard Rock Laboratory. Status Report. January–March 2004. SKB IPR-04-35, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, 2004. Prototype Repository. Sensors data report (Period: 010917-040601). Report No:10. SKB IPR-04-36, Svensk Kärnbränslehantering AB.

Grenier C, 2003. Äspö Task Force. Modeling transfers in a single fracture system: from site characterisation to performance assessment models. Contribution to Task 6A and 6B from the Äspö modeling Task Force exercise. SKB IPR-04-37, Svensk Kärnbränslehantering AB.

Tanaka Y, 2004. Äspö Task Force. Application of FEGM and FERM to Task 6A, 6B and 6B2. Performance assessment modelling using site characterisation data. SKB IPR-04-38, Svensk Kärnbränslehantering AB.

Poteri A, 2002. Äspö Task Force. Modelling of the Tasks 6A, 6B and 6B2 using Posiva streamtube approach. SKB IPR-04-41, Svensk Kärnbränslehantering AB.

Svensson U, Follin S, 2004. Äspö Task Force. Task 6A, 6B and 6B2. Simulation of tracer transport considering both experimental and natural time scales. SKB IPR-04-42, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, Börgesson L, 2004. Backfill and Plug test. Sensors data report (Period 990601-040101) Report No: 8. SKB IPR-04-43, Svensk Kärnbränslehantering AB.

Bäckblom G, La Pointe P, Tullborg E-L, 2004. Preliminary study for developing a practical, stepwise field methodology for determining the acceptable proximity of canisters to fracture zones in consideration of future earthquakes. SKB IPR-04-44, Svensk Kärnbränslehantering AB.

Äspö HRL, 2004. Äspö Hard Rock Laboratory. Status Report. March–June 2004. SKB IPR-04-45, Svensk Kärnbränslehantering AB.

Nyberg G, Jönsson S, Wass E, 2004. Hydro monitoring program. Report for 2003. SKB IPR-04-46, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, Börgesson L, 2004. Backfill and Plug test. Sensors data report (Period 990601-040701) Report No: 9. SKB IPR-04-47, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, 2004. Prototype Repository. Sensors data report (Period: 010917-040901). Report No:11. SKB IPR-04-48, Svensk Kärnbränslehantering AB.

Reichenberger V, Bastian P, Jakobs H, Helmig R, Niessner J, 2003. Complex gas-water processes in discrete fracture-matrix system. Upscaling, mass-conservative discretization and efficient multilevel solution. SKB IPR-04-50, Svensk Kärnbränslehantering AB.

Äspö HRL, 2004. Äspö Hard Rock Laboratory. Status Report. July–September 2004. SKB IPR-04-51, Svensk Kärnbränslehantering AB.

Technical Documents

14 Technical documents were produced during 2004

International Technical Documents

3 Technical documents were produced during 2004

ISSN 1404-0344
CM Digitaltryck AB, Bromma, 2005