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Äspö Hard Rock Laboratory

Annual report 2005

Svensk Kärnbränslehantering AB

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Abstract

The Äspö Hard Rock Laboratory (HRL), in the Simpevarp area in the municipality of Oskarshamn constitutes an important part of SKB's work with the design and construction of a deep geological repository for final disposal of spent nuclear fuel. 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 considerable international interest has been shown in its associated research, as well as in the development and demonstration tasks. The work is managed by the Repository Technology Unit in the Technology Department within SKB. Most of the research is focused on processes of importance for the long-term safety of a final repository for spent nuclear fuel. A summary of work performed at Äspö HRL during 2005 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 experiments focus on different aspects of engineering technology and performance testing.

The *Canister Retrieval Test*, located in the main test area at the –420 m level, aims to demonstrate the readiness for recovering emplaced canisters even after the time when the surrounding bentonite buffer is fully saturated. Bentonite rings, blocks and 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 five years. The bentonite between the rock and the canister is water saturated whereas the bentonite above and below the canister is still unsaturated. At several occasions during the period 2001–2005, heaters have failed due to short circuit to earth and the power has therefore been reduced. The power to the heaters was shut down in October and the mats for artificial wetting were emptied and flushed with air in December as a preparation for the planned termination of the test. As expected the swelling pressure and the temperature decreased after the power was shut off.

The *Prototype Repository* is a demonstration of the integrated function of the repository and provides a full-scale reference for tests of predictive models concerning individual components as well as the complete repository system. It has also been a demonstration of the execution and function of the deposition sequence with state-of-the-art technology in 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. The installation of the inner and outer section took place during 2001 and 2003 respectively and the surface between the outer plug and the rock was grouted in 2004. During 2005 the monitoring of relative humidity, total pressure and temperature in different parts of the test area has continued. The heaters in two of the canisters have malfunctioned during 2005. One canister is now without heating and there is a risk for failures in other canisters as all

heaters are of the same type. A programme for measuring of water pressure close to the tunnel is ongoing. For this purpose a new packer that is not dependent of an external pressure has been developed. In addition, modelling of the thermal evolution in the test area and the thermo-hydraulic evolution in the buffer has been performed.

The *Backfill and Plug Test* is a test of the hydraulic and mechanical function of different backfill materials, emplacement methods and a full-scale plug. The 28 m long test region is located in the Zedex drift at the –420 m level. The inner part of the drift is backfilled with a mixture of bentonite and crushed rock and the outer part is filled with crushed rock. The wetting of the backfill from the rock and filter mats supplying artificial water started at the end of 1999. The wetting continued until autumn 2003 when flow testing in the backfill started. The flow testing between filter mats has been made in both directions and was finalised during 2005. The hydraulic conductivity evaluated from these measurements was a little higher than expected from laboratory results. Measurement of hydraulic conductivity in single points, using pressurising filter equipped tubes, began in late 2005 and so far the results have yielded a hydraulic conductivity that is about a factor 10 lower than the results from the flow tests between the mats. Logging of data from all sensors except relative humidity sensors have continued during 2005.

The *Long Term Test of Buffer Material* aims at validating models and hypotheses concerning physical properties in a bentonite buffer material and of related processes regarding microbiology, radionuclide transport, copper corrosion and gas transport under conditions similar to those in a KBS-3 repository. The testing principle is to emplace "parcels" containing heater, central copper tube, pre-compacted clay buffer, instruments and parameter controlling equipment in vertical boreholes with a diameter of 300 mm and a depth of around four metres. The parcels are extracted and the water distribution in the clay is determined. Subsequent well-defined chemical and mineralogical analyses as well as physical tests are performed. Two pilot tests with the duration of one year are finalised and reported. One of the long-term test parcels, duration more than five years, was extracted in 2004. The remaining four parcels have been functioning well and only minor service was needed during 2005. The power to one of the four parcels was shut down in December and the preparatory work for the uptake in January 2006 was initiated.

In the project *Cleaning and Sealing of Investigation Boreholes* the best available techniques are to be identified and demonstrated. In order to obtain data on the properties of the rock, investigation boreholes are drilled during site investigations and detailed characterisations are performed. These boreholes must be cleaned and sealed, no later than at the closure of the deep repository. The first phase of the project was a state-of-the-art review summarising the development of techniques during the last 10–15 years. A final report from the second phase, focusing on the development of a complete basic concept, has been prepared. The suggested concept for sealing longer holes than about 100 m implies the use of perforated copper tubes with tightly fitting cylindrical blocks of highly compacted smectite-rich clay. A third phase of the project with the aim to perform large-scale testing in boreholes was initiated in 2005. Most of the performed work concerns the preparations for and the plugging of a borehole at Olkiluoto in Finland. The installation was made at a depth of 520 m and comprised of two 5 m long quartz-cement plugs, one below and one above, a 10 m long bentonite plug. In addition, simpler sealing techniques than for the very long boreholes are foreseen to be applicable in shorter boreholes, especially holes drilled from repository rooms. The techniques will be tested in eight 5 m boreholes in Äspö HRL. So far structural modelling of the drilled holes has been made and the hydraulic characterisation of the holes has started. Preparations are also ongoing in Äspö HRL for testing of alternative techniques for plugging the upper wider parts of investigation boreholes.

SKB and Posiva in co-operation are carrying through a programme for the *KBS-3 Method with Horizontal Emplacement* (KBS-3H). The outcome of the feasibility study was that the KBS-3H method is worth further development work. The Basic design study, including the development of technology for excavation of horizontal deposition holes and emplacement of Supercontainers, was finalised and reported in 2004. Preparations for the full scale demonstration at Äspö HRL are in progress. The demonstration comprises two deposition holes: (1) one short hole (15 m) which will be used for construction and testing of a low-pH shotcrete plug and (2) one long hole (95 m) which will primarily be used for demonstration of the deposition equipment and for evaluation of the chosen excavation method. The excavation of the short hole was completed in 2004 and preparation for the installation of the low-pH plug started in 2005. The long hole was excavated and mapped during 2005 and installations for the deposition equipment were performed. The copper canisters have been delivered and the assembly of the two Supercontainers was successfully performed during the year. The next step is to test the deposition equipment.

The aim of the *Large Scale Gas Injection Test* is to perform gas injection tests in a full-scale KBS-3 deposition hole. Our 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 which have to be verified in large-scale experiments. The experiment is performed in a bored full-size deposition hole with a full-scale canister without heaters and a surrounding bentonite buffer. The installation phase, including the deposition of canister and buffer, was finalised in 2005. Water is artificially supplied and the evolution of the saturation of the buffer is continuously monitored. During 2005 the saturation phase of the experiment was examined using numerical models. The results from the model runs show that the impact of a single-flow fracture on the overall saturation process was likely to be limited. In contrast, flow through the general rock mass and associated minor fractures could have a significant effect on the saturation process. The sealing of the gap between canister and bentonite appears to be a critical parameter in determining the overall time to saturate the bentonite. The gas injection tests will start when the bentonite buffer is fully saturated, which is expected to take about 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. This knowledge is needed in order to model the behaviour of the buffer. The French organisation Andra is running this test in co-operation with SKB. Two heater probes are installed in one full size deposition hole. One of the probes is surrounded by an ordinary bentonite buffer and the other is surrounded by a sand buffer closest to the probe and bentonite outside the sand. The sand is intended to serve as a thermal protection between the probe 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 being carried out continuously and the information is transferred via a data link to Andra's head office in France. The initial thermal shock caused local desaturation of the bentonite where the temperature exceeded 100°C. The buffer around the upper probe was close to water saturation already in the end of 2004 whereas the buffer around the lower heater still appears to be desaturated. However, after the plugging of the tubing of a leaking sensor the saturation degree has increased significantly. A mock-up test, which was designed to mimic the conditions at the interior of the buffer around the lower heater, has been modelled during 2005. Both the predictive modelling and the mock-up test showed that moisture redistribution in the buffer takes place as soon as there are thermal gradients.

The aim of the *Rock Shear Experiment* is to observe the forces that would act on a KBS-3 canister if a displacement of 100 mm were to take place in a horizontal fracture that crosses a deposition hole. Such a displacement could be caused by an earthquake. A test set-up is required to provide a shearing motion along the fracture that is equal to the expected shearing motion expected in reality. A feasibility study has been performed and reported. Scoping calculations indicating the forces and shearing speed needed have provided the basis for the design of the test set-up. The test set-up is planned to be installed at the Äspö Pillar Stability Experiment site when the rock mechanic tests have been completed.

Several large-scale experiments have been installed in Äspö HRL during the years and the methods and machines used have provided experiences for refinement and evaluation of the limitations of the methods applied. The aim of the project *Learning from Experiences* is to compile results from performed engineering experiments in Äspö HRL and to evaluate the experiences from methods for emplacement of buffer and canisters, backfilling of tunnels and also to estimate acceptable water inflow for the applied methods. A number of practical issues have been investigated and the experiences have been documented.

The objective of the project *In Situ Corrosion Testing of Miniature Canisters* is to obtain a better understanding of the corrosion processes inside a failed canister. This information will form the basis for identification of the possible scenarios for radionuclide release from the canister. The processes have been studied in the laboratory and with models. In Äspö HRL in situ experiments with miniature copper canisters with cast iron inserts will be performed where the copper canisters will be exposed to both natural reducing groundwater and groundwater which has been conditioned by bentonite for several years. The design of the miniature canisters has been completed, the components of five canisters have been manufactured and five horizontal deposition boreholes have been drilled during 2005.

The *Task Force on Engineered Barrier Systems* was activated in 2004. The task force starts with a first phase that comprises four years. This phase addresses two tasks: (1) THM processes and (2) gas migration in buffer material. The aim is to produce a state-of-the-art report. The focus is on the use of codes for predictions of the conditions in the buffer during specified milestones in the repository evolution. During 2005 benchmark calculations for THM-processes and gas migration have been performed. A suggested EC project named Theresa, which consists of six work packages, has also been presented.

Geoscience

Geoscientific research is a basic activity at Äspö HRL. The main aim of the current studies is to develop geoscientific models and increase the understanding of the rock mass properties as well as the knowledge of applicable methods of measurement.

Geological Mapping and Modelling are performed in order to increase the understanding of the geometries and properties of rocks and rock structures. All the rock surfaces and drill cores at Äspö have been mapped and the resulting information is subsequently used as input in the 3D modelling. During 2005 mapping of the following locations were performed; two horizontal deposition holes of the KBS-3H project on the –220 m level, the slot walls and blocks from the Äspö Pillar Stability Experiment site, the vertical outermost deposition hole in the Q-tunnel and the niche on the –450 m level. The geological 3D model was updated particularly in the areas around the –220 m and –450 m levels during 2005. In the ongoing RoCS-project (Rock Characterisation System) a feasibility study concerning geological mapping techniques is performed in addition to the regular mapping. The aim is to investigate the possible need for a new more automatic method for underground geological mapping in a future repository. Various methods to create 3D-pictures of the tunnel layout have also been tested.

The project on *Heat Transport* aims at decreasing the uncertainties in the estimates of the temperature field in and around 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. Laboratory measurements of the thermal conductivity with different sensor sizes have been made. The investigation shows insignificant scale dependency and was reported during 2005. A prognosis model of the rock thermal properties has also been established. There is a good agreement between prognosis of thermal conductivity in the Prototype Repository and the result from inverse modelling based on the temperature sensors. A methodology for up-scaling of thermal conductivity from measurement scale to a significant scale for the canister has been developed.

The main objective of the project *Inflow Predictions* is to make better predictions of the water inflow into deposition holes and tunnels. The results from a number of large field tests show that the inflow into a large diameter hole is often less than predicted from observations in a borehole. During 2005 extensive numerical analyses was conducted in order to investigate the influence of the effective stress redistribution, caused by excavation, on water inflow. The modelling results show that the hydro-mechanical coupling is of critical importance for estimates of the total inflow. Stress-permeability coupling can be considered as one of the causes for the less than expected inflow into large diameter holes.

Seismic Influence on the Groundwater System will be studied by analysing data on changes in the piezometric head registered by the Hydro Monitoring System (HMS). During 2005, the HMS has registered the absolute pressure of the groundwater in about 280 positions underground in the Äspö HRL. A computer code has been developed with the purpose of finding rapid pressure changes in the HMS data.

Rock Mechanic studies are performed in order to increase the understanding of the mechanical properties of the rock. The studies include laboratory experiments and modelling at different scales. Another objective is to recommend methods for the measurement and analysis of mechanical properties. During 2005, the possibility to link the in situ stress field to hydraulic conductivity data, measured at the Äspö HRL, has been examined. For the data studied, results support a potential link between fracture-plane hydraulic variability and the stress-field. The participation in the Decovalex project aims at improving the understanding of the excavation disturbed zone. Within the Decovalex project laboratory tests have been conducted. The aim was to investigate the effect of waters with different salinities on the uniaxial compressive strength of intact rock samples of the Äspö diorite. A 3D model of the tunnel at the Äspö Pillar Stability Experiment is being produced using laser scanning of the tunnel walls in different scales. The collection of data from the tunnel has been concluded and the data analysis phase has started.

The Äspö Pillar Stability Experiment was initiated to demonstrate the capability for prediction of spalling in deposition holes in a fractured rock mass. 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 were drilled at a distance of one metre in the floor of the tunnel. To simulate the confining pressure in the bentonite buffer, one of the holes was subjected to an internal water pressure via a liner. Reporting and analyses have been the main part of the work in the project during 2005 as all field work were in practice finished during 2004. The temperature in the experiment volume has been back calculated and the thermal induced stresses have been used to determine the spalling strength of the rock. Detailed geological mapping and photographing of the five blocks sawn from the pillar have been performed.

Natural barriers

At Äspö HRL, experiments are performed under the conditions that are expected to prevail at repository depth. The aim is to provide information about the long-term function of repository barriers. The natural barriers are the bedrock with its available fractures and fracture zones, its properties and the physical and chemical processes that occur in the rock and that affect the integrity of the engineered barriers and the transport of radionuclides. The experiments are related to the rock, its properties, and in situ environmental conditions. The strategy for the current experiments is to focus on those of most 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 which aim to evaluate the usefulness and reliability of different models and to develop and test methods to determine parameter values that are required as input to the conceptual and numerical models.

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

The objective of the *True Block Scale Continuation project* is to improve the understanding of transport pathways at the block scale (100 m), including assessment of the effects of geometry, macro-structure and micro-structure. The in situ experiments with sorbing tracers were paralleled during 2005 by model predictions made with four different modelling approaches. Draft evaluation reports were produced by each modelling group and a review seminar was held in mid September.

One of the principal objectives of the *True-1 Continuation project* is to map the porosity which provided the observed retention in the previously investigated Feature A at the True-1 site. The reporting of the Fault Rock Zones Characterisation project and the sorption characteristics of fault gouge material is ongoing and will be completed during 2006. In addition, work has been done to prepare scientific papers for publication on the True team analysis of the True-1 experiments. The planned injection of epoxy resin will be preceded by complementary cross-hole hydraulic interference tests combined with tracer dilution tests. These tests, *True-1 Completion*, are intended to shed light on the possible 3D aspects of transport at the site. As a preparation for the tests the boreholes have been re-instrumented and complementary tests with non-radioactive tracers were performed late 2005.

The *Long Term Diffusion Experiment* complements the diffusion and sorption experiments performed in the laboratory, and is a natural extension of the True-experiments. The difference is that the longer duration of the experiment is expected to give 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 at the bottom of a large diameter telescoped borehole. A functionality test with short lived radionuclides was performed during 2005, and overall, the system was found to work as expected. The functionality test was followed by a decision to adjust and modify the test equipment and to slightly update the project plan. The new plan emphasizes in situ sorption measurements with shorter experimental time frames than the original plan which had more focus on obtaining diffusion data. Laboratory experiments performed at AECL in Canada on core samples from the borehole were completed in 2005 and a draft version of the final report was compiled.

Radionuclide Retention Experiments are carried out to confirm the results of laboratory experiments in situ, where the conditions with respect to groundwater properties are representative of those at repository depth. 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 is in print. Migration of actinides in a natural rock fracture in a drill core has been studied with the Chemlab 2 probe. No breakthrough of Pu or Am has been detected during the laboratory and field experiments. Up to 40% recovery of Np(V) has been observed, while no Np(IV) has been detected in the samples.

The *Colloid Project* comprises studies of the stability and mobility of colloids, bentonite clay as a source for colloid generation, the potential of colloids to enhance radionuclide transport and the measurements of the colloid concentration in the groundwater at Äspö. The laboratory experiments, background measurements and borehole specific measurements are compiled in a final report that was sent for print in December 2005. During 2005, the main part of the work has been to collect data and prepare for the in situ experiments that will be performed in 2006. Stability experiments with bentonite colloids have shown that these colloids are not at all stable in the saline waters at Äspö and the in situ experiments must therefore be performed with another colloid. Results from stability experiments with latex colloids show that they can be used.

Microorganisms interact with their surroundings and in some cases they greatly modify the characteristics of their environment. Several such interactions may have a significant influence on the function of a future repository for spent fuel. These interactions are studied in the *Microbe Project*. The Microbe laboratory has been working well with respect to installed equipment. However, the former stable groundwater conditions in the Microbe laboratory were dramatically changed in January 2005 as a result of the drilling of boreholes for the In Situ Corrosion Testing of Miniature Canisters. Significant drainage has led to a completely new mixing situation with for example an increase in chloride concentration in the Microbe formation. The drainage was blocked in the beginning of December. New analyses of microbes must be performed once the conditions have returned to those prevailing before the drainage. A study performed in the Microbe laboratory indicates that subsurface fracture biofilms reduce the effectiveness of granitic rock to adsorb radionuclides except for trivalent species. The microbial effects on the chemical stability of deep groundwater have been studied in the microbe laboratory and these experiments provide the foundation for the design of future in situ experiments.

The first phase of the *Matrix Fluid Chemistry* experiment gave information about matrix pore space fluids/groundwaters from crystalline rocks of low hydraulic conductivity, and 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. Understanding of the migration of groundwater, and its changing chemistry, is important for repository performance. A feasibility study, carried out during 2005, investigated the impact on hydrogeology and hydrochemistry of the tunnel construction at the Äspö Pillar Stability Experiment, in vicinity of the Matrix Fluid Experiment borehole. The impact of the excavation was found to be limited. Therefore initial hydrochemical and hydraulic characterisation of the presently isolated borehole sections containing micro fractures was judged to be worthwhile. The hydraulic characterisation started during 2005 and is expected to continue to the spring 2006. Porosity measurements on drillcore material have been carried out during 2005 and the results indicate that porosities calculated from laboratory measurements are higher than those evaluated from in situ measurements. This is due to secondary effects such as physical disturbance of laboratory samples including e.g. stress release.

Padamot (Palaeohydrogeological Data Analysis and Model Testing) is an EC-project that is investigating specific processes that might link climate and groundwater in low permeability rocks and includes the development of analytical techniques and modelling tools to interpret data. 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 part of the project has been completed and reported in EC series of reports during 2005. In the resulting conceptual model for Äspö/Laxemar/Simpevarp at least three zones of calcite mineralisation are distinguished: (a) the upper 50–100 m is characterised by dissolution and precipitation of new calcite, (b) from 100 m down to between 500–600 m mainly precipitation of calcite is observed and (c) between 600 and 1,000 m calcite mineralisation consistent with low temperature precipitation from fresh groundwater of meteoric origin can be traced in major zones of steep fractures.

The basic idea behind the project *Fe-oxides in Fractures* is to examine Fe-oxide fracture linings, in order to explore suitable palaeo-indicators and their formation conditions. At the same time, information about the behaviour of trace component uptake can be obtained from natural material as well as from studies in the laboratory under controlled conditions. A fast and precise procedure has been developed to differentiate between several types of Fe-oxides found as fracture fillings in granite. Investigations of green rust have shown that existing literature data for structure and composition are incorrect and revised data have been produced. Methods for investigating green rust reactivity have been developed by using Cr(VI) reduction to Cr(III) as a model redox active compound. Reactive transport modelling involving Fe(II)/Fe(III) species has commenced.

Important goals of the activities at Äspö HRL are the evaluation of the usefulness and reliability of different models and the development and testing of methods to determine parameter values required as input to the models. An important part of this work is performed in the *Task Force on Modelling of Groundwater Flow and Transport of Solutes*. The work in the task force is closely tied to ongoing and planned experiments at the Äspö HRL. Specified tasks are defined in which 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. During 2005, the work has been in progress mainly in Task 6 and Task 7. Task 6 – Performance assessment modelling using site characterisation data – was initiated in 2001 and is planned to be completed during 2006. A large part of the modelling work in Task 6 has been performed and some sub-tasks have been reported. Task 7 addresses the modelling of a pumping test in Olkiluoto, Finland, and will focus on methods to quantify uncertainties in performance assessments based on site characterisation information.

Äspö facility

An important part of the activities at the Äspö facility is the administration, operation, and maintenance of instruments as well as the development of investigation methods. The main goal of the operation is to provide a safe and environmentally sound facility for everybody working or visiting the Äspö HRL. This includes preventative and remedial maintenance in order to maintain high availability in all the systems in the underground laboratory, such as drainage, electrical power, ventilation, fire and evacuation alarms, and communications. The availability (operational time) during 2005 was 99%. Other issues are to keep the stationary Hydro Monitoring System (HMS) continuously available and to carry out the Programme for Monitoring of Groundwater Head and Flow and the Programme for Monitoring of Groundwater Chemistry. The Public Relations and Visitor Services group at Äspö HRL is responsible for presenting information about SKB and its facilities. They arrange visits to the facilities all year around as well as special events. During the year 2005, the Äspö HRL and the site investigation activities were visited by about 11,500 visitors.

International co-operation

In addition to SKB, nine organisations from eight countries participated in the co-operation at Äspö HRL during 2005. Six of them; Andra, BMWi, CRIEPI, JAEA, OPG and Posiva together with SKB form the Äspö International Joint Committee which is responsible for the co-ordination of the experimental work arising from the international participation. Most of the organisations participating in the Äspö HRL co-operation are interested in groundwater flow, radionuclide transport and rock characterisation. Several of the organisations are participating in the experimental work at Äspö HRL as well as in the two Äspö task forces: (1) Task Force on Modelling of Groundwater Flow and Transport of Solutes and (2) Task Force on Engineered Barrier Systems.

Environmental research

Äspö Environmental Research Foundation was founded 1996 on the initiative of local and regional interested parties. The aim was to make the underground laboratory at Äspö and its resources available for national and international environmental research. SKB's economic engagement in the foundation was concluded in 2003 and the activities are now concentrated on the Äspö Research School. The research activities focuses on biogeochemical systems in particular and there are currently a variety of research activities at sites outside Äspö HRL. These activities have during 2005 resulted in several scientific publications. The first Ph.D. dissertation took place in January 2005 and by the end of the year the scientific team consisted of a professor of Environmental geology, a research assistant, four assistant supervisors and five Ph.D. students.

Sammanfattning

Äspölaboratoriet i Simpevarp i Oskarshamns kommun är en viktig del i SKB:s arbete med utformning, byggande och drift av ett slutförvar för använt kärnbränsle samt för utveckling och testning av metoder för karakterisering av en lämplig plats för ett slutförvar. 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 har väckt stort internationellt intresse. Arbetet leds av enheten för djupförvarsteknik inom avdelningen för teknik på SKB. Forskningen är till stor del fokuserad på de processer som har betydelse för den långsiktiga säkerheten hos ett slutförvar. Här följer en sammanfattning av det arbete som bedrivits vid Äspölaboratoriet under 2005.

Förvarsteknik

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

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 drygt fem år. Sensorer som mäter fukthalten indikerar att bentonitblocken som omger själva kapselröret är vattenmättade, men inte bentonitblocken över och under kapseln. Vid flera tillfällen under 2001–2005 har elektriska värmare slutat fungera på grund av kortslutning till jord och värmeeffekten har därför successivt reducerats. Strömförsörjningen till värmarna bröts i oktober och filtermattorna tömdes och genomblåstes med luft i december som en förberedelse inför det planerade återtaget. När strömförsörjningen bröts minskade som väntat svälltrycket och temperaturen i bufferten.

I *Prototypförvaret* pågår en demonstration av den integrerade funktionen hos förvarets barriärer. Prototypförvaret utgör dessutom en fullskalig referens för prediktiv modellering av slutförvaret och barriärernas utveckling. En demonstration av tillgänglig teknik i full skala har genomförts i samband med själva inplaceringen av buffert, kapsel och återfyllnad samt vid förslutningen av deponeringstunneln. 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 installerades under 2001, de två kapslarna i den yttre sektionen deponerades under 2003 och den slutliga injekteringen av den yttre pluggen i tunnelmynningen genomfördes under 2004. Under 2005 har fortsatta mätningar av relativ fuktighet, totalt tryck och temperatur i olika delar av testområdet genomförts. Värmarna i två av kapslarna har fungerat dåligt under 2005. En kapsel är nu utan värmare och det finns en risk att fler värmare kan sluta att fungera eftersom de är av samma sort. Ett program för mätning av vattentrycket nära tunneln har startat och för detta har en ny borrhålsmanschett utvecklats som inte är beroende av det externa trycket. Dessutom har det termiska förloppet i testområdet och den termo-hydrauliska utvecklingen i bufferten modellerats.

I *Återfyllningsförsöket* undersöker man den hydrauliska och mekaniska funktionen 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 på 420 m djup. 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. I slutet av 1999 påbörjades bevätningen och den pågick fram till och med hösten 2003 då flödestester startades. Flödestester har genomförts mellan filtermattor i två riktningar och dessa avslutades under 2005. Utvärderingen av den hydrauliska konduktiviteten från dessa mätningar gav något högre värden än de som utvärderats från laboratorieförsök. Mätningar av den hydrauliska konduktiviteten i enskilda punkter med trycksatta filterrör påbörjades under 2005 och hittills pekar resultaten på en hydraulisk konduktivitet som är ungefär 10 gånger lägre än den som uppmättes i flödestesterna. Under 2005 har insamling av data från alla sensorer med undantag för sensorerna för relativ fuktighet fortsatt.

I *Lotförsöket* genomförs långtidsförsök på buffertmaterial som syftar till att validera modeller och hypoteser som beskriver buffertens fysikaliska egenskaper och processer relaterade till mikrobiologi, radionuklidtransport, kopparkorrosion och gastransport i ett slutförvar. Lotförsöket innebär att ”paket” som innehåller ett kopparrör med elektrisk värmare, kompakterad bentonit, instrumentering och kontrollutrustning placeras i 4 m djupa borrhål med en diameter på 300 mm. När paketen tas upp bestäms vattenmättnaden i bentoniten. Därefter genomförs väldefinierade kemiska och mineralogiska analyser samt fysikaliska tester. Två pilotförsök, som pågick under ett år, har avslutats och rapporterats. Ett av testpaketen i långtidsförsöket, som pågått under mer än fem år, togs upp under 2004. De återstående fyra paketen har fungerat bra och endast mindre service har behövts under 2005. Strömförsörjningen till ett av de fyra paketen bröts i december och förberedelsearbete inför upptaget i januari 2006 initierades.

Ett projekt för att identifiera och demonstrera bästa möjliga tillgängliga teknik för *Rensning och förslutning av undersökningsborrhål* genomförs vid Äspölaboratoriet. I samband med platsundersökningarna borras undersökningsborrhål och en noggrann karakterisering genomförs för att erhålla data på bergets egenskaper. Dessa borrhål måste rensas och pluggas senast när driften av slutförvaret avslutats. Den första fasen av projektet omfattade en inventering av teknikutvecklingen inom området 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 har slutrapporterats. Det föreslagna konceptet för förslutning av hål längre än 100 m innebär att borrhålen försluts med perforerade kopparrör fyllda med kompakterade bentonitblock. En tredje fas av projektet, där målet är att genomföra storskaliga tester i borrhål, initierades under 2005. Det mesta av arbetet har rört förberedelser inför och pluggningen av ett borrhål i Olkiluoto i Finland. Två 5 m långa kvartscement pluggar, en över och en under en 10 m lång bentonitplugg, har installerats på 520 m djup. Enklare förslutningstekniker än för mycket långa borrhål förutses kunna användas för kortare borrhål, speciellt för de hål som borrats från förvarsutrymmena. I åtta 5 m borrhål i Äspölaboratoriet kommer olika tekniker att testas. Hittills har en strukturmodellering av berget kring de borrade hålen genomförts och hydraulisk karakterisering av hålen har inletts. Förberedelser pågår även i Äspölaboratoriet för provning av olika tekniker för pluggning av de övre vidare delarna av undersökningsborrhål.

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 har genomförts 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. Det korta hålet färdigställdes under 2004 och förberedelser inför installationen av en lågalkalisk plugg påbörjades under 2005. Det långa hålet färdigställdes och karterades under 2005 och installationer för deponeringsutrustningen gjordes. Under året har kopparkapslarna levererats och även de två kapselpaketen monterats. Nästa steg är att testa deponeringsutrustningen.

Syftet med ett *Gasinjekteringsförsök 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 full skala. Experiment genomförs i Äspölaboratoriet i ett deponeringshål med en kapsel utan värmare och en omgivande bentonitbuffert. Installationsfasen med deponering av kapsel och buffert avslutades under 2005. Bufferten beväts på konstgjord väg och utvecklingen av vattenmättnadsgraden i bufferten mäts kontinuerligt. Under 2005 har experimentets mättnadsfas modellerats numeriskt. Resultaten från modelleringen indikerar att effekten av en enskild spricka på den övergripande mättnadsprocessen är begränsad. Vattenflödet genom hela bergmassan med tillhörande mindre sprickor kan dock ha en signifikant påverkan på mättnadsprocessen. Förslutningen av spalten mellan kapseln och bentoniten förefaller vara en kritisk parameter för bestämningen av tiden tills bentoniten är vattenmättad. Gasinjekteringsförsöken kommer att starta när bentonitbufferten är helt mättad, 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, vilket behövs för att kunna modellera beteendet hos bufferten. Den franska organisationen Andra ansvarar för experimentet vid Äspölaboratoriet vilket genomförs i samarbete med SKB. Två kapslar med värmare har installerats ovanpå varandra i ett deponeringshål. En av kapslarna är omgiven av en bentonitbuffert medan den andra är omgiven av en buffert bestående av sand närmast kapseln och bentonit utanför sanden. Sanden är tänkt att fungera som ett termiskt skydd 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. Den initiala temperaturhöjningen orsakade en lokal sänkning av vattenmättnadsgraden i bentoniten när temperaturen steg över 100°C. Bufferten runt den övre kapseln var nära vattenmättad redan i slutet av 2004 medan bufferten runt den undre kapseln fortfarande verkar omättad. Efter en pluggning av slangen till en läckande sensor har dock mättnadsgraden ökat signifikant. Ett pilotförsök, som utformades för att efterlikna förhållandena inne i bufferten runt den lägre värmaren, har modellerats under 2005. Både den prediktiva modellering och det genomförda pilotförsöket visar att det sker en omfördelning av vattenmättnadsgraden i bufferten så fort det finns termiska gradienter.

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. Försöksuppställningen måste utformas så att en skjuvrörelse motsvarande den som kan uppkomma i en verklig spricka kan simuleras. En förstudie har genomförts och rapporterats. Genomförda överslagsberäkningar av de krafter och skjuvhastigheter som krävs ligger till grund för utformningen av försöksuppställningen. Denna planeras att installeras vid platsen för Pelarförsöket när de bergmekaniska testerna där har avslutats.

Flera storskaliga experiment har installerats i Äspölaboratoriet under åren. Erfarenheter från använda metoder och maskiner har möjliggjort förfiningar och en utvärdering av begränsningar hos de använda metoderna. Målet med projektet *Kunskapsåterföring* är att sammanställa resultaten från genomförda experiment vid Äspölaboratoriet och utvärdera erfarenheterna från metoder för inplacering av buffert och kapslar samt återfyllnad av tunnlar. En uppskattning av acceptabla inflöden av vatten för de tillämpade metoderna skall också göras. En rad praktiska aspekter har undersökts och erfarenheterna har dokumenterats.

Målet med projektet *In situ testning av korrosion av miniatyrkapslar* är att få en bättre förståelse av korrosionsprocesserna inuti en trasig kapsel. Denna information kommer att utgöra grunden för identifiering av möjliga scenarion för frigörelse av radionuklider från kapseln. Processerna har studerats såväl i laboratorium som genom modellering. Vid Äspölaboratoriet kommer in situ experiment med miniatyrkopparkapslar med gjutjärnsinsats att genomföras. Kopparkapslarna kommer att utsättas för både naturligt reducerat grundvatten och grundvatten som har jämviktats med bentonit under flera år. Miniatyrkapselns design är slutförd, komponenterna till fem kapslar har tillverkats och fem horisontella deponeringshål har borrats under 2005.

Ett internationellt samarbetsprojekt ”*Task Force on Engineered Barrier Systems*” återupptogs under 2004. Den första fasen av projektet, som beräknas pågå i fyra år, omfattar huvudsakligen två områden: (1) THM-processer och (2) gasmigration i buffertmaterial. Målet är att framställa en ”state-of-the-art” rapport. Projektet fokuserar på användandet av numeriska koder för att förutsäga förhållandena i bufferten under betydelsefulla skeden i förvarets utveckling. Under 2005 har riktlinjeberäkningar för THM-processer och gasmigration genomförts. Ett förslag till ett EU-projekt, Theresa, som består av sex arbetspaket har också presenterats.

Geovetenskap

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

Geologisk kartläggning och modellering genomförs i syfte att öka förståelsen för geometrier och egenskaper hos berg och bergstrukturer. Alla bergytor och borrhål i Äspö har kartlagts och den erhållna informationen används i den därpå följande 3D-modelleringen. Under 2005 genomfördes kartering av: två horisontella deponeringshål i KBS-3H projektet på nivån –220 m, bergväggar och block från pelaren i Pelarförsöket, det vertikala yttersta deponeringshålet i Q-tunneln och nischen på –450 m nivån. Den geologiska 3D-modellen har uppdaterats under 2005, framförallt runt nivåerna –220 m och –450 m. I det pågående projektet RoCS (Rock Characterisation System) genomförs en förstudie av metoder för geologiska karläggning utöver den ordinarie kartläggningen. Målet är att undersöka det eventuella behovet av en ny mer automatiserad metod för underjordisk geologisk kartering i ett framtida slutförvar. Olika metoder för att skapa 3D-bilder av tunnellayouten har också testats.

Ett projekt som syftar till att minska osäkerheterna i uppskattningar av *värmetransport* i berg och temperaturfältet runt och i ett förvar pågår. Om osäkerheterna kan reduceras innebär det att avstånden mellan kapselpositioner kan optimeras. Mätningar av den termiska konduktiviteten med olika sensorstorlekar har genomförts i laboratorium. Resultaten visar på obetydligt skalberoende och rapporterades under 2005. En prognosmodell för bergtermiska egenskaper har också upprättats. Prognosen av den termiska konduktiviteten i Prototypförvaret stämmer väl överens med resultaten från inversmodelleringen baserat på temperatursensorerna. En metodik för uppskalning av den termiska konduktiviteten från mätningarna till en för kapseln relevant skala har utvecklats.

Målet med projektet *Prediktion av inflöden* är att göra bättre förutsägelser av vatteninflödet i deponeringshål och tunnlar. Resultaten från ett antal stora fälttest visar att inflödet till ett borrhål med större diameter oftast är mindre än det som predikterats utgående från observationer i borrhål. Under 2005 har omfattande numeriska analyser genomförts för att undersöka hur vatteninflödet påverkas av omfördelning av den effektiva spänningen som uppstår på grund av berguttag. Modelleringsresultaten visar att den hydromekaniska kopplingen är kritisk för uppskattningen av det totala inflödet. Sambandet mellan spänning och permeabilitet kan anses vara en av orsakerna till att flödet till borrhål med större diametrar är lägre än väntat.

Seismisk påverkan på grundvattensystem kan studeras genom att analysera förändringar i data insamlade i hydromoniteringssystemet (HMS). Det absoluta grundvattentrycket har under 2005 registrerats på ungefär 280 platser under jord i Äspölaboratoriet. En programkod har utvecklats för att identifiera snabba tryckförändringar i uppmätta data registrerade i HMS.

Bergmekaniska studier genomförs för att öka förståelsen för bergets mekaniska egenskaper. Studierna omfattar laboratorieexperiment och modellering i olika skalor. Ett ytterligare syfte är att rekommendera metoder för mätning och analys av mekaniska egenskaper. Under 2005 har möjligheten att koppla spänningsfältet in situ till den hydrauliska konduktiviteten som mätts upp i Äspölaboratoriet undersökts. Det studerade datamaterialet stödjer en möjlig koppling mellan sprickplansvariabilitet och spänningsfält. Deltagandet i Decovalex-projektet syftar till att öka kunskapen om bildade störda zoner vid berguttag. Laboratorieförsök har utförts inom projektet. Målet var att undersöka effekten av olika salthalter i vatten på den enaxiala kompressionshållfastheten hos intakta bergprover av bergarten Äspödiorit. Insamlingen av data från tunneln vid Pelarförsöket har slutförts och dataanalysen har startat. En 3D-modell av tunneln har börjat sättas upp med hjälp av laserscanning av tunnelväggarna i olika skalor.

Syftet med *Pelarförsöket* är att undersöka möjligheterna att förutsäga spänningsinducerade bergbrott i deponeringshål i sprickigt berg. Under 2003 drevs en ny tunnel för att säkerställa att experimentet genomförs i berg med jungfruliga spänningsfält. I golvet på tunneln borrades två deponeringshål, i full skala, med ett avstånd på 1 m så att en pelare bildas mellan dem. För att simulera mottrycket i bentonitbufferten sattes ett av hålen under internt vattentryck via en liner. Under 2005 har arbetet i huvudsak inriktat sig på rapportering och analys då praktiskt taget allt fältarbete blev klart under 2004. Temperaturen i experimentvolymen har beräknats och den termiskt inducerade spänningen har använts för att bestämma bergets spjälkhållfasthet. De fem utsågade blocken från pelaren har noggrant karterats och fotograferats.

Naturliga barriärer

I Äspölaboratoriet genomförs experimenten vid förhållanden som liknar de som förväntas på förvarsdjup. Experimenten kopplar till berget, dess egenskaper och in situ förhållanden. Målen med de pågående experimenten är att ge information om säkerhetsmarginalerna i slutförvaret och 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. För tillfället bedrivs arbete inom delprojekten: ”*True Block Scale Continuation*”, ”*True-1 Continuation*” och ”*True-1 Completion*”.

Målet med ”*True Block Scale Continuation*” är att öka kunskapen om transportvägar i berget i blockskala (100 m) med avseende på bland annat betydelsen av geometri, makrostrukturer och mikrostrukturer. Under 2005 genomfördes parallellt in situ experiment med sorberande spårämnen och modellprediktioner med fyra olika modelleringsansatser. Preliminära utvärderingsrapporter producerades av varje modelleringsgrupp och ett utvärderingsseminarium hölls i mitten av september.

Ett av målen med projektet ”*True-1 Continuation*” är att kartlägga porositeten vilken resulterade i den observerade retentionen i en tidigare undersökt sprickzon, ”Feature A”. Rapporteringen av delprojektet ”Fault rock zone characterisation” och sorptionsegenskaperna hos sprickfyllnadsmaterial pågår och kommer att avslutas under 2006. Dessutom har arbetet inriktats på att publicera vetenskapliga artiklar rörande True-programmets analyser av ”True-1” experimenten. Den planerade injekteringen av epoxyharts kommer att föregås av hydrauliska interferenstester mellan två borrhål vilka kombineras med spårämnesförsök. Syftet med dessa tester, ”*True-1 Completion*”, är att belysa betydelsen av platsens tredimensionellitet för spårämnestransporten. Borrhålen har ominstrumenterats och kompletterande tester med icke-radioaktiva spårämnen utfördes under slutet av 2005 som en förberedelse inför testerna.

LTDE-försöket är ett komplement till de sorptions- och spårämnesförsök som genomförts i laboratorium och är också en utvidgning av de experiment som genomförts inom True-programmet. Skillnaden från tidigare försök är att experimentet planeras pågå en längre tid vilket förväntas 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. Ett funktionstest med kortlivade radionuklider under 2005 visade att systemet i stort sett fungerade bra. Funktionstestet efterföljdes av ett beslut att justera och modifiera testutrustningen samt att uppdatera projektplanen något. I den nya planen läggs tonvikten på in situ mätningar av sorption med en kortare experimentell tidsram än i den ursprungliga projektplanen som fokuserade mer på att erhålla diffusionsdata. Under 2005 avslutades laboratorieexperiment på borrkärnor från LTDE-borrhålet vid AECL i Kanada och en preliminär slutrapport har sammanställts.

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 är skickad till tryck. Migration av aktinider i naturliga sprickor i borrkärnor studeras i Chemlab 2. Inga genombrott av Pu eller Am har detekterats under laboratorie- och fältexperimenten. Upp till 40 % av Np(V) har återfunnits men inget Np(IV) har detekterats i proven.

Kolloidprojektet omfattar studier av kolloiders stabilitet och rörlighet, bentonitens betydelse som källa för bildandet av kolloider, risken för att radionuklider transporteras med kolloider samt mätningar av kolloidkoncentrationen i grundvattnet i Äspö. Genomförda laboratorie-experiment, mätningar av bakgrundshalter och borrhålsspecifika mätningar har sammanställts i en slutrapport som skickades till tryck i december 2005. Det huvudsakliga arbetet under 2005 har inneburit insamling av data och förberedelser inför in situ experimenten som kommer att genomföras under 2006. Stablitetsexperiment med bentonitkolloider har visat att dessa kolloider inte alls är stabila i det salta vattnet i Äspö och in situ experimenten måste därför genomföras med en annan kolloid. Genomförda stabilitetsexperiment på latex-kolloider visar att dessa kan användas.

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 förvar för använt bränsle. Detta studeras i *Mikrobprojektet.* Den installerade utrustningen i mikroblaboratoriet har fungerat bra. De tidigare stabila grundvattenförhållandena förändrades dock dramatiskt i januari 2005 som ett resultat av borrningen av borrhål för in situ korrosionsförsök med miniatyrkapslar. En betydande dränering har lett till en situation med helt nya blandningsförhållanden med t ex en ökning av kloridkoncentrationen i omgivande bergformation. Dräneringen stoppades i början på december. Nya analyser av mikroorganismer måste göras när förhållandena har återgått till de som rådde innan dräneringen. En studie som genomförts i Mikroblaboratoriet indikerar att biofilmer på bergsprickor minskar granitens förmåga att adsorbera radionuklider förutom för trivalenta former. Mikroorganismernas effekt på den kemiska stabiliteten i djupa grundvatten har studerats i Mikroblaboratoriet och resultaten utgör grunden för utformningen av framtida in situ försök.

Den första fasen av *Matrisförsöket* har givit ökad kunskap om matrisvattnet i kristallint berg med låg hydraulisk konduktivitet. Detta utgör ett viktigt komplement till tidigare hydro-geokemiska studier som genomförts vid Äspölaboratoriet. Nästa fas av projektet fokuserar på hur småskaliga mikrosprickor i berget bidrar till rörelsen av matrisvatten. Förståelsen av grundvattnets rörelse och ändringar i kemin är viktig för slutförvarets funktion. Under 2005 genomfördes en förstudie för att utvärdera hur tunnelarbetet vid Pelarförsöket påverkat hydrogeologin och hydrokemin i borrhålet för Matrisförsöket. Resultaten av denna studie visade att påverkan var begränsad och en hydrokemisk och hydraulisk karakterisering av de isolerade borrhålssektionerna med mikrosprickor bedömdes därför vara relevant. Den hydrauliska karakteriseringen påbörjades under 2005 och förväntas pågå till och med våren 2006. Porositetsmätningar på material från borrkärnor har utförts under 2005. Resultaten indikerar att porositeter som är beräknade från mätningar i laboratorium är högre än de som utvärderats från mätningar in situ. Detta beror på sekundära effekter t ex fysisk störning av laboratorieprover genom t ex spänningsavlastning.

Projektet *Padamot* är ett EU-projekt med syfte att undersöka de specifika processer som beskriver hur klimatet påverkar grundvattenkemin i berg med låg permeabilitet. Inom projektet utvecklas även analysteknik och modelleringsverktyg för att utvärdera paleo-hydrogeologiska data. Paleohydrogeologi är en benämning som används för att beskriva den information om förflutna hydrogeokemiska och hydrogeologiska system som erhålls vid utvärdering av sprickfyllnadsmaterial. EU-delen av projektet har avslutats och rapporterats under 2005. I den framtagna konceptuella modellen för Äspö/Laxemar/Simpevarp kan åtminstone tre zoner av kalcitmineraliseringar urskiljas: (a) de översta 50–100 m karakteriseras av upplösta och utfällda nya kalciter, (b) från 100 m ner till 500–600 m observeras huvudsakligen utfällningar av nya kalciter och (c) mellan 600 och 1 000 m kan i de större sprickzonerna spåras kalcitmineraliseringar utfällda vid låga temperaturer från grundvatten av meteoriskt ursprung.

I projektet *Järnoxider i sprickor* undersöks järnoxidbeklädda sprickytor för att hitta lämpliga palaeoindikatorer och beskriva under vilka förhållande dessa bildas. Upptaget av spårämnen kan erhållas både från mätningar på naturliga material och från laboratoriestudier. För att särskilja mellan olika typer av järnoxider som hittas som sprickfyllnadsmaterial i granit har både en snabb och exakt metod utvecklats. Undersökningar av grönrost har visat att befintlig litteraturdata som beskriver struktur och sammansättning är felaktiga och en uppdatering av datamaterialet har därför gjorts. Metoder för att undersöka reaktiviteten hos grönrost har utvecklats genom att använda reduktionen av Cr(VI) till Cr(III) som modell för ett redoxkänsligt ämne. Reaktiv transportmodellering av specierna Fe(II)/Fe(III) har initierats.

Aktiviteterna vid Äspölaboratoriet omfattar projekt med syfte att utvärdera användbarhet och tillförlitlighet hos olika beräkningsmodeller. I arbetet ingår även att utveckla och prova metoder för att bestämma vilka parametrar som krävs som indata till modellerna. En viktig del av detta arbete genomförs i ett internationellt samarbetsprojekt ”*Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes*”. Arbetet i projektet har anknytning till pågående och planerade experiment vid Äspölaboratoriet. Flera internationella modelleringsgrupper arbetar med definierade uppgifter och använder samma fältdata. Modelleringsresultaten jämförs sedan med experimentella data och utvärderas av grupperna. Under 2005 har arbetet huvudsakligen bedrivits inom ”Task 6” och ”Task 7”. ”Task 6 – Performance assessment modelling using site characterisation data” initierades 2001 och planeras att slutföras under 2006. En stor del av modelleringsarbetet inom ”Task 6” har utförts och några delprojekt har rapporterats. I ”Task 7” modelleras ett pumptest i Olkiluoto i Finland. Arbetet kommer att fokusera på metoder för att kvantifiera osäkerheter i funktions- och säkerhetsanalyser baserade på information från de pågående platsundersökningarna.

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. Detta innefattar förebyggande och åtgärdande underhåll med syfte att upprätthålla en hög tillgänglighet på alla system i den underjordiska anläggning, t ex dränering, strömförsörjning, ventilation, brand- och utrymmningsalarm och kommunikation. Tillgängligheten (driftstid) under 2005 var 99 %. Andra aktiviteter är att se till att det stationära hydromoniteringssystemet (HMS) är kontinuerligt tillgängligt, att genomföra programmen för mätning av grundvattentryck och flöden samt programmet för grundvattenkemi. Ansvarig för att presentera information om SKB och dess anläggningar är PR och besöksgruppen vid Äspölaboratoriet. De arrangerar besök till SKB:s anläggningar under hela året och ordnar speciella evenemang. Under 2005 besöktes Äspölaboratoriet och aktiviteterna vid platsundersökningsområdena av ungefär 11 500 besökare.

Internationellt samarbete

Under 2005 har nio organisationer från åtta länder deltagit i det internationella samarbetet vid Äspölaboratoriet förutom SKB. Sex av dem, Andra, BMWi, CRIEPI, JAEA, OPG och Posiva utgör tillsammans med SKB ”Äspö International Joint Committee” vilken ansvarar för att koordinera det experimentella arbetet som uppkommer från det internationella deltagandet. Flertalet av de deltagande organisationerna är intresserade av grundvattenströmning, radionuklidtransport och bergkaraktärisering. Många organisationer deltar både i det experimentella arbetet i Äspölaboratoriet och i modelleringsarbetet inom de två ”Äspö task force” grupperna: (1) ”Task Force on Modelling of Groundwater Flow and Transport of Solutes” och (2) ”Task Force on Engineered Barrier Systems”.

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 är nu i stället koncentrerade till Äspö forskarskola. Forskningen fokuseras på biokemiska system och för närvarande pågår en mängd aktiviteter, dock mestadels utanför Äspölaboratoriet. Dessa aktiviteter har resulterat i flera publikationer i vetenskapliga tidskrifter under 2005. Den första disputationen ägde rum i januari 2005 och i slutet av året bestod det vetenskapliga teamet av en professor i miljögeologi, en forskarassistent, fyra biträdande handledare och fem doktorander.

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 final repository for disposal of spent nuclear fuel. This work includes development and testing of 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 final 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 fuel.

The underground part of the laboratory consists of a tunnel from the Simpevarp peninsula to the southern part of Äspö where the tunnel continues in a spiral down to a depth of 460 m, see Figure 1-1. The total length of the tunnel is 3,600 m where the main part of the tunnel has been excavated by conventional drill and blast technique and the last 400 m have been excavated by a tunnel boring machine (TBM) with a diameter of 5 m. The underground tunnel is connected to the ground surface through a hoist shaft and two ventilation shafts.

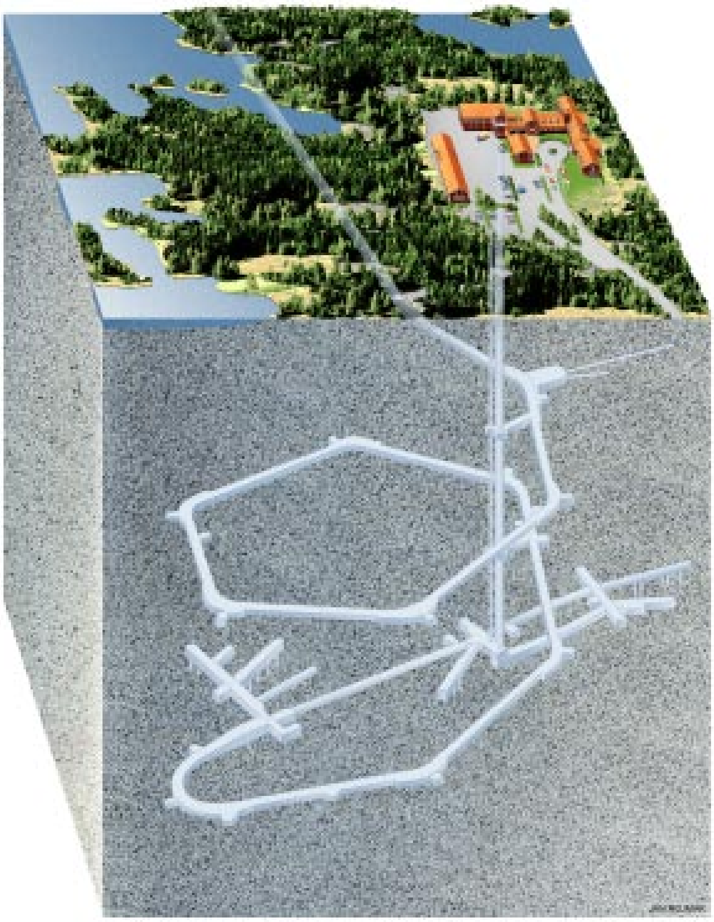


Figure 1-1. *Overview of the Äspö HRL facilities.*

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

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

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

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

1.2 Goals

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

1. *Verify pre-investigation methods.* Demonstrate that investigations on the ground surface and in boreholes provide sufficient data on essential safety-related properties of the rock at repository level.
2. *Finalise detailed investigation methodology.* Refine and verify the methods and the technology needed for characterisation of the rock in the detailed site investigations.
3. *Test models for description of the barrier functions at natural conditions.* Further develop, and at repository depth, test methods and models for description of groundwater flow, radionuclide migration and chemical conditions during operation of a repository and after closure.
4. *Demonstrate technology for and function of important parts of the repository system.* In full scale test, investigate and demonstrate the components of importance for the long-term safety of a final 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 Simpevarp/Laxemar in the municipality of Oskarshamn and at Forsmark in the municipality of Östhammar.

In order to reach present goals (3 and 4) the following important tasks are 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 final repository concept without sacrificing quality and safety.
- Increase the scientific understanding of the final repository's safety margins and provide data for safety assessments of the long-term safety of the repository.

- Provide experience and train personnel for various tasks in the repository.
- Provide information to the general public on technology and methods that are being developed for the final repository.
- Participate in international co-operation through the Äspö International Joint Committee (IJC) as well as bi- and multilateral projects.

1.3 Organisation

SKB's work is organised into six departments: Technology, Nuclear Safety, Site Investigations, Operations, Environmental Impact Assessment (EIA) and Public Information and Business Support. The research, technical development and safety assessment work are 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 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 is organised in four 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 geoscientific 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* is responsible for providing administrative service and quality systems.
- *Public Relations and Visitor Services* is responsible for presenting information about SKB and its facilities with main focus on the Äspö HRL. The HRL and SKB's other research facilities are open to visitors throughout the year.

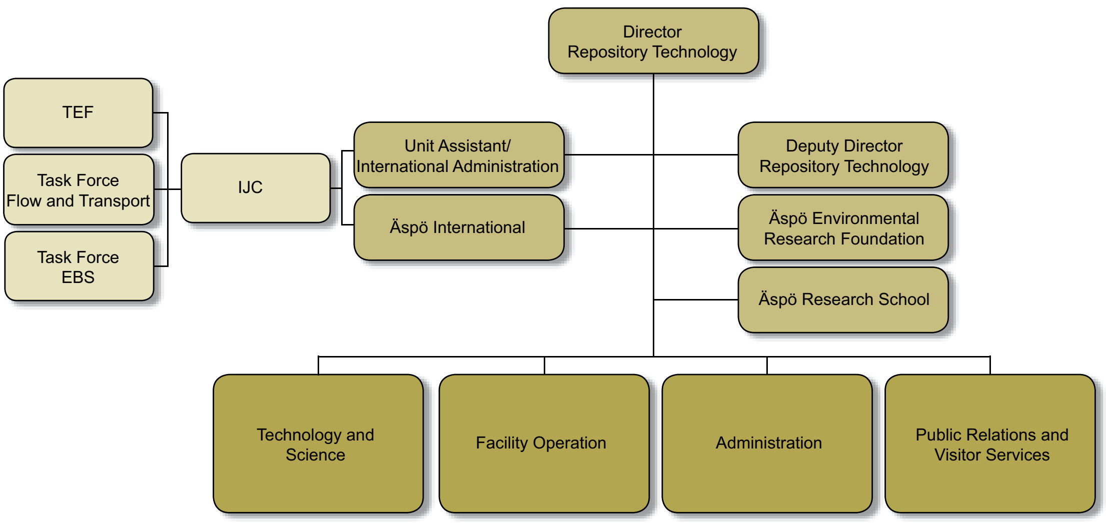


***Figure 1-2.** Organisation chart for Repository Technology and Äspö HRL.*

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 Manager 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. Nine organisations from eight countries participated during 2005 in the Äspö HRL or in Äspö HRL-related activities in addition to SKB. The participating organisations were:

- Agence Nationale pour la Gestion des Déchets Radioactifs (Andra), France.
- Bundesministerium für Wirtschaft und Technologie (BMWi), Germany.
- Central Research Institute of Electric Power Industry (CRIEPI), Japan.
- Japan Atomic Energy Agency (JAEA), Japan.
- Ontario Power Generation Inc. (OPG), Canada.
- Posiva Oy, Finland.
- Empresa Nacional de Residuos Radiactivos (Enresa), Spain.
- Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (Nagra), Switzerland.
- Radioactive Waste Repository Authority (RAWRA), Czech Republic.

For each partner the co-operation is based on a separate agreement between SKB and the organisation in question. Andra, BMWi, CRIEPI, JAEA, OPG and Posiva together with SKB form the Äspö International Joint Committee (IJC), which is responsible for the co-ordination of the experimental work arising from the international participation.

Task forces are another form of organising the international work. Several of the international organisations in the Äspö co-operation participate in the two Äspö task forces on (a) Modelling of groundwater flow and transport of solutes and (b) THMC modelling of engineered barrier systems. SKB also takes part in several international EC-projects and participates in work within the IAEA framework.

1.5 Allocation of experimental sites

The rock volume and the available underground excavations 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 a selection of the experimental sites within the Äspö HRL is shown in Figure 1-3.

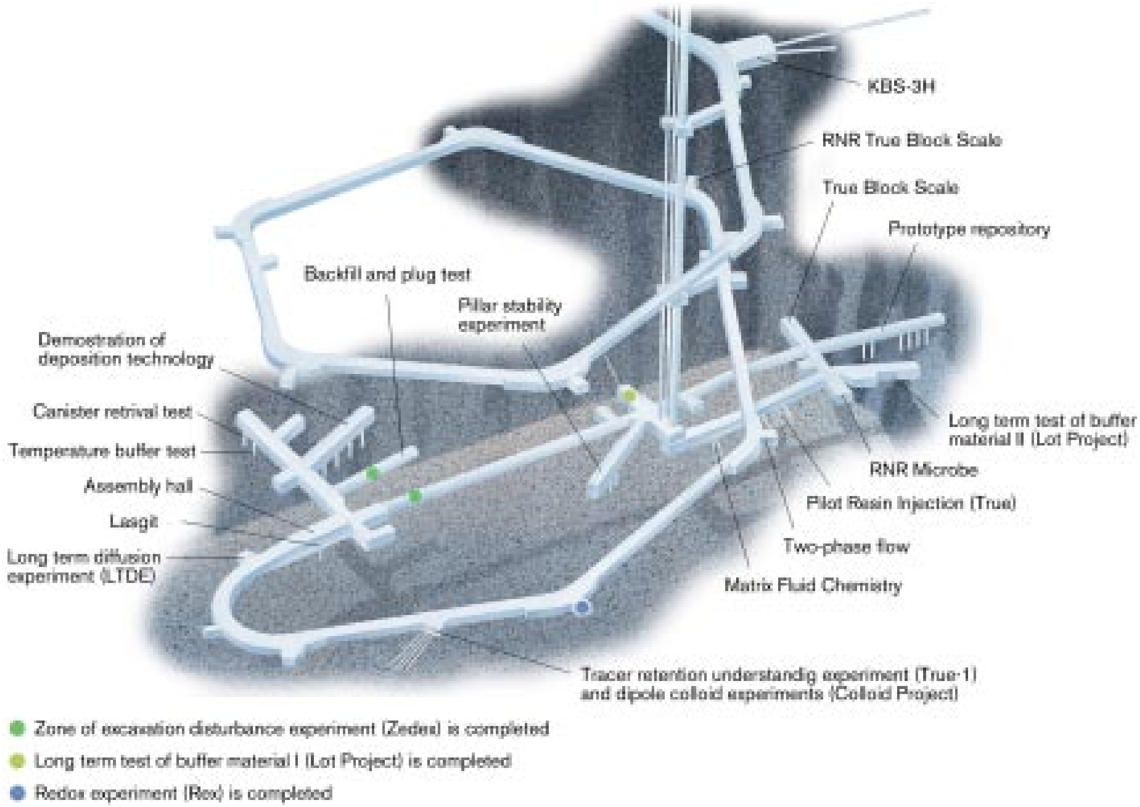


Figure 1-3. *Allocation of some of the experimental sites in Äspö HRL from –220 m to –450 m level.*

1.6 Reporting

Äspö HRL is an important part of SKB's RD&D-Programme. The plans for research and development of technique during the period 2005–2010 are presented in SKB's RD&D-Programme 2004 /SKB 2004/. The information given in the RD&D-Programme related to Äspö HRL is detailed in the Äspö HRL Planning Report /SKB 2005/. This plan is revised annually and the report gives an overview of the planned activities for each calendar year. 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. This report describes the achievements during 2005.

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

The structure of the management system is based on procedures, handbooks, instructions, identification and traceability, quality audits etc. The overall guiding documents for issues related to management, quality and environment are written as routines. The documentation can be accessed via SKB's Intranet, where policies, common routines for SKB (SD-documents) as well as specific routines for Äspö HRL (SDTD-documents) can be found. Employees and contractors related to the SKB organisation are responsible that work is performed in accordance with SKB's management system.

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

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

- Safety.
- Efficiency.
- 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 every three months. Key assessment parameters for the selection of suppliers include security, environmental aspects and quality.

1.8 Structure of this report

The work performed at Äspö HRL during 2005 is in this report described in six chapters:

- Technology – demonstration of technology for and function of important parts of the repository system.
- Geoscience – 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, monitoring, public relations 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 future repository.

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

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

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

With respect to repository function, 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 or underway 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.
- Rock Shear Experiment.
- In Situ Corrosion Testing of Miniature Canisters.

2.2 Canister Retrieval Test

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 tests, the results from monitoring of the buffer and the laboratory testing of excavated parts of the buffer will be used to increase the understanding of thermal, hydraulic and mechanical (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 canister with heaters. The 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 is left open for access and inspections of the plug support. The experimental set-up is shown in Figure 2-1.

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. The instrumentation in the buffer is similar to the instrumentation in the Prototype Repository and yield comparable information during the saturation period. Decision to make the retrieval test in spring 2006 was taken in 2005.

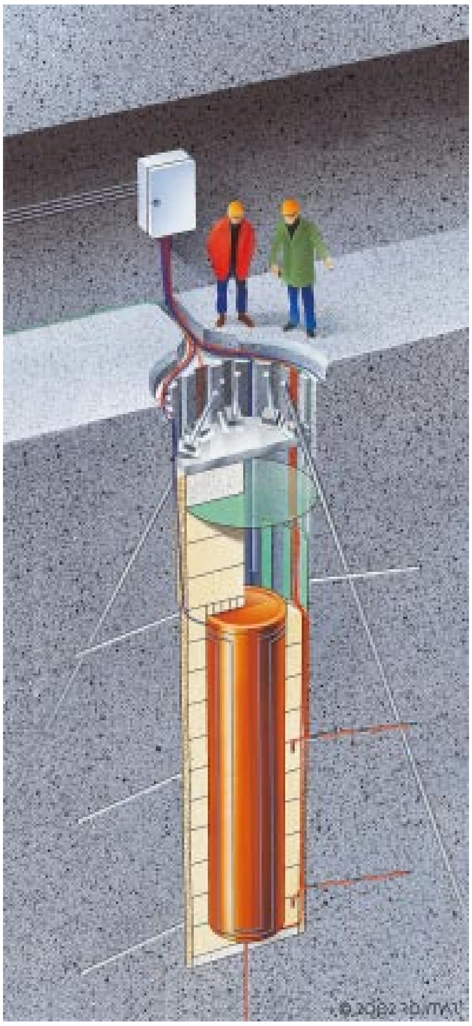


Figure 2-1. *Illustration of the experimental set-up of the Canister Retrieval Test.*

2.2.4 Results

Status

The Canister Retrieval Test was installed during year 2000. The heaters were turned on in October with a constant power of 1,700 W and the power was increased to 2,600 W in February, 2001. At the end of 2001 two of the 36 electrical heaters failed due to short circuit to earth. The power in the heaters were reduced from 2,600 W to 2,100 W in September, 2002 and to 1,600 W in November, 2003, in order to lower the temperature in the canister and in this way increase the resistance to earth in the heater elements. At the end of 2004 eleven heaters were working and during 2005 additional heater failures enforced a reduction of the power to 1,200 W in March since only 4 heaters were still working. In preparation for the planned termination of the test the power was shut down in the middle of October.

The mats for artificial wetting were flushed and the water pressure was increased from 50 kPa to 850 kPa in September and October 2002 and kept constant with a few short exceptions. The mats have been flushed regularly since 2002. The water pressure in the mats has been kept at 850 kPa until March 2005, when it was reduced to atmospheric pressure in order to try to preserve the function of the last heaters. Finally the mats were emptied and flushed with air in December. The test will be terminated and the excavation and retrieval will start in the beginning of January 2006.

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 2005-05-01 /Goudarzi et al. 2005a/ and the period up to 2005-11-01 /Goudarzi et al. 2006a/ have been released. Selected characteristic values from 2000-10-26 until 2005-11-30 are shown in the figures below. Figure 2-2 shows the evolution of the relative humidity about 10 cm above the canister. The evolution of the temperature and the total pressure in the buffer in the mid plane of the canister is shown in Figure 2-3 and Figure 2-4 respectively.

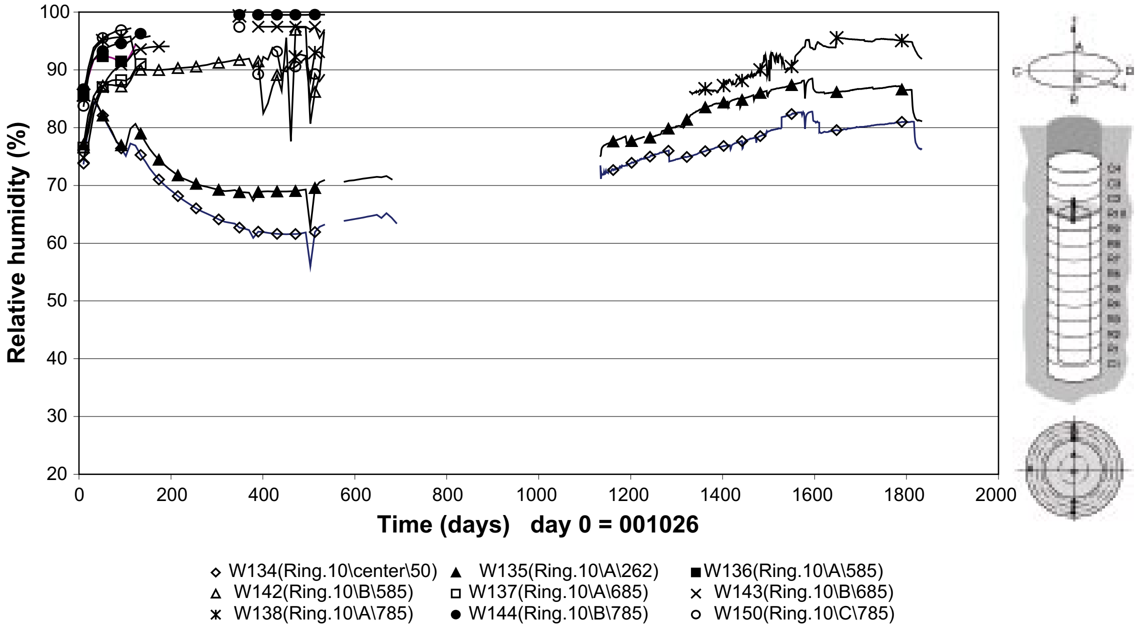


***Figure 2-2.** Measured relative humidity in the buffer in a horizontal plane located about 10 cm above the canister (Ring 10, 2000-10-26 to 2005-11-01).*

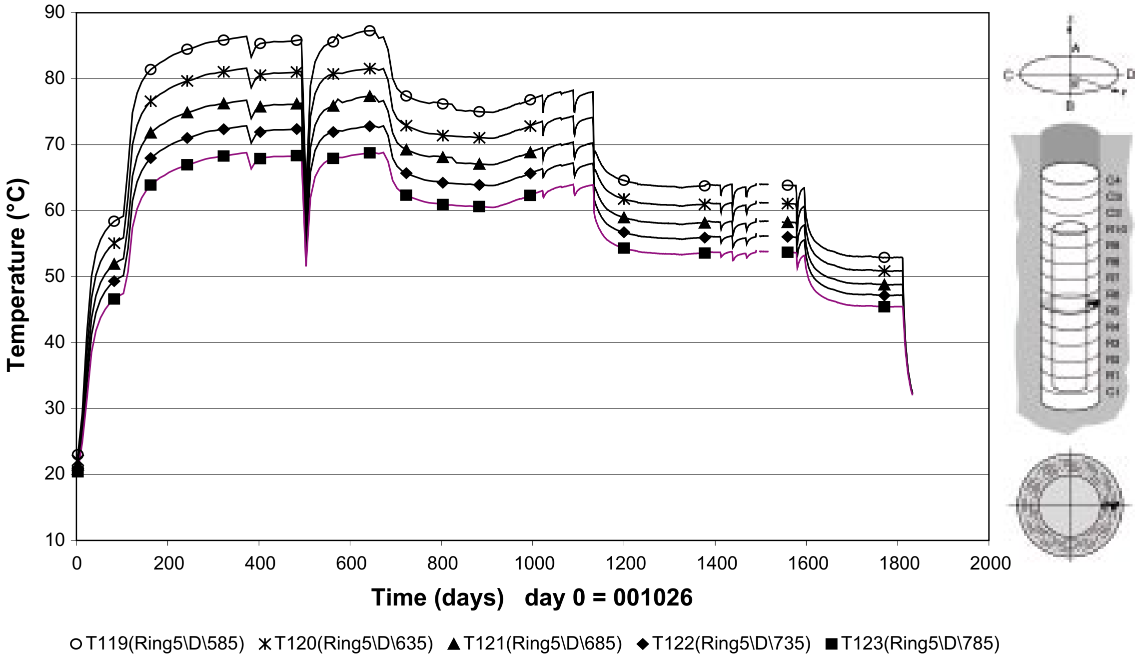


Figure 2-3. *Measured temperature in the buffer in a horizontal plane located in the centre of the canister (Ring 5, 2000-10-26 to 2005-11-01).*

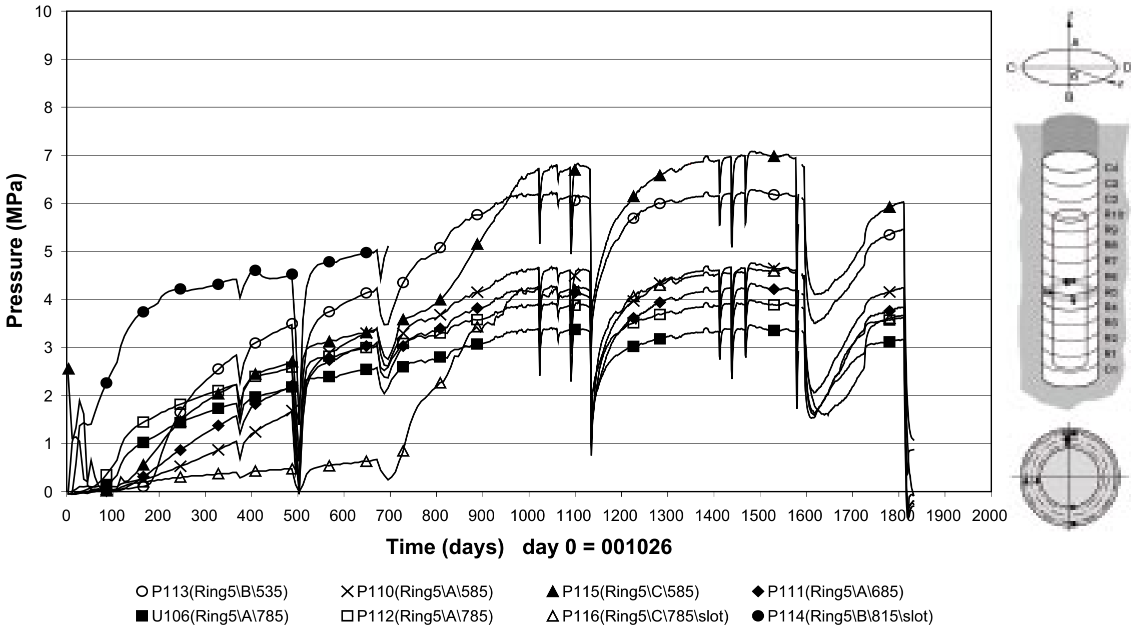


Figure 2-4. *Measured total pressure in the buffer in a horizontal plane located in the centre of the canister (Ring 5, 2000-10-26 to 2005-11-01).*

The decrease in temperature at the different power reductions is clearly seen in Figure 2-3. The temperature increase after about 900 days is caused by the Temperature Buffer Test that was started a little earlier. The relative humidity sensors indicate that the bentonite between the rock and the canister is water saturated whereas the bentonite above and below the canister is still unsaturated. As expected the swelling pressure and the temperature decreased after the power to the heaters was shut off.

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

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

The installation of the Prototype Repository has been co-funded by the European Commission with SKB as co-ordinator. The EC-project started in September 2000 and ended in February 2004. The continuing operation of the Prototype Repository is funded by SKB.

2.3.2 Objectives

The main objectives for the Prototype Repository are to:

- Test and demonstrate the integrated function of the 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 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 provides two more or less independent test sections. Canisters with dimension and weight according to the current plans for the final repository and with heaters to simulate the thermal energy output from the waste have been positioned in the holes and surrounded by bentonite buffer. The deposition holes are placed with a centre distance of 6 m. This distance was evaluated considering the thermal diffusivity of the rock mass and the maximum acceptable surface temperature of the canister.

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

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

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.

2.3.4 Results

The installation of Section I was done during summer and autumn 2001. The heating of the canister in hole 1 started with an applied constant power of 1,800 W the 17th September, 2001 and this date is also marked as start date. The backfilling was finished in November and the plug was cast in December 2001. 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 year 2004 the power in deposition 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 the 8th May, 2005 and this date is also marked as start date. The backfilling was finished in the end of June and the plug was cast in September. In the beginning of September 2004 the power in deposition holes 5–6 was decreased with about 30 W to 1,770 W. The interface between the rock and the outer plug was grouted at the beginning of October 2004.

At the beginning of November 2004 the drainage of the inner part of Section 1 and the drainage trough the outer plug were closed. This affected the pressure (both total and pore pressure) in the backfill and the buffer in the two sections dramatically. Example of data from the measurements in the backfill of the total pressure is shown in Figure 2-6. The maximum pressures were recorded around 1st January, 2004. At that date the heating in canister 2 failed. It was then decided to turn off the power to all of the six canisters. Four days later, 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 again applied 15th January, 2004 and the drainage of the tunnel was kept open. At the beginning of August 2005 another failure of canister 6 was observed. The power to this canister was switched off until beginning of October 2005.

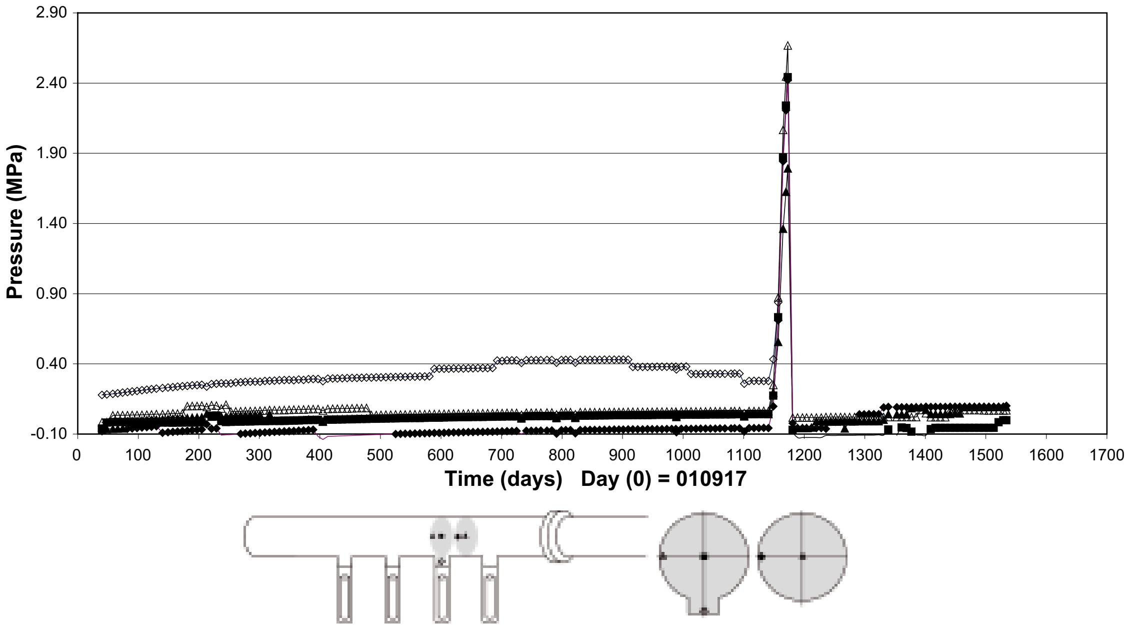


***Figure 2-6.** Measured total pressure in the backfill around deposition hole 3 (2001-09-17 to 2005-12-01).*

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

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

A large program for measuring the water pressure in the rock close to the tunnel is 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 1st November, 2004 been drained. Most of the water coming into the inner section has been drained. This affects the water uptake both in the buffer and in the backfill. The saturation of the buffer has reached different levels in the six deposition holes due to variation in the access to water.

Deposition hole 1 can be considered a "wet" deposition hole while deposition hole 3 is very dry. In Figure 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 RH-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. The measurements in deposition hole 1 indicate a rapid increase both in total pressure and relative humidity. The RH-sensors have at the end of the measuring period (2005-12-01) 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 indicating an increase in pressure caused by the closing of the drainage and then a sudden drop in pressure when the heating was interrupted and the drainage was opened. After reopening the drainage and restarting the heaters the pressure increased to almost the same level as before closing of the drainage. Corresponding measurements in deposition hole 3 indicate very small changes in both relative humidity and total pressure with time. One of the RH-transducers indicates a faster hydration after the reopening of the drainage. The measured total pressure in hole 3 is much lower compared to the measurements made in hole 1.

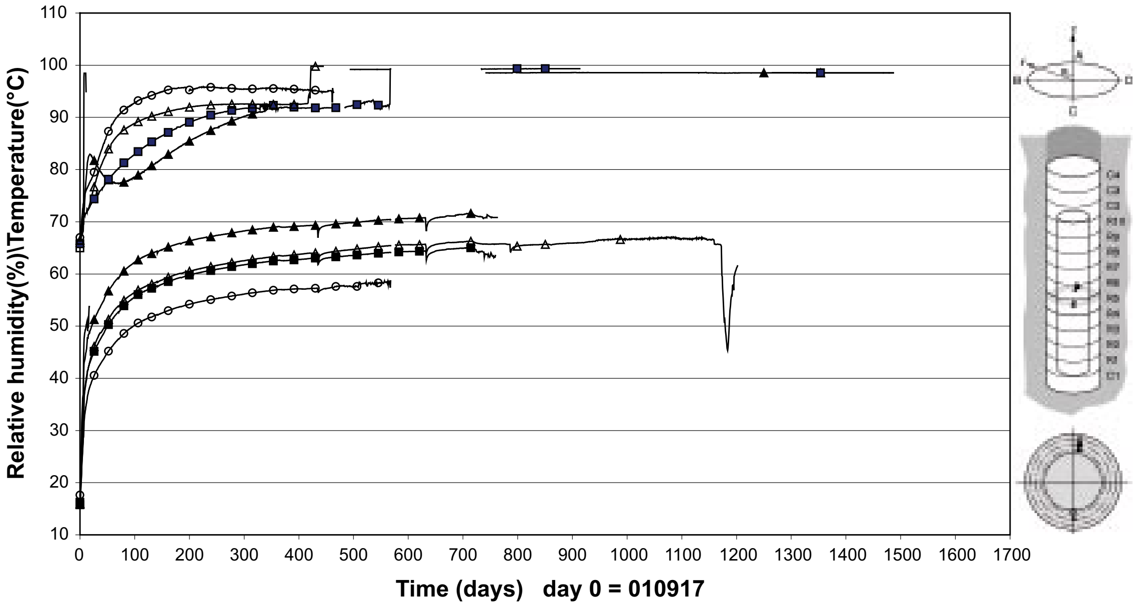


Figure 2-7. *Measured relative humidity and temperature (lower curves) with the RH sensors in deposition hole 1 (Ring 5, 2001-09-17 to 2005-12-01).*

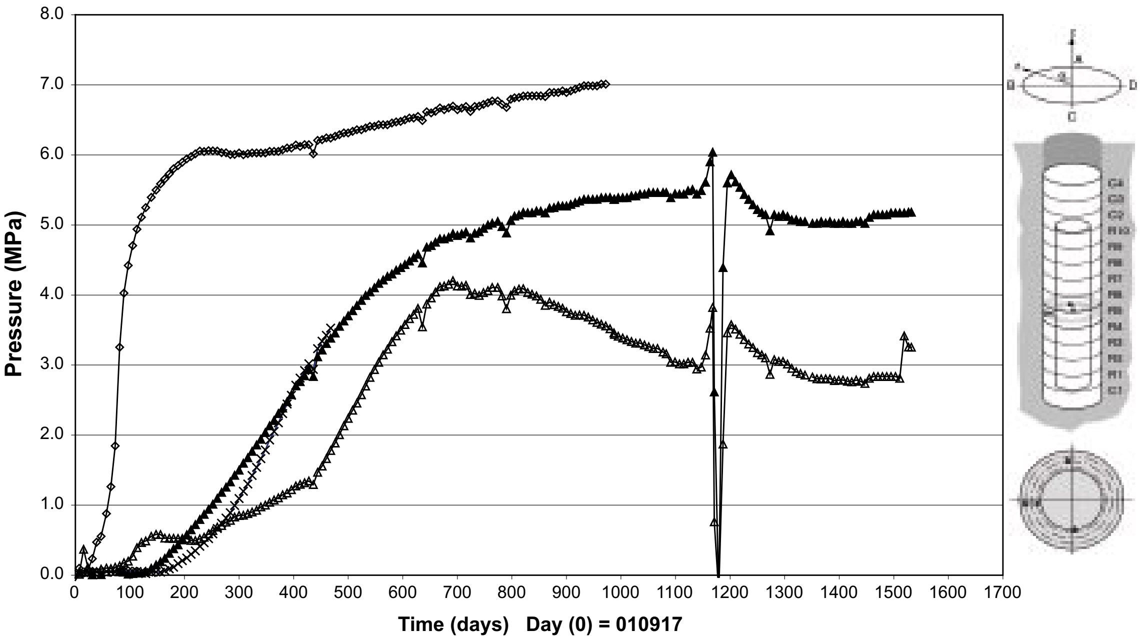


Figure 2-8. Measured total pressure in deposition hole 1 (Ring 5, 2001-09-17 to 2005-12-01).

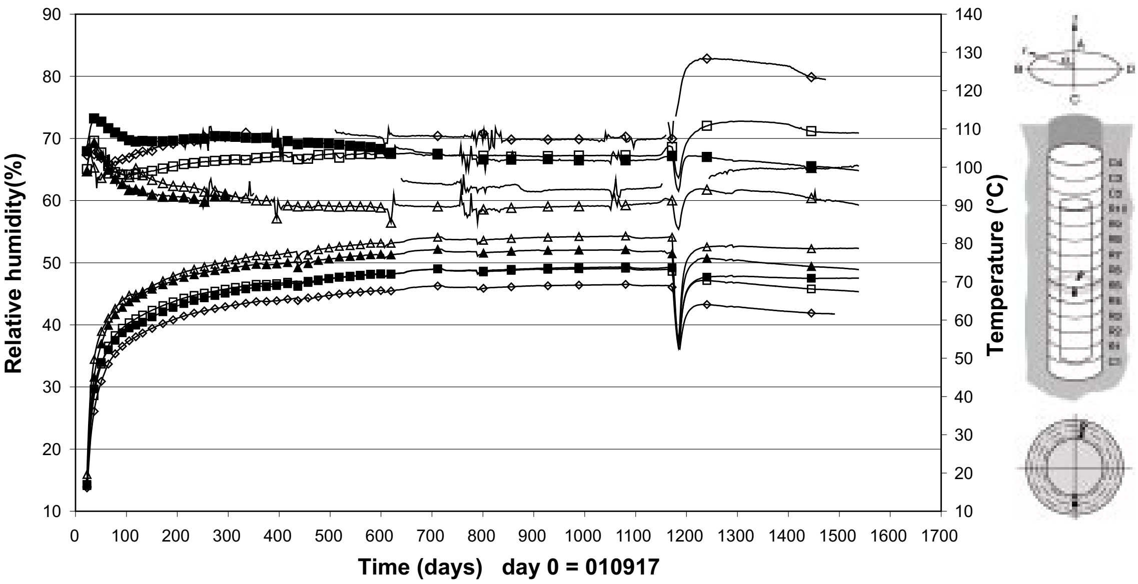


Figure 2-9. Measured relative humidity and temperature (lower curves) with the RH sensors in deposition hole 3 (Ring 5, 2001-09-17 to 2005-12-01).

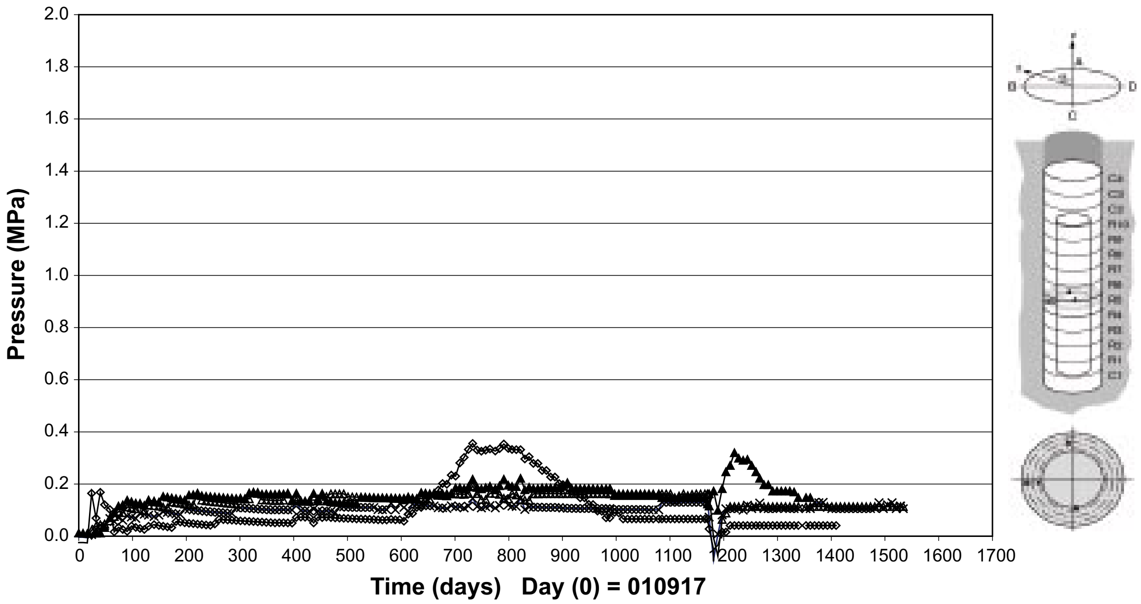


Figure 2-10. *Measured total pressure in deposition hole 3 (Ring 5, 2001-09-17 to 2005-12-01).*

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

In Figure 2-11 the temperature in the buffer is plotted as function of the radius from the centre of the deposition hole. The measurements are made with different type of sensors in block R5 (at mid height of the canister). A straight line is fitted to the measured values. The temperature gradient is determined from the fitted line in the figure. This gradient together with the temperature on the canister surface and the temperature in the buffer close to the outer radius of the ring shaped block (r = 785 mm) are plotted as function of time in Figure 2-12. The shaded part of the plot represents the time when the power to the canister was switched off at the beginning of December. The plot shows that the temperature after this is somewhat lower than before, probably due to the fact that no power is applied to canister 2 after December, 2004. However, the temperature gradient over the buffer is similar before and after the power to the canisters was switched on/off.

In Figure 2-13 the temperature in deposition hole 3 is plotted as function of the radial distance from the centre of the deposition hole. Compared to the corresponding plot for deposition hole 1 this plot shows a significant drop in temperature between the surface of the canister and the buffer (inner diameter of the ring). This indicates that the initial slot (of about 10 mm) between the canister and the buffer is still open.

The temperature gradient over the inner slot together with the temperature on the canister and the temperature on the inner radius of the ring shaped block are plotted as function of time in Figure 2-14. The shaded part of the plot represents the time when the power to canisters was switched off. Immediately after the power was switched off, the temperature gradient increased which indicate that the slot was isolating the canister resulting in a much faster drop in temperature of the buffer than the canister surface. When the power was switched on again the temperature gradient over the slot reached the same level as before the closing of the drainage. This indicates an open slot between the canister and the buffer. However, the figure also shows that the gradient is decreasing with time, which might be an indication of that the gap is getting smaller.

The temperature gradient over the buffer is plotted in Figure 2-15 together with the temperature on the inner surface of the block and the temperature at the radius of r = 785 mm. After the power was switched on again also this gradient stabilised on the same level as before the power was switched off.

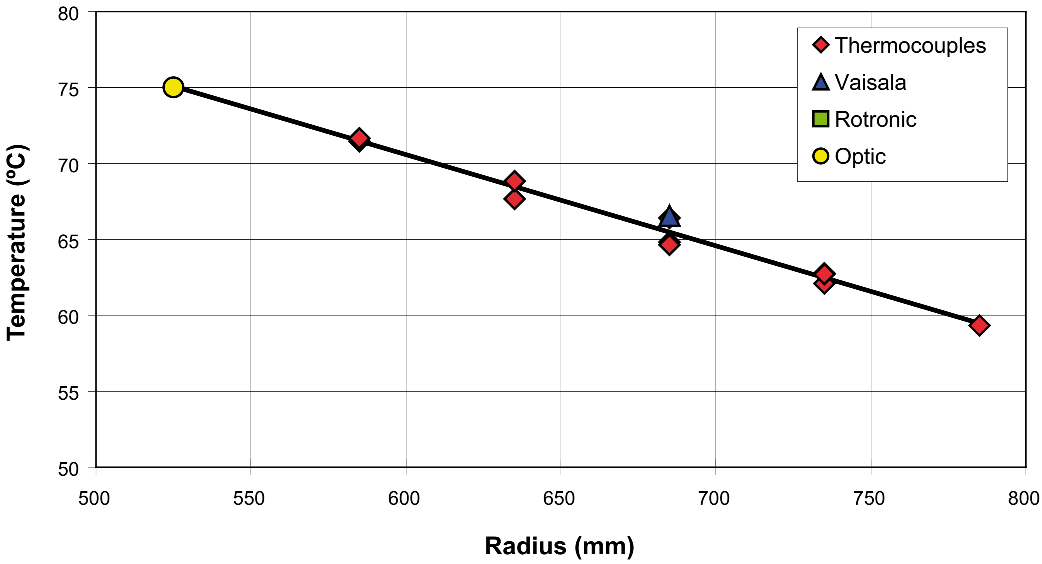


Figure 2-11. *The temperature in ring 5 in deposition hole 1 as function of radius from the centre of the deposition hole on 15th November, 2004.*

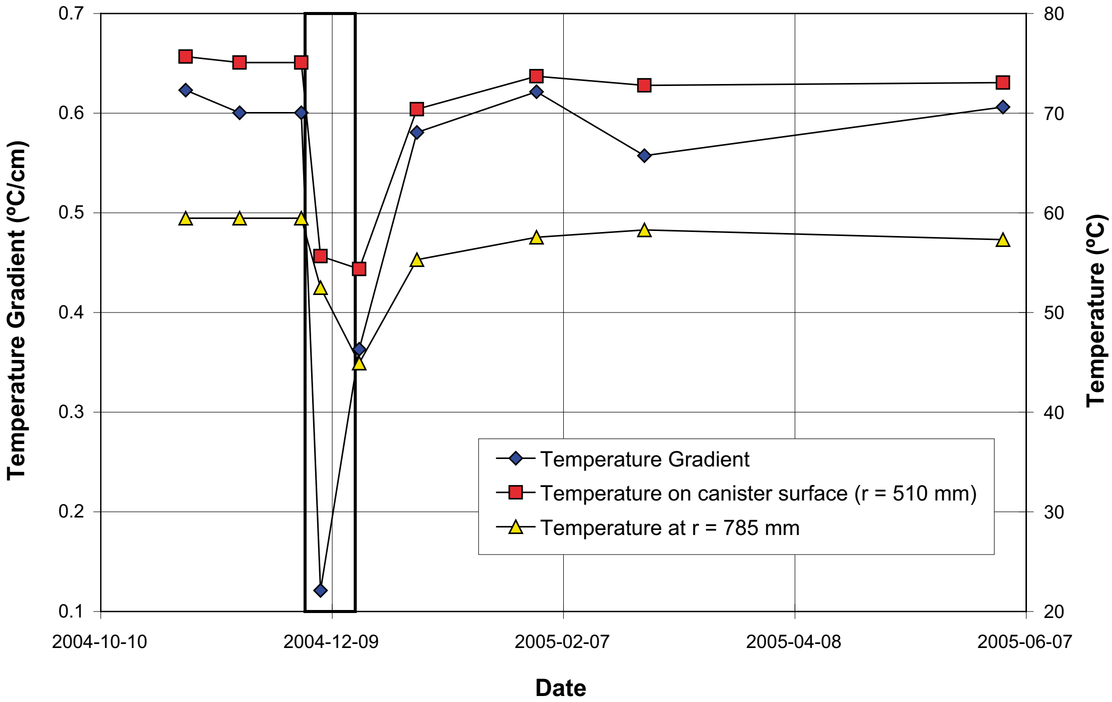


Figure 2-12. *The temperature and temperature gradient in deposition hole 1 plotted as function of the date.*

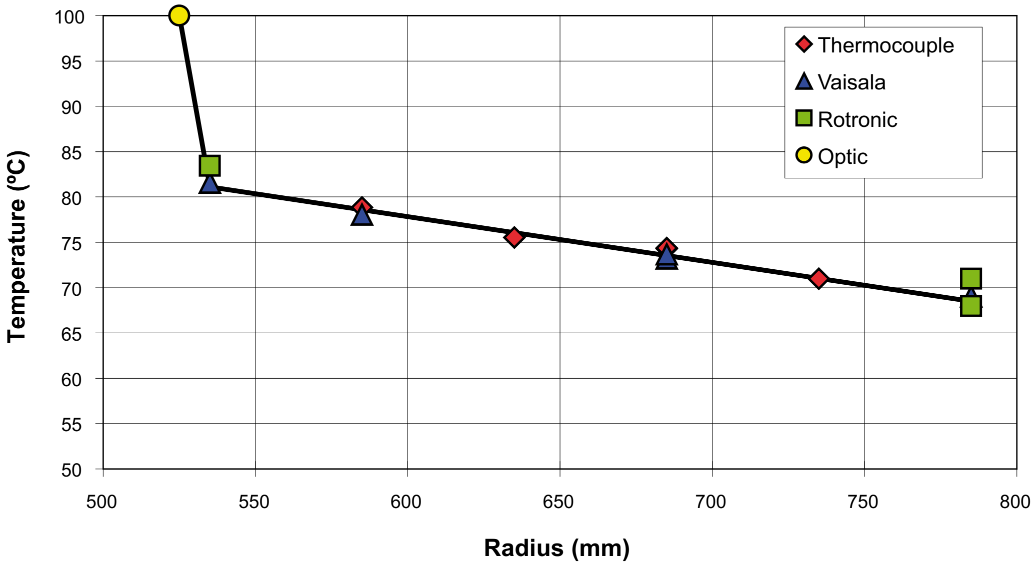


Figure 2-13. *The temperature in ring 5 in deposition hole 3 as function of radius from the centre of the deposition hole on 15th November, 2004.*

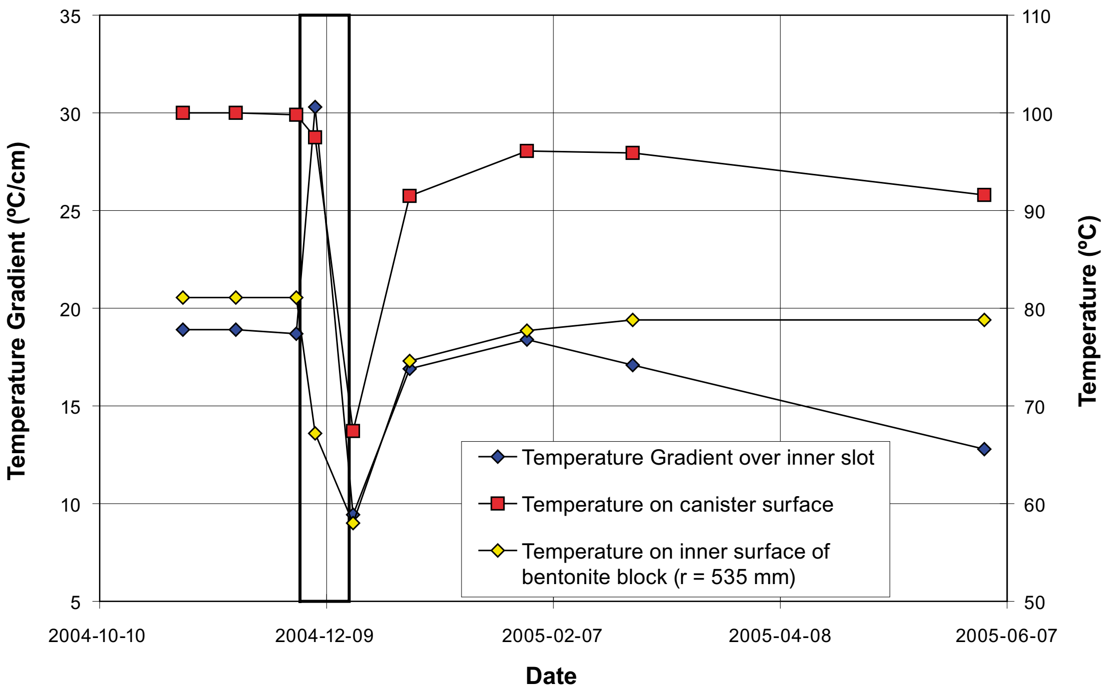


Figure 2-14. *The temperature and temperature gradient over the inner slot in deposition hole 3 plotted as function of the date.*

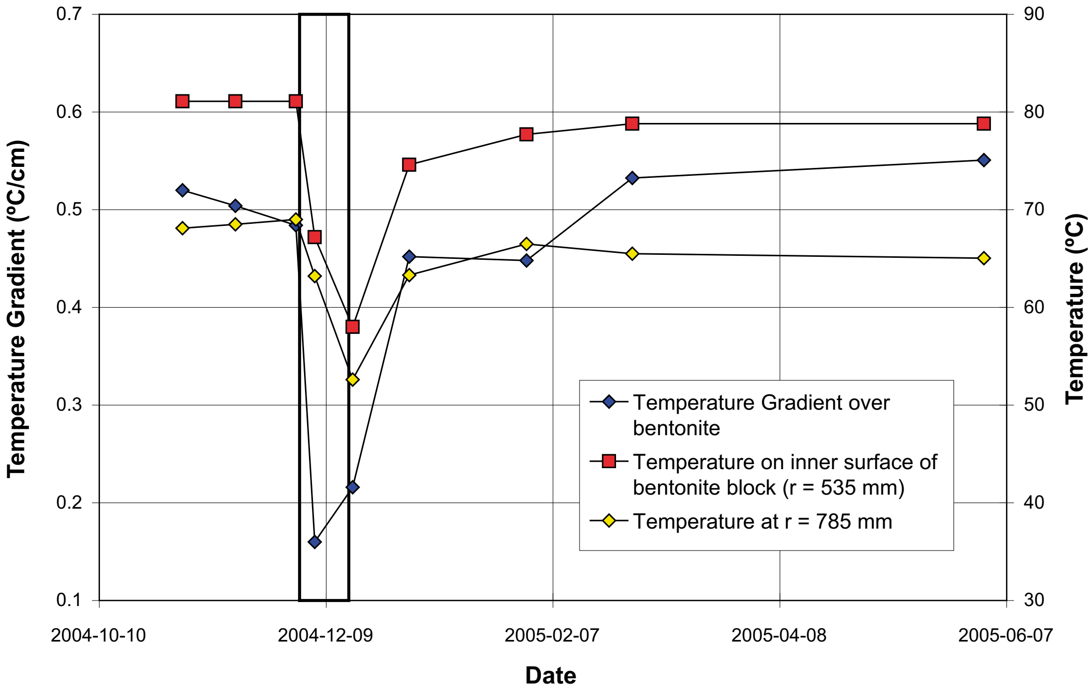


***Figure 2-15.** The temperature and temperature gradient over the buffer in ring 5 in deposition hole 3 plotted as function of the date.*

Hydration of the backfill in Section I

Figure 2-16 shows some results from measurements of suction in the backfill of Section 1 over deposition hole 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, which still gave reliable data, indicated similar hydration rate as before the closing of the drainage.

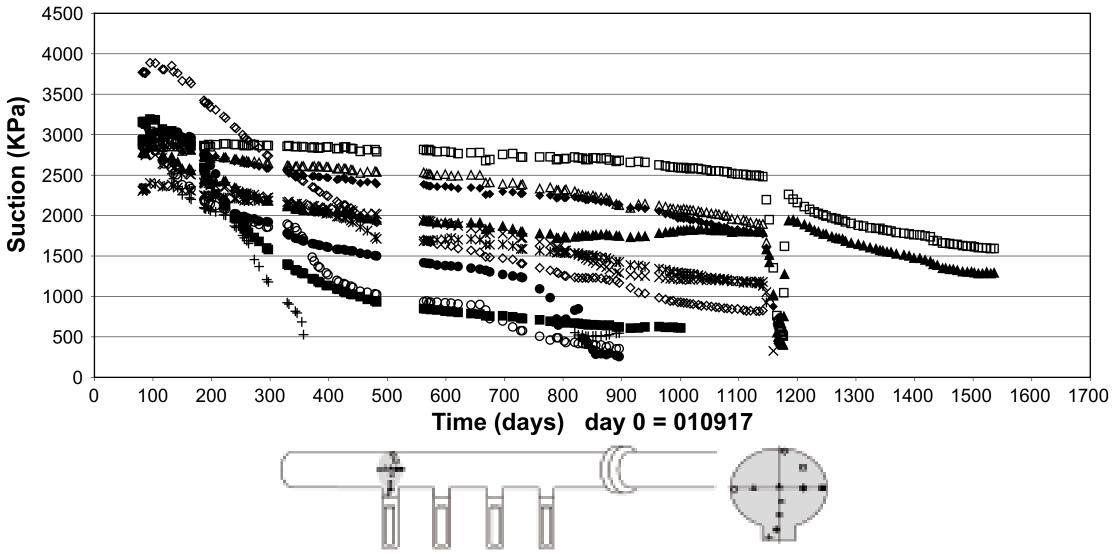
Modelling of THM processes

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

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

The 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).
- Code Bright (O Kristensson, Clay Technology AB, SKB).



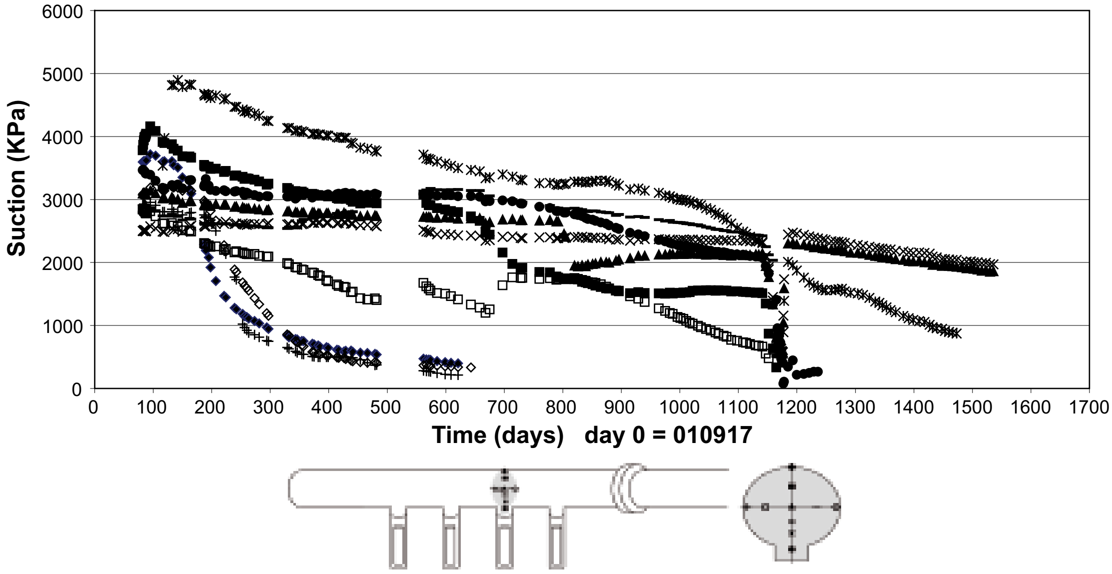


Figure 2-16. *Suction measured in the backfill in tunnel sections above deposition hole 1 (upper figure) and deposition hole 3 (lower figure) (2001-09-17 to 2005-12-01).*

2.4 Backfill and Plug Test

2.4.1 Background

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

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 tunnel. Figure 2-17 shows a 3D visualisation of the experimental set-up. The test region, which is about 30 m long, is divided into the following three test parts:

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

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

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

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.

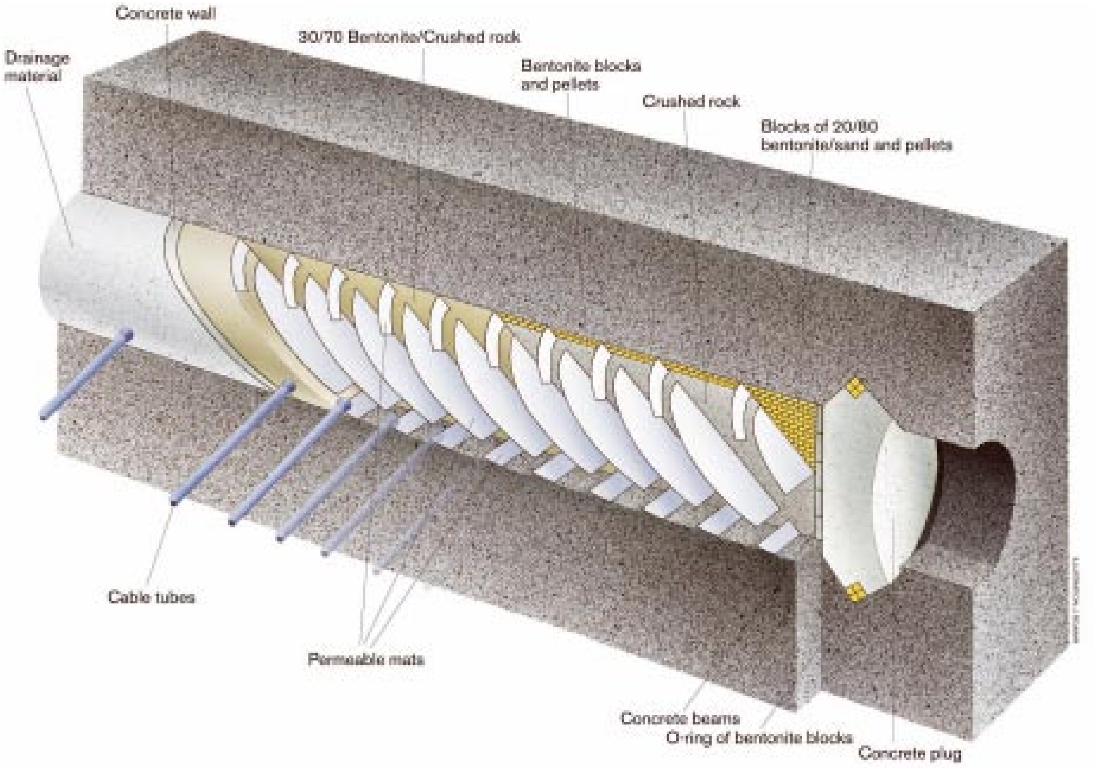


Figure 2-17. *Illustration of the experimental set-up of the Backfill and Plug Test.*

The backfill and rock are instrumented with piezometers, total pressure cells, thermocouples, moisture gauges, and gauges for measuring the local hydraulic conductivity. The axial conductivity of the backfill and the near-field rock is after water saturation tested by applying a water pressure gradient along the tunnel between the mats and measuring the water flow. All cables from the instruments are enclosed in Tecalan tubes in order to prevent leakage through the cables. The cables are led through the rock in boreholes drilled between the test tunnel and the neighbouring demonstration tunnel hosting the data collection room.

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. 2004 and most of 2005 have been devoted to flow testing of the 6 test sections of the 30/70 mixture.

The flow testing was done by decreasing the water pressure in the permeable mats sections (one by one) to 400 kPa and measuring the flow between the mat sections, starting with the filter at the plug. Tests have been done with flow in both directions. The results are summarised in Table 2-1. Both the inflow into the mats at the high pressure filter and the outflow out from the mats at the low pressure side were measured and the hydraulic conductivity for each section is evaluated as the average of the in- and outflow.

There is good agreement between different tested sections and between the different flow directions, which yields confidence in the results. The evaluated hydraulic conductivity is a little higher than expected from the laboratory results, which have yielded values between 10^{-9} m/s and 10^{-10} m/s for a dry density of 1,700 kg/m^3 and water with 1.2% salt content.

Table 2-1. Hydraulic conductivity (m/s) of 30/70 backfill evaluated from the flow results. → mean flow directed towards the plug (to the right in Figure 2-17).

Layer Flow direction	Top →	Top ←	Centre →	Centre ←	Bottom →	Bottom ←
A6	–	$5.3 \cdot 10^{-8}$	–	$2.1 \cdot 10^{-9}$	–	$5.0 \cdot 10^{-9}$
A5	$1.5 \cdot 10^{-8}$	$6.2 \cdot 10^{-8}$	$1.4 \cdot 10^{-9}$	$2.4 \cdot 10^{-9}$	$2.1 \cdot 10^{-8}$	$2.6 \cdot 10^{-8}$
A4	$9.1 \cdot 10^{-8}$	$8.4 \cdot 10^{-8}$	$1.2 \cdot 10^{-9}$	$5.4 \cdot 10^{-9}$	$7.9 \cdot 10^{-9}$	$2.3 \cdot 10^{-8}$
A3	$6.7 \cdot 10^{-8}$	$4.5 \cdot 10^{-8}$	$3.3 \cdot 10^{-9}$	$2.1 \cdot 10^{-9}$	$1.8 \cdot 10^{-8}$	$2.2 \cdot 10^{-8}$
A2	$4.4 \cdot 10^{-8}$	$4.2 \cdot 10^{-8}$	$1.0 \cdot 10^{-9}$	$3.4 \cdot 10^{-9}$	$1.4 \cdot 10^{-8}$	$1.4 \cdot 10^{-8}$
A1	$3.2 \cdot 10^{-8}$	$2.4 \cdot 10^{-8}$	$8.8 \cdot 10^{-11}$	$2.7 \cdot 10^{-9}$	$0.77 \cdot 10^{-8}$	$2.6 \cdot 10^{-9}$
Average	$5.0 \cdot 10^{-8}$	$5.2 \cdot 10^{-8}$	$1.4 \cdot 10^{-9}$	$3.0 \cdot 10^{-9}$	$1.4 \cdot 10^{-8}$	$1.9 \cdot 10^{-8}$
Average	$5.1 \cdot 10^{-8}$		$2.2 \cdot 10^{-9}$		$1.7 \cdot 10^{-8}$	

The high values in the bottom are judged to be caused by flow in the fractured rock floor while the high values measured from the flow through the top mats are most likely caused by low density at the roof.

The flow testing of the backfill materials has been finalised in both directions. Additional flow testing in individual points has started and so far the results have yielded a hydraulic conductivity that is about a factor 10 lower than the results from the flow tests between the mats.

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 2-18.

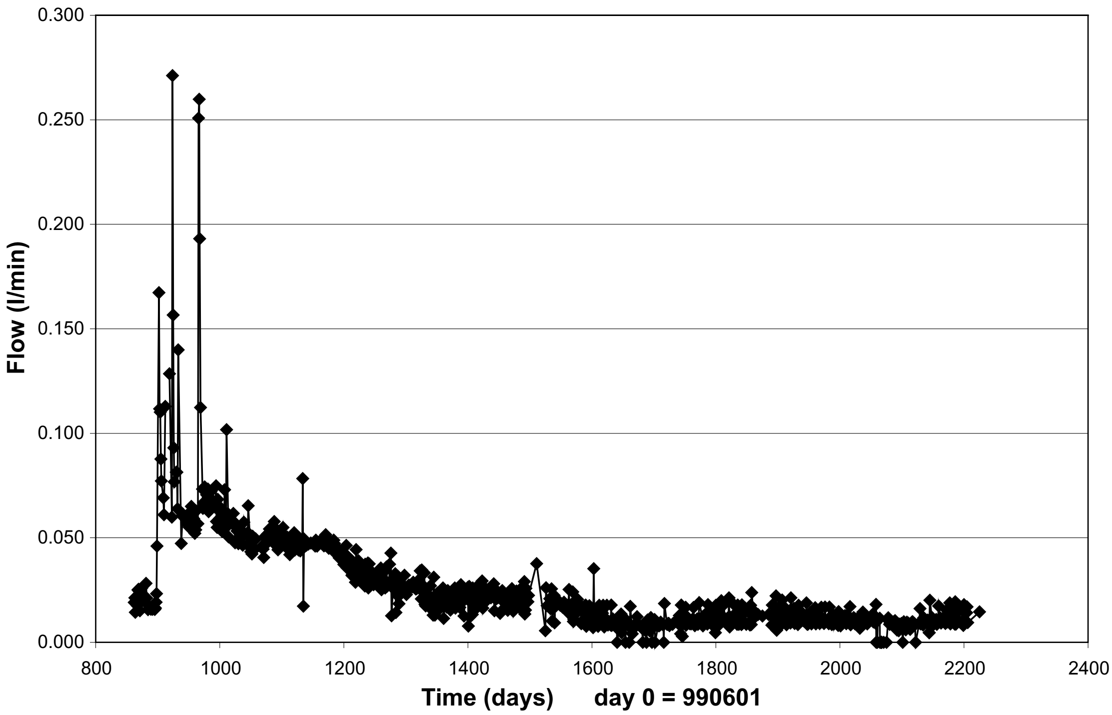


Figure 2-18. *Measured water flow past the plug and its surroundings, 400–500 kPa has been kept inside the plug from day 965 (1999-06-01 to 2005-07-01).*

Logging of measured results from all sensors have continued during 2005 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 1st, 2005 /Goudarzi et al. 2005b/ and the period up to January 1st, 2006 /Goudarzi et al. 2006b/ have been released.

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

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 minimize water flow over the deposition holes.

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

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. illitization 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.
- Collect information which may facilitate the realization of the full scale test series with respect to clay preparation, instrumentation, data handling, subsequent analyses 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 2-19. The test series given in Table 2-2, concern realistic repository conditions except for the scale and the controlled adverse conditions in three tests.

Table 2-2. Buffer material 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	terminated
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.

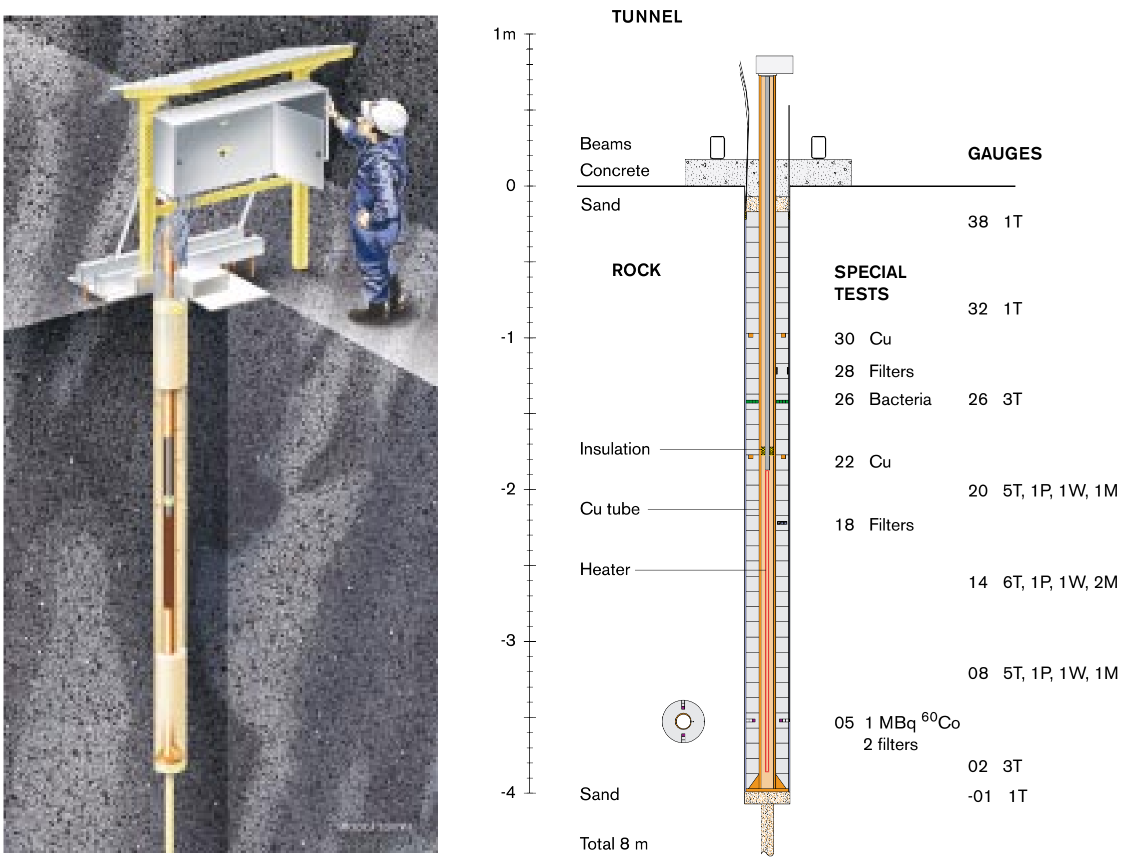


Figure 2-19. *Illustration of the experimental set-up in the Long Term Test of Buffer Material (left) and a cross-section view of one S-type parcel (right). In the gauges column, the first figure represents the block number, second figure represents the number of sensors and T, P, W, M indicate temperature, total pressure, water pressure and moisture sensors, respectively.*

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

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. A new version of the Siroquant software for quantitative mineralogical analyses has been tested and will be used in the forthcoming analyses.

The 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 bentonite swelling pressure is still increasing in several positions in two parcels, showing that water uptake is still ongoing, although the tests have been running for almost 6 years.

The power supply to parcel A2 was shut down 1st December and the measuring equipment was removed 15th December when the temperature in all positions had decreased to below 30°C, see Figure 2-20. Percussion drilling in the rock around the parcel is planned to start in the first week of January 2006.

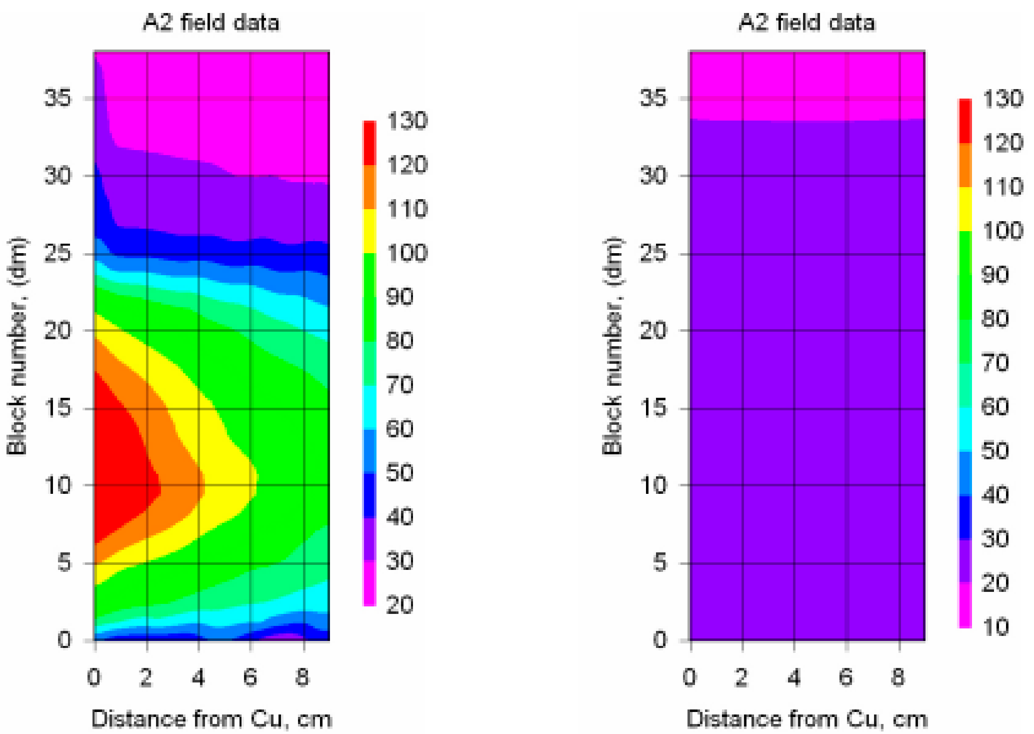


***Figure 2-20.** Temperature distribution in one side of the bentonite buffer in the A2 parcel before power shut down (left) and 2 weeks after (right).*

2.6 Cleaning and Sealing of Investigation Boreholes

2.6.1 Background

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

Sealing of boreholes with cementitious materials is commonly used in construction work and can be performed with well-known techniques. Earlier studies, e.g. the Stripa project, have shown that sealing with cementitious material include a potential risk for degradation due to leaching and the sealing can not be guaranteed over time-periods longer than hundreds of years. Another 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. The project comprised initially two phases. Phase 1, mainly an inventory of available techniques, was finalised in 2003. Phase 2 aims to develop a complete cleaning and sealing concept “Basic concept” and to demonstrate it. A third phase of the project (Phase 3) with the aim to perform large-scale testing in boreholes has been initiated in 2005. The work is divided in four sub-projects.

Sub-project 1

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

- Theoretical modelling of the hydration and maturation of clay components in perforated tubes, taking perforation geometry and clay density as main variables.
- Definition of most suitable density and water content of clay components according to the modelling.
- Lab and small-scale field testing of erodability of clay components in perforated tubes.
- Lab testing of the maturation rate for assessment of the theoretical model using different water salinities and perforation geometries.
- Manufacturing of clay components for plugging of short and long holes.
- Investigation and pre-testing of alternative methods for plugging short holes by use of clay.

Sub-project 2

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

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

Sub-project 3

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

- Demonstration of the feasibility of the basic plugging method, i.e. placement of segments of jointed units of perforated copper tubes filled with highly compacted Na-bentonite columns (the basic concept).
- Demonstration of the feasibility of filling parts of the borehole that intersect fracture zones with chemically stable quartz-based fill.
- Demonstration and evaluation of a technique to bring down a dummy for checking the clearance of a real plug segment before installing it.
- Demonstration of the accuracy of replacing natural water in the hole by tap water.

Sub-project 4

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

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

2.6.3 Results

Sub-project 1 – A report "Theoretical study of water saturation and homogenisation of borehole plugs" has been completed by Clay Technology. It has been taken as a basis for selecting the geometry of the perforation of the copper tubes used in the various plugging tests. In addition, tests of prototype equipment for installation of bentonite without any copper pipe have been performed.

Laboratory test on erosion rate by flushing water in a pipe equipped with bentonite copper tube has been performed, see Figure 2-21. A separate report has been completed by Clay Technology for selecting a suitable clay density and the way of manufacturing clay columns for the various plugging tests.

Sub-project 2 – Preliminary structural modelling of the 5 m holes has been made for selecting suitable holes for plugging and pressuring in the pair-wise arranged holes. Hydraulic characterisation has started (inflow tests) and the remaining packer tests will start during the first quarter next year.

Sub-project 3 – Most of the performed work concerns the deep hole OL-KR-24 at Olkiluoto. The work was finalised in the end of 2005 and has comprised:

- Borehole and core inspection for identifying sections that needs to be stabilised.
- Study of the stabilisation work in OL-KR24.
- Preparation of perforated copper tubes for 76 mm holes by reducing the dimensions of standard 76.1 mm tubes to 72 mm.
- Development and manufacturing of techniques and tools for placing clay plugs in deep holes.
- Testing of the joints between copper tubes.
- Development and manufacturing of techniques and tools for placing cement/quarts plugs in holes.
- Placement of plug comprising of cement/quartz (top and bottom) and clay (middle) at the –520 m level in borehole OL-KR24.

Sub-project 4 – Preliminary plans have been worked out for plugging of wide holes. Three techniques will be tested and the design of equipments to mill slots in 200 mm holes has been initiated.

Figure 2-21. *Lab and small-scale field testing of erodability of clay components in perforated tubes.*

2.7 KBS-3 Method with Horizontal Emplacement

2.7.1 Background

The KBS-3 method based on the multi-barrier principle is accepted by the Swedish authorities and the government as base for the planning of the final disposal of the spent nuclear fuel. The possibility to modify the reference method and make serial deposition of canisters in long horizontal holes (KBS-3H), see Figure 2-22, instead of vertical emplacement of single canisters in the deposition hole (KBS-3V), has been considered since early nineties. The deposition process requires that each copper canister and its buffer material are assembled into a prefabricated so-called Supercontainer.

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

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

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

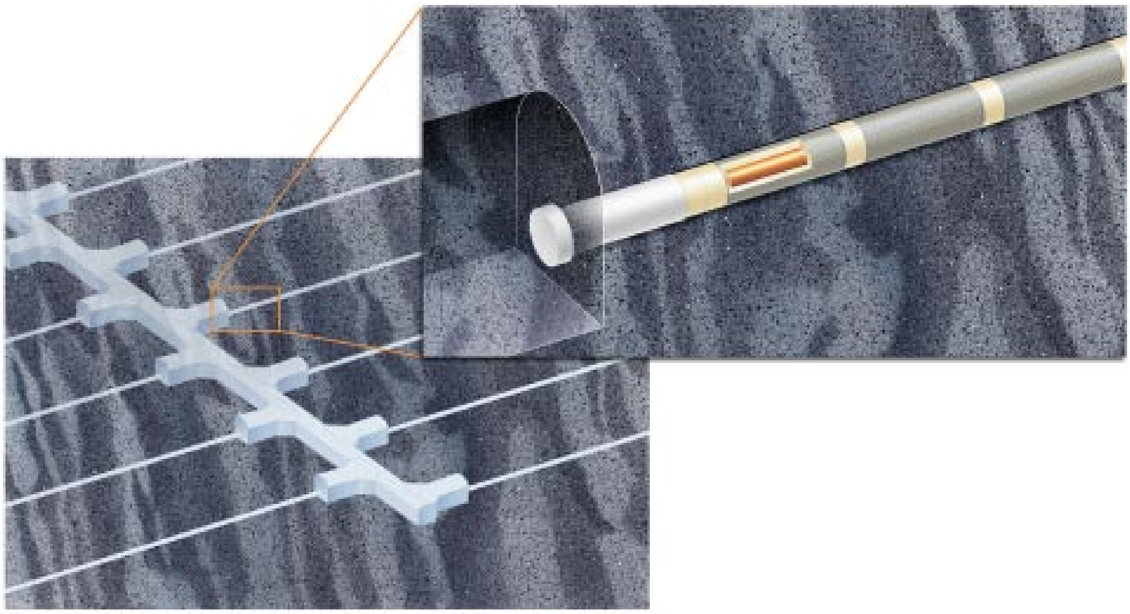


Figure 2-22. Schematic illustration of KBS-3H.

2.7.2 Objectives

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

The second step, the Basic design study /Thorsager and Lindgren 2004/, focuses on technology for excavation of holes, emplacement of Supercontainers, but also the design of the bentonite buffer inside the Supercontainer. In addition, an evaluation of the long-term safety of the concept is carried out.

2.7.3 Experimental concept

A need for a demonstration of the KBS-3H concept was foreseen in the KBS-3H feasibility study and it was decided to investigate a suitable location and prepare a site at Äspö HRL. The demonstration site is located at the –220 m level in a niche, 15 times 25 m. The niche is designed to accommodate vehicles, machinery and auxiliary equipment for drilling of the holes. Two horizontal holes with a diameter of 1.85 m have been excavated, one hole is 15 m long and the other is 95 m. The short hole will be used for construction and testing e.g. of a low-pH shotcrete plug and other design components, and the long hole will primarily be used for demonstration of the deposition equipment but also for evaluation of the chosen excavation method, see Figure 2-23.

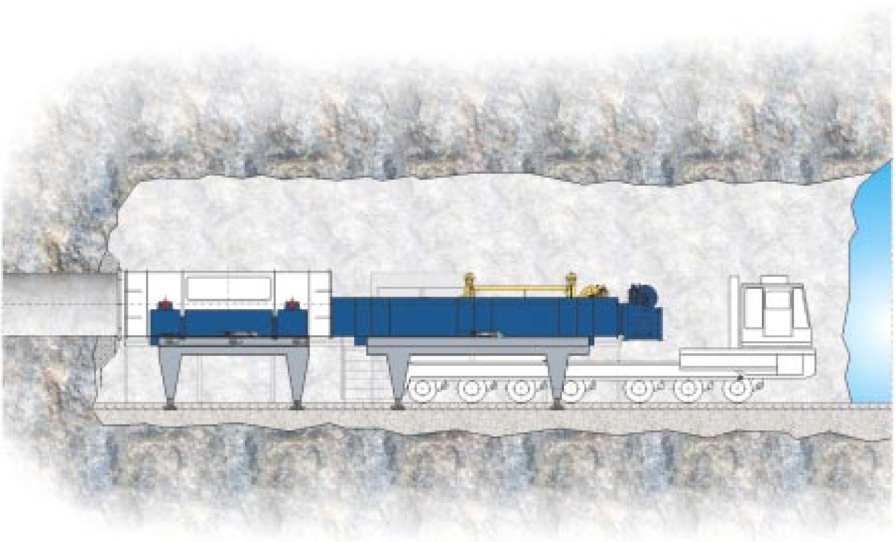


Figure 2-23. *Illustration of KBS-3H deposition equipment.*

2.7.4 Results

During 2005 work has been focused on the following parts:

- Excavation of the long hole for the full scale demonstration of the deposition equipment.
- Assembly of two Supercontainers.
- Manufacturing of deposition equipment.
- Continued research regarding buffer design and design of the different components in the hole.
- Resolving of critical issues related to the long-term safety of the concept and modelling.

The long hole was excavated in the first quarter of 2005 /Bäckblom and Lindgren 2005/. The long hole will primarily be used for demonstration of the deposition equipment but also for evaluation of the chosen excavation method. During the second quarter of the year, the hole was mapped and also the diameter along the hole was measured. The preparation work in the niche, for the deposition equipment, started in May and was finished in December. The work started with the foundation for the position blocks and also to prepare the roadway for the terminal vehicle. This work was performed during May to August. The docking- and gating flange was delivered in November and the mounting work, in the front of the long hole, was done in December.

The preparation work in the short hole, for a low-pH shotcrete plug, started in August with accomplishing slots for the pipes and instrumentation. The location for the plug is 2.5 m from the end of the hole. The shotcrete plug has a length of 1 m and behind it is a 1.5 m long water chamber. The responsible company Aitemin, installed the data sensors in the beginning of September. In October they started to spray a membrane on the rock wall for the water chamber. The company then had some problems when mixing the low-pH concrete. The concrete was stuck in the shotcrete gun, and the work stopped. After some changes in the recipe and equipment, the plug was made in the beginning of November. The plug was constructed in four layers and are now hardening until the planned pressure test in the middle of February, 2006. This part of the KBS-3H project is partly financed by the EC-project Esdred "Engineering studies and demonstration of repository designs".

The preparation work for the assembly of Supercontainers started in the third quarter of the year. The rebuilding of the existing hall near the tunnel entrance and the set up of the framework for the Supercontainers started in August and was finished in November. The work to manufacture concrete buffer, with the same density and compression strength as bentonite, for the Supercontainer started with some tests during the spring. The concrete buffer was manufactured during September to November. The high demands on density, compression strength and measurements were successfully fulfilled.

The copper canisters, gamma gates and perforated steel sheets were delivered in November and the assembly could start in the beginning of December. The assembly of the two Supercontainers were successfully performed during three days and they are now ready for the tests of the deposition equipment. The deposition machine will be delivered the first quarter of next year. This part of the KBS-3H project is partly financed by the EC-project Esdred.

Other parts in the KBS-3H project is the Safety Case work, the design of the repository layout and the adaptation of the KBS-3H concept to Olkiluoto data. Work with the buffer design has continued throughout the year /Börgesson et al. 2005/.

2.8 Large Scale Gas Injection Test

2.8.1 Background

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

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

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

2.8.2 Objectives

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

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

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

2.8.3 Experimental concept

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

In the field laboratory instruments continually monitor variations in the relative humidity of the clay, the total stress and pore water pressure at the borehole wall, the temperature, any upward displacement of the lid and the restraining forces on the rock anchors. The experiment is a "mock-up test" which does not use any radioactive materials. An illustration of the experimental set-up is shown in Figure 2-24.

The Lasgit experiment consists of three operational phases; the installation phase, the hydration phase and the gas injection phase. The installation phase was undertaken from 2003 to early 2005 and consisted of the design, construction and emplacement of the infrastructure necessary to perform the Lasgit experiment. The hydration phase began on the 1st February, 2005 with the closure of the deposition hole. The aim of this phase of the experiment is to fully saturate and equilibrate the buffer. This will be done by:

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

The saturation will be monitored by measuring pore pressure, total pressure and suction at both the buffer/rock interface and key locations within individual clay blocks. The hydration phase will provide an additional set of data for (T)HM modelling of water uptake in a bentonite buffer.

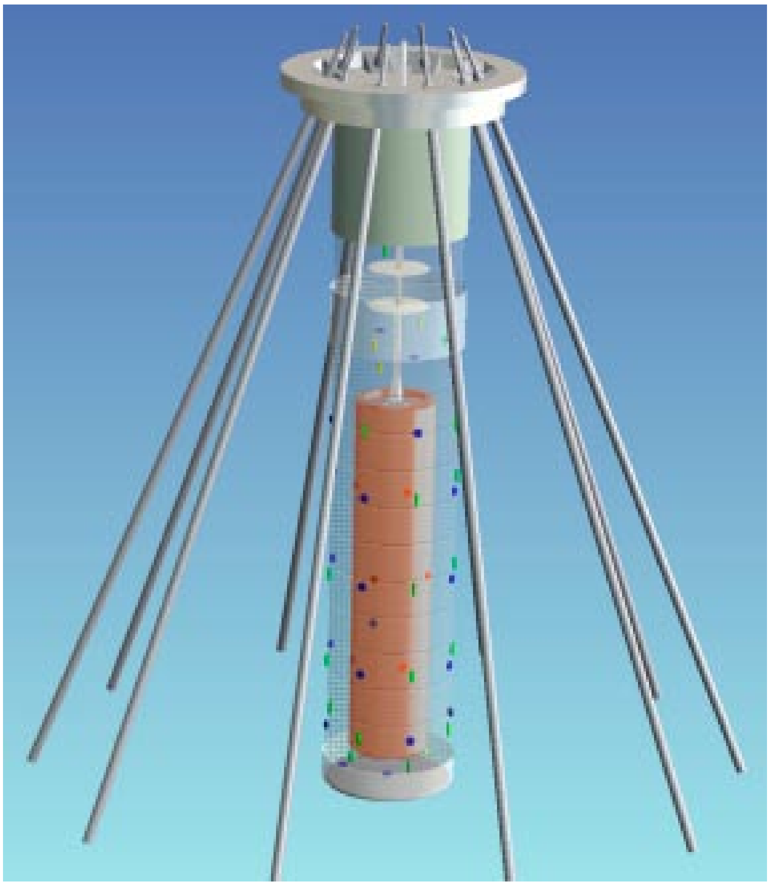


Figure 2-24. *Layout of the Lasgit experiment showing the copper canister, the bentonite buffer, the location of some of the instrumentation, the plug and rock anchors.*

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

2.8.4 Results

The Lasgit deposition hole was closed on the 1st February, 2005, signifying the start of the hydration phase. Groundwater inflow through a number of conductive discrete fractures resulted in elevated pore water pressures. This problem was addressed by drilling two pressure-relief holes in the surrounding rock mass.

Artificial hydration began on the 18th May, 2005 after 106 days of testing. Initial attempts to raise pore water pressure in the artificial hydration arrays often resulted in the formation of preferential pathways. These pressure dependent features were not focused in one location but occurred at multiple sites at different times in the test history. These pathways appear to be relatively short lived, closing when water pressure is reduced.

Monitored pore water pressures within the clay remain low, ranging from 15 kPa to 130 kPa. This is in contrast to the water pressure measured at the face of the deposition hole which ranges from 85 kPa to 600 kPa. Monitored radial stress around the clay continues to increase steadily ranging in value from 910 kPa to 2,640 kPa, with an average value of 1,935 kPa. Analysis of the distribution in radial stress shows a narrow expanding zone of elevated stress propagating vertically upwards to around 3.5 m. Stress measurements on the canister surface indicate radial stresses in the range 1,710 kPa and 1,920 kPa, which is comparable with the average value of radial stress monitored on the rock face.

Axial stress is significantly lower at 770 kPa. Axial stress within the clay ranges from 2,710 kPa to 3,450 kPa (excluding sensor PB901). Axial stress is non-uniformly distributed across the major axis of the emplacement hole and generally exhibits only minor sensitivity to changes in pore water pressure.

The axial force acting on the steel lid has reduced since the deposition hole was closed. The continuum axial swelling pressure within the bentonite is now greater than the initial pre-stress applied by the lid.

The axial force acting on the steel lid has reduced since the deposition hole was closed. The continuum axial swelling pressure within the bentonite is now greater than the initial pre-stress applied by the lid. The slight reduction in force during the latter stages of the test can be explained by convexing deformation of the steel lid in response to the uneven distribution in axial stress.

Displacement sensors indicate a fairly uniform drop in lid height relative to the gallery floor during the early part of the test history, mirroring the relaxation in the initial pre-stressing applied to the lid. Analysis of the subsequent displacement data suggests that a slight distortion of the lid may have occurred as it deforms to accommodate the uneven distribution in axial stress.

Analysis of the volumetric flow rate data indicates a disproportionably large flux into the bentonite around the canister, indicating a higher permeability value in this region of the system. Volumetric flow rate through the artificial hydration filters is not particularly sensitive to the modest pressures applied to the filters.

During 2005 the resaturation phase of the Lasgit experiment was examined using numerical models developed with the TOUGH2 code and the EOS3 equation of state module. The results from the model runs show that the impact of a single-flow fracture on the overall saturation process was likely to be limited. In contrast, flow through the general rock mass and associated minor fractures could have a significant effect on the saturation process depending on the permeability value selected. The second group of models incorporating explicit representation of the individual bentonite rings and cylinders found that the rings around the canister were the most difficult to resaturate fully within the timescale of the experiment. In particular, if the gap between canister and bentonite rings seals quickly and effectively then full resaturation could take many years. The effectiveness of the seal between canister and bentonite appears to be a critical parameter in determining the overall time to saturate the facility.

The test is operating successfully and since closure of the deposition hole there have been no instrumentation failures. The Lasgit experiment continues to yield data of the highest quality amenable to the development and validation of process models aimed at repository performance assessment.

2.9 Temperature Buffer Test

2.9.1 Background

The aim of the Temperature Buffer Test (TBT) is to extend 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 systems carried out in underground laboratories: the Buffer Mass Test (Stripa), the Buffer/Container Experiment (URL in Canada), Febex (Grimsel Test Site), Canister Retrieval Test and Prototype Repository (Äspö HRL).

2.9.2 Objectives

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

2.9.3 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 between the probe and the bentonite, as thermal protection for the bentonite, to keep the temperature below 100°C.

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

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

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

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

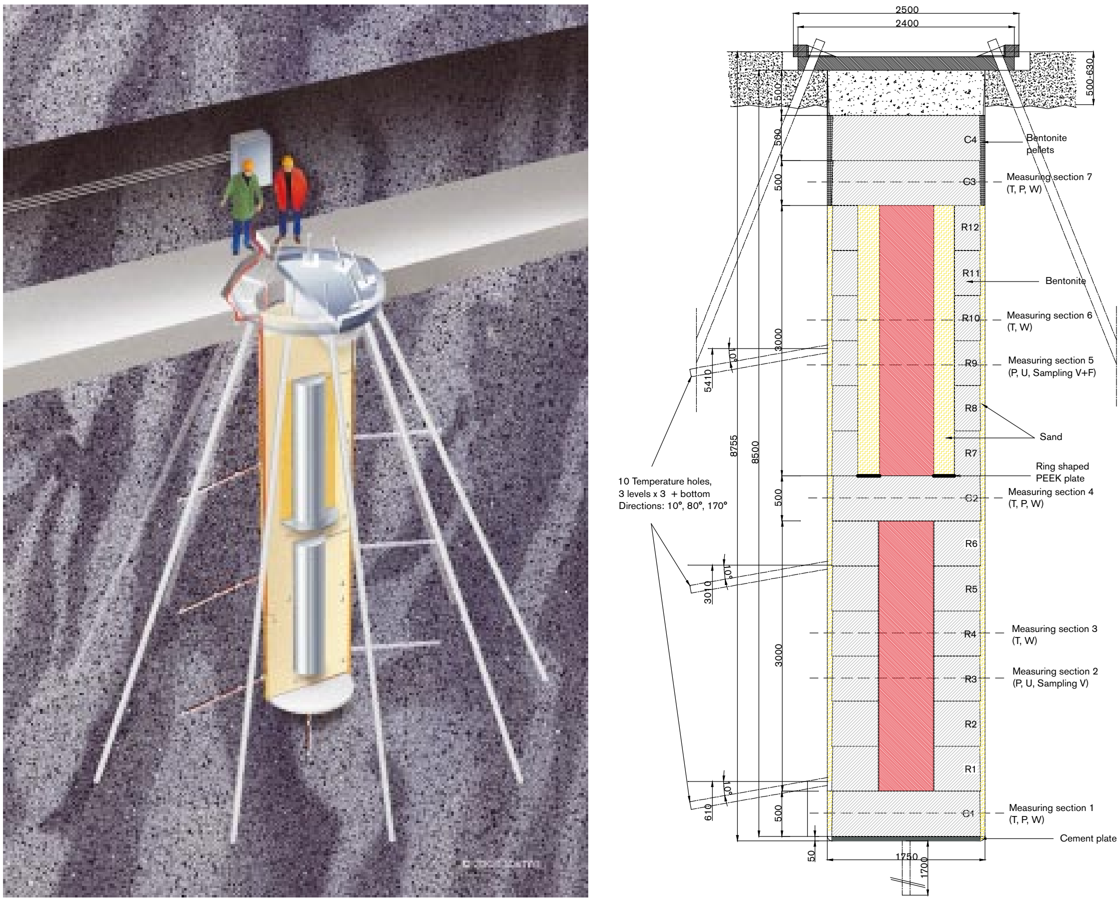


Figure 2-25. Principle design and experimental set-up of the Temperature Buffer Test.

2.9.4 Results

Experimental results

The experiment has generated data since the start in March 2003. The results include measurements of temperature, relative humidity, total pressure, pore pressure and cable forces in the anchoring system. The water inflow into the sand filter surrounding the experiment is also recorded. The data are reported in sensor data reports /Goudarzi et al. 2005c/.

The thermal conditions in the experiments at the end of 2005 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.

The hydration of the buffer is illustrated in Figure 2-27. These results indicate that the buffer around the upper heater was close to full saturation already at the end of 2004, whereas the interior of the buffer around the lower heater still appears to be desaturated. The developments around the lower heater are shown in Figure 2-28. The relative humidity at the innermost sensor was fairly constant at 62% up till 2nd August, 2005, after which the value has increased significantly. The change coincided with the plugging of the tubing to a leaking pressure transducer, located 0.25 m directly below the RH-sensor in question. This leakage therefore appears to have maintained desaturated conditions, at least locally, up till this event.

The filter mats between the upper cylinders were activated on 9th December, 2005. This is reflected by the recent saturation event in the upper part, see Figure 2-27.

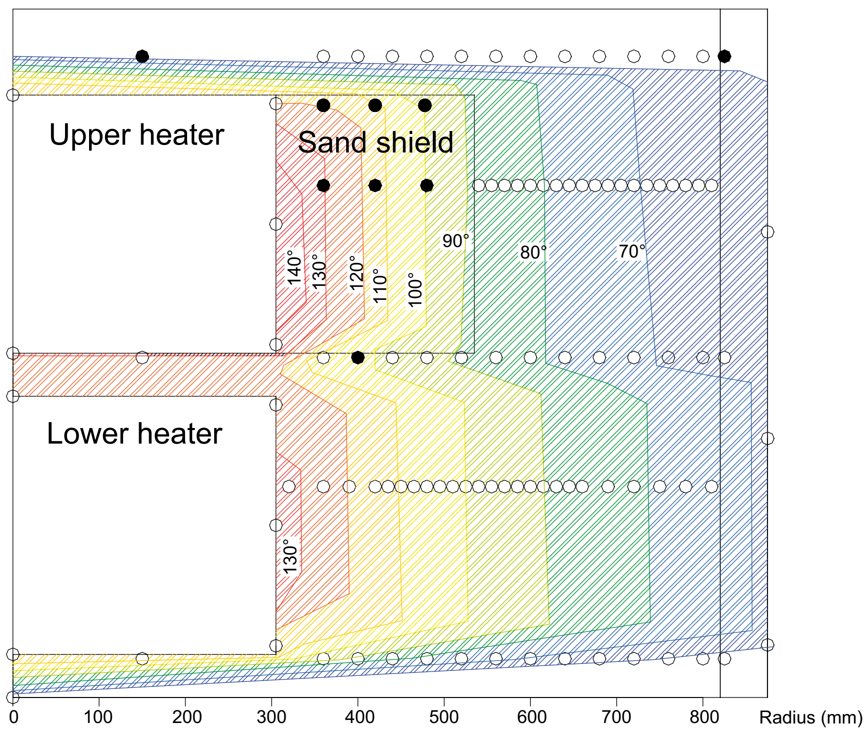


Figure 2-26. *Temperature distribution at the end of 2005 (rings indicate sensor positions and filled rings indicate sensors out of order).*

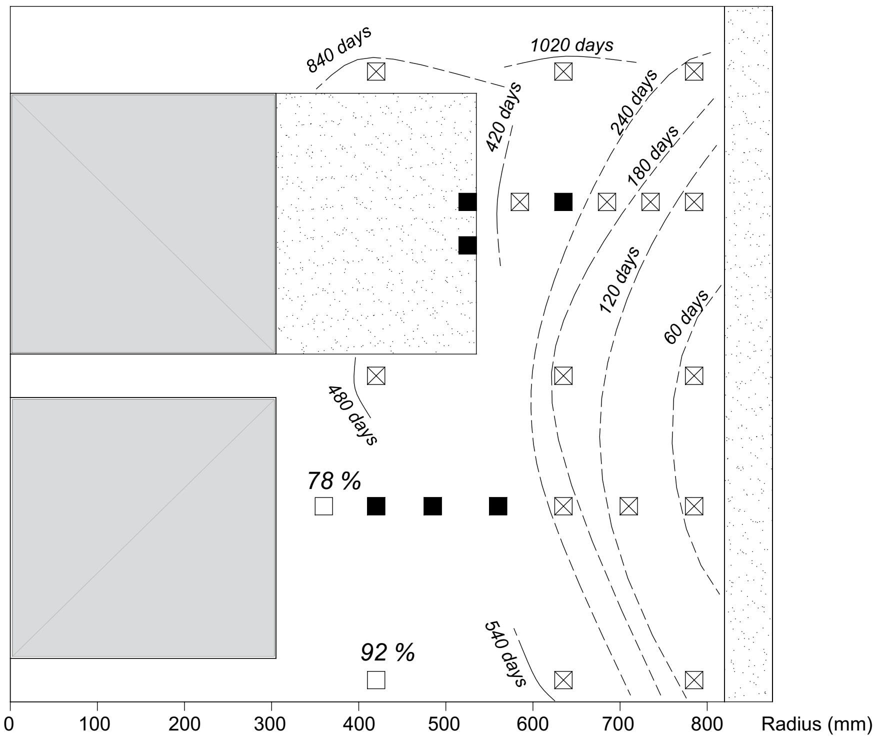


Figure 2-27. *Occurrences of saturation at the end of 2005 (boxes represent sensor positions, ticked boxes indicate saturation, filled boxes indicate sensors out of order and percentages are current RH values).*

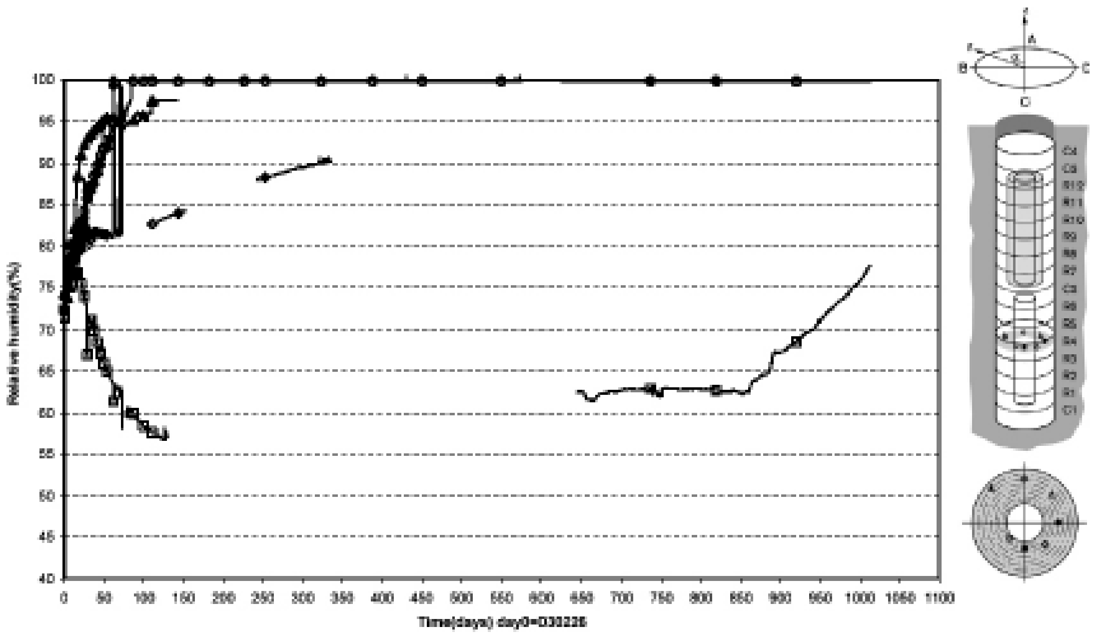


Figure 2-28. *Measured relative humidity in ring 4 around the lower heater as a function of time (2003-03-26 to 2006-01-01).*

A compilation of recent total pressures is shown in Figure 2-29. From this a number of observations can be made. Higher pressure levels occur in the outer parts throughout the experiment. An exception is the upper cylinders, which display the lowest pressure levels. The conditions in the lower and the mid-section cylinders are quite isostatic, while the sections around the heaters are characterised by deviatoric stresses, with relatively lower radial stresses.

Modelling results

One modelling task has been performed during 2005. This was a blind prediction of a mock-up test, denoted TBT_2. The mock-up test was conducted by CEA (France) and designed to mimic the conditions at the interior of the buffer around the lower heater in TBT. The objective of this test was to study the phenomena of desaturation and the role of temperature gradients and temperature levels and to check the possible existence of threshold temperature gradients.

The modelling task was carried out by groups from UPC (Spain), EDF (France) and Clay Technology (Sweden) during the period April–June 2005. Predictions and experimental results were presented at the modelling meeting in Barcelona in October 2005. The predictions were based on information of geometry (Figure 2-30), initial density and water ratio, and a prescribed thermal protocol (Figure 2-31). Results on temperature, relative humidity and stresses were requested for certain scan-lines and points in time.

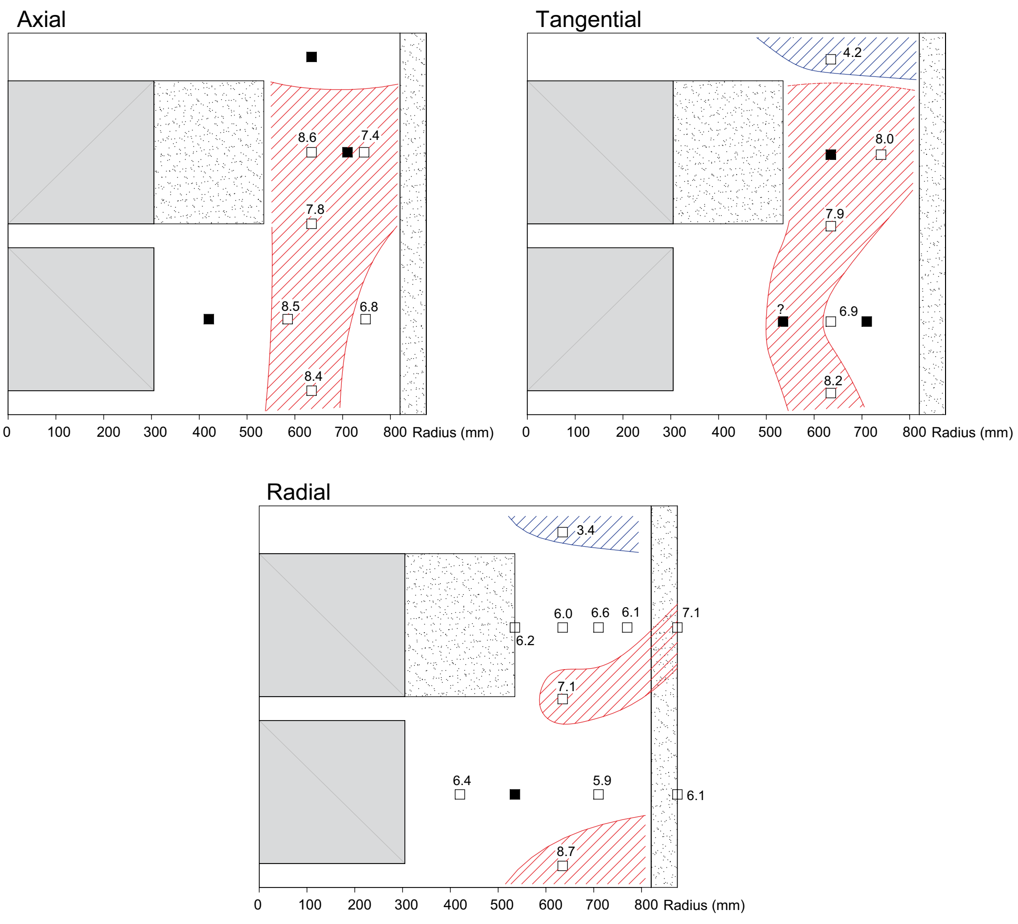


Figure 2-29. *Total pressure distribution (values in MPa) at the end of 2005 (boxes represent sensor positions, filled boxes indicate sensors out of order, levels above 7 MPa are marked red and below 5 MPa are marked blue).*

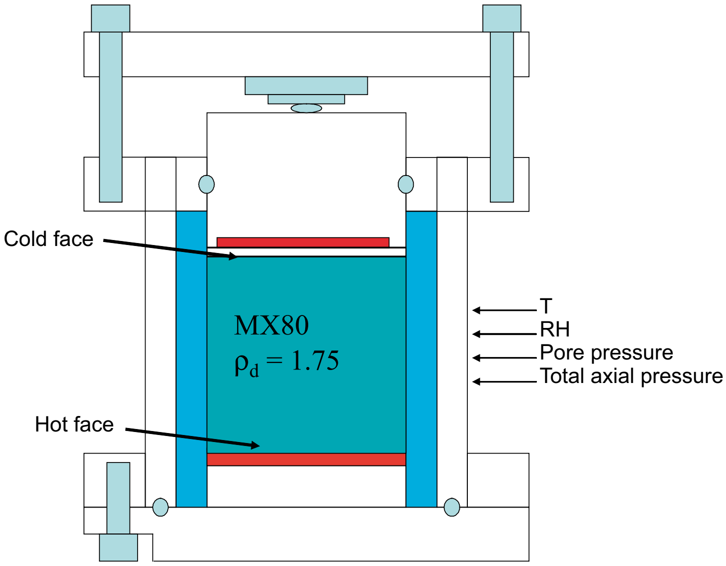


***Figure 2-30.** Design of the TBT_2 mock-up test.*

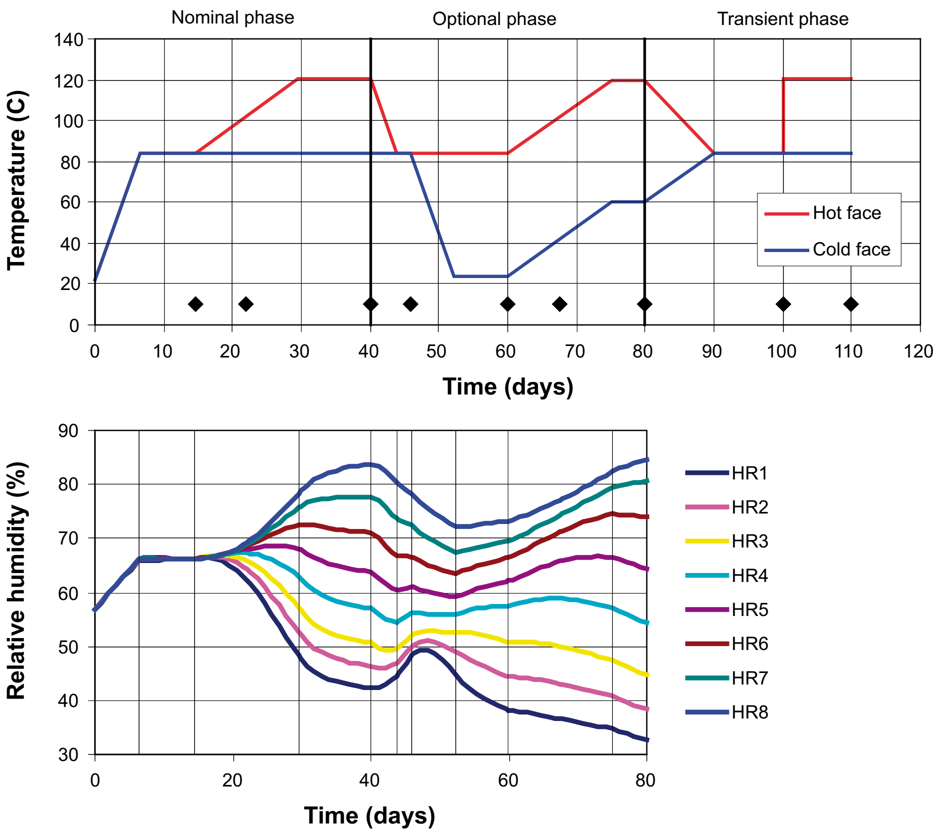


***Figure 2-31.** Prescribed thermal protocol (upper figure) and modelling results from the Clay Tech-team (lower figure) for TBT_2 mock-up test.*

Both predictions and the mock-up test showed that moisture redistribution takes place as soon as there are thermal gradients (Figure 2-31 and Figure 2-32). The results therefore do not support the notion of thermal threshold gradients. In addition, the modelling of different sample lengths showed that the temperatures at the hot and cold ends determine the extent of moisture redistribution rather than the thermal gradient.

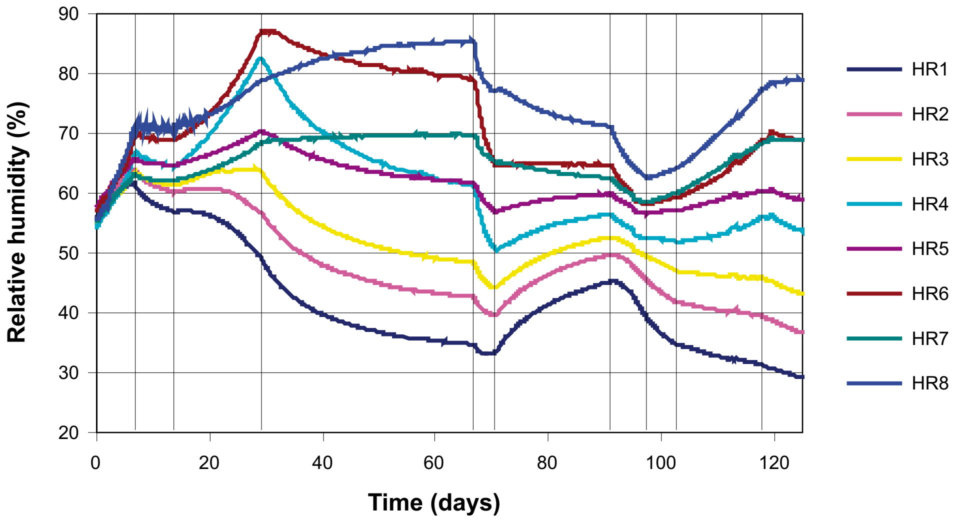


Figure 2-32. *Experimental results from TBT_2 mock-up test. The actual time-scales were slightly different than the prescribed protocol /Gatabin and Billaud 2005/.*

2.10 Rock Shear Experiment

2.10.1 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 these properties is the possible displacement along the fracture caused by seismic events. The buffer in KBS-3 is assumed to protect the canister from loosing its integrity for instant displacements up to 100 mm. The forces on the canister at such a major displacement have been modelled as well as analysed based on experiments in laboratory scale (small up to 1:10 scale). The results are, however, proposed to be verified in larger scale than 1:10, if a significantly more accurate criterion shall be feasible to apply in the accepting/rejecting process.

2.10.2 Objectives

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

2.10.3 Experimental concept

The test set-up is planned to use the site of the Äspö Pillar Stability Experiment when the Rock Mechanics test there has been completed. Two full scale deposition holes then exist with a rock pillar of one metre in between. Figure 2-33 illustrates the present, schematic idea for a test set-up. The left deposition hole is used for the buffer and canister, while the right deposition hole is used for the shearing equipment. Half of the rock between the holes is removed (is partly fractured after the Apse test) 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 steel structure and is mobile in the direction of the shearing. The hole is plugged by a combined steel and concrete structure, which is anchored to the rock by a steel beam or by cable bolts as in the Canister Retrieval Test and the Temperature Buffer Test.

The shearing may not be done before the buffer has saturated, but this time can be reached after about two years by using highly saturated bentonite blocks, 95–98% saturation, and lining the hole with permeable mats for artificial water supply. Planned shearing speed is 0.1 m/s. For this shearing speed pistons may be used as shown in Figure 2-33.

2.10.4 Results

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

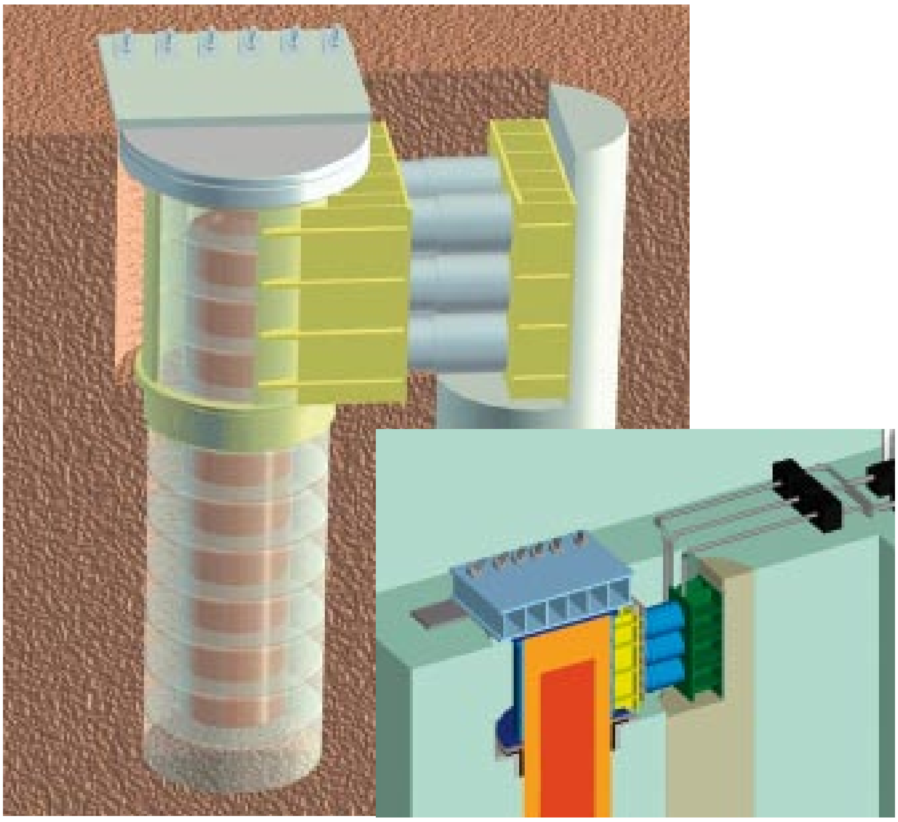


Figure 2-33. *Schematic view of a possible test set-up for verification of the stress and strain a canister may exhibit during an instant shearing of 100–200 mm.*

2.11 Learning from Experiences

2.11.1 Background

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 performed in the projects: Canister Retrieval Test, Prototype Repository and Backfill and Plug Test.

2.11.2 Objectives

In this project these experiences are documented and analysed with respect to possible improvements as well as acceptable water inflows. The prime objective is to answer questions and provide information to the work on the SKB's applications for an encapsulation plant and a final repository for spent fuel. The aims are to:

- Compile results from more than ten years of performed engineering experiments in Äspö HRL.
- Compile and evaluate experiences from methods for emplacement of buffer and canisters, backfilling of tunnels, and estimate acceptable water inflows for the applied methods.

2.11.3 Results

The experience from the large-scale experiments has been documented and analysed with respect to the practicality in handling of buffer and backfill materials as well as of full-scale canisters and to selection of instrumentation for recording important processes in the evolution of these materials on site. This has led to improved understanding of the performance of the various components and to confirmation of the applicability of the KBS-3V concept.

In certain respects the experience gained is very valuable, like the conclusion that the instrumentation may control some processes like the rate of water saturation of the buffer and backfill by water migration along cables to the sensors, which thereby yield signals that may not represent uninstrumented material. Other findings of importance is that the electrical installations for providing the canister heaters with power can malfunction because of chemical processes and that electrical potentials can be set up that affect the accuracy of the measurements. Water inflow in tunnels and deposition holes in the phase of placing buffer and backfill has been found to be a controlling factor of the constructability. No general safe limit with respect to inflow per metre tunnel and time unit can be defined, it depends on the technique (clastic or block backfills) and on the rate of backfilling.

A draft list of questions to be answered as a basis for the applications has been compiled and a number of practical issues have been investigated, primarily:

- Water inflow in tunnels and deposition holes in the phase of placing buffer and backfill; this work continues.
- Performance of instruments in buffer and backfill.
- Accuracy of recordings of temperature, wetting rate and build-up of swelling pressure compared to predictions.
- Identification and assessment of major chemical processes in buffer and backfill in the wetting phase and a few years thereafter.

2.12 In Situ Corrosion Testing of Miniature Canisters

2.12.1 Background

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

2.12.2 Objectives

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

2.12.3 Experimental concept

Miniature copper canisters, with a diameter of 15 cm, will be emplaced in boreholes, with a diameter of 30 cm. The canisters will be exposed to natural reducing groundwater during several years and the experiment will be monitored.

2.12.4 Results

During 2005, the copper canister components have been designed and manufactured and the preparation of the deposition holes was initiated. The components are currently being prepared for electron beam welding. The support cages to hold the model canisters have been designed and the first one is being manufactured, see Figure 2-34.

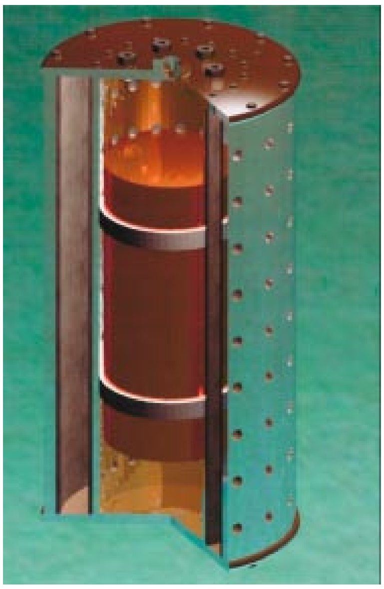


Figure 2-34. *Miniature canister with supporting cage.*

Long-term durability testing of the sensors is in progress and the sensors chosen have performed satisfactorily. The customised electrochemical monitoring kit is being manufactured. Five 76 mm holes 5 m deep have been drilled and these holes have been reamed to 350 mm down to a depth of 2.5 m. Five casings have been installed and grouted in the right rock wall in the niche NASA 3384 A.

In the niche, the rock volume behind the right wall will be grouted to a depth of 1 m in order to get a higher groundwater pressure in the boreholes. The experiment will be installed and initiated during the next year. The activities comprise e.g. reaming of the last part of the boreholes to 302 mm, emplacement of support cages with canisters and installation of instrumentation.

2.13 Task Force on Engineered Barrier Systems

2.13.1 Background and objectives

The Task Force on Engineered Barrier Systems (EBS) was in 2000 decided to focus on the water saturation process in buffer, backfill and rock. Since the water saturation process also was a part of the modelling work in the Prototype Repository project, the work was transferred to this project, and the task force was put on a stand-by position. As the European Commission funding of the Prototype Repository project ceased in February 2004 it was judged most convenient to activate the task force on EBS and continue the modelling work in the Prototype Repository project within this frame, where also modelling work on all other experiments can be conducted. One possibility is also to incorporate the modelling work on EBS experiments carried out in the Grimsel Test Site (GTS) in Switzerland.

2.13.2 Results

The first phase of the project is ongoing. It comprises four years and addresses two tasks: (1) THM processes and (2) gas migration in buffer material, and ends with a state-of-the-art report. The work will take into account the interaction between the buffer and backfill barriers and the host rock. Experimental data are in both tasks taken from small scale laboratory experiments as well as large scale field experiments, which will be selected by the task force in the course of the work.

Two benchmark tests for task 1 (THM-processes) was delivered in spring 2005 and the modelling teams were requested to simulate these laboratory tests:

- Benchmark 1.1 – THM mock-up experiments on compacted MX-80 bentonite, with two different initial water contents. A thermal gradient was applied in the axial direction of the samples and water was supplied at the cold end. The experiments have been performed by CEA.
- Benchmark 1.2 – Large-cell experiments on compacted Febex bentonite, which are currently being performed by Ciemat in their laboratory in Madrid. One of the tests is kept under isothermal conditions and the other test is performed under a thermal gradient.

The modelling results were reported at the Task Force meeting that was held in October. At this meeting the benchmark tests for task 2 (gas migration) was presented. The reports from the modelling teams with code descriptions and modelling results will be audited. For more information see Chapter 6.

A suggested EC project named Theresa was also presented. It consists of 6 work packages. The present Task Force on Engineered Barrier Systems is proposed to be included in WP4 – Coupled Processes in Buffer and Near-Rock Interfaces. Theresa will be concluded 2009.

3 Geoscience

3.1 General

Geoscientific 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. The major aims are to:

- Establish and maintain geoscientific models of the Äspö HRL rock mass.
- Establish and develop the understanding of the Äspö HRL rock mass properties as well as the knowledge of applicable measurements methods.

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 is done in order to increase the understanding of geometries and properties of rocks and structures, which is subsequently used as input in the 3D modelling, together with other input data. 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 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

Geological mapping and rock characterisation

Besides that some computer work is lagging, geological mapping of the Äspö tunnels, deposition holes etc is at present in phase with the demands. During the year of 2005 e.g. mapping of the two horizontal deposition holes of the KBS-3H project on the –220 m level of Äspö HRL, the slot walls and blocks of the Äspö Pillar Stability Experiment and the vertical outermost deposition hole in the Q-tunnel as well as the niche NASA3384A on the –450 m level was performed. All the major deformation zones have been marked out temporarily in the tunnels. Permanent signs will later replace the temporary markings. Old photographs from the tunnel mapping etc have been converted to digital format and are now available on CD:s and on the SKB's computer network. Almost all cores, mostly from the short holes, have been shipped to external companies who also performed the core logging.

The work with the final report concerning the feasibility study (phase 1) of the ongoing RoCS-project (Rock Characterisation System) commenced at the end of 2005. Various methods (laser scanning and photogrammetry) to create 3D-pictures of the tunnel layout have been tested. Information about software associated with these methods as well as software for 3D rock characterisation has been collected. The present rock characterisation system TMS, now with two working stations, has been provided with new and more powerful computers.

In addition, the geologist group has participated in a number of projects as advisors on geological matters. Such projects were for example: (a) In Situ Corrosion Testing of Miniature Canisters, (b) Cleaning and Sealing of Investigation Boreholes, (c) KBS-3 method with horizontal displacement, (d) Äspö Pillar Stability Experiment and (e) Large Scale Gas Injection Test.

Geological model and tunnel geometry

Updating of the geological model of Äspö HRL continues. During the year of 2005 it was particularly the areas around the –220 m and –450 m levels that were of special interest due to some of the ongoing projects on these levels. When needed, other parts of the Äspö HRL 3D-tunnel geometry will be upgraded too. An upgraded model version that will fit RVS (Rock Visualization System) is already available in the Simone model database.

3.3 Heat Transport

3.3.1 Background and objectives

The canisters in a final repository 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 temperature field is dependent also on the layout of the repository. The design criterion is the maximum temperature allowed on the surface of the canisters or the buffer. A low thermal conductivity in the rock leads primarily to a larger distance between canisters than in the case of a high thermal conductivity.

The aim is to analyse the thermal properties of the rock in different scales to decrease the uncertainties in the estimates of the temperature field in and around the repository. Less uncertain estimates of the temperature field make it possible to optimise the distance between canisters in the repository layout. The work includes inverse modelling of thermal properties, measurements of thermal properties of the rock at different scales and examination of the distribution of thermal conductivities from density loggings.

3.3.2 Results

The scale at which variations of thermal conductivity is significant for the maximum mean temperature on the canister has been investigated by numerical modelling. The results show that no significant variation of the temperature occurs on the canister at scales below 1 m. The variation (standard deviation) increases linearly up to about 10 m. For small scales of thermal conductivity variations, the temperature on the canister surface is levelled out, see Figure 3-1.

The scale dependence for laboratory measurements of thermal conductivity with different sensor size has been investigated on samples from Äspö HRL. The difference in results seems to be non significant. During 2005 the project was finalised and the results reported /Sundberg et al. 2005/.

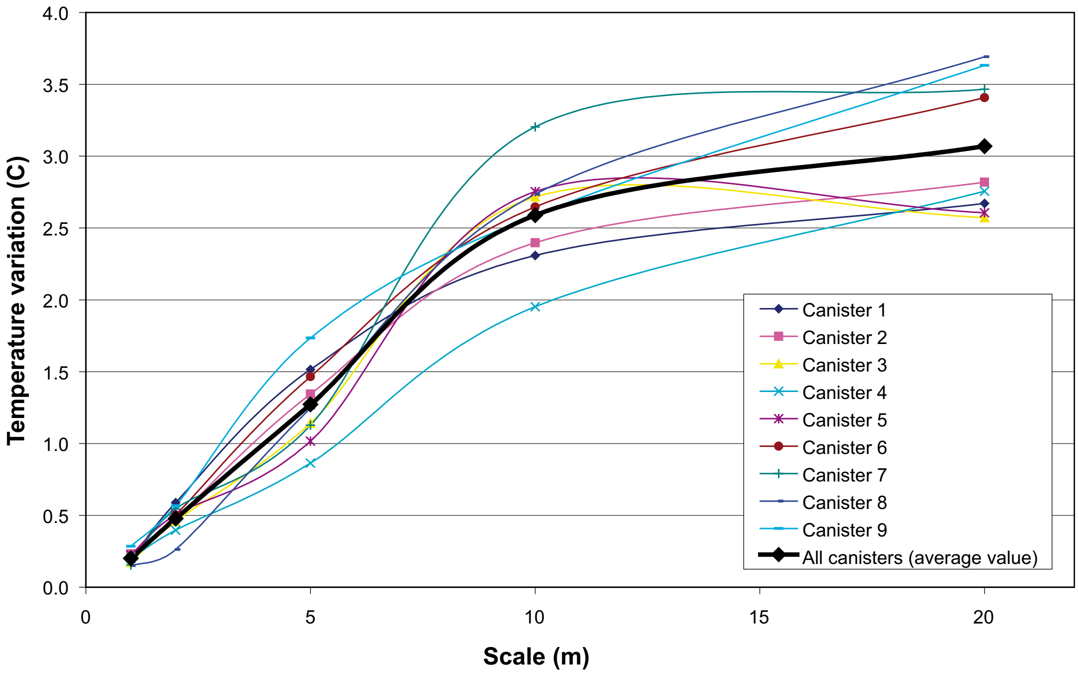


Figure 3-1. *Maximum temperature variations based on average value of one standard variation for each canister /Sundberg et al. 2005/.*

In earlier project a relationship between density and thermal conductivity has been observed /Sundberg 2002/. Within the density range of Ävrö granite, the thermal conductivity is inversely proportional to density. By the use of density logging, the relationship makes it possible to predict the spatial variability of conductivity in the rock mass. In this report, a physical explanation is suggested of the relationship, based on magma composition and mineralogy.

In the Prototype Repository at Äspö HRL, measurements of temperatures have been conducted. Earlier, measurements of the rock thermal properties have been conducted both in laboratory and in situ. A prognosis model of the thermal properties has been established based on these data. The prognosis model is evaluated towards thermal conductivity values calculated through inverse modelling. The inverse modelling is based on an iterative process where a fitting of measured and calculated temperatures is performed with a numerical model. There is good agreement between prognosis of thermal conductivity in the Prototype Repository and the result from inverse modelling based on 37 different temperature sensors. The rather low thermal conductivity in the Prototype Repository is verified, see Figure 3-2. However, some sensors seem to be influenced by water movements. The evaluation also shows that the initial conditions before the heating started
where not stable, regarding temperature and water movements.

Different types of variograms can be used to analyse the spatial distribution of conductivities, preferably calculated from density loggings (semi variograms of thermal conductivity) and the spatial distribution of rock types (indicator variograms), see Figure 3-3. The main challenge is to determine the spatial variability in rock domains where Ävrö granite is absent or subordinate. In order to model the spatial variability for these domains in a reliable way more measurements are required, especially for the dominating rock types.

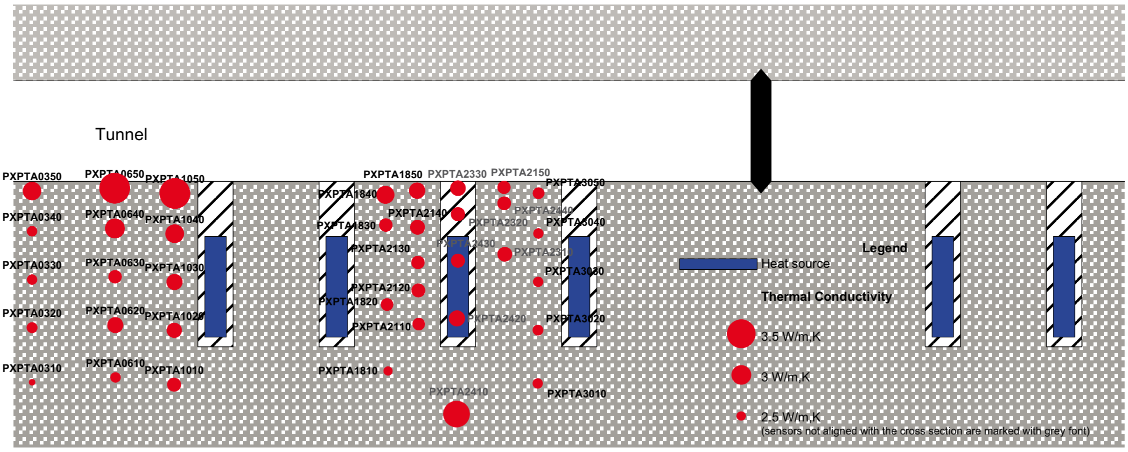


***Figure 3-2.** Estimated thermal conductivity values from inverse modelling of temperature data. Simulation including curve fitting for 160 through 525 days including a correction for thermal drift of 0.2°C annually /Sundberg et al. 2005/.*

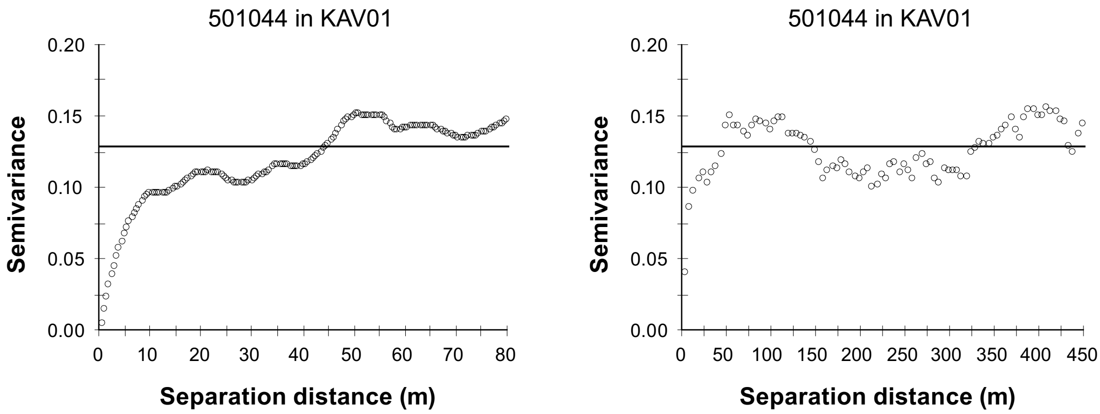


***Figure 3-3.** Indicator variogram of the occurrence of Ävrö granite (501044) in borehole KAV01 for two different scales: 0–80 m and 0–450 m separation distance. The diagrams are constructed based on lithological classification (boremap) /Sundberg et al. 2005/.*

A methodology for upscaling of thermal conductivity from measurement scale to a significant scale for the canister has been developed, see Figure 3-4. The variance is reduced when the scale increases but for some rock types the decrease in variance is low, mainly because of the high large-scale spatial variability. The methodology is used in the ongoing work with site descriptive models for Oskarshamn and Forsmark.

A Value of Information Analysis (VOIA) has been performed in order to estimate the value of additional investigations by studying how the new information reduces uncertainty in the *mean* thermal conductivity. Field measurements in a relevant scale yields most value while producing an improved relationship between density and thermal conductivity is the most cost-efficient alternative of the four studied investigation methods.

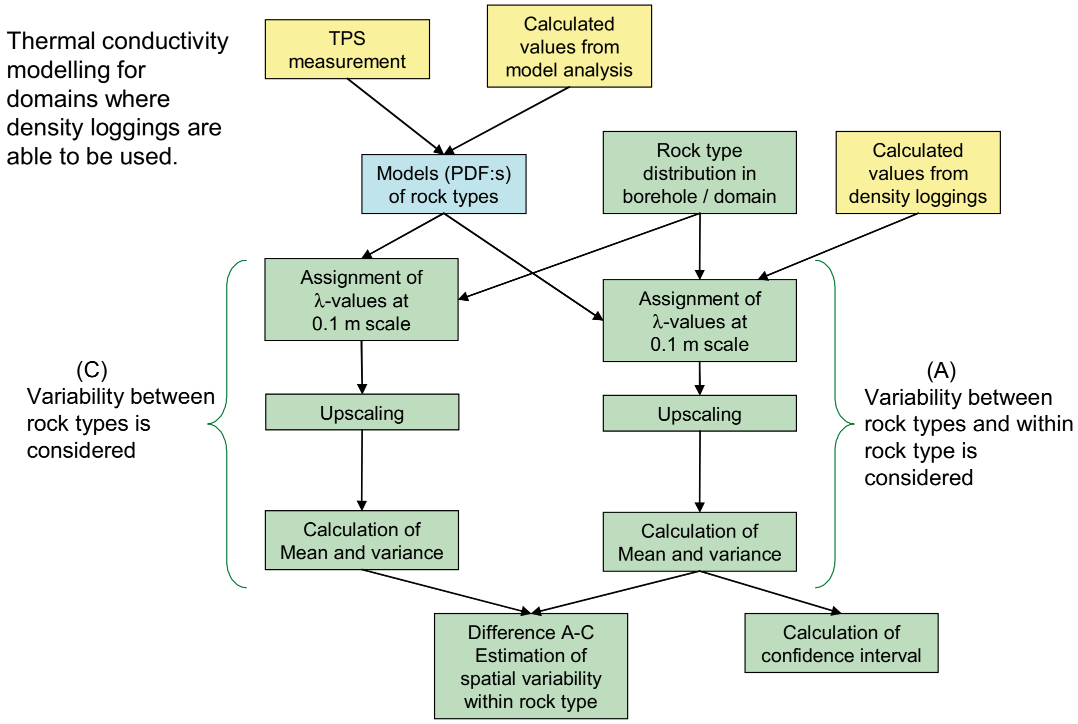


Figure 3-4. *Main approach (A) and (C) for modelling of thermal conductivity for domains where density loggings are applicable /Sundberg et al. 2005/.*

3.3 Inflow Predictions

3.3.1 Background

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

- Evaluation of experimental results from Äspö HRL. A good understanding of the mechanisms controlling inflow would improve the possibilities for good experimental set-ups and accurate result interpretation.
- Evaluation of potential repository sites. It is desirable to be able to predict the inflow conditions into the excavations, already before the construction work starts, based on hydraulic measurements made in small diameter boreholes.
- Evaluation of the expected bentonite buffer behaviour. The amount of inflow into deposition holes will influence the time needed for saturation and also the expected performance of the buffer.
- Design and optimisation of the repository layout. Poor prediction of inflow could lead to less optimal design alternatives.

3.3.2 Objectives

The main objectives for this project are to:

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

3.3.3 Results

Numerical study

So far, a comprehensive numerical analysis using the three-dimensional distinct element code 3DEC /Itasca 2003/ has been conducted to improve the knowledge about the effect of the effective stress redistribution caused by excavation on the fracture inflow into deposition holes in hard rock considering single-phase flow /Mas Ivars 2004/.

The objectives of this numerical study can be summarised as follows:

- To conduct a number of numerical simulations in order to increase the understanding of the coupled hydro-mechanical aspects of inflow into deposition holes and thereby improve the possibilities to predict inflow.
- To demonstrate that results of numerical analyses can be used in the planning of full-scale field tests of inflow at the Äspö HRL.

The results from the numerical study showed that:

- Considering the hydro-mechanical coupling is of critical importance for the total inflow in the models simulated.
- The most relevant parameters for the inflow, within the uncertainty ranges considered in this study, were the fracture shear and normal stiffness, fracture friction angle, fracture dilation angle and magnitude of minimum horizontal stress, σ_{zz}. Also of prime importance is the initial and residual hydraulic aperture of the fractures since the flow along the fractures is assumed to follow the "cubic law".
- The inflow into excavations can be largely underestimated when a linear fracture deformation model is used.
- Stress-permeability coupling can be considered as one of the causes for the less than expected inflow into large diameter holes (Figure 3-5).

Field experiment

The next phase of this project was performed in coordination with one of the last phases of the Äspö Pillar Stability Experiment (Apse), which involved the extraction of the pillar between the holes to study the effect of high stress concentrations obtained during the experiment. Before cutting and extracting the pillar, it had to be de-stressed. The de-stressing of the pillar was carried out by drilling a semicircular array of boreholes (destressing slot in Figure 3-6). The aim of this phase of the Inflow Predictions project was to acquire coupled hydro-mechanical data during the drilling of the slot.

Table 3-1. Fracture parameters for the different cases shown in Figure 3-5.

Fracture case	Normal stiffness GPa/m	Shear stiffness GPa/m
Case1	20.0	12.0
Case2	61.5	35.5
Case3	180.0	105.0
Case4	360.0	210.0
Case5	700.0	410.0

Friction angle = 30°, Dilation angle = 5°.

Hydraulic aperture (Initial = 30 µm, Residual = 5 µm and Maximum = 60 µm).

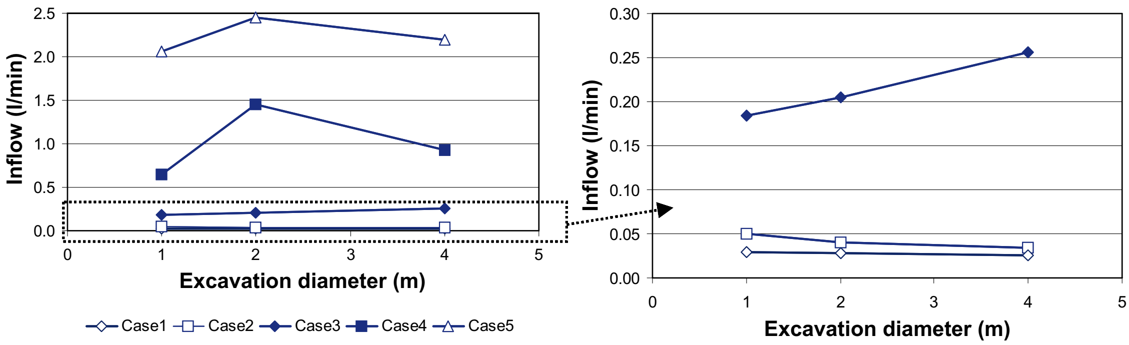


Figure 3-5. Calculated inflow versus excavation diameter for different fracture cases according to Table 3-1.

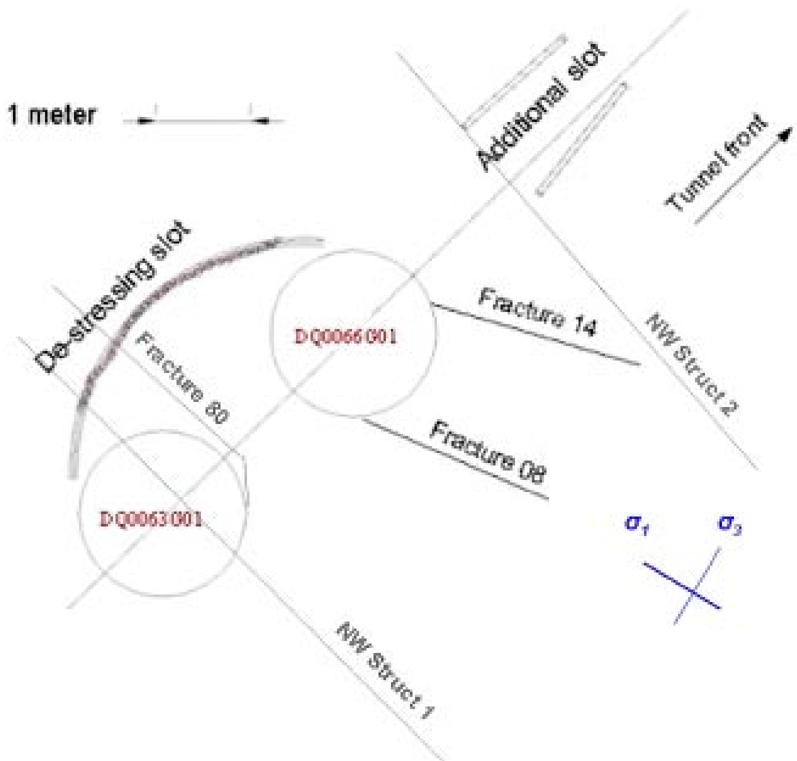


Figure 3-6. Layout of the hydro-mechanical data acquisition experiment at the Apse site (not to scale).

The de-stressing of the pillar was expected to cause a number of coupled hydro-mechanical effects in two NW-SE striking sub-vertical conductive fractures (fractures 08 and 14) intersecting the deposition hole (DQ0066G01). The effective normal stress acting on the conductive fractures was expected to change with the consequent influence in inflow. Besides, the change in normal stress would affect the fracture shear strength, which, combined with the change in shear stress along the fracture, could lead to slip and dilation of the fracture. Therefore, fracture displacements, fracture inflow and total inflow into the deposition hole were monitored during the drilling of the de-stressing slot.

Fracture normal displacements (opening) of up to 0.6 mm and shear displacements of up to 0.9 mm were registered during the drilling of the slot. The inflow coming from fracture 08 (Figure 3-6) increased from 2.4 l/min to 4 l/min and the inflow from fracture 14 increased from 6.1 l/min to 18 l/min. Before the drilling of the slot the water inflow from the two sub-vertical fractures monitored accounted for 60% of the total inflow into the hole. After the drilling of the slot the inflow coming from these two fractures was 72% of the total inflow.

Several boreholes in the HMS system (Hydro Monitoring System) were selected to assess the influence of the drilling of the de-stressing slot on the water pressure response on other locations at the Äspö HRL. Strong responses were found in boreholes KA3385A, KA3386A01 and KA2598A and a weak response was also registered in borehole KI0025F. A report on these and other results regarding the hydro-mechanical data acquisition experiment has been published /Mas Ivars 2005/.

There were no stress measurements while drilling the de-stressing slot. For this reason, to better understand the data acquired in the previously mentioned HM data acquisition project, a three-dimensional discontinuum mechanical modelling study of the de-stressing of the Apse pillar has been carried out using 3DEC. Previous to the definition of the conceptual model, mapping of the Apse pillar walls as well as the pillar blocks was carried out. The most relevant fractures for the purpose of this study were carefully selected and included in the model. The results from this modelling exercise show the stress redistribution in the Apse tunnel during the drilling of the de-stressing slot (Figure 3-7). A good match between the monitored and modelled fracture displacements has been achieved. The complete draft report is under review and will be published during 2006.

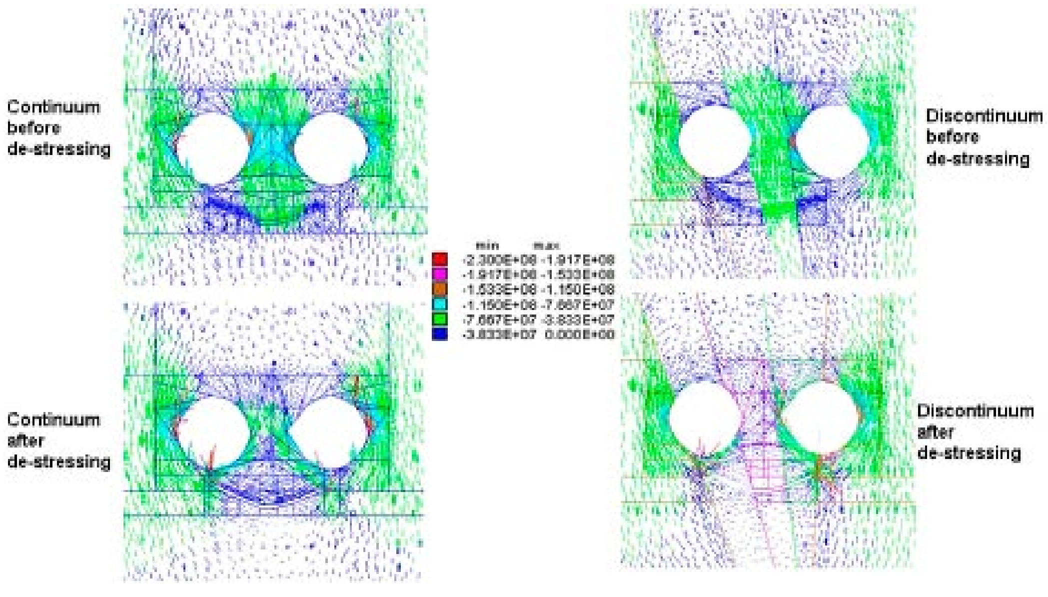


Figure 3-7. Horizontal cross-section showing the projected principal stress at 1.5 m depth from the floor of the APSE tunnel before and after the de-stressing slot has been excavated (colours by magnitude of σ_1).

3.5 Seismic Influence on the Groundwater System

3.5.1 Background and objectives

The Hydro Monitoring System (HMS) registers at the moment the absolute pressure of the groundwater in about 280 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 in a database.

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. The work is a reference for the understanding of dynamic influences on the groundwater around a repository.

3.5.2 Results

Data registered by the Hydro Monitoring System during 2005 have been stored in the database pending analyses. A computer code has been developed that may be used to find rapid pressure changes in the HMS data. Impact of earthquakes in Sweden and abroad and of blasts in Äspö HRL will be documented and analysed next year.

3.6 Rock Mechanics

The rock mechanic studies aim to increase the understanding of the mechanical properties of the rock and also to recommend methods for measurements and analyses. This is done by laboratory experiments and modelling at different scales and comprises:

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

3.6.1 Stress measurements and stress interpretation methods

Background and objectives

State of stress has a significant impact on the possibility for tunnelling at large depth, such as the planned final repository. Both improvements of existing measurement methods, as well as alternative methods for evaluation of the state of stress have strategic importance in tunnelling design and tunnelling works at large depth. Activities are planned within both these fields. The project is a joint SKB and Posiva project.

The main objectives of the study are to:

- Develop further possibilities for so called transient strain analysis of stress measurements by over coring for anisotropic conditions.
- Develop the overall strategies for back analyse of state of stress based on convergence measurements during tunnelling, and estimate the uncertainty bounds.

Results

The possibility to link the in situ stress field to hydraulic conductivity data, measured at the Äspö HRL, has been examined. Data from the TASQ tunnel were used and a few well-investigated fractures/fracture zones were analysed and modelled in detail. The aim was to examine the extent to which hydraulic heterogeneity (which is often perceived as stochastic) can be deduced by an idealised hydro-mechanical relationship. In particular, within-fracture-plane hydraulic variability for fractures that undulate within an anisotropic stress field is modelled by using a fracture-closure relationship that is assumed to apply "locally".

The study consists of (a) an analysis of existing field data, in particular for fractures for which good stress and hydraulic data exists. Special emphasis is given on geometry and hydraulic heterogeneity at the level of individual fracture planes and (b) modelling potential stress-aperture relations and borehole inflow for selected data.

Results imply that fracture undulation can appear as a unimodal, bimodal or trimodal fracture set in a stereonet projection. For the data studied, results support a potential link between within-fracture-plane hydraulic variability and the stress-field.

3.6.2 Understanding of variability of rock under different load conditions

Background and objectives

The strength of both intact rock and a fractured rock mass depends on the material properties, as well as the stress path a volume of rock is exposed to. The stage of knowledge in rock stability, to large extent based on the Zedex experiments in Äspö HRL, was published in 2001 /Martin et al. 2001/.

One of the concerns when building a repository is that, when blasting a tunnel, a zone of damaged rock will be produced around the tunnel periphery, and this zone, termed the Excavation Damaged Zone (EDZ), could act as a conductive structure for water flow and hence radionuclide migration by connecting fractures and creating a path out of the repository.

The overall objective of participation in the international project Decovalex Task 2 is to: (a) improve understanding of the evolution of the EDZ and (b) be able to numerically model the EDZ Thermo, Hydro, Mechanical and Chemical (THMC) mechanisms in a fractured crystalline rock mass.

Results

Within the Decovalex project SKB has funded a Ph.D. student during a three year period to develop strategies to characterise the EDZ from tunnels with the purpose to be a part of a quality assurance program during construction of a future final repository. This will also provide characterisation of a tunnel from the Äspö HRL to the modelling teams of the Decovalex project. The tunnel for the Äspö Pillar Stability Experiment (Apse) and the available excavation records provide unique opportunities for development of systematic methods to characterise the EDZ from inside of the tunnel.

During the first year of work for the Ph.D., laboratory tests have been conducted to investigate the effect of waters with different salinities on the uniaxial compressive strength of intact rock samples of the Äspö diorite. This information has been used to validate the results from several of the numerical models being used within the Decovalex project. The test results indicate a decrease of the uniaxial compressive strength for saturated samples compared to dry samples. The largest effect can be found for samples saturated with high salinity water. The results are presented in the two SKB reports /Savukoski 2005, Jacobsson and Bäckström 2005/.

A literature study concentrating on likely processes in the EDZ concerning the mechanical and chemical effects and mechanical testing of samples affected by different chemical processes are currently in progress.

A three dimensional model of the tunnel are being produced using laser scanning of the tunnel walls in different scales. The collection of data from the Apse tunnel has been concluded and the data analysis phase has just started.

3.7 Äspö Pillar Stability Experiment

3.7.1 Background

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

A pillar stability experiment 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.

3.7.2 Objectives

The Äspö Pillar Stability Experiment (Apse) is a Rock Mechanics experiment which can be summarised in the following three main objectives:

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

3.7.3 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 drift a vertical pillar was 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 is one metre. To simulate the confining pressure in the buffer (0.7 MPa), one of the holes was subjected to an internal water pressure via a liner. Convergence measurements, linear variable displacement transducers (LVDT), thermistors and an acoustic emission system were used to monitor the experiment. The experiment drift has a rounded floor to concentrate the stresses in the centre of the drift, see Figure 3-8.

Figure 3-8. *The Apse experimental drift shortly after the excavation.*

3.7.4 Results

The experiment was carried out as planned during 2004. The pillar was sawn into five large blocks which were removed from the experiment site during late 2004 and early 2005, see Figure 3-9. The remaining rock walls between the holes and the block themselves has been geologically mapped. Reporting and analyses have been the main focus of the work in Apse this year.

The field part of the experiment has been documented in three reports (a) /Andersson and Eng 2005/ (b) /Eng and Andersson 2005/ and (c) /Haycox et al. 2005/. In /Andersson and Eng 2005/ the final design of the experiment is described and the monitoring results presented. Detailed descriptions of the failure process are also included. /Eng and Andersson 2005/ describes the displacement and temperature monitoring system in detail. /Haycox et al. 2005/ reports the results from the acoustic monitoring and describes the acquisition system.

Analysis of data and observations from the experiments has progressed quite far. As a part of this the temperature in the experiment volume has been back calculated and reported in /Fälth et al. 2005/. The thermal induced stresses have been used to determine the spalling strength of the rock. Back calculation of the elastic deformations has been initiated. Preliminary results were published in /Andersson 2005/. In addition, detailed geological mapping and photographing of the five pillar blocks have been performed.

Figure 3-9. *Photography of the experimental site after removal of the five one metre high pillar blocks between the two large holes.*

4 Natural barriers

4.1 General

To meet stage goal 3, experiments are performed to further develop and test methods and models for description of groundwater flow, radionuclide migration, and chemical conditions at repository depth, see Figure 4-1.

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. The programme includes projects with the aim to evaluate the usefulness and reliability of different models and to develop and test methods for determination of parameters required as input to the models. The overall purposes are to:

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

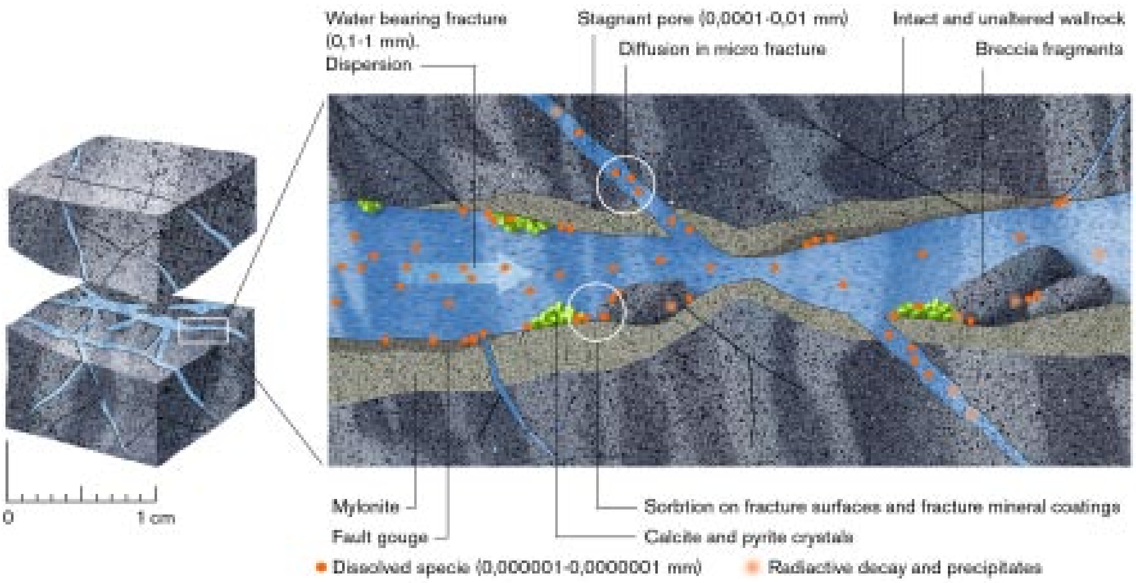


Figure 4-1. *Illustration of processes that influence migration of species along a natural rock fracture.*

The ongoing experiments and projects 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.
- Äspö Task Force on Groundwater Flow and Transport of Solutes.
- Padamot (Palaeohydrogeological Data Analysis and Model Testing).
- Fe-oxides in Fractures.

4.2 Tracer Retention Understanding Experiments

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

During 2005 the True work was mainly performed in the projects: True Block Scale Continuation and True-1 Continuation with the sub-project True-1 Completion. Although the experimental focus is placed on the respective True experimental sites developed at the Äspö HRL, integration and co-ordination of experimental activities at and between the sites are emphasised in the planned future work.

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 project is divided into two separate phases:

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

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

Objectives

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

Results

During 2005 the four modelling teams involved have carried out individual evaluation of the BS2 sorbing tracer test results and have also produced individual draft evaluation reports. Below a summary of the collective integrated evaluation of the project group is provided. For a full account of the individual evaluations, the reader is referred to the individual evaluation reports which are under preparation. The results of the integrated evaluation are presented in the final report of the True Block Scale Continuation project, also under preparation.

Geometries of investigated flow paths

The geometries of the two investigated flow paths have been visualised using various techniques. Flow path I is a relatively straight forward flow path, approx. 20 m long and assumed essentially contained within the fault type Structure #19 with a mean travel time of approx. 10 hours. The modelled lengths are close to the Cartesian distance (mean length 22 to 44 m).

Flow path II is a network flow path involving one or more background fractures (including BG#1) in combination with Structure #19. The Cartesian distance between the source and the sink is about 22 m and the mean travel time is about 140 hours /Andersson et al. 2005/. The modelled path lengths vary between 40 and 150 m between realisations, of which between 0–40 m is attributed to the leg in Structure #19. The latter flow paths is illustrated in Figure 4-2, both as contained in a realisation of the generated fracture network (all fractures shown) and undressed, revealing only those modelled fractures that account for approx. 90% of the tracer transport.

Effective immobile zone retention properties

In a case of a homogeneous and infinite immobile zone the retention by matrix diffusion is governed by a grouped parameter:

$$B = \kappa\,\beta = \varepsilon\sqrt{D_p R_p}\,\frac{t_w}{b} \qquad (4\text{-}1)$$

where $\kappa = \varepsilon\sqrt{D_p R_p}$ determines the immobile zone transport properties and $\beta = t_w/b$ determines the effects of the flow field and where

D_p is the pore diffusivity $[L^2T^{-1}]$

ρ_b is the density of the rock matrix $[ML^{-3}]$

b is the fracture half-aperture [L]

t_w is the water residence time [T]

ε is the matrix porosity [–]

R_p is the retardation factor = $1+(K_d\rho_b/\varepsilon)$ [–]

K_d is the volume sorption coefficient of the rock matrix $[L^3M^{-1}]$

In case of a homogeneous immobile zone it is straightforward to define that the immobile zone retention properties are specified by κ. For heterogeneous immobile zone this is not that obvious and the structure of the heterogeneity may also influence the retention properties. The two possible types of the heterogeneity may be conceptualised into two groups: (a) heterogeneity parallel to the fracture plane and (b) heterogeneity in the direction of the matrix diffusion (usually perpendicular to the fracture plane).

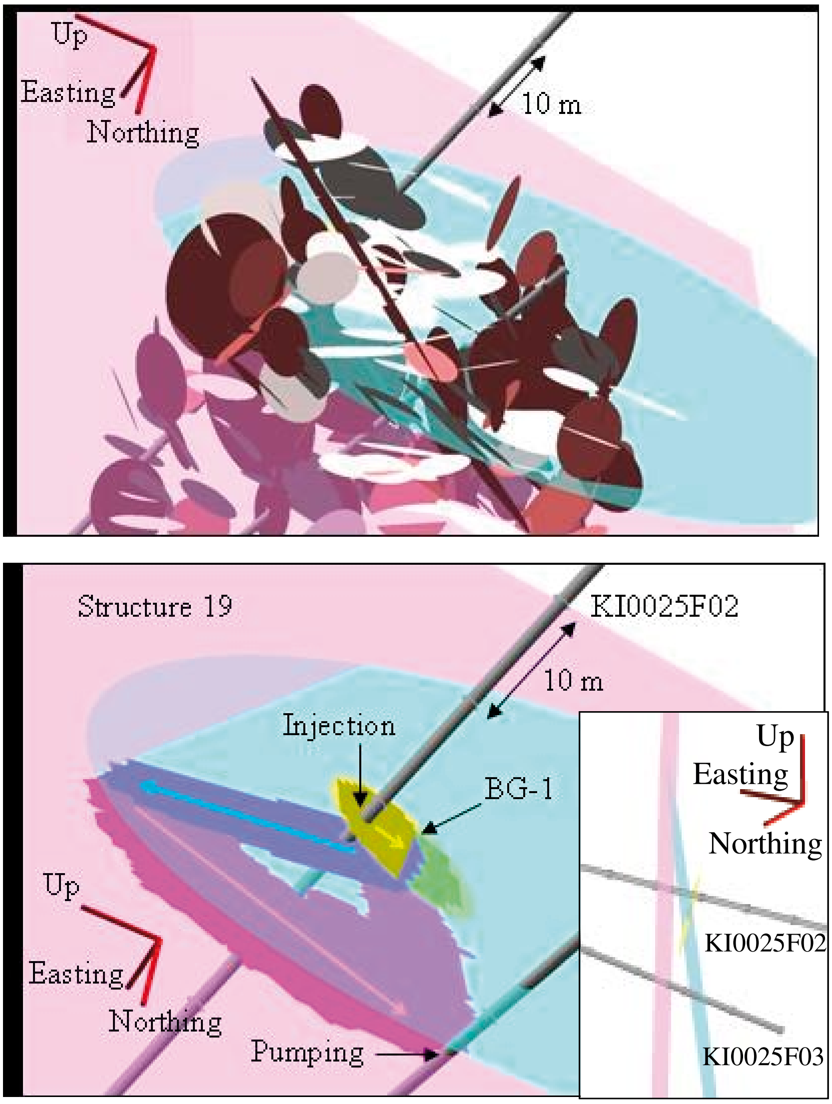


Figure 4-2. *Perspective view of flow path II (BG#1): Upper figure showing all modelled fractures for a selected realisation of the Andra-Itasca DFN-model. Lower figure showing only those fractures which make up the main flow path, indicating the principal transport route, and also showing in alternate view the relative positioning of Structure #19 in relation to BG#1.*

The assessment of the effective immobile zone retention properties along the two studied flow paths is based on the results from the four individual BS2b model evaluations available. The main emphasis is on the retention caused by matrix diffusion, that depends both on the properties of the flow field and those of the corresponding immobile zones. This means that the properties of immobile zones need always to be assessed in close conjunction with assumptions regarding the flow field and the flow path.

A microstructural model of the immobile zones has been developed for the fractures involved in the BS2b experiments. Two major fracture types have been identified with very distinct microstructural models. Type 1 fractures are fault type that exhibit a high degree of heterogeneity and include also layers of porous geological materials (fault gouge). Type 2 fractures are non-fault type and are not as heterogeneous as the Type 1 fractures. Furthermore, the volumes (thicknesses) of the high porosity geological materials, if any, are much smaller than for Type 1 fractures.

Most of the developed transport models describe Flow Path I by a few hours of advective residence time and the Flow Path II as being characterised by about 150 hours mean advective residence. All models show clear differences in the advective transport between the two flow paths. The Euclidian distance from the injection point to the sink is about the same for both flow paths, but the models indicate an order of magnitude difference in the advective water residence times. This suggests that Flow Path II is geometrically much more complex than Flow Path I. However, it is also interesting to note that the spread in advective transport between the models is greater for Flow Path I than it is for Flow Path II. This may suggest that the tracer transport is not that much controlled by advection for the Flow Path I than it is for the Flow Path II.

Figure 4-3 shows the average β along the two flow paths as obtained from the evaluation models. Along both flow paths the hydrodynamic control of retention is fairly consistent amongst the models. The deviations from the general characteristics are small β for the Flow Path I in the case of the Posiva-VTT model and small β for the Flow Path II in the case of the JNC-Golder model. Strikingly, the average level of the β is almost two orders of magnitude higher (higher retention) for the Flow Path II than it is for the Flow Path I.

The effective retention material properties along the flow paths and for most of the tracers were calculated by SKB-WRE. Figure 4-4 shows the estimated effective κ as red pentagrams. There seems to be a clear difference between Flow Path I (first five tracers, Tb to Cs) and Flow Path II (last five tracers, Eu to Mn). Flow Path I shows effective immobile zone retention properties that are close to the properties specified for the cataclasite in the microstructural model (high retention). Contrary to this, Flow Path II shows effective immobile zone retention properties that are close to the properties of the altered zone. This finding is also supported by the nature of the flow paths. It is known that both injection and extraction points of Flow Path I are located in the Structure #19. This is a complex fault type structure that is composed of multiple immobile zones and also high porosity immobile

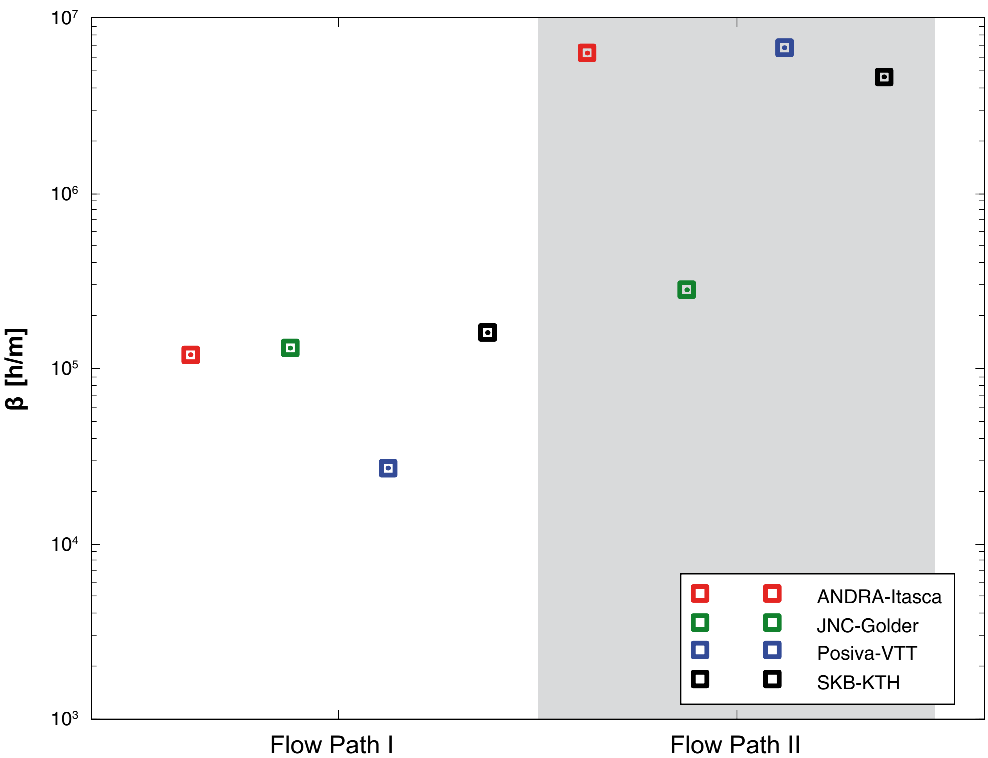


***Figure 4-3.** Hydrodynamic control of the retention in the different evaluation models (mean β).*

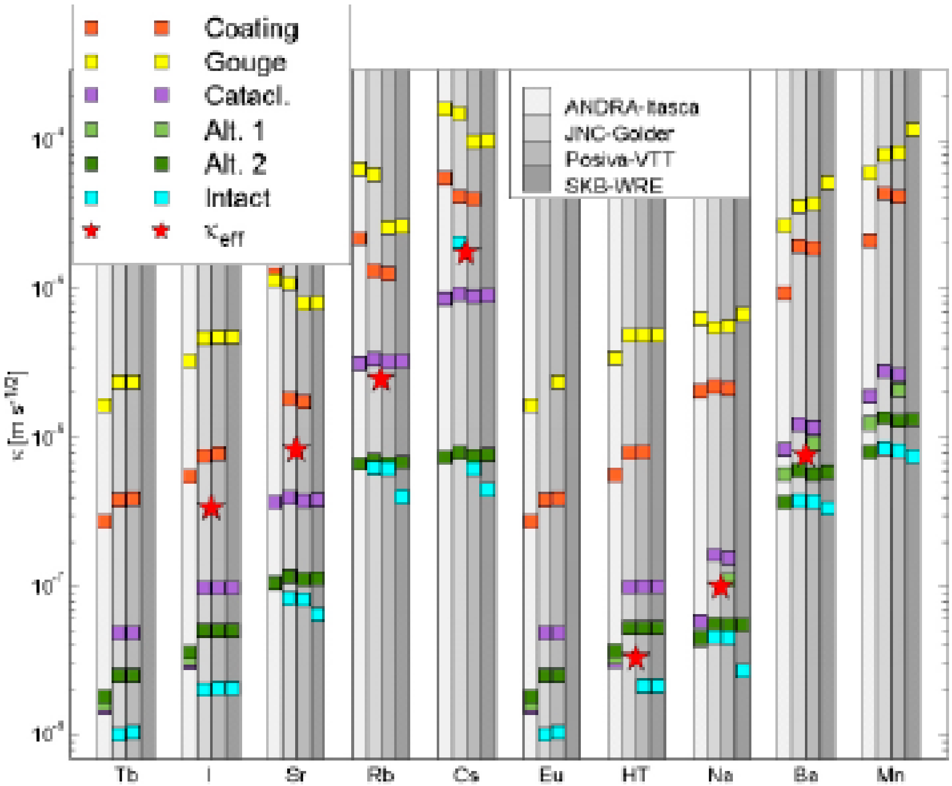


Figure 4-4. *Immobile zone retention properties (κ's) presented for different modelling approaches. The background colours indicate modelling team according to the legend given in the figure. The coloured squares in the figure show the κ's applied in different models (Alt. 1 means altered zone in Type 1 fracture, Alt. 2 means altered zone in Type 2 fracture). Evaluated effective κ for some the tracers are indicated by red pentagrams. First five tracers (from left) are for the Flow Path I and last five tracers are for the Flow Path II. HT = tritiated water.*

zones (fault gouge) are available. The injection point of Flow Path II is located in a simple non-fault type fracture and results of both the numerical flow modelling and the advective water residence time distributions suggest that this flow path is geometrically more complex and dominated by the background fractures.

The performed joint evaluation emphasise the following tentative results:

- Geological information (hydrostructural and microstructure models) is important for understanding sorbing tracer transport.
- Lower immobile zone retention material properties assigned to background fractures compared to those assigned to the structure flow path have been verified by means of back-calculations. Those of the structure flow path (Structure #19) are one order of magnitude higher than for the background fracture flow path.
- Overall retention in the background fracture flow path is found to be higher while the flow rate is significantly lower than the corresponding structure flow path of equitable length (implying higher β in the background fracture flow path).

Assessment of the hydrostructural model

The hydrostructural model at Structure #19 is substantially confirmed by the results of BS2a and BS2b hydraulic tracer tests between sections located at the interpreted location of Structure #19. In particular:

- The hydraulic inherence tests (pre-tests) /Andersson et al. 2004/ clearly show evidence that Structure #19 is acting as a planar effectively homogeneous conductive structure. Flow in Structure #19 is essentially radial at intermediate distances, and is similar for the different borehole intersections. This behaviour is similar to that for Structure #20 investigated in True Block Scale /Andersson et al. 2002/. From a hydraulic point of view, this evidence refutes the concept that these structures could be adequately represented as 3D heterogeneous porous media, unless such media were discretised to approximate 2D planar (DFN) media.
- The conservative tracer tests /Andersson et al. 2004, 2005/ carried out between boreholes intersecting what is interpreted as Structure #19 have advective travel times and dispersion values consistent with flow in a single, planar structure.
- The magnitude of the effective solute retention values from the BS2b sorbing tracer experiments, see Figure 4-4, are consistent with those that would be expected for transport on a fracture plane in contact with the immobile zones defined in the microstructural mode.

The background fracture BG#1 was the point of injection for the BS2b test in Path II. The designation “background fracture” is used because of the lack of direct evidence of this fracture in other boreholes. The evidence for the existence of this fracture is limited to a single flow log and BIPS log. Due to the lack of evidence of BG#1 in additional boreholes, it is not possible to definitively assign a fracture size. Furthermore, in our experience in the True Block Scale project, the local fractures intersections have orientations which are generally 10 to 30° different from the average orientation of the fracture plane. Consequently, the hydrostructural model is very uncertain concerning BG#1. The following conclusions can be drawn:

- BG#1 must connect to Structure #19 since a strong hydraulic response was noted.
- Only very small portions of Path II can be along Structure #19 due to the distinctly different immobile zone solute retention properties. BG#1 can therefore either be of the scale of greater than 20 m radius (to approach borehole KI0025F03), or Path II must be made up of either a large number of stochastic background fractures or a stochastic background fracture of this scale.
- Because the effective dispersion length back calculated for Path II is relatively small, it is more likely that Path II contains a small number of background fractures.
- The lower immobile zone retention observed for Path II supports the hypothesis that BG#1 is a Type 2 fracture with limited high porosity immobile zones.

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

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 (see section on True-1 Completion below).
- To provide an improved understanding of the constitution, characteristics and properties of fault rock zones (including fault breccia and fault gouge) (Fault Rock Zones Characterisation).
- To provide quantitative estimates of the sorption characteristics of the altered rim zone and fault rock materials of fault rock zones.

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

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

Results

Results from the True-1 Continuation project are available from the Fault Rock Zones Characterisation project and from production of scientific articles on the True-1 tracer tests. Furthermore, progress has been made in the True-1 Completion project which is aimed at assessment of the internal structure of porosity using epoxy resin. No progress during the past year in the complementary laboratory tests of the sorption characteristics of fracture rim zone and fault gouge materials. However, the main results have already been produced and are being used, only reporting remains.

Fault rock zones characterisation

Activities in the Fault Rock Zones Characterisation include work in three areas: (a) image processing with the aim to get images with desired colour and contrast of the slices, (b) image analysis to find the desired parameters and (c) various types of visualisations to get the overall variability within and between rock slices. A draft report has been produced of the image analysis of the resin-impregnated rock material.

Included in these results are estimates of near fracture rim porosity (partially including fault gouge) as obtained by analysis of binary images, amounting to between 10 to 60%. It was also shown that porosity estimates from this type of analysis cannot be taken as given, due to the effect of the resolution in the underlying photographs. By increasing the resolution by a factor of three, the porosity in the corresponding picture frames were found to increase by between 8 to 72% (relative measure).

True-1 scientific articles

A series of three scientific papers on the True team analysis of the True-1 experiments is now available in draft. The first two in the series will be submitted to WRR early 2006. The papers cover the following topics under the joint header of "Sorbing tracer experiments in a crystalline rock fracture at Äspö (Sweden)":

Part 1) Experimental results, conceptual model and effective parameter estimation.

Part 2) Micro-scale characterisation of retention parameters.

Part 3) Effect of micro-scale heterogeneity.

The results of Part 1 provides a consistent picture on the nature of the retention processes, indicating that the classical model (power-law memory function) characterised by diffusion-controlled mass exchange is sufficiently accurate to capture the main features of the measured breakthrough curves on the considered time scale. Moreover, the results indicate that the close vicinity of altered fractures (rim zone) will generally exhibit considerably stronger retention properties than can be inferred from unaltered rock samples of the surrounding rock. From the safety assessment aspect, this finding implies that there may be additional safety margin associated with altered fractures (common in Scandinavian crystalline rocks), dependent on the rim zone extent, material properties and penetration of tracers. Part 2 investigates the micro-structural properties of the Feature A rim zone, whereas in Part 3 focus is on the effects of micro-scale heterogeneity on tracer transport over the time scales of the True-1 experiments. Part 3 is available in a preliminary draft, submittance pending review comments on the first two papers.

4.2.3 True-1 Completion

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

Objectives

The general objectives of True-1 Completion are:

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

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

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

Results

The progress in True-1 Completion during 2005 mainly constitutes of infrastructural activities at the True-1 and True Block Scale sites. Furthermore, the complementary tracer tests were initiated during the end of 2005 with the performance of a non radioactive Swiw-test.

The infrastructural work was completed in November of 2005 and composes the re-instrumentation of KXTT3 and KXTT4 at the True-1 site, the dismantling of the True Block Scale site and assembly and installation of tracer test equipment at the True-1 site. The complementary tracer tests were initiated with a non radioactive Swiw-test during November and December of 2005. The objectives of the Swiw-tests are:

- To verify the performance of a Swiw-test at the True-1 site without loosing tracer in the rock and also to provide vital information on the design of the Swiw-test with radioactive tracers.
- To verify the tracer distribution surrounding the Swiw-test borehole by passive sampling in the surrounding multi-borehole array intersecting Feature A.
- To evaluate the Swiw-test and to compare the results to previously performed tracer tests at the True-1 site.

The result of the Swiw-test indicates a radial distribution of tracer solution from the injection borehole. Passive sampling in the surrounding multi-borehole array intersecting Feature A shows tracer breakthrough in the four sampled boreholes (Figure 4-5). It has, until now, not been possible to monitor and verify the spreading of tracer solution in the rock mass surrounding the injection borehole. The results of the test provides counter-evidence that tracer transport during Swiw-tests only takes place in channels with high conductivity.

The Swiw-test resulted in a very low tracer recovery, about 3%. This recovery stands in sharp contrast to the expected recovery of more than 80%. The low recovery may be the effect of a larger gradient towards the tunnel than expected. In the case of a larger gradient, the length of the tracer injection phase is most probably too long in proportion to the prevailing gradients at the site. The effect is that the tracer solution is pushed outside the influence radius of the withdrawal stage of the test, resulting in loss of tracer and hence a low tracer recovery. Detailed evaluation of the performed Swiw-test is pending. Renewed Swiw-tests are planned based on the experiences of the performed test.

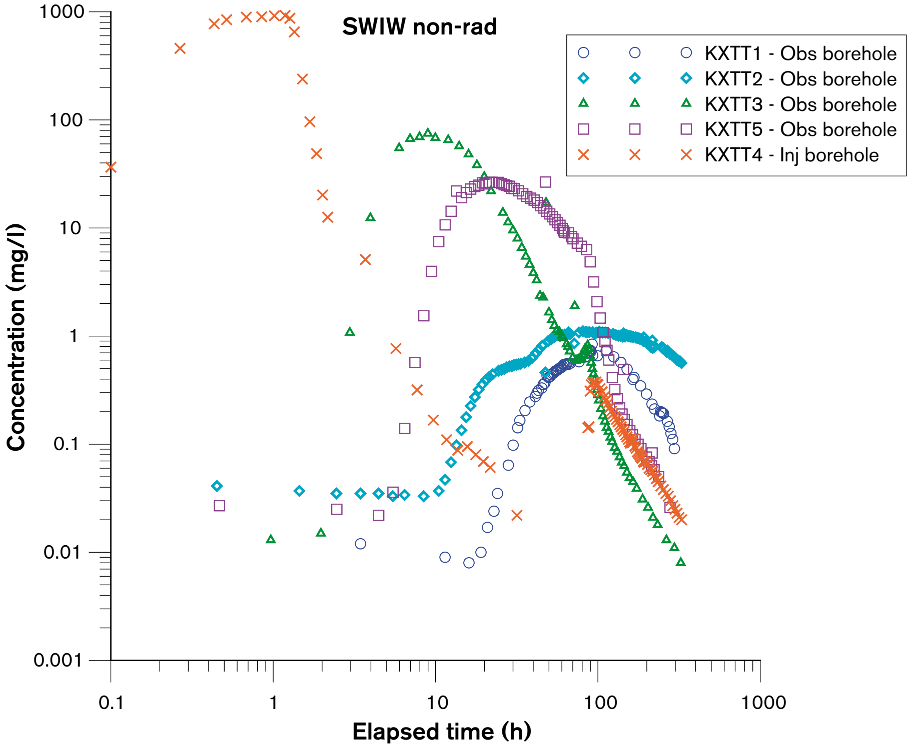


Figure 4-5. *Tracer injection and breakthrough curves for the non-radioactive Swiw-test with injection in KXTT4 and discrete sampling in KXTT1, KXTT2, KXTT3 and KXTT5.*

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 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 one uses rock specimens 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 one will also obtain some information of the adsorption behaviour of some radionuclides on exposed granitic rock surfaces.

Scoping calculations, for the planned experiment, have been performed /Haggerty 1999/ using the multi-rate diffusion concept which accounts for pore-scale heterogeneity. A test plan was drafted and presented at a combined True/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/.

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

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 will be 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 4-6.

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.

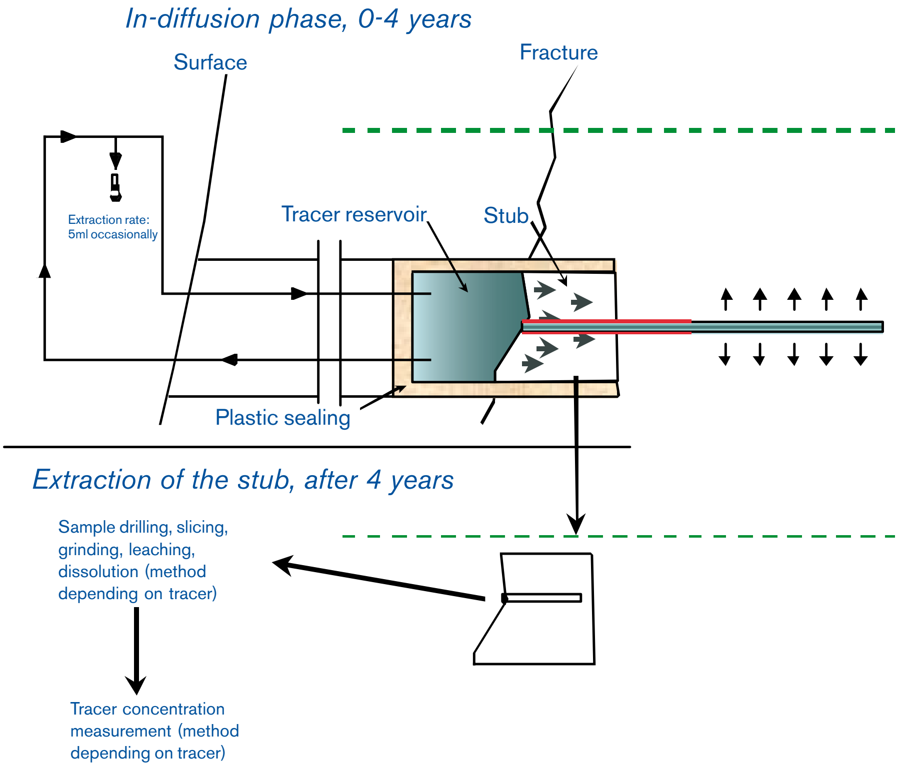


***Figure 4-6.** LTDE experimental concept including injection borehole in contact with a fracture surface.*

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) extension 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 4-7.

During the circulation of tracer, samples of water will be collected at various times over the duration of the experiment. The red-ox situation in the circulation loop will be monitored continuously with a flow through 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.

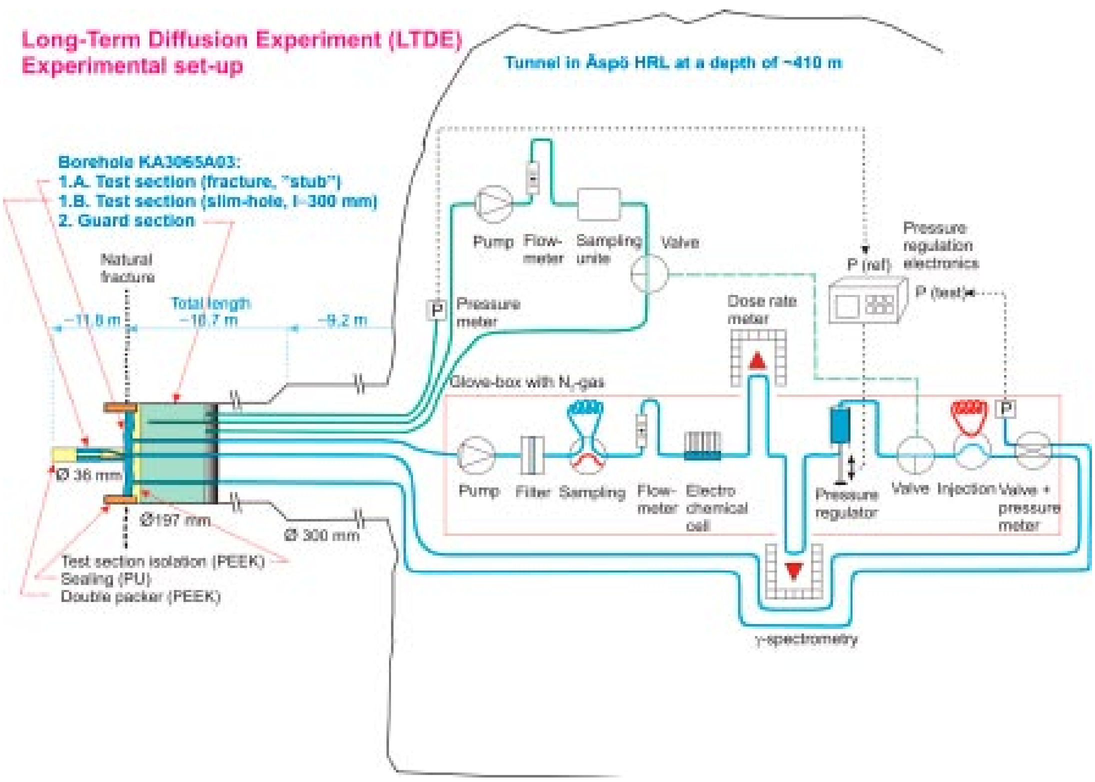


Figure 4-7. *LTDE experimental set-up in the experimental borehole including the water circulation system to the test-section and the hydraulic pressure control system.*

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. 2003/.

4.3.4 Results

A functionality test with short lived radionuclides was started in September and terminated according to plan after five weeks. The objectives of the test were to:

- Test the complete experimental set up with respect to functionality and safety.
- Optimise circulation flow rate and injection and sampling procedures.
- Investigate if sorption processes on the stub-surface and on the matrix rock surface in the small-diameter borehole can be monitored with the present experimental set up, i.e. measurement of the decrease of tracer concentration in the test section volume.

It could be concluded from the functionality test that all systems worked overall as expected. Also, the injection and sampling procedures concerning the tracers functioned as planned. Both non-sorbing and sorbing tracers were used (^{24}Na, ^{47}Ca, ^{64}Cu, ^{115}Cd, ^{131}I, ^{131}Cs, ^{177}Lu, ^{181}Hf, ^{239}Np). Results showed that concentration versus time curves based on sampling and on-line measurements of the radioactivity in the test section can be produced with the present experimental set-up (Figure 4-8). The successively decreasing concentrations with time for the sorbing tracers show that sorption processes on fracture surfaces and matrix rock can be studied at the LTDE site. Only a minor sorption on tubing was obtained for the most strongly sorbing tracer (^{181}Hf). No tracers were detected in the guard section which indicates that the test section is tight towards the guard section.

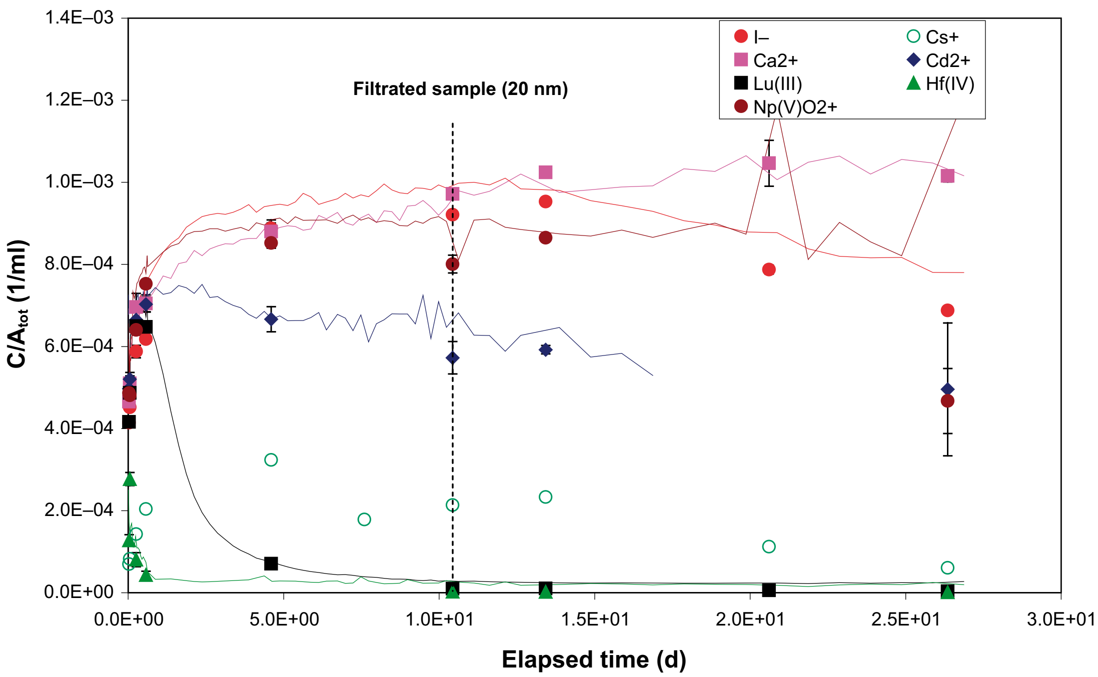


__Figure 4-8.__ The measured radioactivity divided by the total activity injected (relative concentration) versus elapsed time for samples (dots) and on-line measurements (lines).

Some adjustments and modifications are proposed to increase the functionality prior to the forthcoming long-term test, i.e. automatic alarm functions and complementary electrical control in the system. At the end of the functionality test, after seven months continuous operation, a small leakage was observed in the circulation and pressure regulating equipment in container 1. Rearrangement of the placement of the electrochemical flow cell in the glove box is also proposed in order to improve the practical work in the glove box and to reduce disturbances in the measurements. Furthermore, the experiment container needs cooling in order to reduce the temperature from 30 to 20°C.

The redox potential was slowly decreasing during the experiment, but still positive. Thus, low negative redox potentials have not been obtained in the test section during the test period with nitrogen flushing of the inert gas boxes. The redox potentials in the test section may be affected by mineral oxidations that occurred during the time that the borehole was open prior to the borehole installations. Consequently, more circulation time with a closed system may be needed to obtain reducing conditions. About 2 weeks of circulation time were needed to obtain good mixing (constant concentration) for the inert and weakly sorbing tracers. The slow mixing is likely caused by the existence of zones of relatively stagnant groundwater within the circulation system such as in front of the stub surface and in the pressure regulator cylinder. The mixing behaviour in the test section is of minor importance for a sorption-diffusion test that will last for several months or more.

The functionality test was followed by a decision to adjust and modify the test equipment and run the forthcoming experiment based on a slightly up-dated project plan. The new plan emphasizes in situ sorption measurements with shorter experimental time frames than the original plan which had more focus on obtaining diffusion data.

The supporting laboratory experiments on core samples from LTDE borehole KA3065A03, performed by AECL's Whiteshell Research Laboratories within the framework of collaboration between SKB and OPG, were completed in December. The experimental programme consisted of porosity measurements, diffusion cell experiments, permeability measurements and radial diffusion experiments. A Status Report was published in February /Vilks and Miller 2005/ and draft version of final report compiled in December /Vilks et al. 2005/.

4.4 Radionuclide Retention Experiments

4.4.1 Background

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

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

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

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

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 shown.

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).
- The influence of primary and secondary formed water radiolysis products on the migration of the redox-sensitive element technetium (final report in print).
- Migration of actinides (americium, neptunium, and plutonium) in a rock fracture (final report is under production, planned to be finished June 2006).

4.4.4 Results

Two different kinds of radiolysis experiments were performed. In both set-ups reduced technetium ($TcO_2{\cdot}nH_2O$) was placed in a cell containing compacted bentonite. The cells were exposed to groundwater via a filter in one end of the cell. In one (indirect radiolysis) the water was irradiated before coming in contact with the filter while in the other (direct radiolysis) the radiation source was placed in direct contact with the reduced technetium at the far end of the cell.

The major finding from the radiolysis experiments was that Tc had not moved in the indirect radiolysis experiment, i.e. had probably not been oxidised to the more mobile pertechnetate ion, while in the direct radiolysis experiment Tc had started to diffuse, indicating that some of the Tc had been oxidised. The reason for the oxidation can be contributions from primary formed radiolysis products or that the H_2O_2 concentration was locally much higher compared with the indirect radiolysis case.

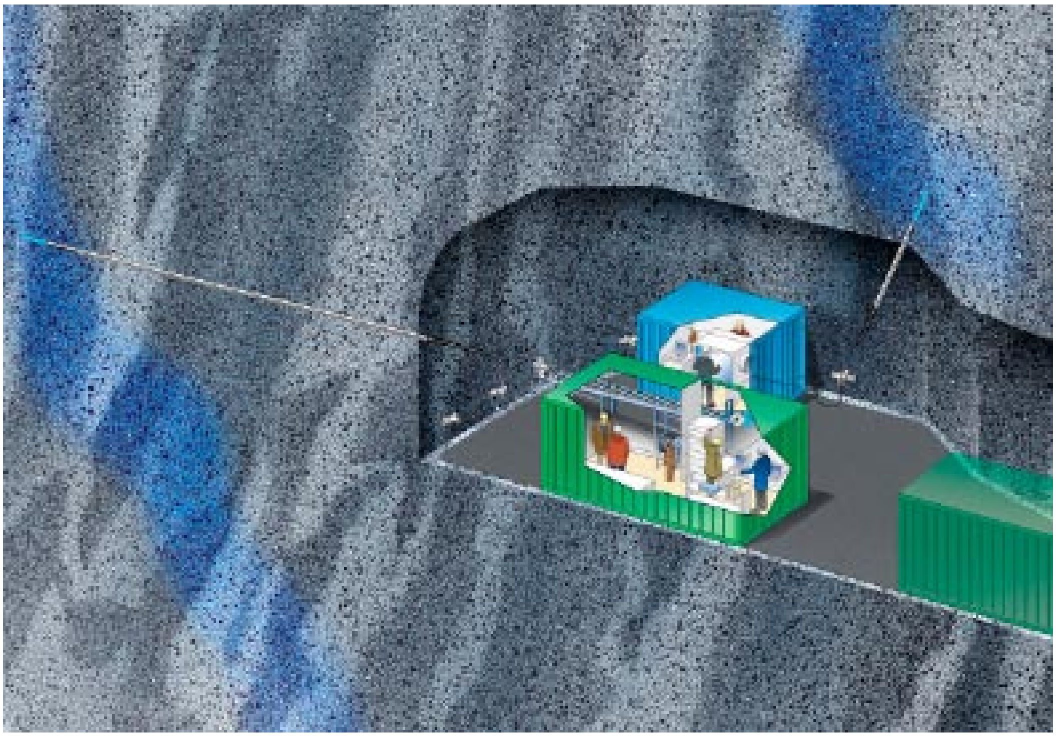


Figure 4-9. *Illustration of the experimental set-up of the Radionuclide Retention Experiments.*

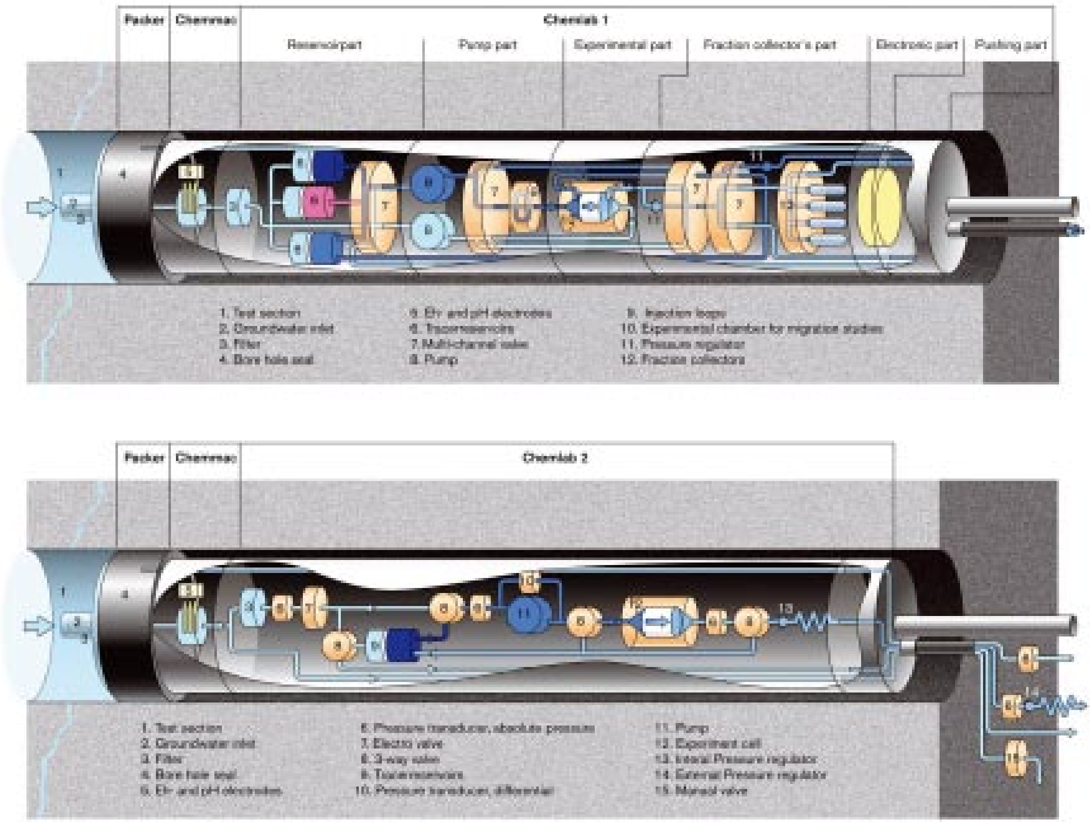


Figure 4-10. *Schematic illustration of Chemlab 1 and 2 borehole laboratories.*

In the actinide migration experiment a radionuclide cocktail is injected into a rock core with a longitudinal fracture. After the injection, groundwater is pumped through the fracture. All water exiting the core is collected in a fraction collector situated in a glove box in the gallery.

No breakthrough of Pu or Am has been detected during the laboratory and field experiments. Up to 40% recovery of Np(V) has been observed, while no Np(IV) has been detected in the samples.

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 released from a defect waste canister to the biosphere. SKB has for more than 10 years conducted field measurements of colloids. The outcome of the studies performed nationally and internationally concluded that the colloids in the Swedish granitic bedrock consist mainly of clay, silica and iron hydroxide particles and that the mean concentration is around 20–45 ppb which is considered to be a low value /Laaksoharju et al. 1995/. The low colloid concentration is controlled by the attachment to the rock, which reduces both the stability of the colloids and their mobility in aquifers.

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

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

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, see Figure 4-11.

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 results from the background measurements indicate that the natural colloid content is decreasing with groundwater salinity and depth. 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 2002ab, Vuorinen 2002, Gurban 2002, Mattsén 2002, Rantanen and Mäntynen 2002, Pedersen 2002b/.

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 four boreholes along the Äspö tunnel and two 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 container/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. The colloid content was measured by using conventional filtering and ultra

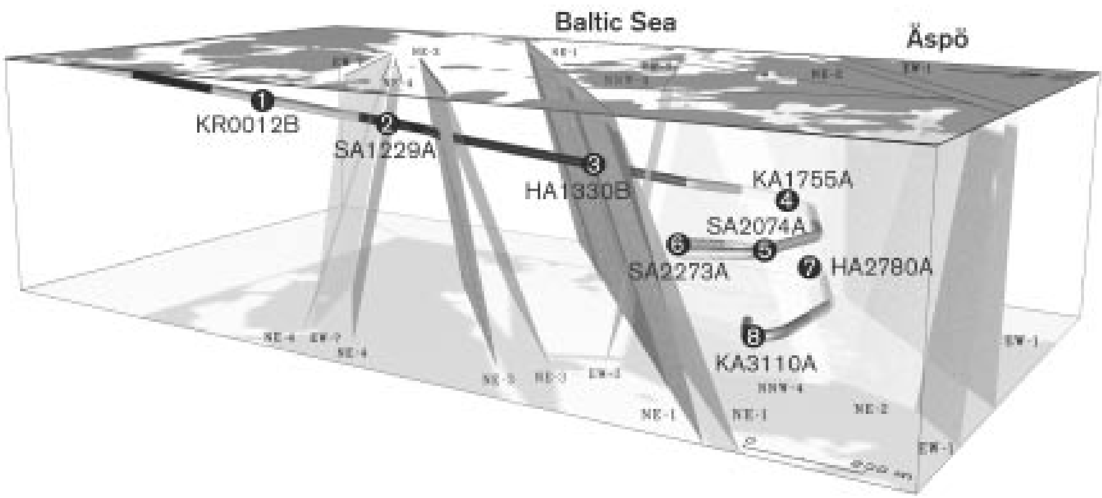


Figure 4-11. *The eight boreholes sampled for colloids along the Äspö tunnel.*

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 experiment

The dipole colloid experiment is a fracture specific experiment planned to be performed within the Colloid Project during the time period 2004–2007. 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, a colloid source will be dissolved in ultra pure water to form colloidal particles. The colloids are labelled with e.g. a lanthanide and the fluid is labelled with a water conservative tracer. The mixture will be injected into the injection borehole, see Figure 4-12. The colloidal content will be measured with laser (LIBD/LLS), the water is filtered and the amount of tracers is measured. The result of major interest is the changes in colloid content prior and after the transport through the fracture. The outcome of the experiment will be used to check performed model calculations and to develop future colloid transport modelling.

4.5.4 Results

During 2005, the main part of the work has been to collect data and prepare for the Dipole Colloid experiment that will be performed in situ. At KTH stability experiments with bentonite colloids have been performed which has shown that these colloids are not at all stable in the saline waters at Äspö. High amount of dissolved organic carbon (DOC) can not compensate for the high salinities. Therefore other colloids had to be chosen for the in situ

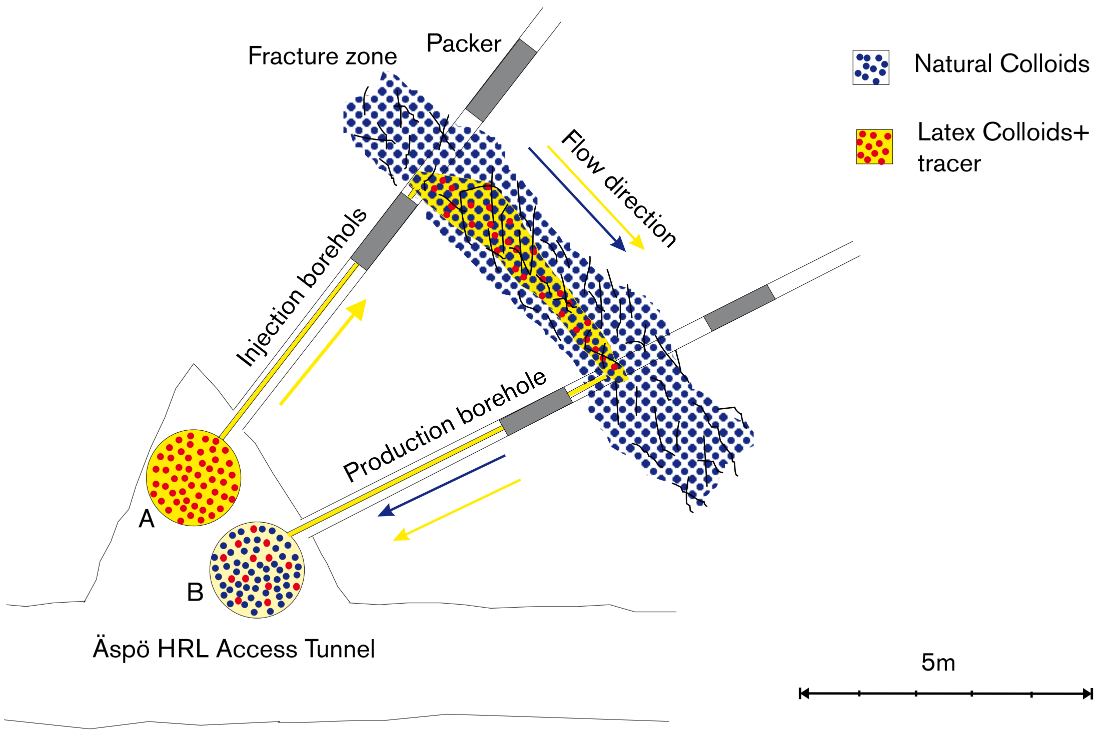


__Figure 4-12.__ Dipole colloid experiments – injection of latex colloids and monitoring of the injected and natural colloids in the production borehole.

experiments. Bentonite colloid migration in a fracture in a granite block with very dilute waters has shown that bentonite and latex colloids actually behaves accordingly. Stability experiments with fluorescence latex colloids with different sizes have shown that these can be used in in situ experiments. Predictive modelling has been performed to dictate the design of the in situ experiments.

4.6 Microbe Project

4.6.1 Background

Microorganisms 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 radioactive waste repository /Pedersen 2002a/. The study of microbial processes in the laboratory can yield valuable information about possible microbial effects on such a repository. However, the effects suggested by laboratory studies must be tested in a repository-like environment for several reasons. 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, however, is best suited for studies of pure cultures. Therefore, the effect of processes arising from many contributing species in natural ecosystems cannot 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 Project in 2001. The year 2005 was formally the last year of the Microbe framework. New projects have been initiated, that will focus on microbial influence on radionuclide migration (Micomig) and the redox potential (Micored) in deep groundwater.

4.6.2 Objectives

The major objectives for the Microbe framework sites are:

- To provide in situ conditions for studying the bio-mobilisation of radionuclides.
- To present a range of conditions relevant for studying the bio-immobilisation of radionuclides.
- To provide the proper conditions for research into the effect of microbial activity on the long-term chemical stability of the repository environment.
- To enable investigation of the bio-corrosion of copper under conditions similar to those of a repository for spent fuel.

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 exploring how microbial processes may influence the repository and migration of radionuclides.

Table 4-1 and Figure 4-13 summarise microbial processes that can influence the speciation and thereby the migration behaviour of radionuclides. Microbial processes can have either an immobilising or a 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, therefore, must include a proper understanding of microbial energy turnover rates in deep rock aquifers. All processes presented in Table 4-1 are being or will be investigated to various degrees of detail at the Microbe framework sites. The emphasis is on their importance for understanding geosphere mobilisation and immobilisation phenomena in the safety assessment of radioactive waste disposal. They are briefly introduced below.

Table 4-1. 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	

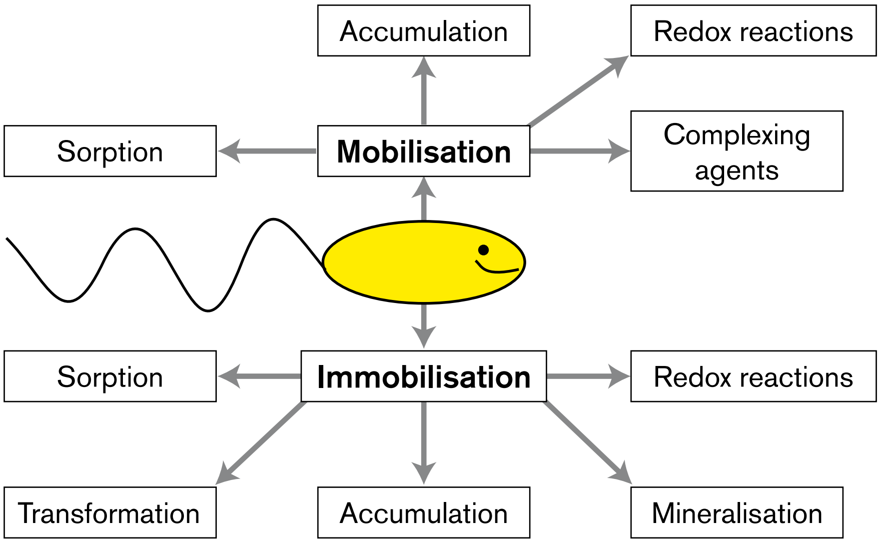


Figure 4-13. *Schematic representation of microbial processes that may influence radionuclide migration.*

Bio-immobilisation of radionuclides

Biosorption

The term biosorption 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 microorganisms commonly excrete extra-cellular material supporting attachment, and this material 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 4-1). Very few in situ experimental data existed regarding the importance of biofilm biosorption processes in understanding geosphere retention phenomena. In response to this lack, a series of investigations have been performed at the Microbe framework sites. The results have been reported in scientific papers /Anderson and Pedersen 2004, Anderson et al. 2006ab/ and in a thesis /Anderson 2005/.

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 effects of Bios (bioaccumulation and biomineralisation, Table 4-1) have been studied in the Microbe framework. Recently, it was found that Bios in the Äspö HRL tunnel have radiation levels above the background, due to its accumulation of naturally occurring radionuclides in the groundwater that seeps into the tunnel. The results have been reported in scientific papers /Anderson and Pedersen 2003, Anderson et al. 2006c/ and in a thesis /Anderson 2005/.

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 iron in surface waters, are not bioavailable 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 /Kalinowski et al. 2004, 2006/. In the process of capturing the metalligand complex, microbes sort toxic metals from essential ones and expel the toxic elements back to the environment /Lloyd and Macaskie 2002/. 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 microorganisms isolated from the deep groundwaters of the Äspö HRL /Johnsson et al. 2006/. In situ experiments will follow the laboratory experiments starting 2006 in an Äspö HRL project denoted Micomig. 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

Microorganisms 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 so as to reduce possibly introduced oxygen. Circulation systems and analytical instrumentation for studying gas dissolved in groundwater have been installed at the deepest (–450 m) Microbe site. The oxidation of added lactate by indigenous microbes in the KJ0052F01 circulation at Microbe has been investigated /Nielsen et al. 2006/.

Microbial energy metabolism requires a reduced electron and energy donor and an oxidised electron acceptor (Table 4-2). 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.

Table 4-2. 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	$\underline{C}O_2$			O_2	$H_2\underline{O}$
Amino acids	$\underline{C}O_2$	$\underline{N}H_4^+$	$\underline{N}O_3$	$\underline{N}O_3$	N_2
Organic acids	$\underline{C}O_2$	Mn^{2+}	Mn^{4+}	Mn^{4+}	Mn^{2+}
Fat	$\underline{C}O_2$	Fe^{2+}	Fe^{3+}	Fe^{3+}	Fe^{2+}
		$H_2\underline{S}$	$\underline{S}O_4^{2-}$	$\underline{S}O_4^{2-}$	$H_2\underline{S}$
		$\underline{C}H_4$	$\underline{C}O_2$	S^0	$H_2\underline{S}$
		$\underline{C}O$	$\underline{C}O_2$	$\underline{U}^{6+}$	$\underline{U}^{4+}$
		H_2	$\underline{H}_2O$	$\underline{C}O_2$	$\underline{C}H_4$

Microbial corrosion of copper

The bio-corrosion, if any, of copper canisters 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. 2000ab/. 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 is studied under in situ conditions at the Microbe laboratory.

4.6.4 Experimental concept

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 /Pedersen 2005a/. The systems operate at the pressures 24, 32 and 24 bars in boreholes 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.

A detailed description of the Microbe laboratory at –450 m can be found in /Pedersen 2005a/.

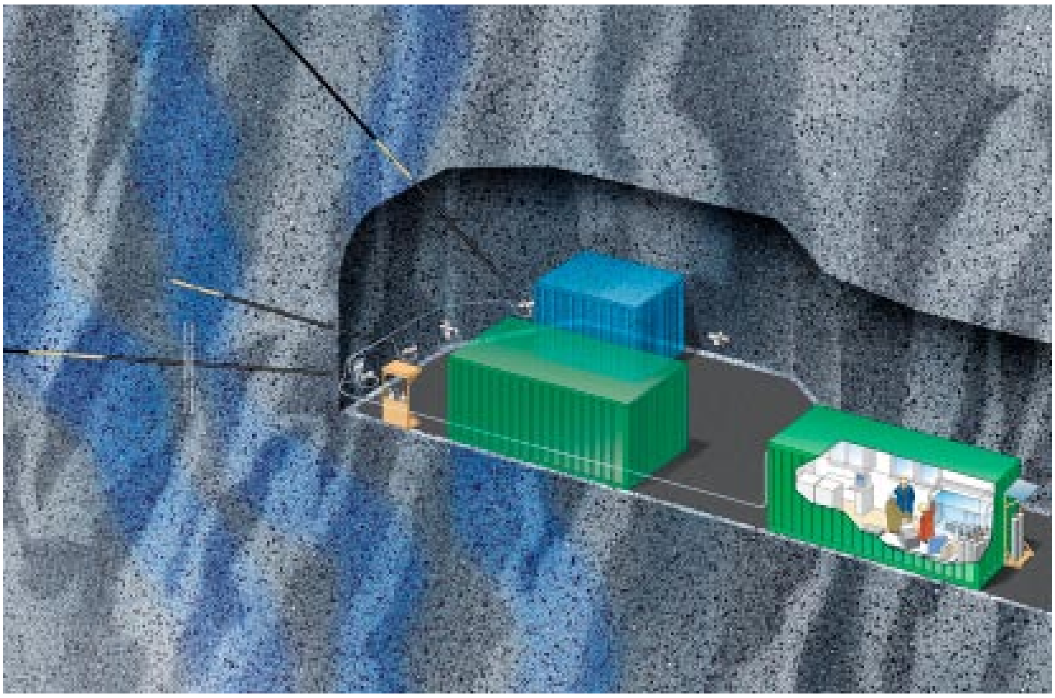


Figure 4-14. *The artists view of the Microbe –450 m site and the metal free packer configuration. The laboratory is situated in a steel container and connected to three discrete fractures in the rock matrix. PEEK tubing connects the systems in the laboratory with the groundwater (See text for details).*

The Bios site at 2,200A 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 oxides). 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 2005/. One particularly good site for investigations was 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 was connected to two 200×30×20 cm artificial channels denoted Bric, that mimic ditches in the tunnel. The channels have rock and artificial plastic support that stimulate Bios formation (Figure 4-15). 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/. A follow up study has been completed and published /Anderson et al. 2006c/.

4.6.5 Results

Bio-mobilisation of radionuclides

There has been no activity in the tunnel on this objective during 2005. Research is planned for 2006 in a new Äspö HRL project denoted Micomig.

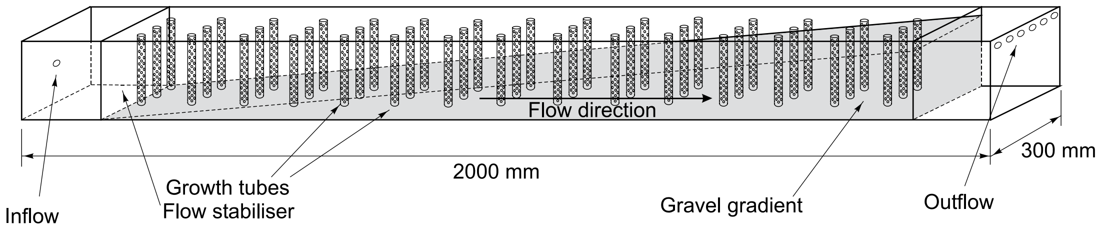


***Figure 4-15.** Schematic diagram of a Bric installed at the 2,200 m site.*

Bio-immobilisation of radionuclides

Sorption to biofilms

The migration of radionuclides is expected to be mitigated by adsorption to host rocks surrounding hydraulically conductive fractures. Fluid rock interfaces are considered to adsorb radionuclides, but their adsorptive capacity can be affected by the growth of microbial biofilms. A study in the Microbe –450 m laboratory indicates that subsurface fracture biofilms reduce the effectiveness of the granite rock for adsorbing migrating radionuclides except for trivalent species /Anderson et al. 2006a/. In the study the adsorptive capacity of in situ anaerobic biofilms grown 450 m underground in 'repository' conditions on either glass or granite slides was compared to the capacity of the same surfaces without biofilms. Surfaces were exposed to $^{60}Co(II)$, $^{147}Pm(III)$, $^{241}Am(III)$, $^{234}Th(IV)$, $^{237}Np(V)$ and $^{233}U(VI)$ and depleted U(VI) for a period of 660 hours in a pH neutral anaerobic synthetic groundwater. Adsorption was investigated at multiple time points over the 660 hours using liquid scintillation for the radioactive tracers and ICP-MS for non-radioactive species. Results indicate that these surfaces adsorb between 0 and 85% of the added tracers under the conditions of the specific experiments. The distribution coefficients (ratio between what is sorbed and what is left in the aqueous phase), $R_{s/l}$, after 660 hours approached 3×10^4 m for ^{60}Co, 3×10^5 m for ^{147}Pm and ^{241}Am, 1×10^6 m for ^{234}Th and 1×10^3 m for ^{237}Np and U. The rate of adsorption was the fastest over the first 200 hours of the adsorption experiments and started to approach equilibrium after 500 hours (Figure 4-16). Between 0 and 20% of adsorption in the ^{60}Co, ^{147}Pm, ^{241}Am, ^{237}Np and U systems could be accounted for by colloidal interactions. In the ^{234}Th system 95% of aqueous ^{234}Th was removed by colloidal interactions. Although the range of $R_{s/l}$ values for each surface tested generally overlapped, the biofilms consistently demonstrated lower $R_{s/l}$ values except for the ^{147}Pm and ^{241}Am adsorption systems. This adsorption was demonstrated to be reversible within a period of 156 hours or greater.

Characterisation of a Bios microbial community

The initial development and diversity of an in situ subsurface microbial community producing bacteriogenic iron oxides (Bios) was investigated at the initiation of biofilm growth (2 month period) and after a 1 year period of undisturbed growth /Anderson et al. 2006c/. Water chemistry data, samples of iron encrusted biofilm material and groundwater were collected from Bric (Bios reactor, in situ, continuous flow) apparatuses (Figure 4-15) installed 297 m below sea level in the Äspö HRL tunnel. Comparisons between the Bios Bric system and an anaerobic control (AC) Bric (Figure 4-17) revealed that water mixing at the inflow leads to profuse development of Bios related to a slightly elevated level of O_2 (up to 0.3 mg L^{-1} at the transition zone between Bios development and non-development) and elevated Eh (> 120 mV) in the first 70 mm of water depth (Figure 4-18). Decreases in dissolved and particulate iron were connected to the visible appearance of Bios biofilms.

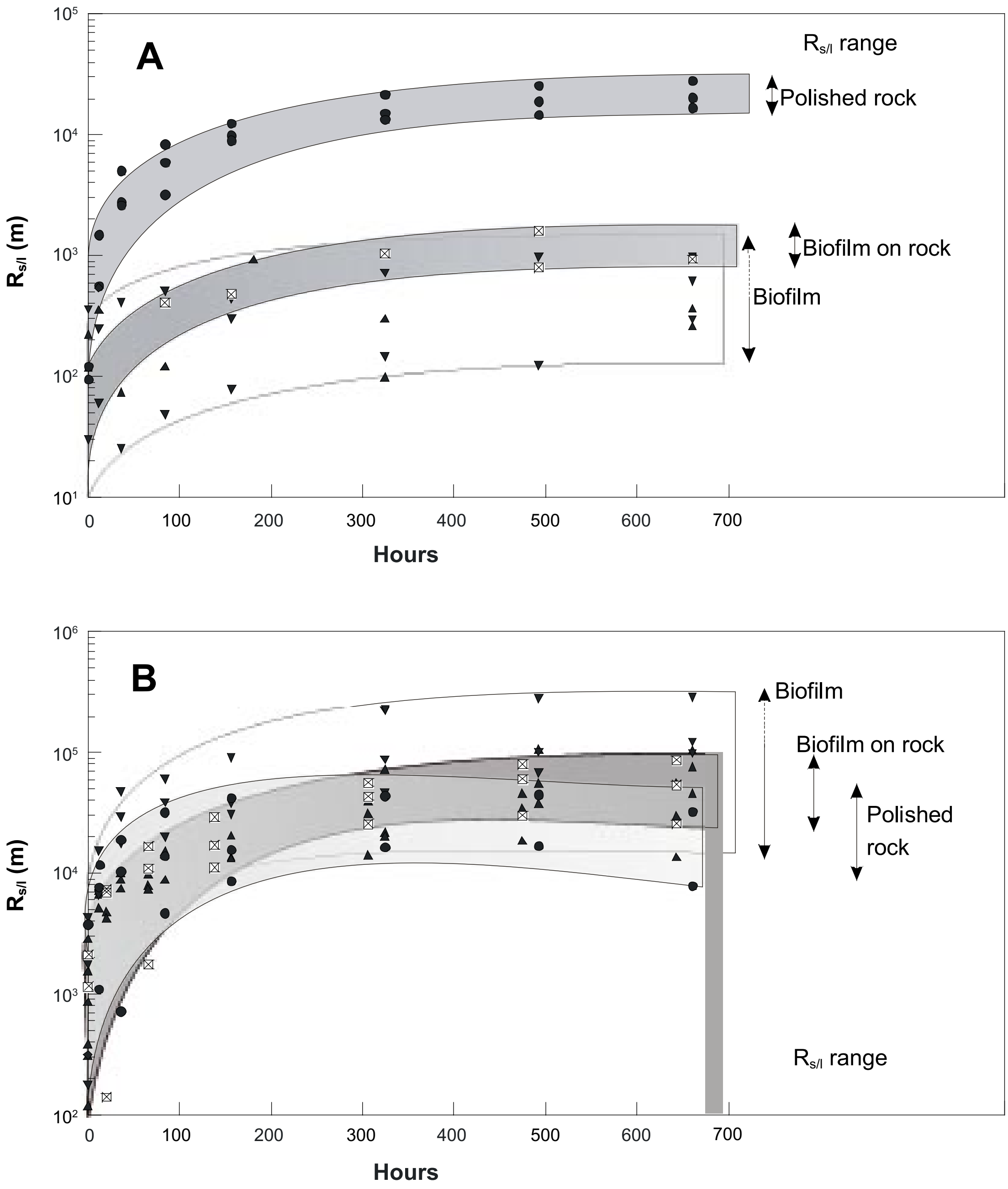


Figure 4-16. *Representative graphs of Rs/l values over time for* [60]*Co (II) (A) and* [147]*Pm (III) (B). Adsorption is to polished rock slides (●), biofilm on rock slides (☒), biofilm on glass slides (▲) and stripped biofilm slides (▼). Values represented are combined from all experiments and do not include zero sorption. The range of values collected from each treatment surface is shaded differently to distinguish each treatment. The final Rs/l range from where the adsorption is approaching equilibrium is represented by the double ended arrows at the right of the figures. The dotted extensions within the biofilm Rs/l range arrows represent the stripped biofilm data. The profiles presented in these graphs are similar to the adsorption profiles for* [241]*Am,* [234]*Th,* [237]*Np and U.*

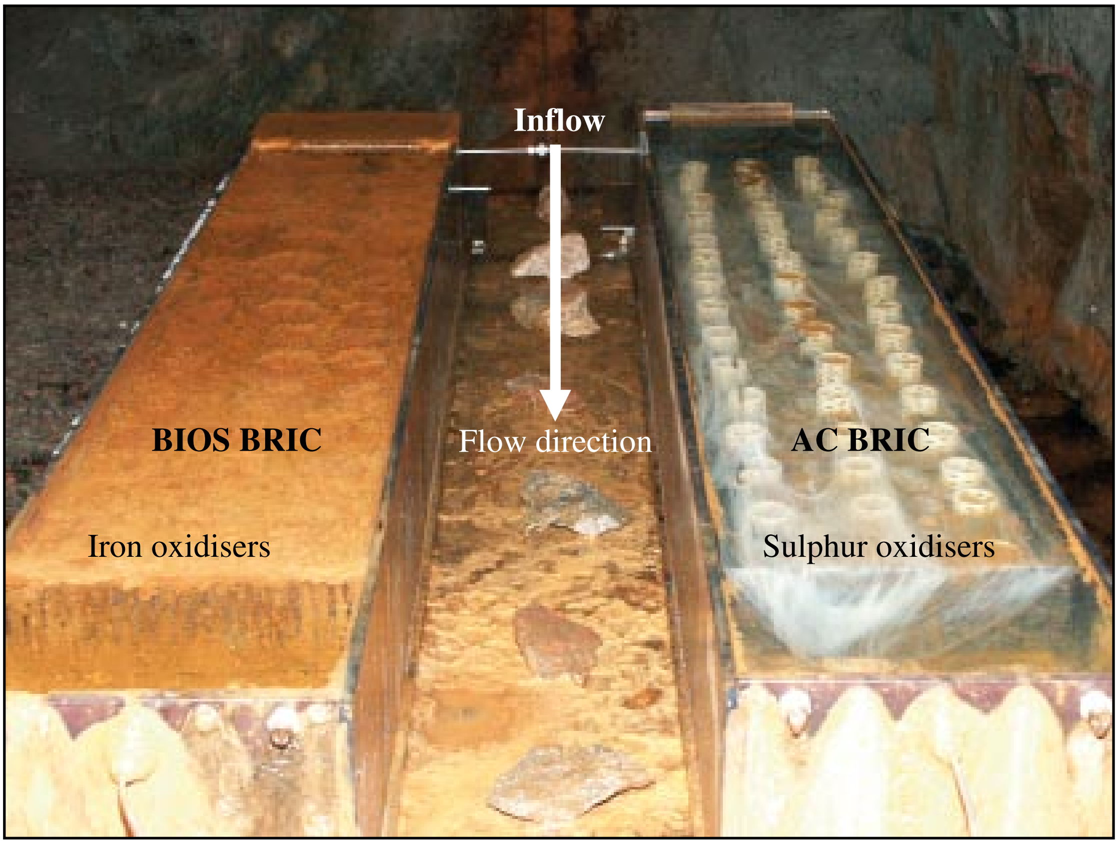


Figure 4-17. *The Bric apparatuses installed at the 2,200 m site. The Bric on the left is the Bios Bric and the Bric on the right is the AC Bric. The Brics are 2 m long, 300 mm wide and 250 mm deep (see Figure 4-15) and are supplied by groundwater from a borehole that intersects a water conducting fracture behind the rock face. Note the prolific growth of sulphur oxidising bacteria within the AC Bric and masses of iron oxide stained biomass in the Bios Bric. This figure represents 8 months of biofilm development (i.e. 4 months before sampling for phylogenetic analysis).*

The basic phylogenetic diversity of this site was evaluated using amplified ribosomal DNA restriction enzyme analysis (ARDRA), denaturing gradient gel electrophoresis (DGGE) and partial sequencing of 16S rDNA. From 67 clones that were positive for 16S rDNA inserts a total of 42 different ARDRA profiles were recognised representing 4 bacterial phyla and 14 different metabolic lifestyles. DGGE profiles indicated that there are differences in the representative bacteria when considering either Bios biofilms or groundwater. DGGE also indicated that the DNA extraction protocols and any PCR biases were consistent. Bacterial metabolic groups associated with indirect metal adsorption and reduction along with bacteria utilising many alternative electron acceptors were strongly represented within the clones. This study indicates that the microbial diversity of Bios is greater than previously thought. The importance of understanding Bios composition and growth dynamics has increased since the discovery of its radionuclide sorbing capacity. The Bios in the Äspö HRL tunnel have radiation levels above the background, due to its accumulation of naturally occurring radionuclides in the groundwater that seeps into the tunnel.

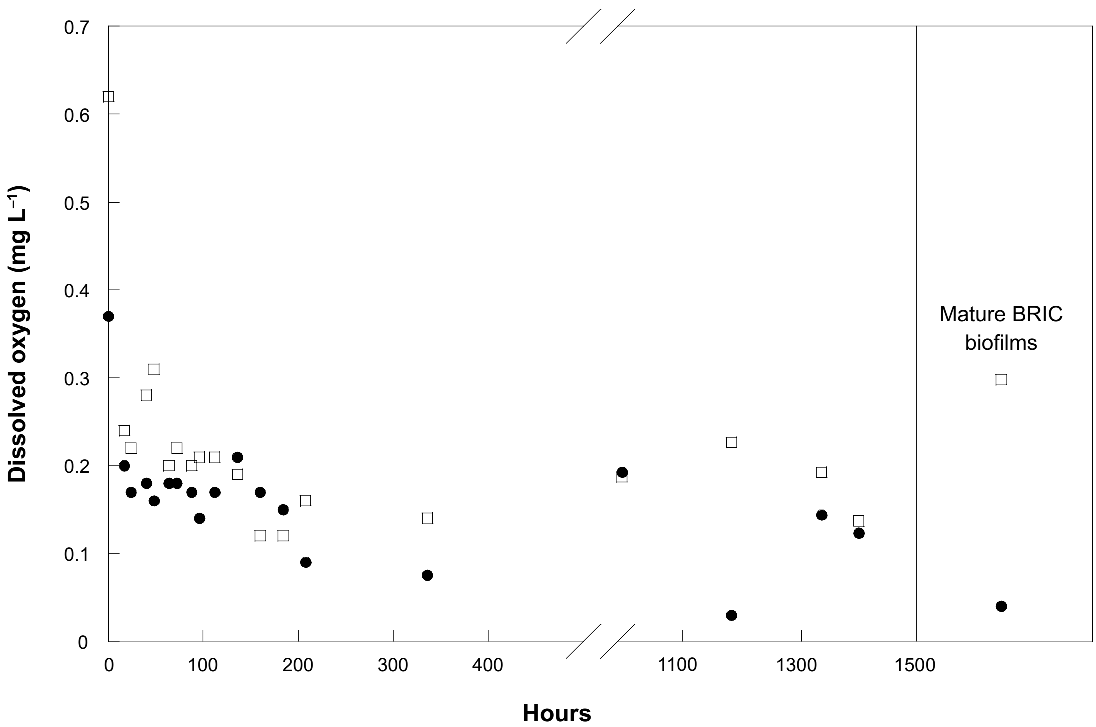


Figure 4-18. Dissolved oxygen decline at 70 mm depth over 2,000 hours (3 months) for the Bios Bric (□) and the AC Bric (●). Mature biofilms sampled after 8,700 hours (1 year) indicate that the decrease in oxygen is preserved in the AC Bric but oxygen levels in the Bios Bric can increase.

Microbial effects on the chemical stability of deep groundwater environments

Redox reactions

There is widespread interest in developing methods to investigate in situ microbial activity in subsurface environments. Novel experiments based on single borehole push-pull methods were conducted to measure in situ microbial activity at the Microbe –450 m site. Experiments were conducted to measure microbial nitrate reduction and lactate consumption in the circulation system connected to KJ0052F01. The system was used to circulate groundwater from the aquifer through the pressure-maintaining flow cells in the circulation system containing coupons for biofilm growth. Four experiments were conducted in which a combination of a conservative tracer, nitrate and lactate were injected into the circulation system. For each experiment samples were collected periodically over four days to measure the consumption of nitrate and/or lactate. Rate of nitrate utilisation was 5 μM h^{-1} without an exogenous electron donor (lactate) and 13 μM h^{-1} with an exogenous donor (Table 4-3). Similarly, the rate of lactate consumption increased from 30 μM h^{-1} to 50 μM h^{-1} with the addition of an exogenous electron acceptor (nitrate). Attached and unattached cells were enumerated before and after each experiment using epifluorescence microscopy to allow the determination of cell-specific rates of activity. The biofilm had an average cell density of 1×10^6 cells per cm^2 and there was an average of 6×10^5 unattached cells per ml in circulation. The cell-specific rates of lactate consumption were higher than those previously reported using radiotracer methods in similar environments (Table 4-3). The differences highlight the importance of conducting microbial investigations at in situ conditions. The results demonstrate that an indigenous community of microbes proliferate at a depth of 450 m in the Fennoscandian shield aquifer with the potential to oxidise simple organic molecules such as lactate. Accordingly, the role of microbial processes in the geochemistry of deep repositories warrants continued investigation.

Table 4-3. Cell-specific rates of activity are determined by dividing the rate of substrate utilisation by the total number of attached and unattached cells in the system. These rates are compared with cell-specific rates of lactate uptake in similar environments as measured by radiotracer methods.

Site	Borehole	Test	Depth	Numbers of cells[5]		Nitrate utilisation[6]	Lactate consumption[6] (μMhr^{-1})	Cell specific consumption rate (μmoles $cell^{-1}$ hr^{-1})	
				Unattached (cells ml^{-1})$\times 10^5$	Attached (cells cm^{-2})$\times 10^6$	(μMhr^{-1})		Nitrate ($\times 10^{-10}$)	Lactate ($\times 10^{-10}$)
Äspö[1]	KJ0052F01	0[4]	448	7.08 ± 1.15 (n = 30)	1.13 ± 0.42 (n = 15)	–	–	–	–
Äspö[1]	KJ0052F01	Control	448	5.40 ± 0.72 (n = 20)	1.17 ± 0.22 (n = 20)	–	–	–	–
Äspö[1]	KJ0052F01	nitrate utilization	448	4.78 ± 1.00 (n = 20)	1.04 ± 0.16 (n = 20)	5.00 ± 1.7	–	25.7 ± 1.1	–
Äspö[1]	KJ0052F01	lactate consumption	448	6.11 ± 0.88 (n = 20)	1.33 ± 0.23 (n = 20)	–	30 ± 9	–	119 ± 43
Äspö[1]	KJ0052F01	nitrate utilization/lactate consumption	448	5.84 ± 0.95 (n = 20)	1.17 ± 0.26 (n = 20)	12.9 ± 4.2	50 ± 23	57.8 ± 2.5	222 ± 120
Stripa[2]	V2	lactate consumption	799–807	0.05	1.20	–	–	–	1.2
Stripa[2]	V2	lactate consumption	812–820	0.02	7.10	–	–	–	41
Stripa[2]	V2	lactate consumption	970–1,240	1.20	5.90	–	–	–	51
Laxemar[3]	KLX01	lactate consumption	831–841	0.15	0.09	–	–	–	16
Laxemar[3]	KLX01	lactate consumption	910–921	0.21	0.12	–	–	–	5.6
Laxemar[3]	KLX01	lactate consumption	999–1,078	0.68	0.10	–	–	–	3.6

[1] This investigation; [2] /Pedersen and Ekendahl 1992b/; [3] /Pedersen and Ekendahl 1992a/; [4] Test 0 denotes population counts conducted prior to any perturbation experiments; [5] given range is based on standard deviation, n = number of fields counted; [6] uncertainty of rate is calculated from the error of the slope of linear regression; uncertainties were propagated through all calculations from this investigation.

These experiments provide a foundation for designing future in situ experiments. Tests measuring microbial nitrate respiration of lactate were successful when conducted in an enclosed circulation system maintained at in situ conditions. The method shows promise for measuring microbial activity at in situ conditions. However, several conditions are needed to make the tests informative and relevant to natural systems. First, sites should be carefully chosen with a prime criterion avoiding aquifers with high groundwater gradients caused by pumping or natural discharge. Second, a series of tests could be conducted with a variety of substrate concentrations. Third, measurement of reaction products would further constrain calculated rates. Thus kinetic relationships could be determined relating concentrations to activity. Such relationships could be used to better understand expected actual in situ rates of microbial activity in the subsurface rather than potential rates. A better understanding of this environment will be valuable in the design and monitoring of underground repositories for radioactive waste. A new project denoted Micored will deal with the issues listed above. Hydrogen and acetate are among the first substrates to be studied.

Disturbance of the Microbe –450 m site from other experiments

The site selection of the Microbe laboratory in the F-tunnel of Äspö has, until January 2005, assured the stable conditions required for the in situ experiments described above. However, the situation changed when drilling of boreholes in January 2005 at the –450 m level for the *"In Situ Corrosion Testing of Miniature Canisters",* Minican. This drilling caused a significant pressure drop (3 Bars) and a drainage of the Microbe formation from which Microbe takes its groundwater. During 2005 more than 15,000 m^3 groundwater has been drained from KA3386A01, via the Minican boreholes. This is a very significant drainage. A completely new mixing situation has developed in the Microbe formation during 2005. The drainage was eventually blocked in the beginning of December 2005. The effects from this disturbance are reported in /Pedersen 2005b/.

Significant increases in chloride concentrations indicate that deeper and saltier water is moving up from large depths towards the Microbe formation (Figure 4-19). It remains to analyse the mixing history with M3 modelling. This should be done when the pressure and drainage conditions have been restored. Complete class 5 analyses will be performed in January 2006 to establish the new chemical conditions that have originated as a result of the Minican drainage. Deeper water is expected to carry more hydrogen and noble gases, and less CO_2. Although the gas data are a bit erratic, some individual gas analyses also suggest that deeper water is moving up towards the Microbe boreholes. However, intensive mixing is expected with the measured drainage and this mixing may introduce variability over time. Variability of groundwater pressure due to opening and closing of boreholes, tide effects etc may introduce wobbling effects over time that masks clear trends. The data on microbes has changed from being very reproducible to very variable after the Minican drainage started (Figure 4-20 and Figure 4-21). Microorganisms are very sensitive to changes in the environmental conditions. New analyses of microbes will be performed once the conditions have returned to those prevailing before the Minican. This is expected to be the case in March 2006. However, it will be a totally new situation, because the introduction of new, deeper water to the Microbe formation has introduced a new situation.

Biocorrosion

There has not been any activity on biocorrosion during 2005. New in situ experiments are planned for 2006.

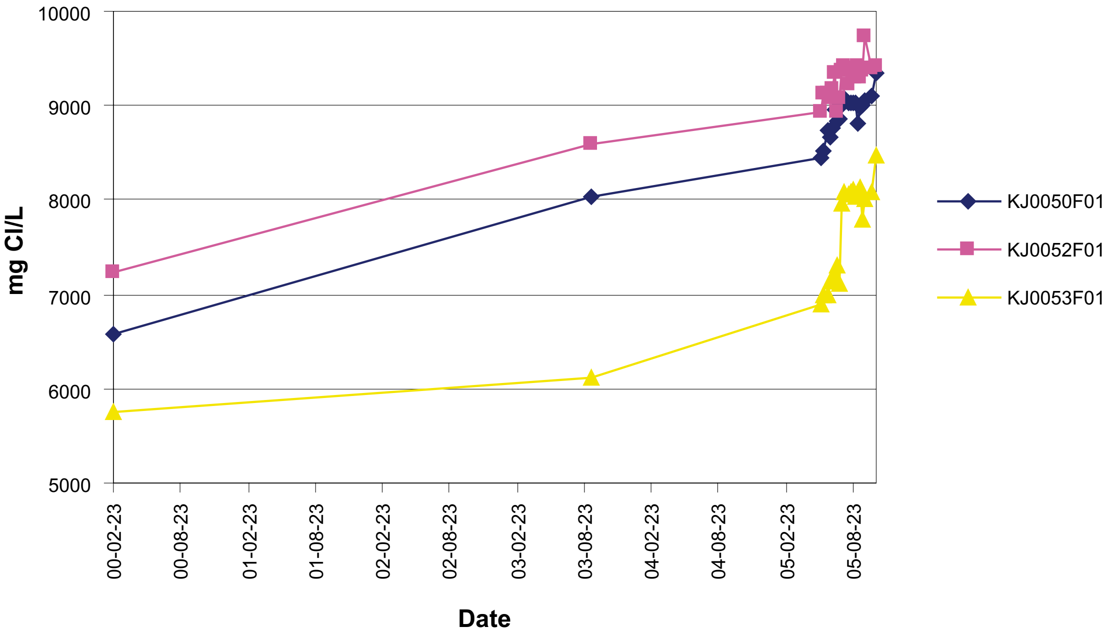


Figure 4-19. *The long-term increase of chloride in the groundwater at the Microbe –450 m site.*

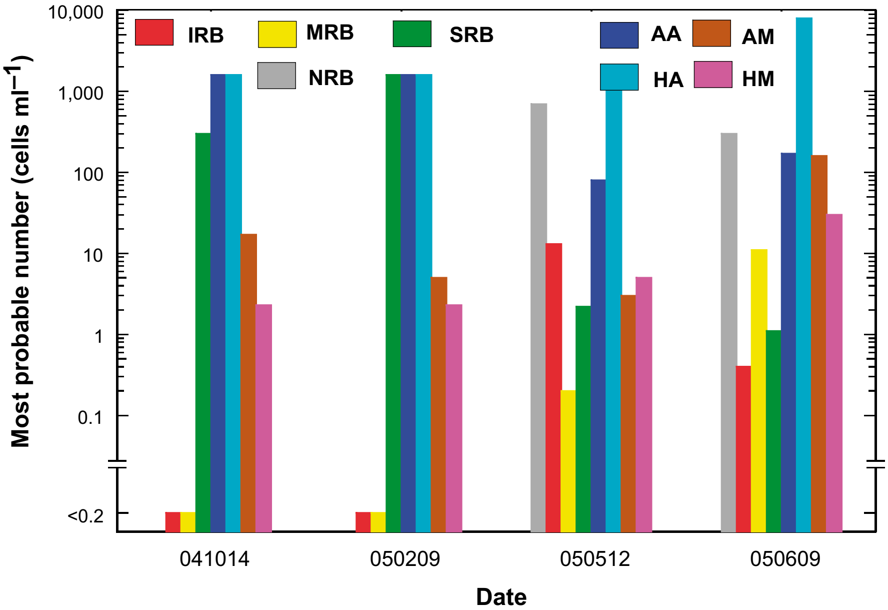


Figure 4-20. *Most probable number of physiological groups in KJ0052F01 over time before and during the disturbance from Minican.*

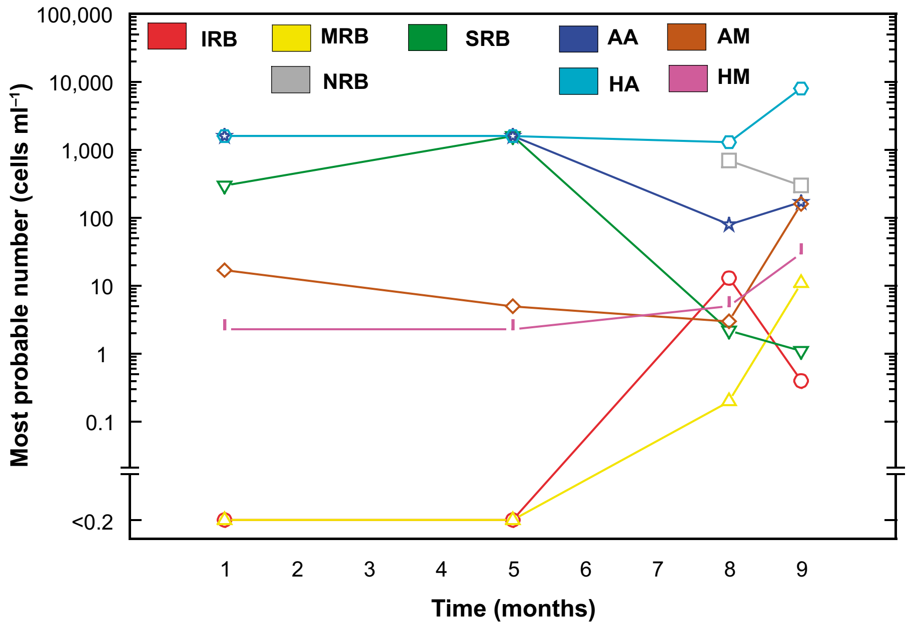


Figure 4-21. *Most probable number of physiological groups in KJ0052F011 over time before and during the disturbance from Minican.*

4.7 Matrix Fluid Chemistry

4.7.1 Background

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

The continuation phase (2004–2006) focussed on areas of uncertainty which remained to be addressed. These were:

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

This continuation phase, however, required an unforeseen initial feasibility study to assess the potential for further characterising the matrix borehole. This was necessary because of the untimely excavation of a new tunnel close to the matrix borehole for the Äspö Pillar Stability Experiment carried out in April/May, 2003. Because repercussions from this excavation may have influenced the hydraulic (and therefore the hydrochemical) character of the matrix borehole and the host rock vicinity, the feasibility study was carried out initially to quantify these effects. If the impact effects would be shown to be negligible, then the original objectives of sampling waters from small microfractures in the matrix borehole (to complement the earlier sampling of matrix waters from fracture-free lengths of the matrix borehole) and measuring the hydraulic parameters of the borehole lengths sampled could be carried out.

4.7.2 Objectives

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

- To establish the impact of tunnel construction on the matrix borehole by evaluating the monitored pressure profiles for the isolated borehole sections registered by the Hydro Monitoring System during the period of construction (small-scale).
- To establish the impact of tunnel construction on boreholes located in the 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 hydraulically characterise the original fracture-free borehole sections already hydrochemically evaluated.
- To carry out additional porosity measurements on drillcore samples to confirm or otherwise those values already measured in the first phase.

4.7.3 Experimental concept

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

Special downhole equipment, see Figure 4-22, was constructed ensuring: (a) an anaerobic environment, (b) minimal contamination from the installation, (c) minimal dead space in the sample section, (d) the possibility to control the hydraulic head differential between the sampling section and the surrounding bedrock, (e) in-line monitoring of electrical conductivity and drilling water content, (f) the collection of pore waters (and gases) under pressure and (g) convenient sample holder to facilitate rapid transport to the laboratory for analysis.

This experimental equipment, with some modifications, would be used in the continuation phase to sample groundwaters from the fracture-containing borehole lengths and to measure the hydraulic parameters of both the fracture-containing and fracture-free borehole lengths already sampled for hydrochemical characterisation.

4.7.4 Results

The feasibility study focussing on 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 carried out during the period March–August, 2005. The impact of the tunnel construction was judged to have had little effect on the hydraulic properties of the rock mass which hosts the borehole for the Matrix Fluid Chemistry experiment. It was therefore deemed worthwhile to initially hydrochemically and hydraulically characterise the presently isolated borehole sections containing microfractures and, secondly, to hydraulically characterise the original fracture-free borehole sections sampled during the first phase of the matrix experiment.

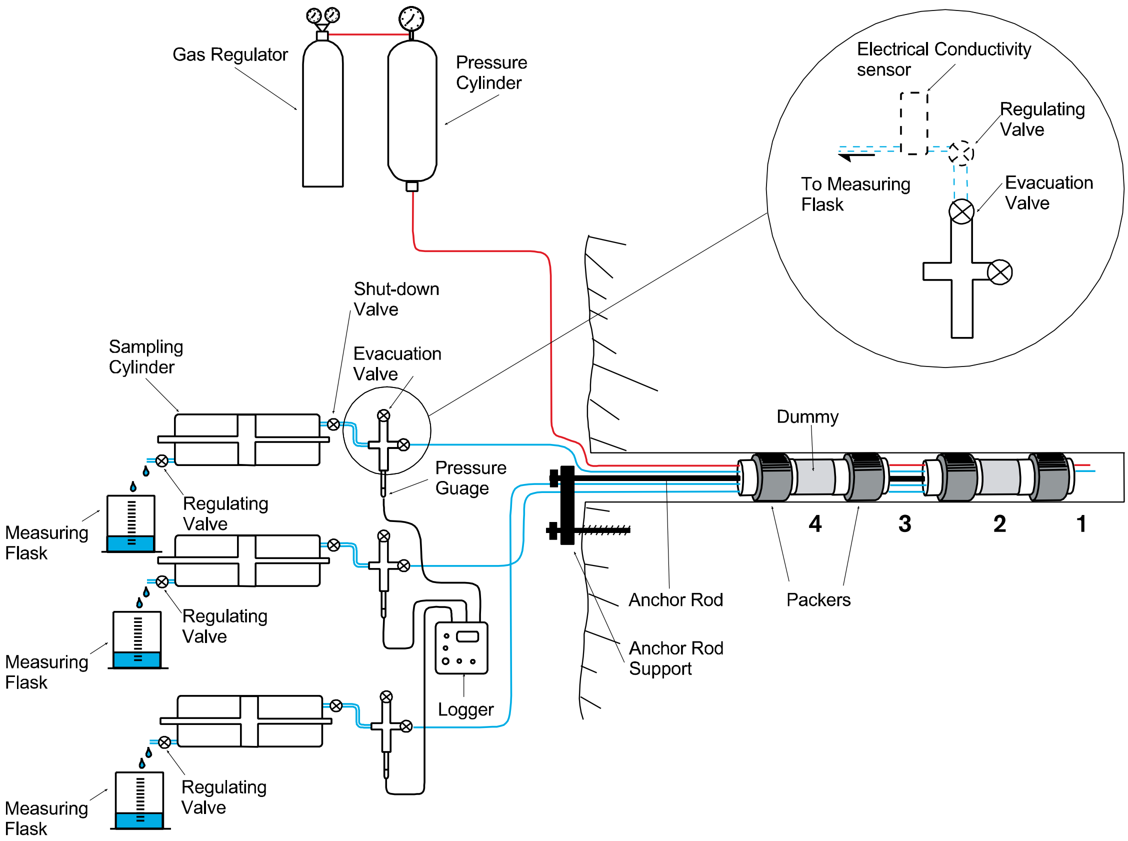


Figure 4-22. *Matrix Fluid Chemistry experiment set-up. Borehole sections 2 and 4 were selected specifically to collect matrix fluid; sections 1–4 were continuously monitored for pressure. In practice, all sections were sampled.*

Prior to hydraulic characterisation, sampling of waters from fracture-containing sections of the matrix borehole was carried out in April and November 2005. These waters are presently being chemically and isotopically analysed to complement earlier data from the fracture-free borehole lengths /Smellie et al. 2003/.

Preparation for the hydraulic characterisation of matrix borehole was successfully completed in 29th November, 2005. Hydraulic characterisation of the borehole is presently on-going and is expected to continue to the Spring of 2006.

With respect to the final objective, porosity measurements on drillcore material (borehole KA2599G01) to supplement data from the Matrix Fluid Chemistry borehole have been carried out successfully and a draft report is available. The report is presently being reviewed prior to being published as an internal TD early in 2006; a parallel article has been submitted and accepted for publication in Engineering Geology. The main conclusions found are:

- Total porosity in the samples studied from the Äspö quartz monzodiorite ranges from 0.89 to 1.51 vol.% (~ 70% of the measurements are within the range of 1.10 ± 0.13 vol.%), and connected porosity (by water saturation) of 60 mm long drillcore pieces ranges between 0.32 to 0.44 vol.%.
- The total and connected porosities measured in thinner samples are enhanced and can be explained by the contribution of microfractures formed at the cutting ends of the drillcores which is relatively higher for thinner than for thicker samples.

- Approximately 33–60% of the total porosity is connected porosity. The thicker samples show the lowest connected porosity values, and probably better represent the bulk rock. The unconnected porosity in the thicker samples constitutes the major part (~ 65%) of the total porosity.
- Drillcore samples < 20 mm thick show higher connected porosity but have a larger variability in porosity and density values than the thicker samples. This demonstrates that a significant portion of connected pores have a length exceeding the thicknesses of these samples.
- Connected pores are preferentially aligned parallel to the foliation such that flow and diffusion in foliated rocks are likely dependant on the foliation and its orientation.
- Porosity calculated from laboratory measurements are higher than the in situ porosity due to secondary effects such as physical disturbance of laboratory samples including e.g. stress release. These differences may be even more pronounced in laboratory measurements when using small/thin samples. The porosity will be increased also by mineral weathering and alteration.

4.8 Padamot

4.8.1 Background

Palaeohydrogeology is a relatively new term used as a common name for information from fracture minerals that is used for interpretations of past hydrogeochemical and hydrogeological systems. The need for such interpretations has become evident in the geological/hydrogeological modelling of sites within the radwaste programmes of several countries and therefore an EC founded 3 year project with the name EQUIP (Evidences from Quaternary Infills for Palaeohydrogeology) was started in 1997. When the EQUIP project ended in 2000 /Bath et al. 2000/ there was a need for continued fracture mineral investigations and model testing of the obtained results 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).

4.8.2 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 of 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: (a) WP2 involving applications of several analytical techniques on fracture filling calcites dominantly from KLX01 and (b) WP5 that deals with performance assessment applications of palaeohydrogeological data and modelling.

4.8.3 Results

The EC part of the project is finished and was reported in EC series of reports in 2005. The results from Äspö are included as a part of Workpackage 2; "Application of mineralogical, petrological and geochemical tools for evaluating the palaeohydrogeological evolution of the Padamot study sites". In this report, results from several British sites (Sellafield, Dounreay and Cloud Hill), one Spanish site (Los Ratones) and one Czechish site (Melechov Massif) are also included. Geological, palaeoclimatic and hydrogeological setting of the sites are summarised. Mineralogical and geochemical investigations of fracture mineralisations are reported. The different experiences are summarised and implications for palaeohydrogeology are given.

The resulting description for Äspö/Laxemar/Simpevarp can be summarised as follows. The tentative models of the past and present groundwater circulation proposed in /Bath et al. 2000/ and /Tullborg 2003/ are largely supported by the results from the Padamot study. A summary of the conceptual model of the distribution of the different types of late-stage calcite, and of the processes influencing calcite precipitation in the Laxemar-Simpevarp-Äspö groundwater system is illustrated in Figure 4-23. At least three different zones of calcite mineralisation are distinguished:

- The upper 50–100 m of the system is characterised by a dynamic situation involving dissolution and precipitation of new calcite. At times, biogenic activity has been significant and produced reducing conditions, whereas during other periods oxidising conditions may have prevailed.
- From 100 m down to between 500–600 m mainly precipitation (or re-crystallisation) of calcite is observed. Several generations of calcite (zoned) are common at these depths. Redox conditions have probably been stable and reducing, and contributions from biogenically-mediated carbonate precipitation are detected in terms of low carbon isotope values and high contents of Mn and La.
- Between 600 and 1,000 m, the biogenic carbonate influence decreases drastically but calcite mineralisation, consistent with low temperature precipitation from fresh groundwater of meteoric origin, can be traced in the major zones of steep fractures that were intersected at 850 and 950 m in borehole KLX01. Some of these calcites show bands with low cathodoluminescence indicating low Mn content, but Mn-rich calcite growth bands are also found.

It has not been possible to identify any late calcite that has precipitated from water with a significant glacial component. Groundwater with a glacial meltwater component has however been identified at depths varying from 100 m (in isolated pockets) to 1,100 m. One possibility is that the glacial water intrusion did not form any calcite. Alternatively, a possibility is that calcite precipitated from glacial-recharged groundwater simply has not yet been identified in the specific drillcore samples examined to date.

At greater depth (> 1,000 m) recent calcite precipitation is rare, and the biogenic input seems to be insignificant due to relatively stagnant conditions that pertain at this depth in the system.

The observed distribution pattern of the different calcite generations is the net effect of calcite-fluid interactions (and also of subsurface microbiological activity during long periods) during the entire geological history of the granitoids of the area. The hydrothermal calcite (*Type 6*) is the most widespread fracture calcite precipitation. It is probably related to the regional hydrothermal alteration, focussed along fractures and fracture zones that occurred early in the geological history of the granitoids at Äspö. The subsequent dissolution of the hydrothermal calcite, and its replacement of by calcite of younger groundwater regimes, has been repeated many times since the initial mineralisation in the Proterozoic.

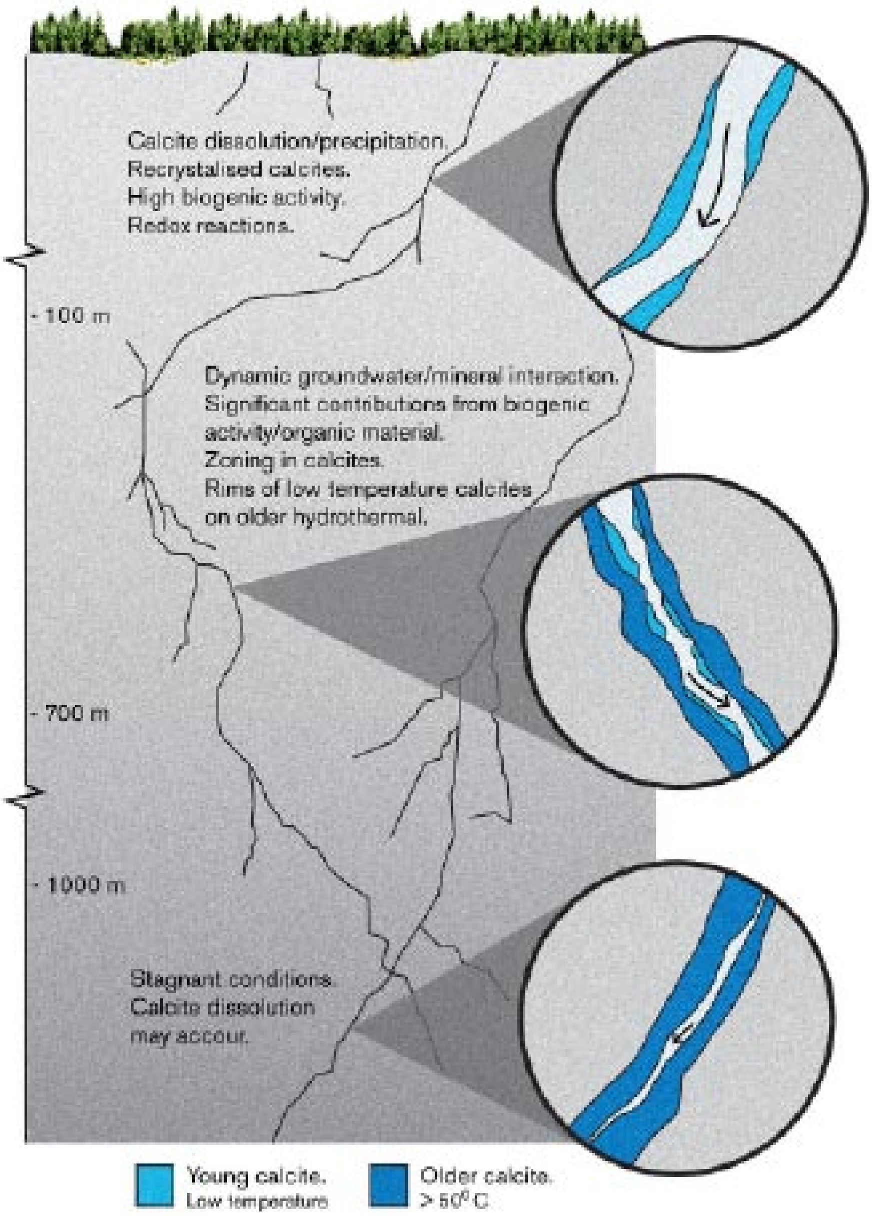


Figure 4-23. *Potential calcite-groundwater interaction at various depth at Äspö.*

When a thick sedimentary cover on the Fennoscandian shield was present during the Late Palaeozoic, *Type 5* calcite was precipitated from warm brines. It is believed that the present rock surface has been exposed since at least the Late Tertiary, and therefore *Type 5* calcites must pre-date this time. *Type 5* calcite precipitate from a brine-type water at elevated temperatures. This has been demonstrated by detailed fluid inclusion studies, which show that calcite contains two-phase fluid inclusions with salinities over 1,000 ppm Cl /Milodowski et al. 2005/. *Type 5* calcite forms c-axis elongated scalenohedral shaped euhedral crystals, which is also indicative of formation from saline groundwater. Temperature estimates from fluid inclusion homogenization observations, together with $\delta^{18}O$ values mostly in the range of –10 to –17‰ SMOW (Standard Mean Ocean Water), indicate possible formation temperatures in the range of 60 to 150°C. This type of calcite is probably older than late Mesozoic (100 Ma) and younger than 1,400 Ma, and is interpreted to have precipitated from sedimentary (diagenetic) brines that percolated through the basement when the Scandinavian Shield was covered with sedimentary rocks during the Riphean or Palaeozoic.

The distribution and abundance of low-temperature calcites (*Types 2 and 3*) of possible marine-brackish water origin ($\delta^{18}O > -7‰$) seems to be more extensive in the Äspö site, where they are found down to 500 m depth. In Laxemar borehole KLX01 these calcites are found only to 200 m. In contrast, low-temperature calcite of dilute meteoric water origin (*Type 1*) are found at over a wide depth range from the surface down to at least 950 m, indicating a deeper penetration of fresh groundwater sometime in the past.

4.9 Fe-oxides in Fractures

4.9.1 Background

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

Fractures lined with Fe-oxides are found in the Äspö bedrock and 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. Amorphous Fe(II)-oxyhydroxides, 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 crystalline Fe(III)-oxides is essentially unknown at present. These minerals could be an important sink for radioactive species where Fe is abundant in the natural fractures or in materials brought into the repository and Fe itself can be an indicator of redox state. Fe-isotope fractionation, a very new topic of research, might give clues about redox conditions during Fe-mineral formation or as a result of its inclusion in other secondary fracture minerals.

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

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

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

- Can more detailed information about the uptake of higher valent elements such as Eu^{3+} provide a model for actinide behaviour and Cr^{3+} as a palaeo-redox-indicator?
- Can stable Fe-isotopes from Fe-oxides or from other minerals tell anything about solution conditions during genesis?
- What is the uptake and retention capacity of green rust under solution conditions relevant for Äspö?

- Is it possible to find evidence to support or dispute the hypothesis that, at the time of glacier retreat, oxidising water might have penetrated to or below the depth of the planned repository for spent fuel?
- How might secondary Fe-minerals affect the migration of radionuclides accidentally released from a repository?

4.9.2 Objectives

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

4.9.3 Experimental concept

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

4.9.4 Results

The following results have been achieved:

- An effective and precise procedure has been developed to differentiate between several types of Fe-oxides found as fracture fillings in granite.
- Together with data from Mössbauer spectroscopy, X-ray diffraction (XRD) and rare-earth element (REE) analysis, three genetic environments for Fe-oxide formation have been demonstrated.
- The natural, low-temperature, recent Fe-oxides likely formed from weathering of chlorite fracture linings.
- From the samples studied, no evidence was found to indicate penetration of oxidising, low temperature solutions exceeding about 100 m below current ground level. This conclusion is, of course, fracture specific. Within more hydraulically active fractures greater depths may have been reached.
- Very recent, X-ray amorphous ($< \sim 10$ nm), low temperature Fe-oxides have resulted from drilling at Oskarshamn and Forsmark. Studies showed that metallic iron and maghemite, a common corrosion product of steel, were also present in minor amounts.
- Investigations of green rust (GR) have shown that existing literature data for structure and composition are incorrect. Revised data, which are required for PA modelling, have been produced and more will be available.
- Methods for investigating GR reactivity have been developed by using Cr(VI) reduction to Cr(III) as a model redox active compound. Preliminary studies with Np(V) and Se(VI) show the same behaviour.
- Reactive transport modelling involving Fe(II)/Fe(III) species has commenced.

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

4.10.1 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 solute transport in fractured rock. A task force delegate represents each participating organisation and the modelling work is performed by modelling groups. The Task Force meets regularly about once to twice a year.

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

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

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

Task 3: The hydraulic impact of the Äspö tunnel excavation (completed).

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

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

Task 6: Performance assessment modelling using site characterisation data (ongoing).

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

4.10.2 Objectives

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

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

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

Six sub-tasks have been defined within Task 6:

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

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

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

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

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

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

Task 7 was initiated at a Task Force meeting in September 2004 and addresses modelling of the OL-KR24 long-term pumping test at Olkiluoto in Finland. The task will focus on methods to quantify uncertainties in performance assessment approaches based on site characterisation information. It is also an opportunity to increase the understanding of the role of fracture zones as boundary conditions for the fracture network and how compartmentalisation affect the groundwater system. The possibilities to extract more information from interference tests will also be addressed.

4.10.3 Results

In the Task Force on Groundwater Flow and Transport of Solutes, work has been in progress mainly in Task 6 and 7. Task 6 addresses performance assessment modelling using site characterisation data and Task 7 addresses a long-term pumping test in Olkiluoto, Finland.

The 20th International Task Force meeting, hosted by SKB was held 13th–15th May, 2005 at Äspö HRL. Minutes and proceedings of the 20th International Task Force have been published on the task force web site at SKB.

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 are printed. The review report for sub-tasks 6A, 6B and 6B2 /Hodgkinson and Black 2005/ and also the review report for sub-task 6C /Black and Hodgkinson 2005/ have been published.

Modelling work for sub-tasks 6D, 6E and 6F has been performed and presented at the Task Force meeting in May 2005. At the Task Force meeting, it was decided that the sub-tasks 6D, 6E, 6F and 6F2 are to be reported together, and the work with this combined report is in progress. In the meeting, data and conditions for Task 7 were presented. In addition, a workshop on Task 7 was held at Riddersviks Gård in Hässelby outside Stockholm in September 2005.

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.

The Public relations and Visitor Services group is responsible for presenting information about SKB and its facilities e.g. the Äspö HRL. They arrange visits to the facilities all year around as well as special events.

5.2 Facility operation

5.2.1 Background

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

5.2.2 Results

The facility consists of a tunnel of about 3,600 m extending to a depth of 450 m with the slope of 14%. The tunnel can be accessed via a ramp or an elevator. The elevator can be used to reach the levels where SKB's research is carried out, on the levels –220 m, –340 m and –450 m. The facility is well maintained and has a very high degree of operational time; 99% in 2005.

The facility is equipped with an operational and monitoring system and any alarms are sent to operational personnel who are prepared for emergency action even out of office hours. Operational and maintenance contracts have been set up with a number of contractors. A PC-based maintenance system has been implemented and the aim is that the system will facilitate the planning of maintenance of the facility, vehicles and machinery.

The facility is equipped with fire and evacuation alarms both above and below ground. Each year fire-fighting and first-aid courses are organised for all the personnel. Both the under- and above-ground facilities are equipped with a telephone network with cordless telephones and cameras have been installed in order to monitor the most important places in the facility.

The ventilation below ground consists of two intake fans that are used alternately and an extraction fan which is placed in the above-ground facility. On the occurrence of a fire alarm, the ventilation system is automatically switched to maximum flow.

The inflowing water from the rock is pumped in four stages up to a sedimentation dam before release to the Baltic Sea. The pump stations are placed at levels –450 m, –340 m, –220 m and –110 m.

The below-ground facility has two alternative electricity supplies which can be coupled in as required; via a high tension cable from OKG or via the above-ground facility. Investigations have been performed in order to secure the operation of the facility and its experiments during longer power cuts and to ensure operation of emergency systems for the emergency services during, for example, fires. Options for back-up power that have been considered are diesel generators and extra electricity supply cables.

Extension of storage space and adaptation for the KBS-3H project has been made. An existing and unheated storage building at the tunnel entrance has been extended. The highest part of the existing storage building has been insulated and equipped with heating and ventilation. Two roof-windows have been installed to enable construction of Supercontainers for the KBS-3H project.

5.3 Hydro Monitoring System

5.3.1 Background and objectives

The monitoring of groundwater changes during the construction and operation of the laboratory is an essential part of the documentation work aiming at verifying pre-investigation methods and a support to the experiments. 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 /Nyberg et al. 2005/.

The Hydro Monitoring System (HMS) collects data on-line of groundwater head, electrical conductivity and water flow in the tunnel. The data are recorded by numerous transducers installed in boreholes and in the tunnel. 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 in Äspö HRL as well as surface boreholes on the island of Äspö. The responsibility of the surface boreholes on the islands of Ävrö, Mjälen, Bockholmen, and on the mainland at Laxemar was handed over to the Oskarshamn site investigation in 2004. Weekly quality controls of preliminary groundwater head data are performed. Absolute calibration of data is performed three to four times annually. This work involves comparison with groundwater levels checked manually in boreholes.

5.3.2 Results

Improvements, new installations and other measures carried out during 2005 are:

- Instrumentation and started registration in borehole KA3386A01 (–450 m level) in the tunnel and addition of an extended module to the data acquisition unit.
- Installation of new gauges for measuring air temperature, air humidity and air pressure has started throughout the whole tunnel. The work will continue during 2006.
- Continuous maintenance and calibration of the system regarding gauges and data acquisition system.

5.4 Programme for Monitoring of Groundwater Head and Flow

5.4.1 Background

The monitoring programme is an important part of the hydrogeological research and a support to the experiments undertaken in the HRL. The HMS implemented in the Äspö HRL 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 143 boreholes (44 surface boreholes and 99 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 office 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 25 weirs where the flow is measured.

5.4.2 Objectives

The scope of maintaining such a monitoring network has had 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 is necessary to have information about the hydraulic boundary conditions for the experiments in Äspö HRL.
- 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. This legal requirement was thus gone by the end of the year 2004.

5.4.3 Results

The Hydro Monitoring System continued to support the different experiments undertaken at Äspö HRL. It provided 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 is put to use in different ways and it provides the means to continuously monitor the groundwater head in the rock volume where the experiments are conducted.

In addition, it is a necessary requirement during the rock characterisation stage preceding the experiments. The number of information points in the beginning of 2005 is compiled in Table 5-1. The number of measured sections in surface boreholes is somewhat lower than the year before, since a number of boreholes have been handed over to the site investigations Oskarshamn and since some malfunctioning packer systems have been removed. Automatic monitoring in surface boreholes is also successively replaced by monthly manual levelling.

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

Type of measurement	Number of measurement points
Groundwater pressure in tunnel boreholes	276
Groundwater level in surface boreholes	63
Flow of tunnel water	25
Electric conductivity of tunnel water	11

5.5 Programme for Monitoring of Groundwater Chemistry

5.5.1 Background

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

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

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. 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 the water composition in the sampled borehole section from the level of the lower packer position up to the upper packer position which level may vary. The KAS-borehole is drilled from the surface whereas all the other boreholes are located in the tunnel.

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	KA3110A	–416
SA2074A	–284	KA3385A	–449
SA2600A	–346	KA3573A	–447
KA2862A	–382	KA3600F	–446
SA3045A	–409	KAS03	–612

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 (about 370–380 m below 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 below sea level). This may also support a possible up-coning effect which needs to be further studied.

During 2005 the biogeochemical parameter ATP has been included in the monitoring programme. This will be evaluated during 2006.

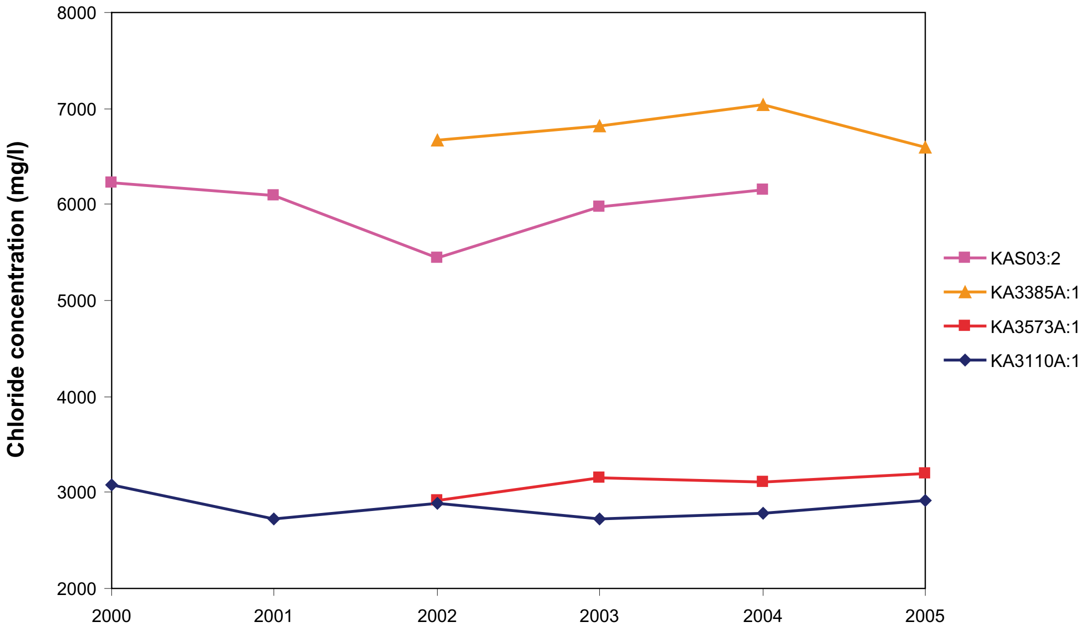


Figure 5-1. *Chloride concentrations (mg/l) in selected boreholes. The boreholes KA3110A (–416 m) and KA3385 (–449 m) are located in the Äspö tunnel and KAS03 is a borehole from the surface with a packed-off section at about –612 m.*

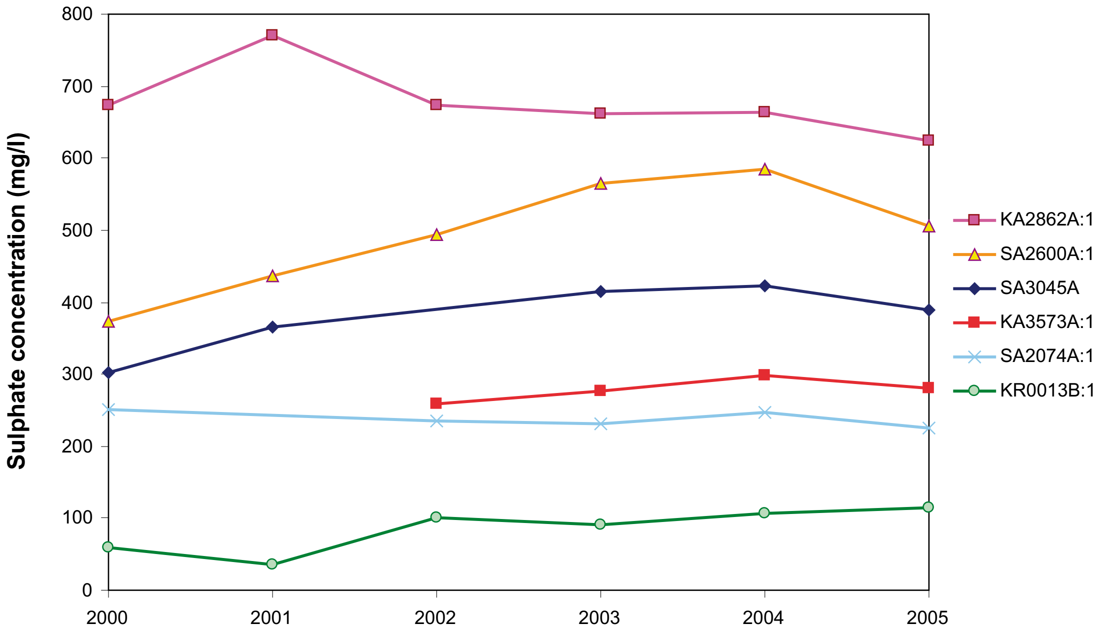


Figure 5-2. *Sulphate concentrations (mg/l) in selected boreholes in the Äspö tunnel. KR0013B (–69 m) is the shallowest and KA3573A (–447 m) the deepest.*

5.6 Public Relations and Visitor Services

5.6.1 General

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

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

During the year 2005, the Äspö HRL and the site investigation activities were visited by about 11,500 visitors. The visitors represented the general public, municipalities where SKB perform site investigations, teachers, students, politicians, journalists and visitors from foreign countries.

The total number of visitors to all SKB facilities, Äspö HRL, Clab, Canister Laboratory and SFR was almost 26,000, see Figure 5-3. The information group has a special booking team at Äspö HRL which books and administrates all visitors.

5.6.2 Special events

During the year 2005 the summer tours for the general public, called U500, started in June and finished up in August. This year 2,500 visitors took the opportunity to visit Äspö HRL.

An annual event "The Äspö Day" took place on 29th May. It is an open house where the visitors can see the underground laboratory and also participate in tours on the ground. These tours provide information on e.g. geology, history and nature. About 200 visitors from the local district came this year.

"The Geology Day" was celebrated for the fifth time in Sweden on 17th September. More than hundred visitors joined a local train trip with stops to learn more about geology.

On 10th December the Äspö running competition was held in the Äspö-tunnel. Fifty participants ran all the way up from –450 m depth. The length of the race is 3.5 km and the inclination is 14%. This has been an annual event since seven years.

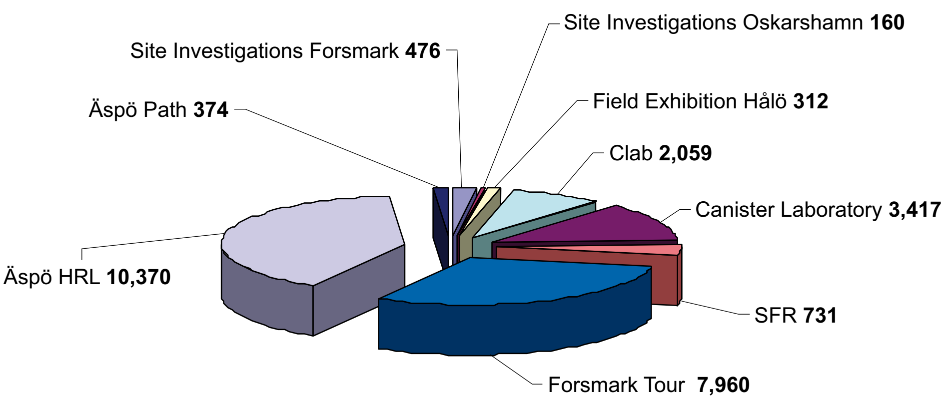


Figure 5-3. *The number of visitors to the different SKB facilities during 2005.*

6 International co-operation

6.1 General

In addition to SKB, nine organisations from eight countries participated in the co-operation at Äspö HRL during 2005. Six of them; Andra, BMWi, CRIEPI, JAEA, OPG and Posiva form together with SKB the Äspö International Joint Committee (IJC), which is responsible for the co-ordination of the experimental work arising from the international participation. The committee meets once every year. In conjunction with each IJC meeting a Technical Evaluation Forum (TEF) is held. TEF consists of scientific experts appointed by each participating organisation. For each experiment the Äspö HRL management establishes a Peer Review Panel consisting of three to four Swedish or International experts in fields relevant to the experiment. Presentations of the organisations represented in the IJC are given below.

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

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

The international organisations are taking part in the projects, experiments and task forces described in Chapters 2, 3 and 4 (Technology, Geoscience and Natural barriers). The co-operation is based on separate agreements between SKB and the organisations in question. The participation by JAEA and CRIEPI is regulated by one agreement. The participation of each organisation is given in Table 6-1.

Table 6-1. International participation in the Äspö HRL projects during 2005.

Projects in the Äspö HRL during 2005	Andra	BMWi	CRIEPI	JAEA	OPG	Posiva	Enresa	Nagra	RAWRA
Geoscience									
Äspö Pillar Stability Experiment					X	X			
Natural barriers									
Tracer Retention Understanding Experiments	X			X		X			
Long Term Diffusion Experiment					X				
Colloid Project		X			X	X			
Microbe Project		X							
Radionuclide retention project		X							
Task Force on Modelling of Groundwater Flow and Transport of Solutes	X		X	X	X	X			
Engineered barriers									
Prototype Repository	X	X		X		X			
Long Term Test of Buffer Material						X			
Temperature Buffer Test	X	X					X		
KBS-3 Method with Horizontal Emplacement						X			
Large Scale Gas Injection Test	X	X			X	X			
Injection grout for deep repositories						X			
Task force on engineered barrier systems	X		X		X	X		X	X

6.2 Andra

Within the framework of the co-operation agreement with SKB, Andra has in 2005 continued work on projects linked to the natural and engineered barriers. The work with the natural barriers included the True Block Scale Continuation project and the Task Force on Groundwater Flow and Transport of Solutes. The work with engineered barriers consisted of the Temperature Buffer Test and the activated Task Force on Engineered Barrier Systems.

The results of these projects are described in their respective sections in Chapters 2 and 4 of the present report. However, work related to the Temperature Buffer Test and the Task Force on Groundwater Flow and Transport of Solutes are presented below.

6.2.1 Temperature Buffer Test

Modelling, mock-up testing and rereading of field data, were complementary approaches followed during 2005 to better understand observed THM behaviour of the two buffer-heater configurations tested in situ in Äspö HRL since March 2003.

Further development of the test has been addressed during modelling meetings held in Tours, 16th March, 2005 and in Barcelona, 27th October, 2005. Considering that hydration of the clay buffer is still ongoing and considering that the AITEMIN heaters are well operating, decision was taken on request from UPC and Clay Technology modellers to postpone the dismantling phase and keep the test running for years under steady thermal and hydraulic boundary conditions.

It was also considered to plan a gas injection test in the upper buffer when the buffer is fully saturated, prior to dismantling of the experiment. With the updated time table, such a gas test would be implemented after the Large Scale Gas Injection Test has been performed and thus benefiting from its outcome.

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

Task 6 "Performance assessment modelling using site characterisation data", is in its last phase. Results produced by Andra modelling teams concern the sub-tasks 6D and 6E, dedicated to tracer test experiment modelling at block scale as well as performance assessment modelling. A sensitivity analysis was also performed within the sub-task 6F.

Sub-task 6D – Simulation of a tracer test (C2) in block scale (50–100 m) using a semi-synthetic structural model. Two modelling teams from Golder and CEA were involved using different conceptual and mathematical models to achieve this task.

Golder has developed stochastic models to reproduce selected tracer tests with the objective of assessing the constraining power of these tests and the capability to quantify the basic characteristics of processes and parameters affecting the transport in the fractured rock. The tracer test (C2) includes the following tracers: non-sorbing (^{186}Re), slightly sorbing (^{47}Ca), moderately sorbing (^{131}Ba) and strongly sorbing (^{137}Cs). Methodology is built on a continuum approach to simulate the flow and derive parameters needed to simulate the transport by a DFN approach. It aims at analysing the constraining power of tracer tests and determining plausible ranges of geometric and transport parameters. A constrained coupled parameters distribution is used to model the tracer. Major results show:

- Conservative tracer tests with ^{186}Re produce a limited constraining power except when considering the parameters related to stagnant zones and complexity factor.
- ^{47}Ca tracer has constraining power for the K_d and complexity factor of the matrix zones in contact with the flowing water.

CEA modelling work is based on a deterministic approach. The measured breakthrough curves of the tracers are reproduced by affecting a single parameter set involving matrix diffusion along the flow path. A sensitivity analysis was also performed. The calibrated system is not a unique solution. It is difficult to discriminate the spreading of breakthrough curves induced by dispersion in the fracture or by diffusion into the matrix. Most important parameters for the transport are fracture aperture and sorption coefficient. The constraining power of the tracer test was not proved. Results showed that information carried by the tracer test allows only for the identification of simple major features of the system: advective travel time and averaged properties of immobile zones (matrices) in the vicinity of mobile ones (flow paths), combined with dispersion in the fractures. These are mainly responsible for the peak arrival time and the spread of the breakthrough curve. As conclusion this team assumes that tracer tests provide information limited to the fracture and to matrix in contact with the flowing water.

Sub-task 6E – Modelling a tracer transfer over performance assessment time scale (10^8 years) in the geostructural model used for sub-task 6D. The hydraulic gradient applied is very low (0.5%) as compared with the one used for tracer experiment (1,000%). The Golder team has used the same modelling strategy as for sub-task 6D. The Dirac pulse simulations results show that the ^{241}Am has the largest retention and delay factor (50% recovery). The arrival time of the largest peak in mass flow, as well as the time for recovery of the injected mass, are observed in the following order: ^{186}Re, ^{47}Ca, ^{226}Ra and ^{241}Am.

The main conclusions drawn by CEA team from the modelling of this task are:

- The long-term transport (PA time scale) in fractured rock is controlled by matrix diffusion, which induces important retardation effect. The peak arrival time corresponds to a factor 10 for non sorbing Iodine to 5×10^5 for highly sorbing Americium. The penetration depth of diffusion front is much greater then for the modelling of the tracer experiment. This means that all matrices (altered diorite, cataclasite and gouge) contribute to tracer retardation.
- Justifying simplification of the site characterisation model for performance calculation is challenging. A 12 fracture system developed from a 150 fracture network appears to be a robust simplified model for PA calculations compromising between precision, complexity and numerical efficiency. This was demonstrated through a transport tracer calculation.

Task 6F consists in series of "Benchmark" cases based on a simple block scale hydro-structural model integrating two types of fractures. This sensitivity study allows comparing transport and retention behaviour between fault feature 1S and non fault feature 4S. Sensitivity to the groundwater travel time was also investigated. Results of stochastic modelling of sorbing tracers (^{137}Cs and ^{241}Am) transport and retention show larger arrival time of peaks for fault 1S as compared to non fault 4S. Retention capacity of faults seems to be greater than those of non fault features. The F parameter (flow wetted surface over flow) calculated for various water residence times shows that retardation caused by diffusion process into matrix is greater in fault 1S than in non fault 4S. These results will be evaluated and compared to other group results at the next Task Force meeting.

6.3 BMWi

In 1995 SKB and the BMBF (Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie) signed the co-operation agreement being the frame for participating in the activities in the Äspö HRL. In 2003 the agreement was extended for a period of six years. On behalf of and funded by BMWi (Federal Ministry of Economics and Technology) five research institutions are currently performing the work in the Äspö HRL: BGR, DBE Technology, FZK, FZR, and GRS.

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

- In situ investigations of water flow in fractured rock, rock matrix and engineered barrier system.
- Studying 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- and far-field conditions.
- Geochemical modelling of individual processes controlling migration.
- Investigation of the microbial activity with regard to their interaction with radionuclides.
- Thermodynamic databases for radionuclides relevant for long-term safety.

The work carried out in 2005 is described below.

6.3.1 Prototype Repository

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

The measuring programme, agreed on by SKB and GRS, includes the monitoring of two electrode arrays in the backfilled drift above the deposition boreholes 3 and 6, an electrode array in the buffer at the top of deposition hole 5, and three electrode chains in the rock between deposition holes 5 and 6 (Figure 6-1).

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

The array in the backfill in Section I was the first one to be installed. Measurements started in October 2001. The initial resistivity of the backfill ranged around 10 to 14 Ωm, corresponding to a water content of 13 to 14%. 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 left side of Figure 6-2 shows the resistivity distribution in December 2004. A very homogeneous resistivity distribution had been reached; with a value around 3 Ωm corresponding to water content around 22% so the backfill was not far from full saturation. During 2005, a slight further decrease of resistivity meaning an increase of saturation was detected, as shown in the tomogram from November 2005 (right side of Figure 6-2).

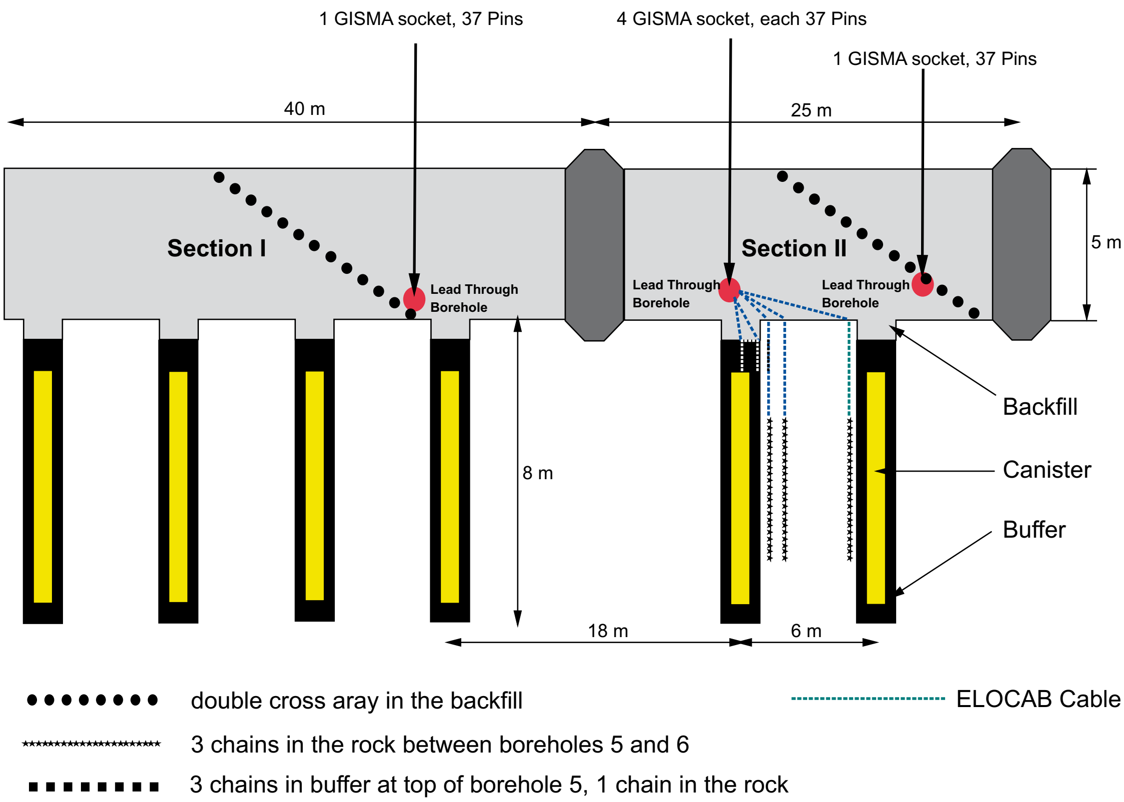


Figure 6-1. Arrangement of electrode arrays in the Prototype Repository.

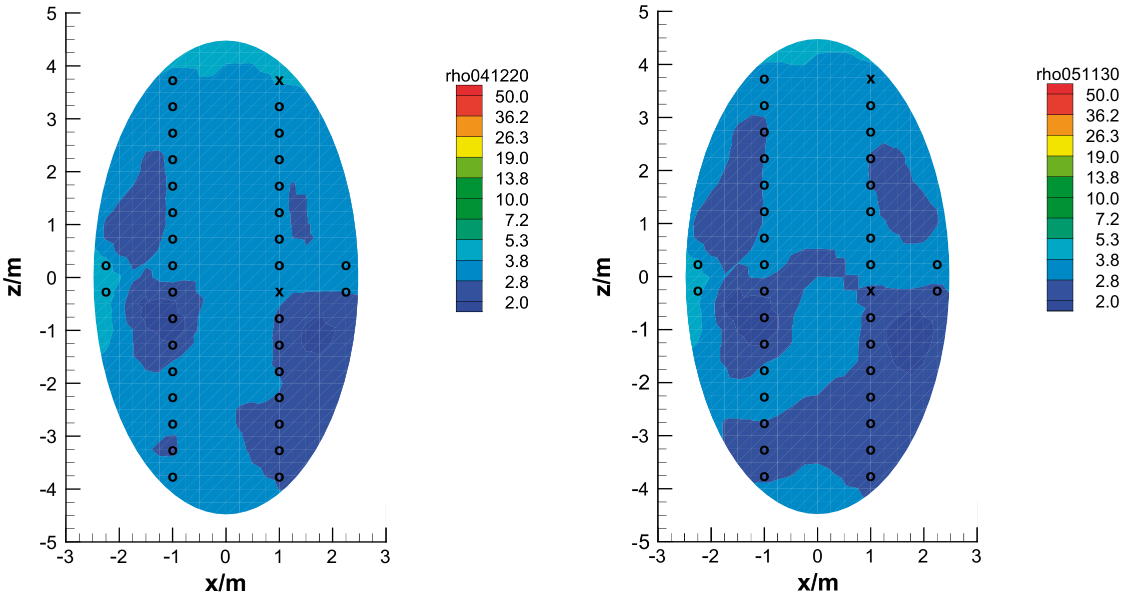


Figure 6-2. *Resistivity distribution (Ωm) in the backfill in Section I, December 2004 (left) and November 2005 (right).*

The array in the backfill in Section II was installed in June 2003. Already from the start of measurements a much lower resistivity than in Section I was encountered, 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 still decreasing further from the drift walls. Figure 6-3 shows the resistivity distributions from December 2004 and November 2005 in comparison. Close to the walls resistivity now ranges below 3 Ωm; the backfill is therefore more or less fully saturated. In the centre, values between 4 and 5 Ωm, corresponding to water content of about 18 to 20%, have been reached.

Resistivity measurements in the buffer were started in May 2003. Figure 6-4 shows the original resistivity distribution and the distribution from August 2005 as an example. The high resistivity (above 1,000 Ωm) of the rock on the right side and the lower values of the buffer (below 80 Ωm) on the left are clearly visible. Along the electrode chains the resistivity is increased in relation to the undisturbed buffer and decreased with respect to the rock, which is a result of electrode installation measures. The high contrasts in resistivity in the small measuring area cannot be completely reproduced. Comparison of the two resistivity distributions of Figure 6-4 shows, however, the progressing saturation of the buffer.

The resistivity distributions along the three electrode chains installed in the rock 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 characteristic for saturated granite /Rothfuchs and Wieczorek 2005/.

6.3.2 Large Scale Gas Injection Test

For the hydraulic characterisation of the excavation damaged zone, BGR has developed surface packer systems. In 2005 tests have been conducted and analysed in the deposition hole for the Large Scale Gas Injection Test, in the TBM-excavated A-tunnel, and in the drill and blast excavated Q-tunnel.

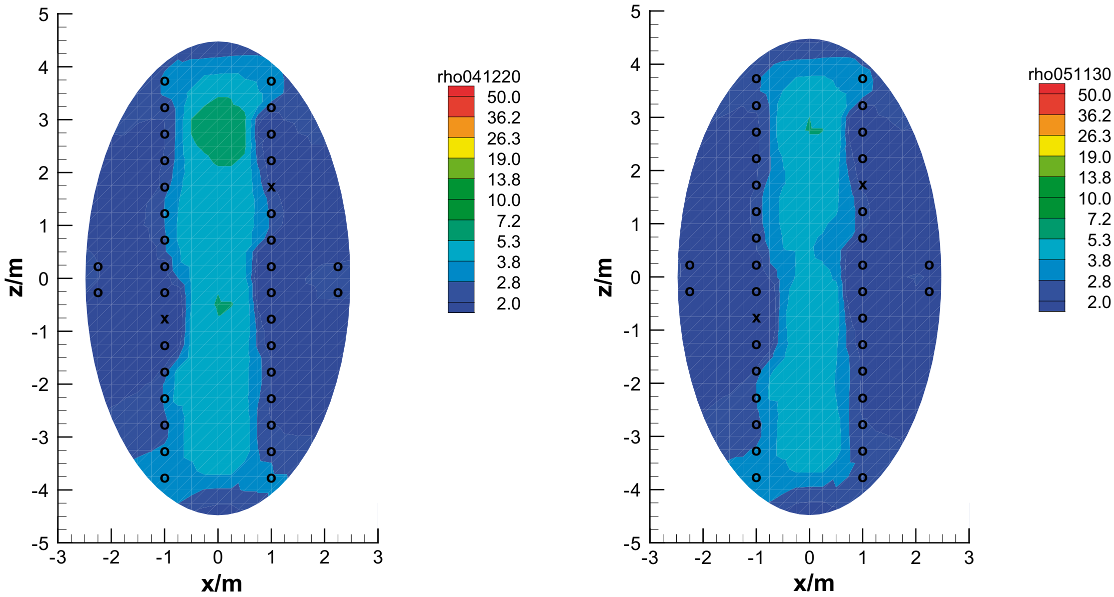


***Figure 6-3.** Resistivity distribution (Ωm) in the backfill in section II, December 2004 (left) and November 2005 (right).*

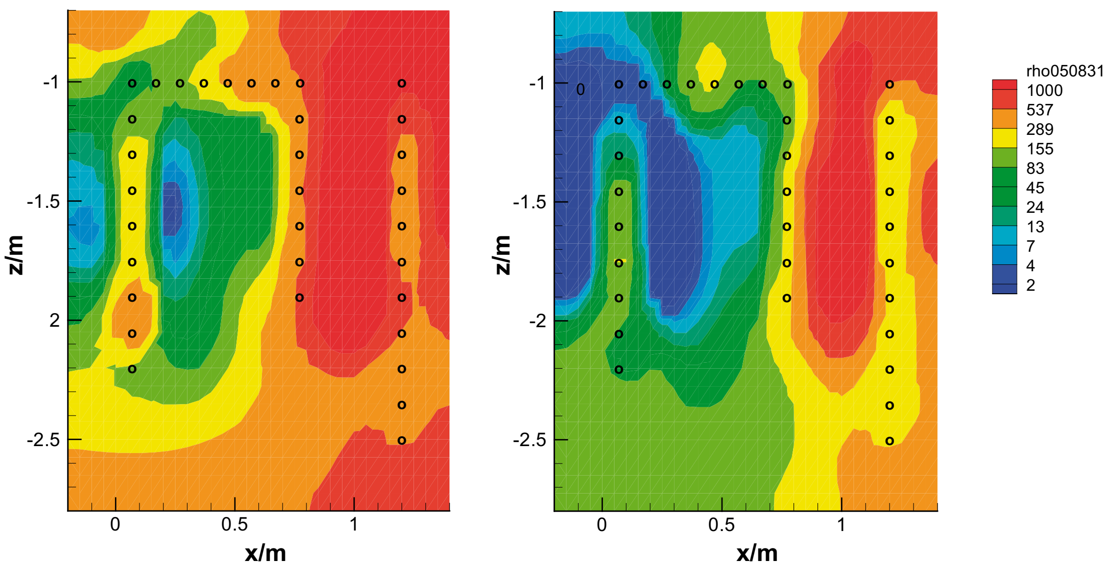


***Figure 6-4.** Resistivity distribution (Ωm) in the buffer at the top of deposition hole 5, August 2005.*

In the deposition hole a permeability value of 10^{-19} m^2 was found at a position without visible fractures or cracks. In the drill and blast excavated Q-tunnel a permeability value < 8×10^{-20} m^2 was found near to a blast hole. This finding emphasises the importance to consider the scale when interpreting a permeability value. Other values found in the Q-tunnel range between 5×10^{-20} m^2 and 5×10^{-19} m^2. For classification of these results Figure 6-5 shows these experimental findings together with the results from the project Zedex /Emsley et al. 1997/, in which permeability of the rock has been measured both on core samples and in boreholes in situ. The y-axis shows the permeability value (in some cases within a range) and the x-axis the distance (borehole depth) to the excavation wall.

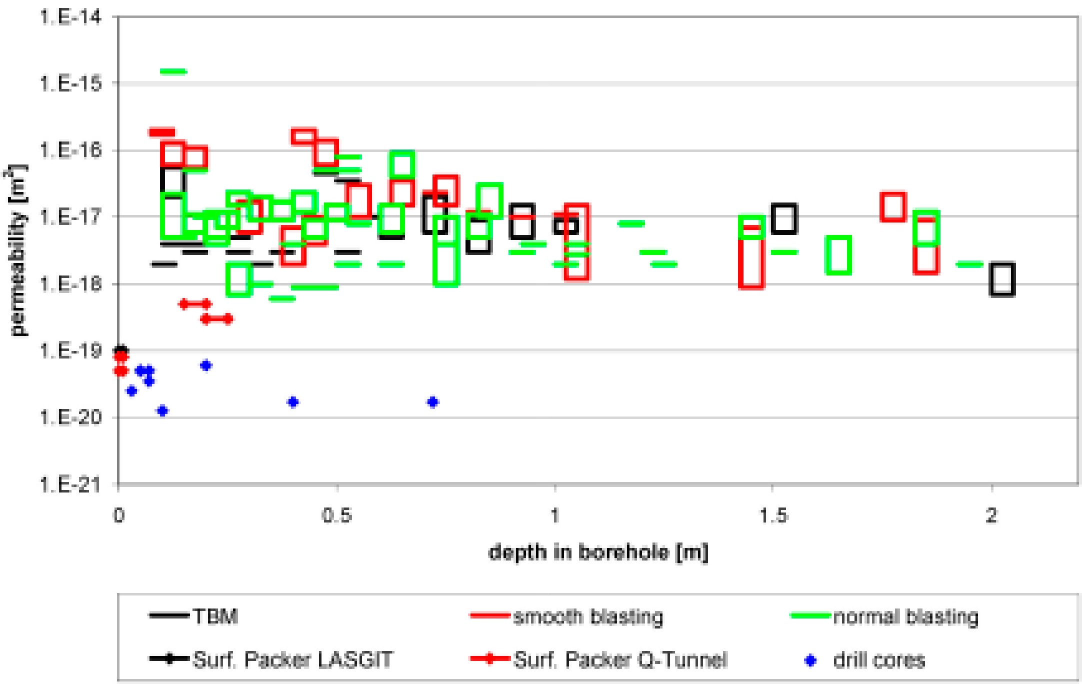


Figure 6-5. *Permeability of rock versus borehole depth.*

In the TBM-excavated A-tunnel, tests with the surface packer/mini packer have been conducted. The results from these tests indicate that the gas entry pressure for the rock matrix is about 1 MPa or higher. The results of BGR's surface packer tests are summarised in /Nowak 2005a/.

6.3.3 Temperature Buffer Test

The objective of the work DBE Technology is performing in the project is to test and evaluate the long-time performance of fibre optic pressure and temperature sensors in an environment with high temperatures and corrosive surroundings. The measurements are accompanied by numerical analyses in order to model and understand the THM-behaviour of the barrier material. For a detailed description of the Temperature Buffer Test, see Section 2.9.

The main focus of the activities in 2005 has been put on the analysis of the measuring results from fibre optic sensors in comparison with other sensors used by the different project partners.

Since a sand buffer between the heat generating canister and the bentonite buffer plays a significant role in German concepts for waste disposal of heat generating waste in clay host rock, numerical analyses have been performed to identify the impact of the sand buffer in comparison with direct canister emplacement in bentonite on the temperature development being an important process for repository design.

Two pressure sensors and two pore water pressure sensors have been installed each including a low resolution temperature grating for compensation purposes. Figure 6-6 and Figure 6-7 show the location of each sensor in addition to all the other sensors.

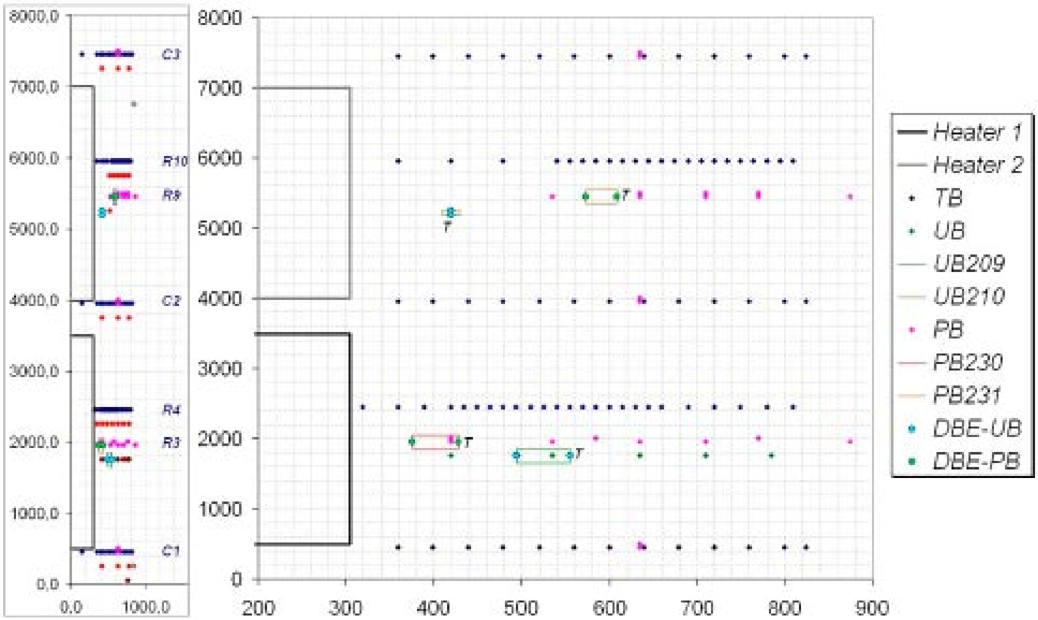


***Figure 6-6.** Vertical location and radial distance of each sensor in mm.*

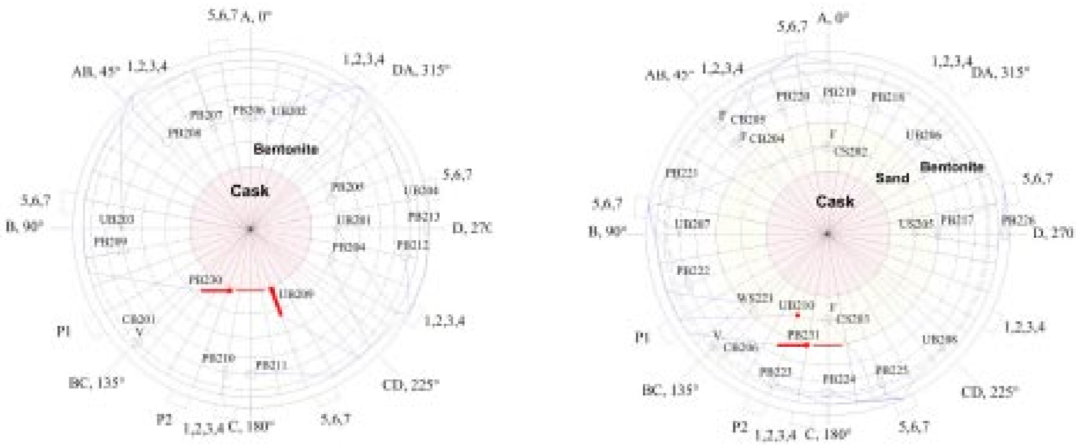


***Figure 6-7.** Radial location of sensors in horizontal cross-sections.*

Looking at Figure 6-8 it can be seen that the temperature of UB209 is higher than the other sensors, especially as time increases. The sensor is embedded in radial direction with the temperature grating at the outer end of the sensor housing as shown in Figure 6-6. Thus, the reason for the higher temperature seems to be the high thermal conductivity of the metal housing. That means that the temperature at the T-grating increases much faster due to the thermal conduction through the housing than it would do in case of temperature conduction through pure bentonite only.

The same effect can be observed if we look at the results of PB230 and PB231. In Figure 6-9 and Figure 6-10 results of the temperature gratings of PB230 and PB231 are given. In addition, the measurements of other sensors in a comparable radial distance and vertical location are plotted. In case of PB230 the temperature difference is higher which can be explained by the nearer distance of this sensor to the heater that causes a higher temperature gradient. Normally the high thermal conductivity of the housing is good to achieve temperature equilibrium for compensation purposes. However, the pressure results indicate the strong influence of the high temperature gradient.

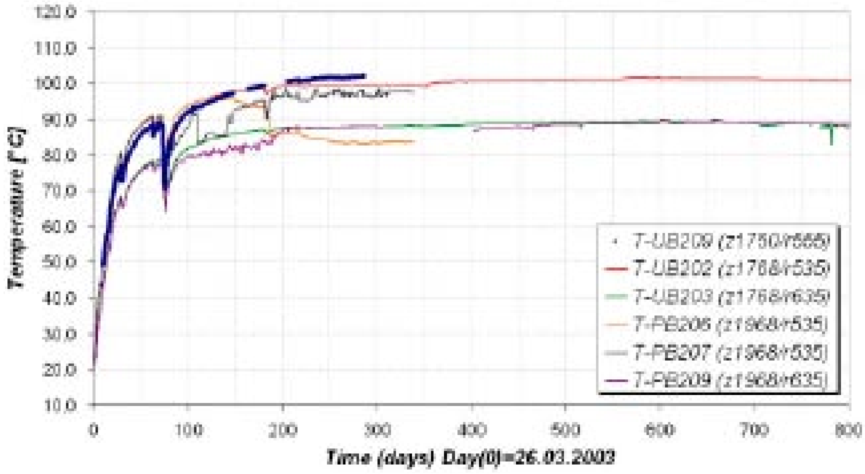


***Figure 6-8.** Results of the temperature grating of sensor UB209 compared to the results of other adjacent sensors (Ring 3).*

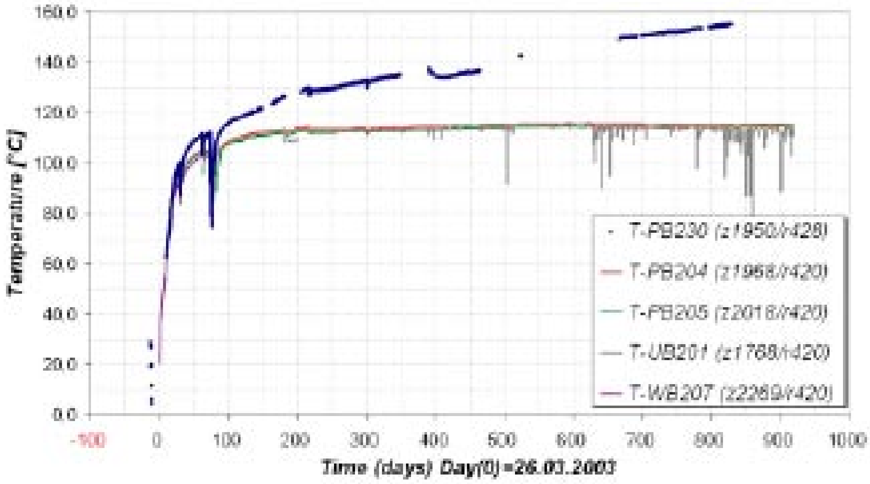


***Figure 6-9.** Results of the temperature grating of sensor PB230 compared to the results of other adjacent sensors (Ring 3).*

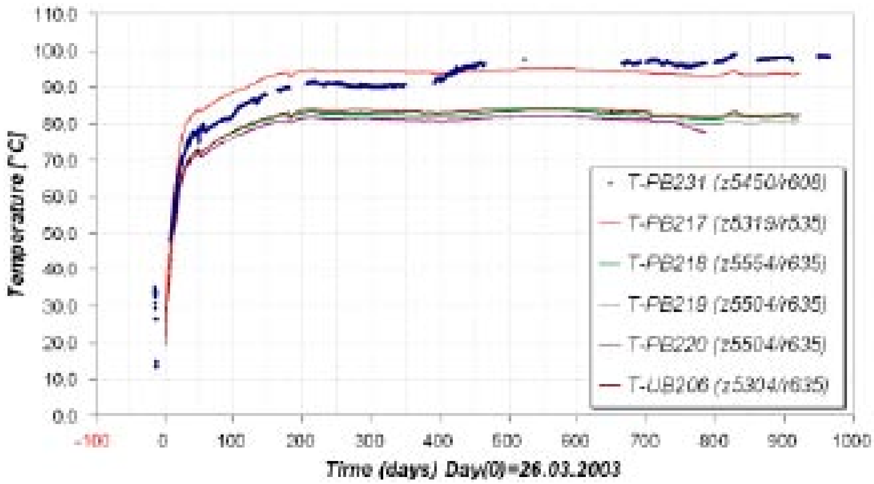


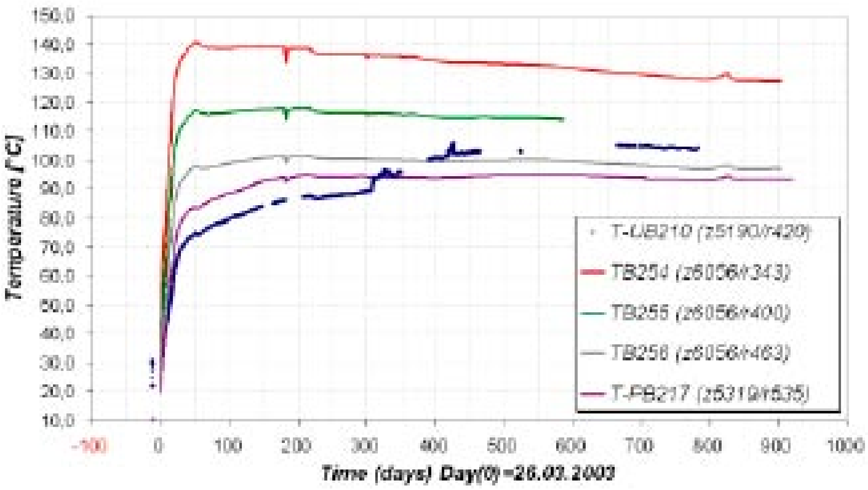
***Figure 6-10.** Results of the temperature grating of sensor PB 231 compared to the results of other adjacent sensors (Ring 9).*

In case of sensor UB210 the situation is different since this sensor is embedded more or less parallel to the heaters surface.

In Figure 6-11 the results of temperature grating of sensor UB 210 are plotted together with other sensor results for comparison. The problem of comparison is due to the different locations of the sensors. Mean values of different sensors have been calculated in order to improve the possibility of comparison. The temperature seems to be plausible at least at later times. Line 4 (violet) is the mean value of line 1, 2 and 3 and line 5 (orange) is the mean value of the two marked sensors more far away. In the beginning there seems to be some inertia in the signal reaction that might be due to a less good contact of the T-grating.

Figure 6-12 shows the results of pressure sensor PB230 that measures the pressure horizontally in radial direction. The sensor is located very close to the lower heater. The pressure reached a maximum value of about 8.8 MPa and goes down to about 4.6 MPa at the time being.

The reason for the pressure peek is due to the fact that sensor PB230 is located more or less directly at the canister surface while the other sensors are more far away as to be seen in Figure 6-7. In this case the canister acts as an abutment and the sensor takes the entire load.



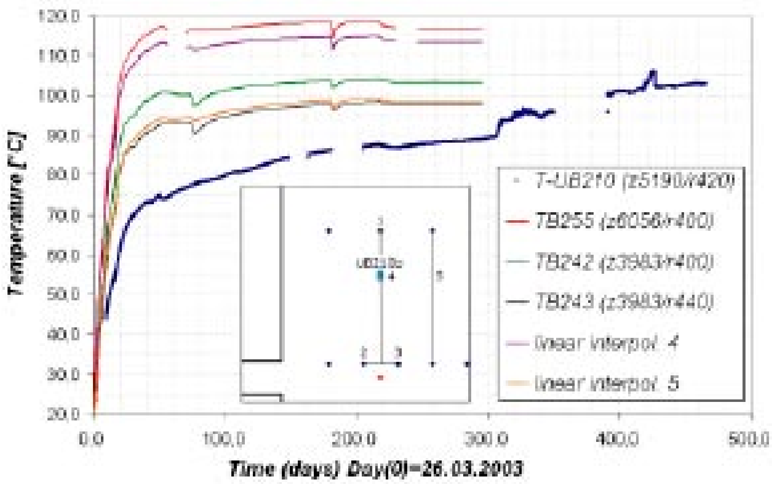


Figure 6-11. Results of the temperature grating of sensor UB210 compared to the results of other adjacent sensors (Ring 9).

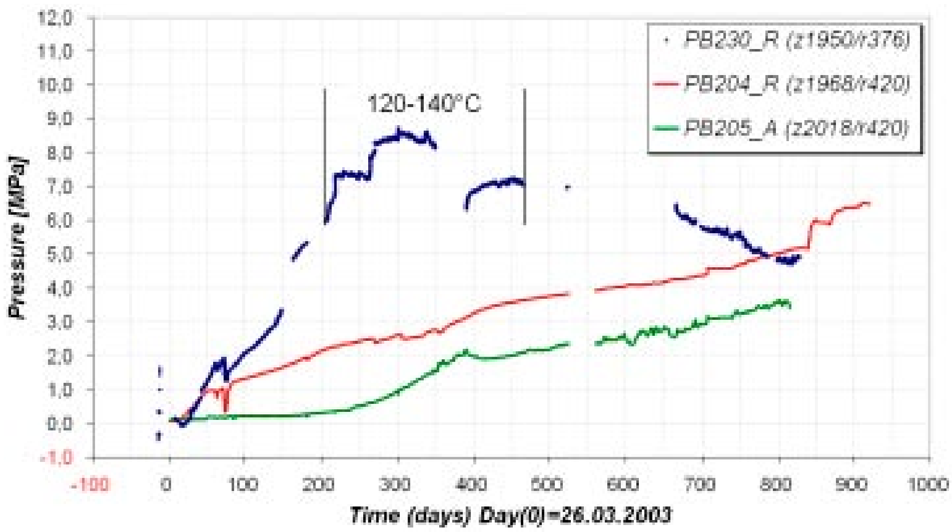


***Figure 6-12.** Results of pressure sensor PB230 compared to the results of other adjacent sensors (Ring 3).*

The maximum pressure has been measured after the temperature exceeded 120°C. In laboratory investigations regarding thermal expansion, a strong dependence of the shrinking as a function of water content has been observed. In Figure 6-13 the results of thermal expansion measurements are shown. The lower graph clearly indicates the temperature range where water release is taking place.

The samples expand up to a temperature of 65°C and shrink with increasing temperatures. In some temperature ranges the samples neither expand nor shrink. This effect depends on the water content of the sample and appears especially at high temperatures. Most of the water was released below 100°C during the heating. The differential coefficient of the relative elongation shows that the samples differ in their mineralogical composition. Whereas the sample with a water content of 17.4% lost a significant amount of water at a temperature of about 140°C, this effect is negligible for the sample with a water content of 10.8%.

A possible explanation of the pressure of PB230 is that after exceeding about 120°C, thermal induced water loss or evaporation occurs in direct vicinity of the canister and the pressure started to decrease down to a value that is measured by the other sensors more far away.

Results of pressure sensor PB231 are plotted in Figure 6-14. In the beginning some negative pressure values have been observed. These negative values are due to the strong temperature gradient within the housing which could not be compensated for. It has been tried to use some other sensors for compensation, but due to the fact that the vertical position has also an influence on the real temperatures, the exact temperature evolution at the pressure grating has still some uncertainties. The sensor is located at the boundary between the sand and the bentonite of the upper heater, thus not as close as PB230 at the lower heater. The effect is less for sensor PB230 due to the fact that the real pressure increase is much higher that close to the heater surface making the temperature effect less significant. The pressure of PB231 reaches a maximum value of about 9.0 MPa at the time being. This is about the same maximum value as measured by PB230 but at a later time.

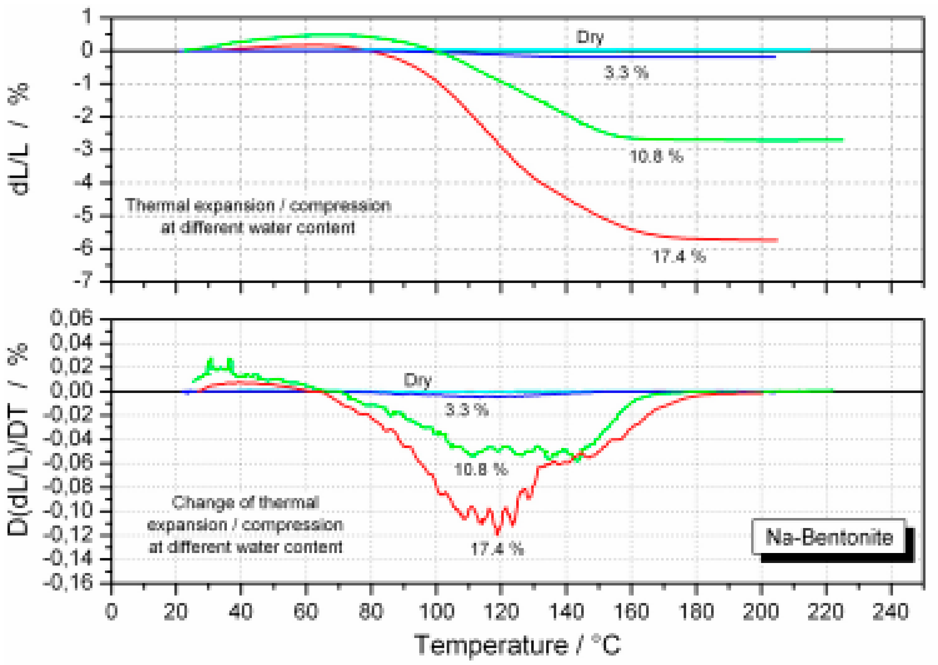


Figure 6-13. *Thermal expansion/compression of the bentonite for different water contents.*

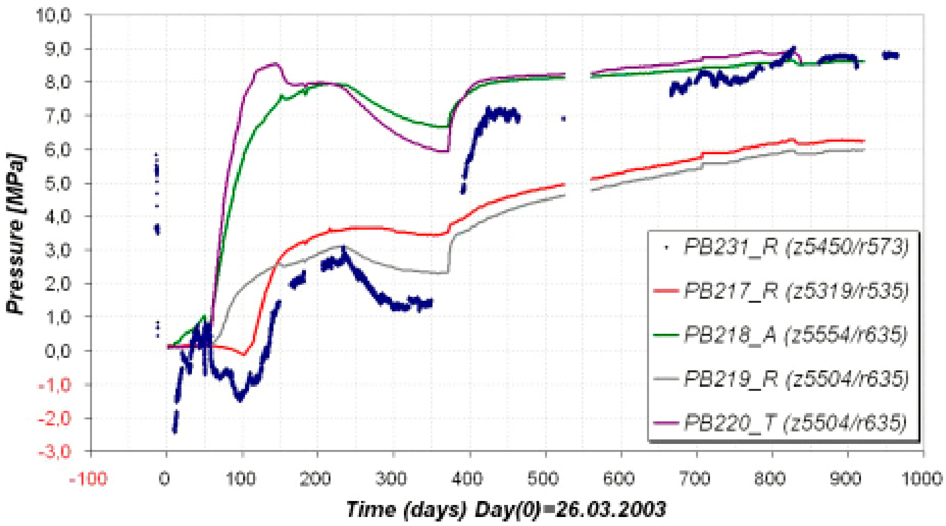


Figure 6-14. *Results of pressure sensor PB231 compared to the results of other adjacent sensors (Ring 9).*

Numerical analysis

Prior to fully coupled THM calculations, preliminary calculations (hydraulic, thermal, and thermal-mechanic) have been performed using the FLAC3D code /Itasca 2005/ to study individual effects and processes.

Hydraulic calculations

A first set of hydraulic parameters has been determined by means of simple hydraulic calculations. Special attention has been paid to the hydraulic conductivity of the bentonite buffer. For this purpose results of pore pressure measurement have been used. Two of the eight pore pressure sensors show a significant increase, while the other ones remain almost constant. Both sensors are nearest to the sand filter (4 cm distance) and show an increase in pore pressure at the 670th day (upper heater; sensor UB208) and the 720th day (lower heater; sensor UB204) respectively.

Preliminary calculations have been performed with an axis symmetric model. Fluid flow was assumed to occur only in the bentonite and sand filter. The heater and host rock were modelled as impermeable boundaries. In the calculations the hydraulic conductivity of the bentonite varied between 1×10^{-14} and 1×10^{-13} ms^{-1}. Only single-phase fluid flow has been applied. The dependence of the hydraulic conductivity on temperature and thermo-mechanical stress was neglected. Capillary suction was not taken into account within this state of investigation. The range of hydraulic conductivities used in calculations was chosen from laboratory investigations found in the literature, giving values of $k = 5\times10^{-14}$ ms^{-1} (at $S_r = 1$ and $T = 20°C$) and approximately 7×10^{-14} to 1×10^{-13} ms^{-1} (at $S_r = 1$ and $\rho = 2{,}000$ kg/m^3) respectively.

Figure 6-15 shows the calculated thickness of the saturated bentonite zone versus time assuming different hydraulic conductivities. For all calculations a slower progress in saturation was obtained for the time period 370–560 days.

Figure 6-16 gives the time for reaching the fully saturated state at a distance of 4 cm away from the bentonite/sand filter interface. This location corresponds to the sensor location of the outermost pore pressure sensors UB208 and UB204. Assuming the in situ pressure build-up at these sensors as indicator for reaching the fully saturated state, the back analysis would give a hydraulic conductivity of approximately 2×10^{-14} ms^{-1}.

For such low conductivities the calculations point out a thin saturated zone of approximately 5 cm at the 800th day of test. Similar results can be obtained from back analysis of thermal conductivity. A saturation of outermost part of bentonite (approximately 5–10 cm)

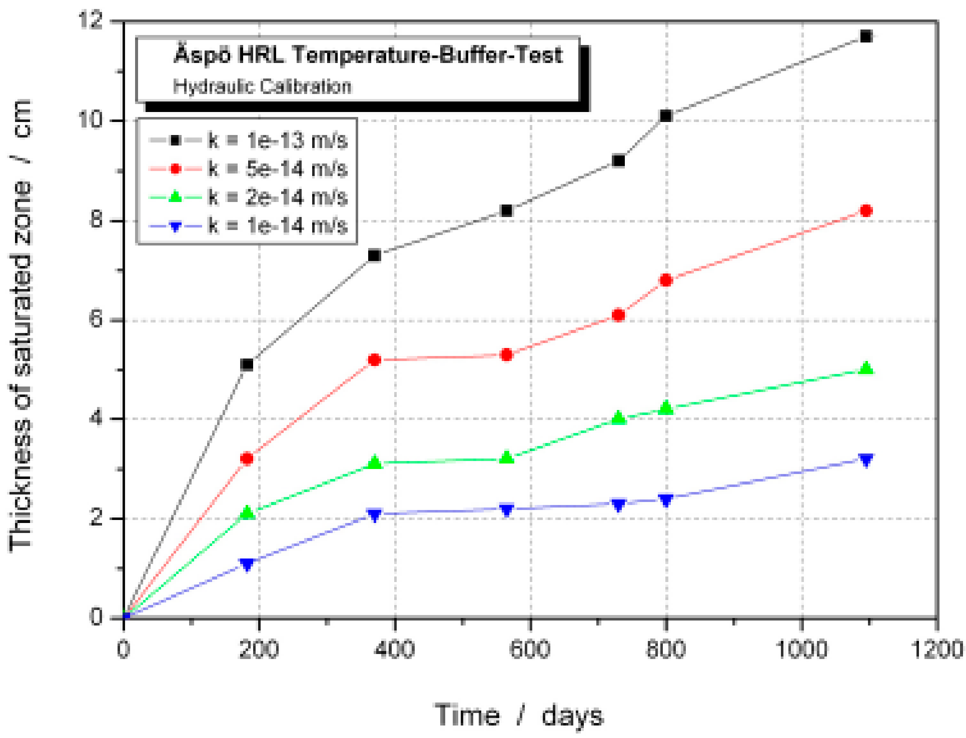


Figure 6-15. *Calculated thickness of saturated zone versus time.*

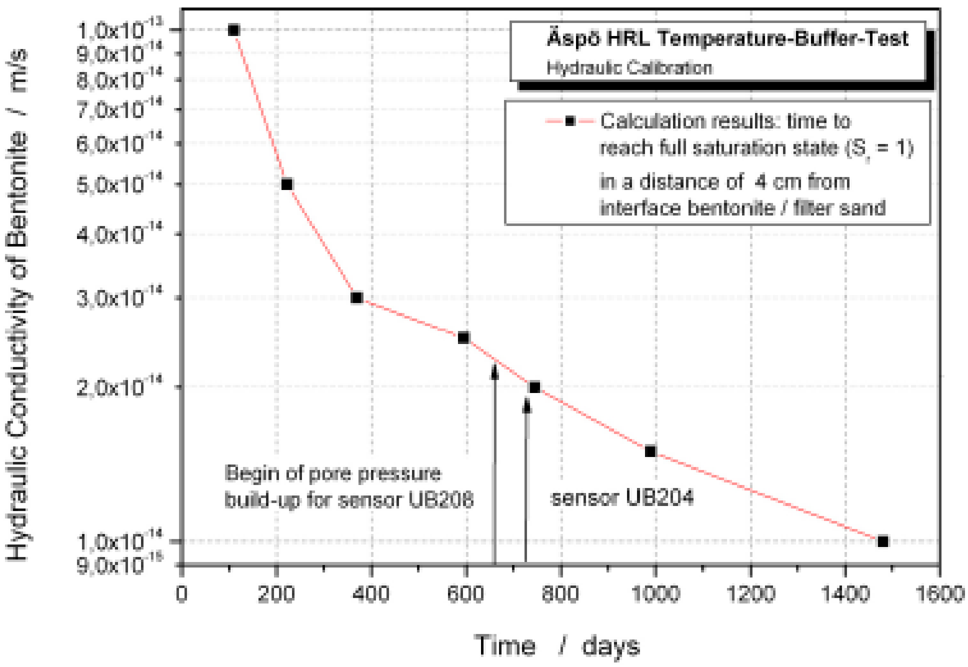


Figure 6-16. *Time of reaching fully saturated state versus hydraulic conductivity.*

leads to an increase of thermal conductivity up to values of 1.6 $Wm^{-1}K^{-1}$ which is in good accordance to analytical values for fully saturated bentonite gained by equation of Kahr, Müller – von Moos (λ (ρ = 2,000, w = 0.28) = 1.54 $Wm^{-1}K^{-1}$).

Thermal calculations

The main focus for the thermal calculations was set on analysing the thermal conductivity of the buffer material based on the previous calculation results from 2004 /Jobmann and Schonebeck 2005/. The temperature difference between different locations of measurement points can be used to estimate the thermal conductivity and a comparison with the calculations can be an indication of well chosen thermal conductivities.

The temperature differences between heater with and without sand filter have been analysed. In Figure 6-17 the results of calculations BF1 to BF4 (without sand filter) are shown. As can be seen calculation BF3 with thermal conductivity of bentonite from /Buntebarth 2004/ yields the best fit to the measured values.

The comparison of measured and calculated temperature differences in the bentonite around the upper canister (with sand filter) are shown in Figure 6-18. The measurements and the calculations BF5, BF6 and BF8 are close together. The temperature differences of BF7 are about 4 K higher than the measured values. Looking at the good correlation of measurements and the calculation BF3 (same calculation run as BF7) this must be due to an insufficient thermal conductivity of the sand filter and thus wrong temperature conditions in the bentonite area.

As a conclusion, the thermal conductivity equation by /Buntebarth 2004/ seems to be quite good for modelling the temperature conditions of the MX-80 bentonite. The value of thermal conductivity for the sand filter $\lambda_{Sand\ Filter}$ = 1.0 $Wm^{-1}K^{-1}$ is probably too high. These results should be used as input for future coupled simulations.

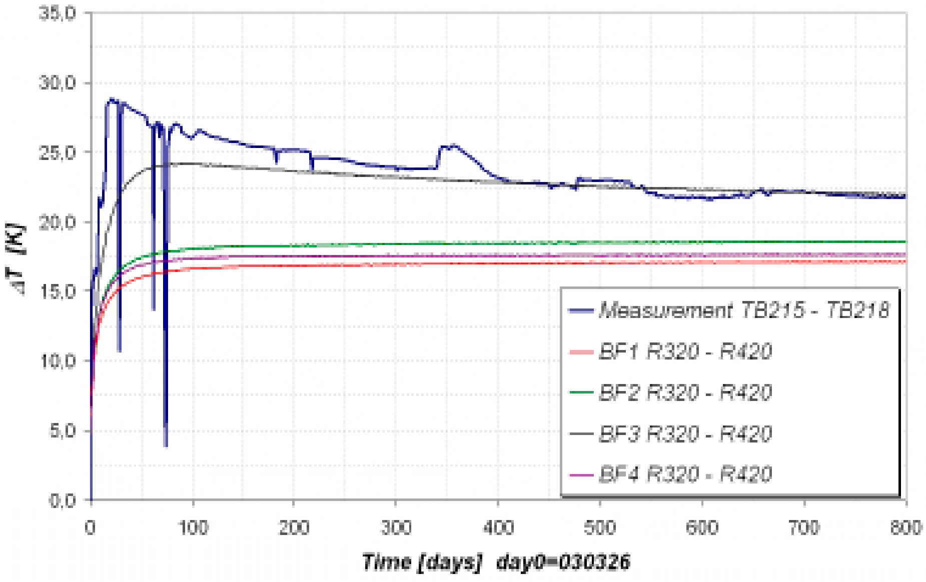


***Figure 6-17.** Measured temperature differences between sensors TB215 and TB218 compared to calculated differences.*

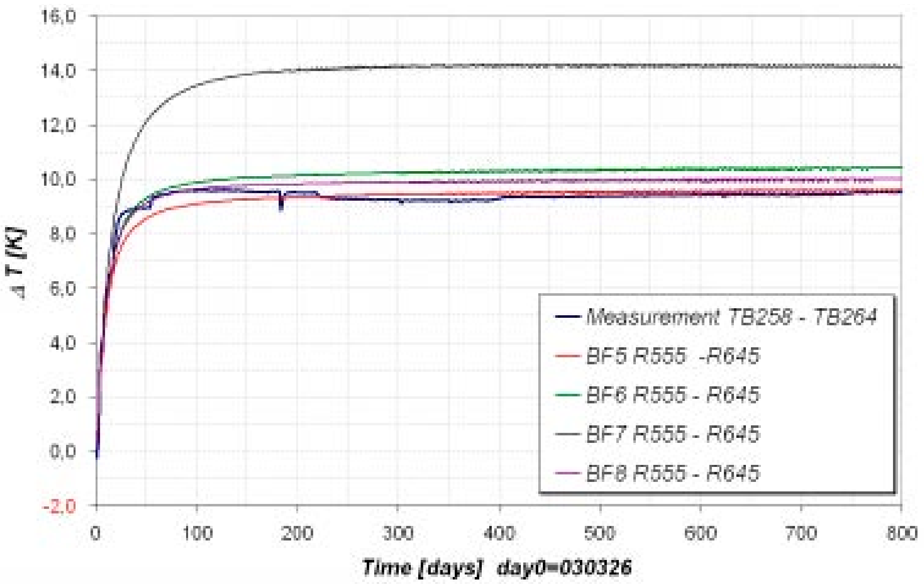


***Figure 6-18.** Measured temperature differences between sensors TB258 and TB264 compared to calculated differences.*

Thermo-mechanical calculations

For understanding of the thermo-mechanical behaviour in the Temperature Buffer Test the same simple model was applied as for the other calculations. In the first analysis the simulations consider only elastic material behaviour. The thermal properties, with a constant value of the thermal conductivity, $\lambda_{Bentonite} = 1.3\ Wm^{-1}K^{-1}$, according to BF1 and BF5 in the thermal calculations were used.

In the bentonite around the lower canister the von Mises stress values vary between 5 and 10 MPa. The maximum values of approximately 10 MPa occur close to the canister. With increasing radial distance the stresses decrease. For the upper canister (with sand filter) the von Mises stress values in the bentonite are 4 to 15 MPa. This is much higher than in the bentonite around the lower canister. Due to the low Young's modulus of the sand filter the radial stress acting at the interface of bentonite and sand is much lower than for pure bentonite buffer. For this reason there is a highly deviatoric stress level at the first zones of bentonite.

The total pressure measurements reported by /Goudarzi 2005c/ give pressures in radial direction between 5 and 7 MPa in the bentonite of the lower canister at a time of 800 days. Hence, the calculations still overestimate the pressure development in the bentonite. It can be assumed that because of the applied simple model with an elastic approach the temperatures and stresses are overestimated.

All these modelling results will be input information for the planned coupled THM calculations.

6.3.4 Task Force on Engineered Barrier Systems

Two German institutions participate in the Task Force. BGR participates in Task 1 (THM-coupled processes) and Task 2 (gas migration processes) in the clay-rich buffer materials and GRS participates in Task 1.

In 2005 the benchmarks test concerning THM-coupled processes in geotechnical barriers (MX80 and Febex bentonite) have been modelled by BGR with the code Geosys/Rockflow /Nowak 2005b/.

The experiments with MX80 (BMT 1.1) require the treatment of vapour diffusion at temperatures up to 150°C. The measured data can be reproduced with the code, in most cases quantitatively, in few cases only qualitatively. Agreement between measured data and calculated data may be enhanced by adjusting parameter values.

The measured data from the experiments with Febex bentonite (BMT 1.2) can be reproduced with the code, but uncertainties (leakages) in the experiment have been included in the corresponding models. For this reason the results are of limited significance.

Thermal, hydraulic and mechanical processes that are considered to be relevant in the benchmarks to Task 1 (THM-coupled processes) are implemented in the code Geo-sys/Rockflow and can be analysed in a coupled way. The modelling of benchmark tests for Task 2 (gas migration) has begun in 2005.

GRS also participates in Task 1 and has modelled the experiments with Febex bentonite (BMT 1.2) with its code Vapmod, which is conceptually different from the common THM-codes. This was the first test of the code Vapmod for modelling re-saturation under increased hydraulic pressure. Like in earlier exercises the results were promising but not quite satisfying.

Parallel to that, theoretical considerations were undertaken that showed the consistency of re-saturation of compacted bentonite purely by vapour diffusion with the well-known empirical "diffusion law" /Kröhn 2005/. This approach allows to quantify the so-called "diffusion coefficient". In the example given in /Kröhn 2005/ the empirical and the theoretically derived coefficient differ just about a factor of two from each other. In combination with the adequate conceptual model /Kröhn 2004/ this physically justified simple balance equation provided results that showed good agreement with the measurements of BMT 1.2, Figure 6-19. It appears that despite earlier believe a Fick's approach is indeed able to reflect re-saturation under increased hydraulic pressure.

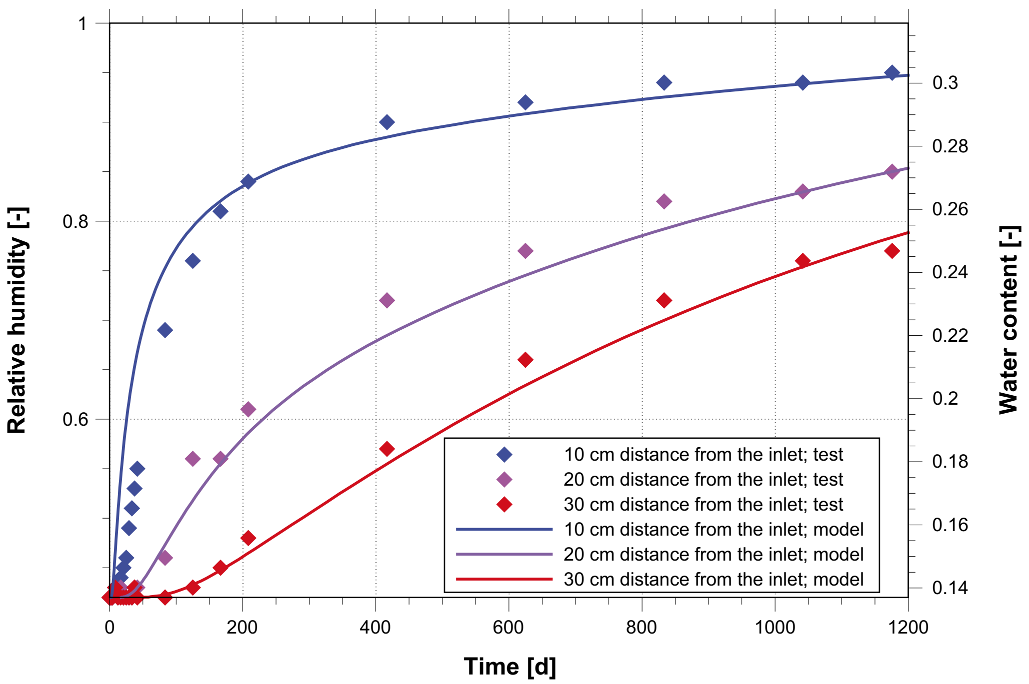


Figure 6-19. *Breakthrough curves of water content and the equivalent relative humidity from the measurements of BMT 1.2 and from the simple balance equation.*

Both models and the results were presented at the Task Force meeting in October 2005 in Barcelona. They are described and discussed in a report submitted to the secretariat of the Task Force. The next step is to test whether the simple balance equation is also valid under non-isothermal conditions.

6.3.5 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. Obtained results will show whether radionuclide retention coefficients measured in laboratory batch experiments can be applied for 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 with the Chemlab 2 probe was started in May 2004 and terminated in April 2005. In this in situ experiment, Tritium (HTO), ^{233}U and ^{99}Tc are used as tracers. The injected cocktail did not contain ^{238}U. The flow rates were in the range of 0.03–0.05 ml h^{-1}. In the previous annual report, breakthrough curves HTO and ^{233}U were shown and the sharp increase of the uranium tracer concentrations was discussed occurring after interruptions of the experiment. To investigate the U elution, the natural U isotopes were also determined. The concentrations followed the ^{233}U tracer concentration (Figure 6-20).

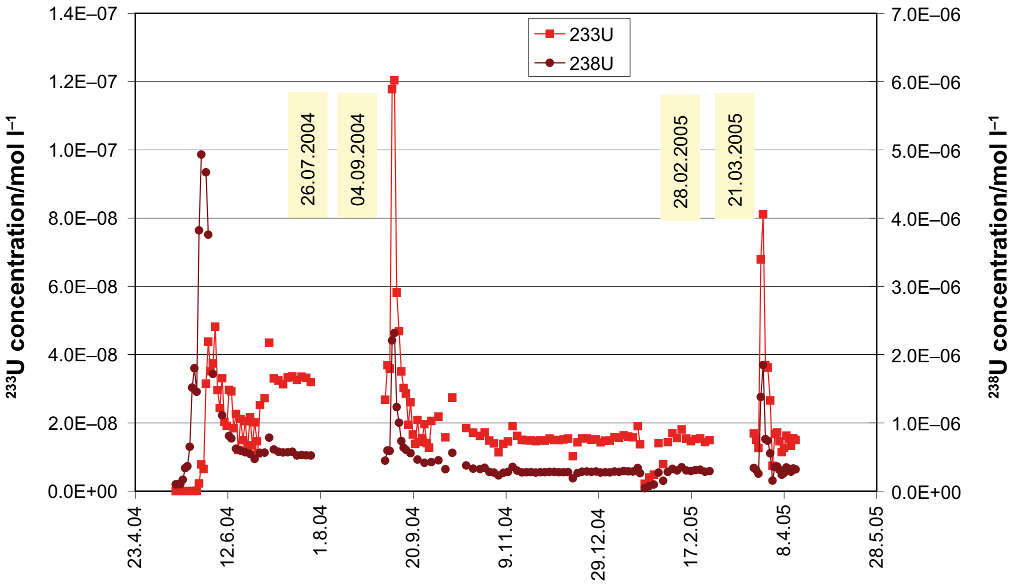


***Figure 6-20.** Breakthrough of ^{233}U tracer and the natural ^{238}U as function of time in the core #7 in situ experiment.*

The simultaneous breakthrough of the artificial and of the natural uranium raises questions: In granite, U(IV) is expected which is kept in the tetravalent state by the presence of Fe(II) minerals. The U concentration in equilibrium with U(IV) minerals, such as UO_2 (am) would result for the in concentrations of $1\text{x}10^{-9}$ mol l^{-1} which is in good agreement with the measured data. However, in core #7 experiments, after more than 200 days elapsed time, the eluted ^{238}U concentration was in the range 2×10^{-7} to 3×10^{-7} mol l^{-1} which surmounts the ^{233}U concentration by a factor of ~ 20. Several assumptions are considered to explain the natural U concentrations. The assumptions cover a pH drop, increase of CO_2 partial pressure and effects due to oxygen contamination either in the Chemlab 2 drill hole KJ0044F01, in the Chemlab 2 probe or in core #7. An increase of pH is ruled out which is additionally confirmed by the constant concentrations of mineral forming elements. Increase of CO_2 would also affect the pH.

The interpretation of the uranium breakthrough bases on the hypothesis that both uranium isotopes are present in the hexavalent redox state in solution and the solubility is controlled by hexavalent mineral phases. The prominent source of oxygen is air which contacted the rock matrix of core since drilling and during storage. Another source is oxygen migration through the excavated disturbed zone in the groundwater bearing fracture. To obtain information, redox measurements at the Chemlab 2 drill hole were preformed (flow through cell) yielding a mean redox potential E_h = +248 mV (SHE). To obtain insight in the U mobilisation and transport behaviour of uranium, the experiment on core #7 was interrupted for three weeks (from 28th February, 2005). Figure 6-20 shows the pronounced concentration peaks of both the artificial ^{233}U tracer and the natural ^{238}U. Both peaks decreased after elution of ~ 6 ml. This behaviour cannot be described by a pre-oxidation of U in the water bearing feature; the U oxidation/mobilisation process takes place within the core. At the present state of knowledge, both U peaks are explained by saturation of the rock matrix with oxygen during drilling and storage and matrix diffusion of U(VI) into the open fracture of core #7.

After termination of the experiment, core #7 was transferred to FZK-INE, cut in slices and analysed with respect to the sorbed tracers. Figure 6-21 shows the ^{99}Tc and ^{233}U distributions along core #7 as well as the distribution of natural uranium. In a distance of ~ 100 mm from injection, significant concentrations of natural U and ^{233}U tracer are found. Also the ^{99}Tc concentration is increased in this region.

The reason for this accumulation may be attributed to the quantity and composition of altered fracture materials or of the geometric instance of the fracture. Details are under investigation by means of SEM-EDX method. Figure 6-22 shows a SEM-EDX mapping together with related element distributions for the fracture zone of slice 23 from core #7 (X = 100 mm, see Figure 6-21).

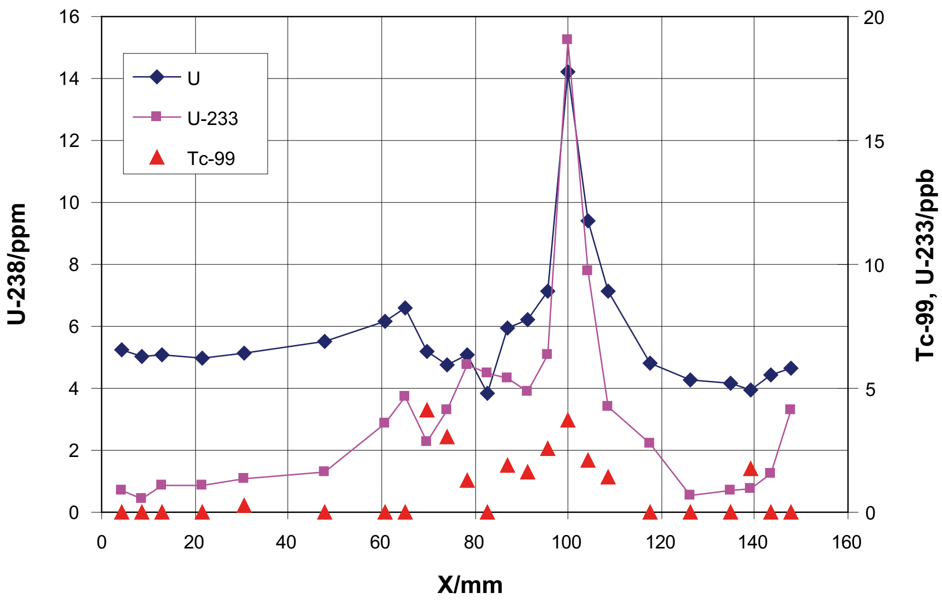


Figure 6-21. *Tracer concentrations determined by dissolution and ICP-MS measurements of the abraded material obtained by slice cutting of core #7.*

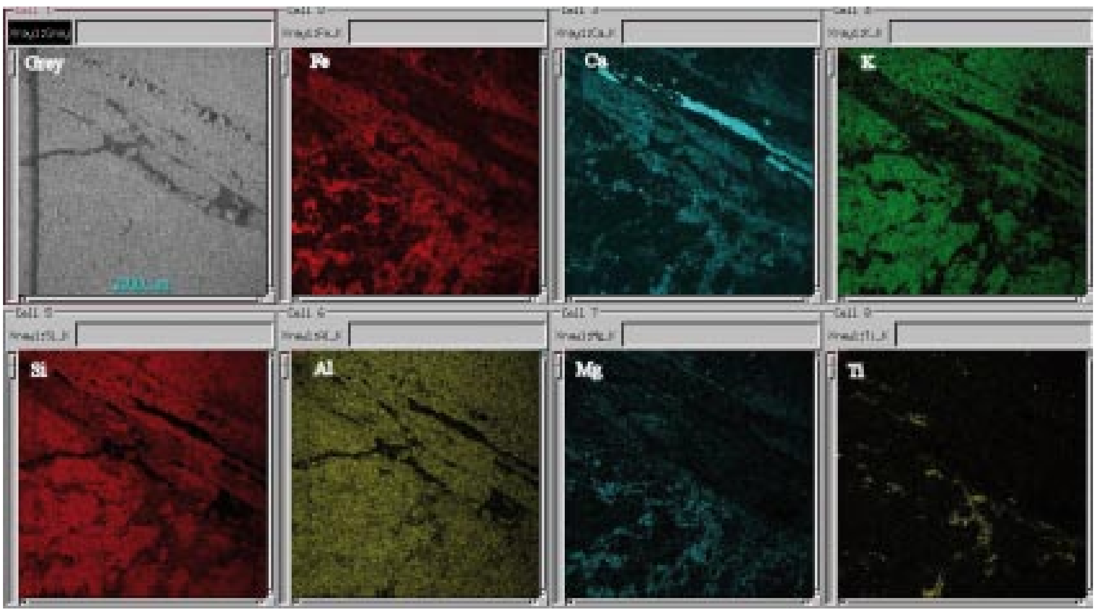


Figure 6-22. *Lateral element mapping of the fracture zone of slice 23 from core #7.*

In some parts, an almost pure calcium phase exists which may be calcium carbonate (such as vaterite). In the other part, grains of the rock matrix are mapped having about 15% Al, 28% K and ~ 55% Si. Fe and Ca are located on boundaries of grains, where Si and K concentrations decreased significantly. In total, the fracture zone is characterised by a high Fe concentration up to 15 atom %. This value is in contrast to other part of the slice, where average values of 2–3% are found. Within the fracture zone, Si concentration is reduced, which may reflect the presence of epidote or chlorite.

6.3.6 Colloid Project

In safety assessment for a repository of radioactive waste, aquatic colloids can play a role for the migration of radionuclides from the repository to the biosphere. Apart from actinide oxide/hydroxide colloids or colloids released from backfill material, or natural background colloids e.g. present in groundwater conducting fracture zones in granite, host rock may act as potential carriers for radionuclides. Therefore, natural colloid concentrations are analysed in granite groundwater from a series of boreholes at the Äspö HRL (Sweden), at the Grimsel Test Site (Switzerland) and in sedimentary groundwater from Ruprechtov (Czech Republic). The aim of this study is to improve the experimental procedure for the colloid analysis and to determine the amount of background colloids as a function of groundwater geochemistry under unperturbed in situ conditions with a minimum of possible interferences by sampling.

Experimental work

A mobile system of the laser-induced breakdown detection (LIBD) combined with a geomonitoring unit for pH, Eh, electrical conductivity and oxygen content detection is applied. The LIBD method has previously been described. The main advantage compared to conventional methods is a several order of magnitude higher sensitivity, especially for colloids < 200 nm (detection limit for 20 nm colloids in the sub-ppt range). The whole arrangement, including an ultra-pure water processing unit is installed in a van for in situ measurements at site. An optical high pressure flow-through detection cell is used. Colloids are detected under hydrostatic groundwater pressures up to ~ 40 bar without contact to atmosphere oxygen.

Additionally, a system for remote groundwater sampling completes the experimental configuration. Pressurised steel cylinders with remotely operated valves can be lowered by cable winch into deep boreholes. A groundwater sampling with cylinders is applied when a direct connection between mobile LIBD and groundwater, e.g. in deep boreholes drilled from above ground, is not possible (Ruprechtov, Forsmark). After sampling, the cylinders are in line connected with the LIBD and the geomonitoring unit for the detection of colloids and geochemical parameters. 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

Earlier colloid studies claimed the existence of a significant correlation of colloid concentrations in groundwater with the salinity (ionic strength) of the groundwater. /Degueldre et al. 2000, Hauser et al. 2003/. New LIBD results from in situ investigations at Äspö demonstrate colloid concentrations < 0.1 µg/l for groundwater chloride contents ≥ 4 g/l. For two different groundwaters with chloride concentrations > 10 g/l, the colloid concentrations were close to the LIBD detection limit.

A comprehensive representation of colloid concentrations in different water samples as determined by LIBD plotted versus the respective ionic strength is given in Figure 6-23. Increasing ionic strength destabilises colloid dispersions which is reflected in the decreasing colloid concentrations in the respective groundwater.

The broad bandwidth of detected colloid concentrations in groundwater of ionic strength < 10 mmol/l (Grimsel and Ruprechtov) suggests that different parameters besides geochemistry as e.g. mechanical forces and groundwater flow may control the actual colloid concentrations. At ionic strengths > 10 mmol/l the upper limit for the colloid concentration may now be governed by colloid stability and thus by the ionic strength of the groundwater. Notably for groundwater samples from Äspö and simulated NaCl solutions, a clear dependency of the maximum colloid concentrations with the salinity of the groundwater is found.

6.3.7 Microbe Project

Introduction

The FZR/IRC contributions in 2005 are divided in two parts. In 2004 the project studying the direct interaction processes between actinides and the Äspö relevant bacteria *Desulfovibrio äspöensis* was finished. The results are published in /Moll et al. 2005/. In 2005, as a continuation and completion, the interaction schema of plutonium with *D. äspöensis* bacteria could be completed and verified by applying X-ray Absorption Spectroscopy (XAS) techniques. These results are summarised below.

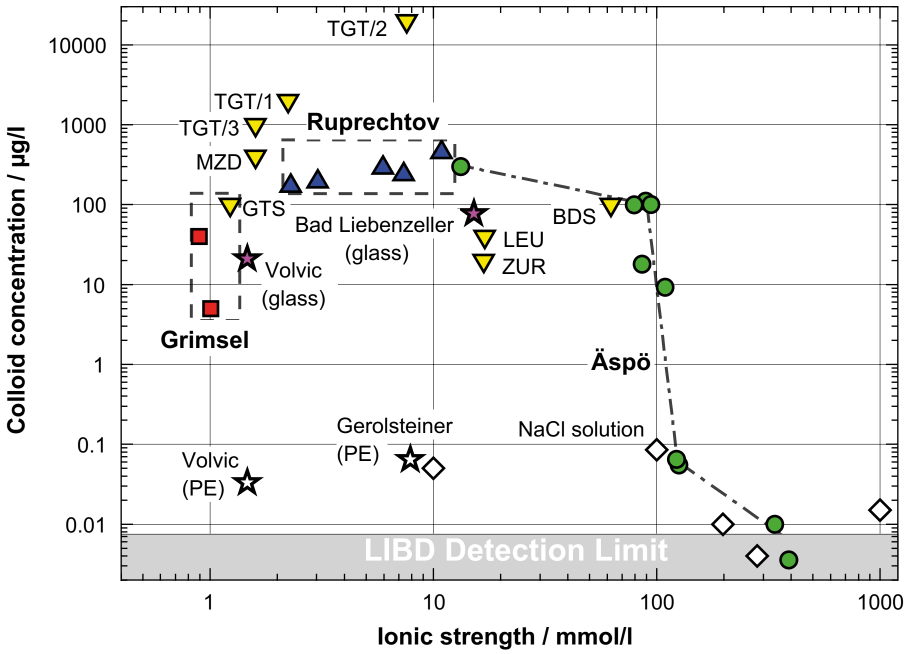


Figure 6-23. *Comparison of colloid concentration in different types of natural groundwater, mineral water and synthetic NaCl-solution versus ionic strength (Ruprechtov (blue triangle); Grimsel CRR tunnel (red square); Äspö tunnel (green circle); mineral water (stars); NaCl solution (white diamond); /Degueldre et al. 1996/ (yellow triangle); TGT: transit gas tunnel, MZD: Menzenschwand, GTS: Grimsel test site, BDS: Bad Säckingen, LEU Leuggern, ZUR: Zurzach.*

A new project was started in the middle of 2005, which addresses the indirect interaction mechanism of a mobilisation of actinides by released bioligands from relevant Äspö bacteria. This study is focused on: (a) isolation and characterisation of microbial ligands produced from Äspö bacteria (e.g. *Pseudomonas fluorescence*), (b) interaction of U(VI), Np(V), and Cm(III) with the microbial ligands including compounds simulating the functionality of the microbial ligands and the surface of the bacteria and (c) spectroscopic characterisation of the formed actinide complexes/compounds. The isolation and characterisation of the bioligands will be done by our Swedish colleagues at Göteborg as part of the cooperation between the FZR/IRC and the group of Prof. K. Pedersen from the Göteborg University (Department of Cell and Molecular Biology). The formation constants determined will be used directly in speciation and transport models. This project should help to identify the dominating process of the interaction between actinides and microbes (direct or indirect ones). To accomplish the proposed goals a new powerful laser system was installed. First results showing the excellent properties of the new equipment are summarised in this report.

Investigation of interaction between *D. äspöensis* and Pu by XAS

X-ray absorption spectroscopy (XAS) is a powerful tool to characterise the speciation of heavy metals in a broad range of systems. X-ray absorption near edge structure (XANES) spectroscopy in combination with extended X-ray absorption fine structure (EXAFS) were applied at the Pu L_{III}-edge in order to verify the plutonium oxidation state distribution and to determine the structure of the cell-bound plutonium. By combining XANES and EXAFS element specific information can be obtained concerning the oxidation state and local structure of an absorbing metal. In this study, XAS was used for a detailed characterisation of the microbial processes taking place in the system Pu – *D. äspöensis*. This strain predominate the indigenous SRB population at the Äspö aquifer system in Sweden.

Experimental work

The spectrum from the Pu(VI) reference sample (0.05 M in 1 M HNO_3) was taken from earlier measurements /Reich et al. 2001/. The Pu(IV) reference sample (0.08 M in 1 M $HClO_4$) was prepared as described in /Charrin et al. 2000/. 1 ml of the bacterial suspension in 0.154 M NaCl was incubated with 5 ml of ^{242}Pu, 127 mgL^{-1}, at pH 5. After shaking the samples for 96 h under N_2 atmosphere, the biomass was separated by centrifugation, washed with 0.154 M NaCl, and sealed in a polyethylene cuvette. The bacterial sample was measured as wet paste. The Pu-XAS data were recorded at the Rossendorf Beamline (ROBL, BM20) at the ESRF in Grenoble, France /Reich et al. 2000/.

Results

The low intensity of the white line (WL) and the feature near 18,080 eV (marked with the arrows in Figure 6-24a) are indicating dominating plutonyl species ($O = Pu = O^{+/2+}$) in the blank, the supernatant and in the Pu(VI) reference, see Figure 6-24.

This shoulder above the WL, results from multiple scattering (MS) processes of the photo electron wave between Pu and the two axial oxygen ions. In contrast to these samples, in the biomass sample and the Pu (IV) reference the WL is more pronounced and the Pu-Oax multiple scattering contribution is missing. It follows that the Pu accumulated by *D. äspöensis* occurs in the tetravalent oxidation state. The characteristic changes in the absorption spectra were used to determine the relative concentrations of the Pu species by applying the iterative transformation factor analysis (FA) as described in /Roßberg et al. 2003/. This new approach aims at a quantitative decomposition of the XANES spectra of

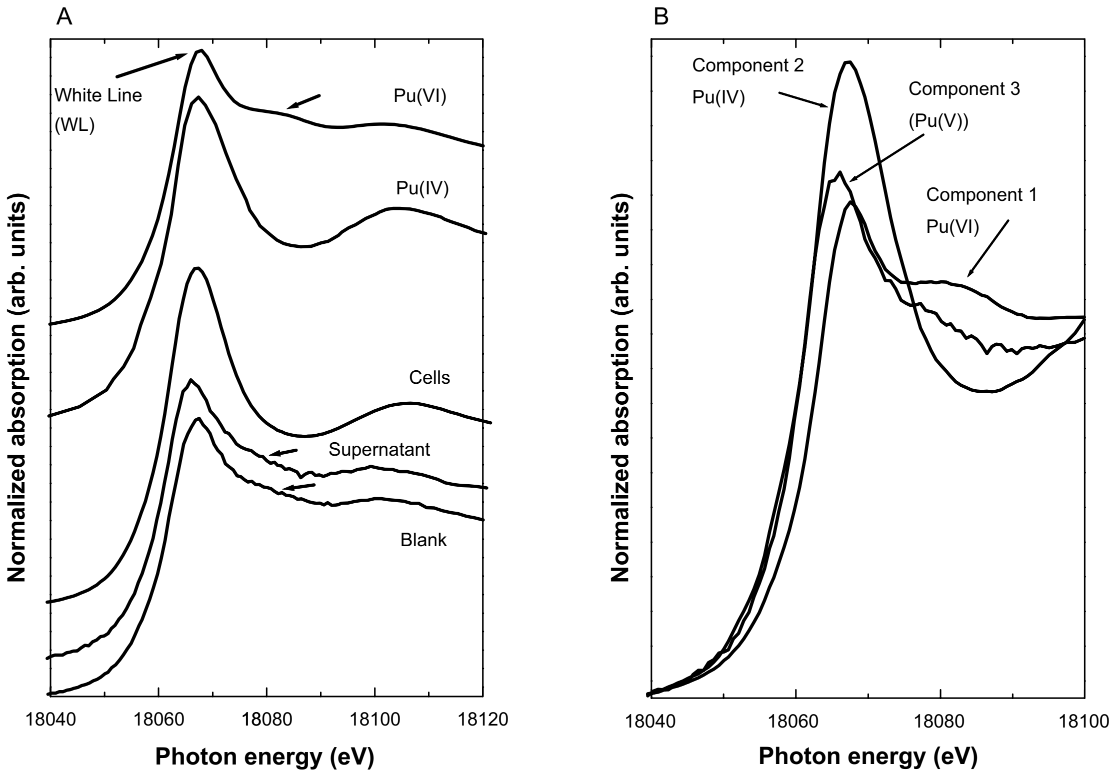


Figure 6-24. *(a) XAS data of the blank solution, the supernatant, the biomass and from Pu(IV) and Pu(VI) reference samples at the Pu L_{III} –edge. (b) Single component XANES spectra as a result from the iterative transformation factor analysis (FA).*

mixtures into the different spectral components/constituents. The calculations showed that every spectrum in Figure 6-24a can be described by a combination of three independent components, see Figure 6-24b. The analysis of the XANES spectrum of the biomass sample shows that the tetravalent Pu dominates the oxidation state distribution of the biosorbed plutonium. Moreover, we can conclude that the plutonium which is not accessible by solvent extraction occurs as Pu(IV), presumably incorporated Pu(IV)-polymeric species, and as Pu(V), residuals of the reduction process of Pu(VI). In general a fair agreement between the results of the plutonium oxidation state distribution by solvent extraction as described in /Moll et al. 2005/ and by FA of the XANES spectra was observed.

The isolated and Fourier-filtered EXAFS oscillations and the corresponding Fourier transforms (FT) of the blank and biomass sample are shown in Figure 6-25. The FTs are not corrected for the EXAFS phase shift, so peaks appear at shorter distances (R+Δ) than the true near-neighbour distances (R). Ideally every peak shown in the FT corresponds to a special backscatter atom around the absorbing Pu atom. The amplitude of the EXAFS oscillation gives information concerning the coordination number of the individual atoms around the plutonium. The Pu in the blank is surrounded by two close axial oxygen ions at 1.77 Å and approximately 5 equatorial oxygen ions at 2.42 Å, see Figure 6-25. These values are in very good agreement with the literature /Reich et al. 2001/. Unfortunately, we cannot present structural parameter of Pu in the supernatant solution. Changes in the XANES from scan to scan showed that the sample was not stable in the synchrotron beam. The EXAFS oscillation of the cell-bound Pu shows close similarities to the spectra of colloidal Pu(IV) species published in /Rothe et al. 2004/. The presence of an additional symmetric EXAFS oscillation giving a FT peak at R+Δ of approximately 2.8 Å gives evidence for an interaction of the Pu(IV)-polymers with light atoms of the biomass. The best fit result could be

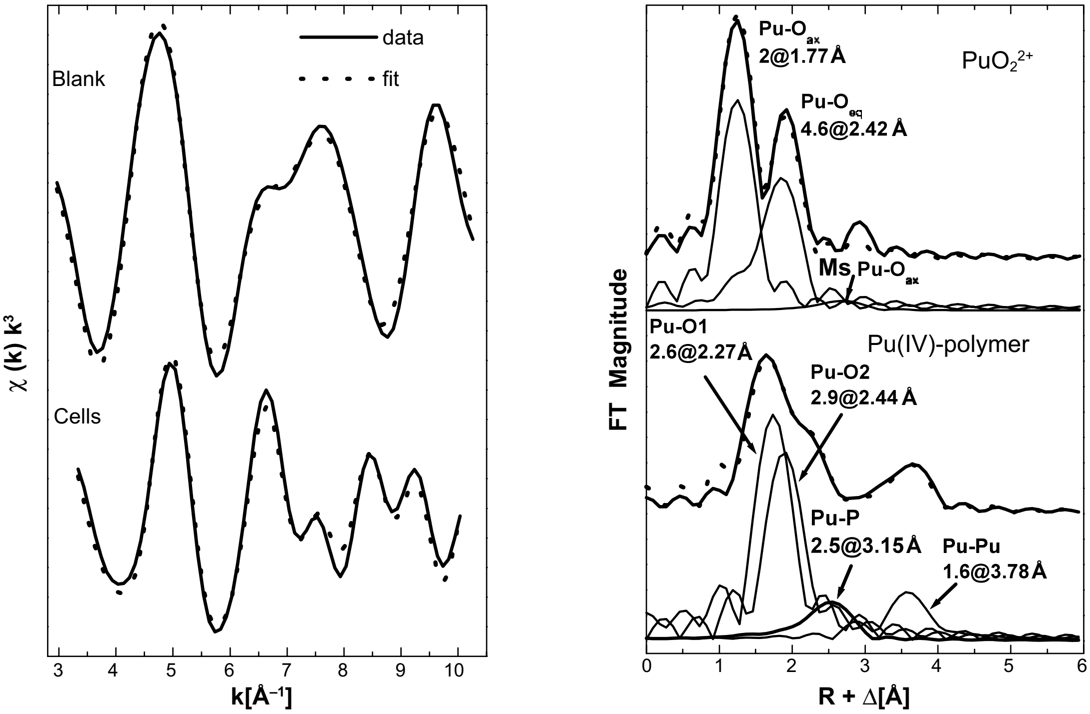


Figure 6-25. *Pu L_{III}-edge k^3-weighted EXAFS spectra (left) and the corresponding Fourier transforms (right) of the blank and the biomass sample and the theoretical fits (dotted line). The data were FT filtered using a Gaussian window (0.3Å^{-1}).*

obtained using phosphorus which points to an interaction with organic phosphate groups of the cell membrane structure as postulated for Cm(III) in /Moll et al. 2004/. The relatively short Pu-P distance of 3.15 Å indicates a bidentate coordination of the phosphate group to plutonium.

In conclusion, the XANES/EXAFS study of Pu interactions with cells of *D. äspöensis* verified the results of the solvent extraction experiments /Moll et al. 2005/ and confirmed the mechanistic conclusions drawn in /Moll et al. 2005/. The results clearly demonstrated that the cell-bound Pu exists as Pu(IV)-polymers which are interacting with the biomass.

A new laser system for time-resolved laser-induced fluorescence (trlfs) studies – first experiences

A new time-resolved laser-induced fluorescence measuring system was installed at the institute, see Figure 6-26. This new system offers an excellent base for challenging complexation studies of selected actinides at trace concentrations (e.g. curium) in a variety of experimental systems (including biological systems).

The system consists of a flash lamp pumped Nd-YAG laser and an Optical Parametrical Oscillator (OPO) laser. The OPO replaces the Dye laser of older conventional systems and has the capability of continuously scanning a wide wavelength range. The Nd-YAG laser has a repetition rate of 20 Hz. The second harmonic of this laser at 532 nm is used for pumping the OPO-system. Rectangular to the laser beam, a fibre optic is arranged to collect the fluorescence light and send it to the detection system. The fluorescence emission spectra were detected by an optical multi-channel analyser. The system consists of a monochromator and spectrograph (Oriel; MS 257) with a 300 or 1,200 lines mm^{-1} grating and an ICCD camera (Andor). The Cm(III) emission spectra were recorded in the 500–700 nm

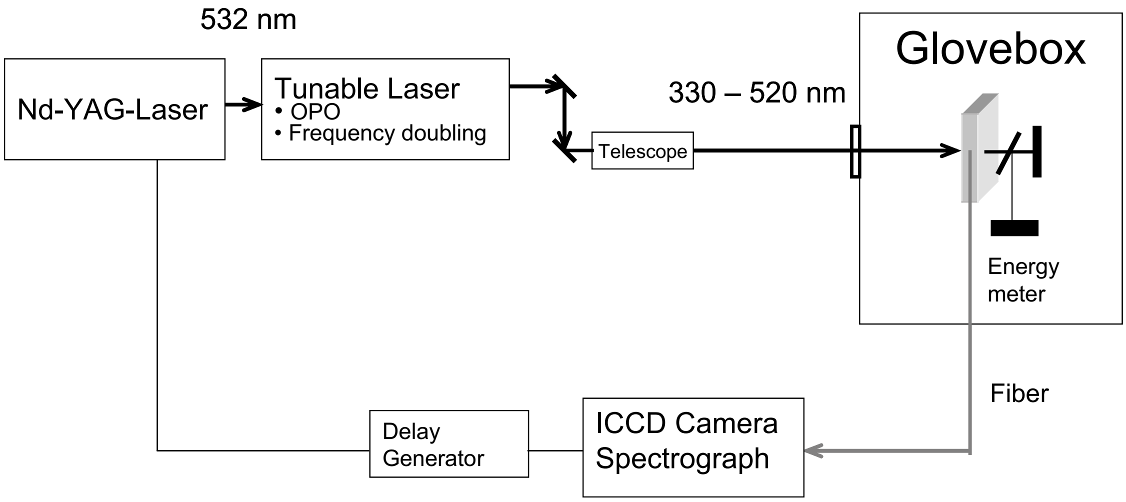


Figure 6-26. *Design of the fluorescence measurement system.*

(300 lines mm^{-1} grating) and 570–650 nm (1,200 lines mm^{-1} grating) ranges, respectively. A constant time window of 1 ms was used. For time dependent emission decay measurements, the delay time between laser pulse and camera grating was scanned with time intervals of 10 µs. The excitation wavelength was 396 nm using laser energy of 2.00 ± 0.14 mJ. 5,000 accumulations per spectrum were measured and averaged.

For testing the system fluorescence emission spectra were measured as a function of the curium concentration ranging from 5×10^{-10} to 3×10^{-7} M in 0.1 M $NaClO_4$ at pH 3. The experiments were performed in a glove box under N_2 atmosphere at 25°C. In Figure 6-27 the fluorescence emission spectra are summarised.

A speciation calculation using the formation constants for the Cm(III) hydrolysis species published in /Fanghänel et al. 1994/ showed that 100% of the Cm(III) exist as the aquo ion, $[Cm(H_2O)_9]^{3+}$, at pH 3.0. This is confirmed by our fluorescence emission measurements as shown in Figure 6-27 by the typical fluorescence emission spectra of the Cm^{3+} aquo ion with a peak maximum at 593.8 nm. By increasing the curium concentration increased fluorescence intensities were measured. Even at the lowest curium concentration used, 5×10^{-10} M, one can clearly identify the Cm(III) emission band. This shows the high performance of our unique laser system.

It follows that speciation studies can be performed at a comparable low curium concentration of 5×10^{-8} M. However, by an optimisation of the apparatus, e.g. increase of the laser energy and the number of accumulations per spectrum, even lower concentrations can be applied. An upper concentration limit of 3×10^{-11} M is given in the literature /Kim et al. 1991a/ for Cm speciation studies using TRLFS at room temperature.

Besides the fluorescence emission spectra, the second spectroscopic characteristic which can be determined using the new laser system is the fluorescence lifetime of a particular Cm species, in this case the Cm^{3+} aquo ion. For Cm^{3+} in 0.1 M $NaClO_4$ at pH 3 a fluorescence lifetime of 67.8 ± 1.5 µs was measured. By applying the Kimura & Choppin equation /Kimura and Choppin 1994/ the number of coordinated water molecules was calculated to be 8.7. The fluorescence parameters measured which are the emission band, the fluorescence lifetime and the number of corresponding water molecules in the first coordination sphere of the Cm(III) aquo ion are in excellent agreement with the literature /Wimmer et al. 1992, Kim et al. 1991b, Beitz et al. 1988/.

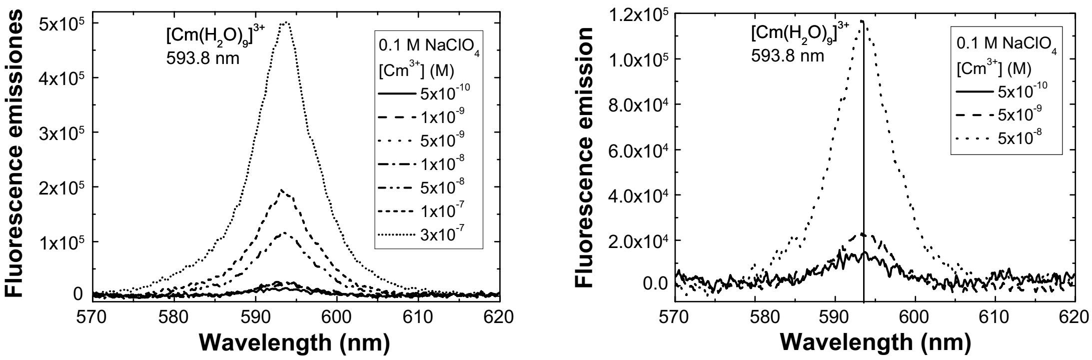


Figure 6-27. *Fluorescence emission spectra of Cm(III) in 0.1 M $NaClO_4$ as a function of the curium concentration at pH 3.*

These measurements demonstrate that the new laser system is well suited for highly sensitive fluorescence spectroscopy studies. This experimental base is required for achieving the goals of the started bioligand project. The new laser system offers also to opportunity to measure the excitation spectra of particular Cm species. The outcome of those experiments provides additional information for a detailed characterisation of the complex formation equilibria of curium with the selected bioligands.

6.4 CRIEPI

The Central Research Institute of the Electric Power Industry (CRIEPI) participates mainly in Äspö HRL modelling activities. CRIEPI has started to participate in the Task Force on Engineered Barrier Systems, tackling benchmark problems and compiling a report on the calculation results. CRIEPI has also participated in the Task Force on Modelling of Groundwater Flow and Transport of Solutes and conducted modelling under Task 6, Performance assessment modelling using site characterisation data. In addition, CRIEPI has been performing its voluntary project on the impact of microbes on radionuclide retention.

6.4.1 Task Force on Engineered Barrier Systems

CRIEPI has been developing the thermal-hydrological-mechanical (THM) coupling code LOSTUF for evaluation of the phenomena that will occur around the engineering barrier system. In 2005, the code LOSTUF was applied to two benchmark tests for Task 1 (THM processes in buffer materials.

Figure 6-28 to Figure 6-30 show the results of analysis of THM mock-up test conducted on MX-80 bentonite by CEA (Benchmark 1.1). In Phase 1 (0–2,700 h) heat is applied to one end of the column while the temperature at the other end is kept constant and equal to 20°C. A maximum and final temperature on the heated end is 150°C. In Phase 2 (> 2,700 h) a constant water pressure is applied to the end where temperature was kept constant at 20°C. Calculated results of temperature are in fairly good agreement with measured data, see Figure 6-28. Calculated results of relative humidity are also in good agreement with measured data, but isn't satisfactory, see Figure 6-29. Calculated relative humidity is so sensitive to intrinsic permeability, turtuosity factor, and retention curve that the determination of those parameters was difficult. Calculated axial stresses are greater than measured values, see Figure 6-30. Shrinkage of bentonite caused by drying near the heater should probably be taken into consideration. In addition, relationship between swelling behaviour and suction during infiltration should be further investigated in LOSTUF.

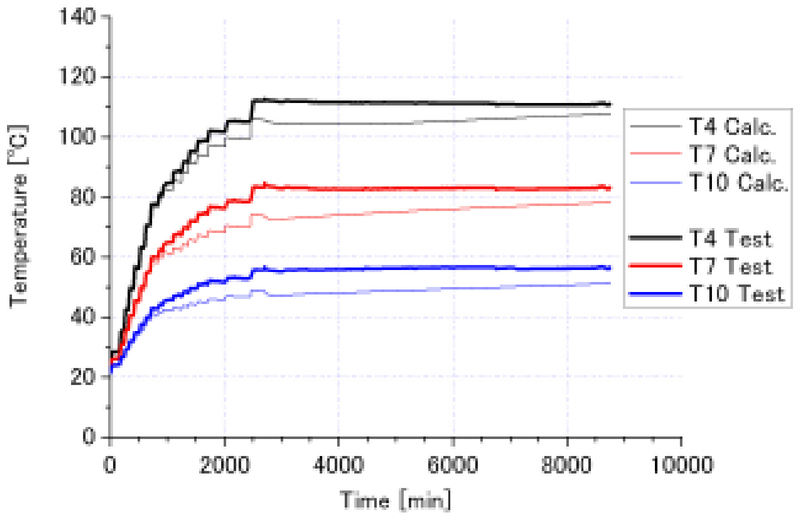


Figure 6-28. *Temperature versus time in cell 1 of Benchmark 1.1.*

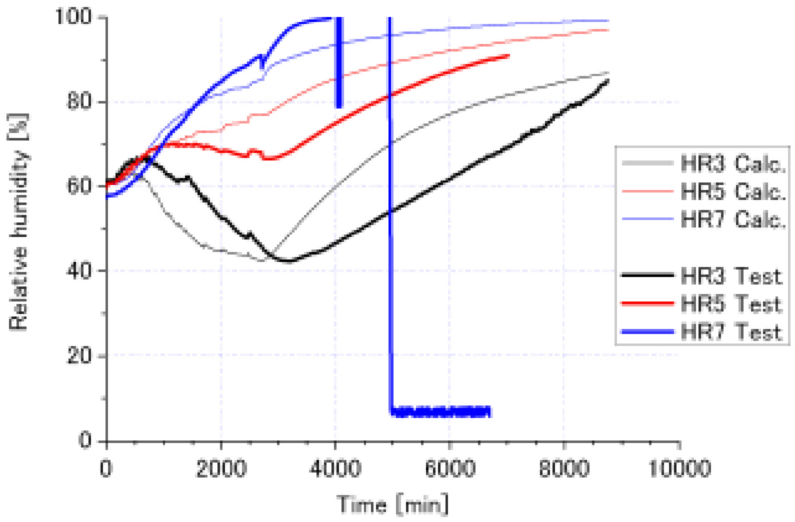


Figure 6-29. *Relative humidity versus time in cell 1 of Benchmark 1.1.*

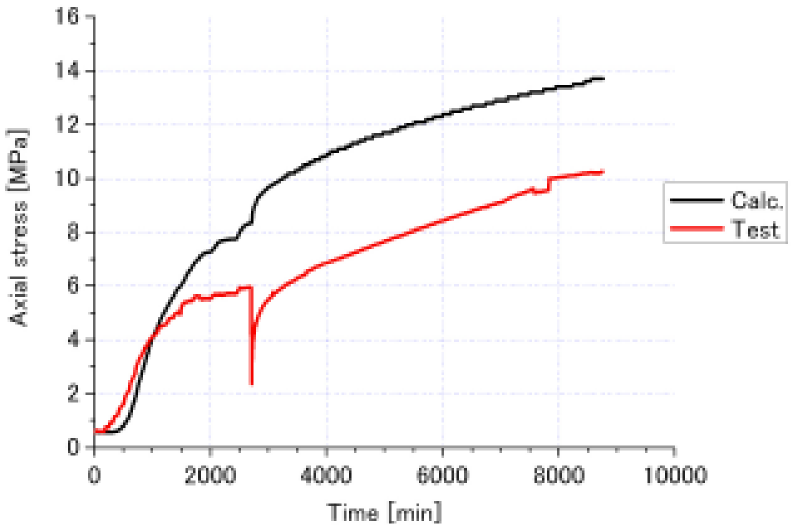


Figure 6-30. *Axial stress versus time in cell 1 of Benchmark 1.1.*

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

During 2005, CRIEPI performed a numerical analysis for Sub-task 6E which concerns transport calculations under a reference set of performance assessment time scales and boundary conditions by using a block scale synthesised structural model. In the model, there are more than 5,000 geological structures. These structures can be classified into two basic types, faults (Type 1) and non-faults (Type 2). Each of the comparatively large structures consists mostly of multiple fractures of different types.

It was difficult to model all the geological structures and their surrounding rock matrix. First, intersection between the geological structures was investigated and it became clear that 1,370 structures took part in groundwater flow and solute migration in the rock block.

Secondly, a preliminary migration analysis of non-adsorptive solute was performed to extract geological structures which greatly influenced the solute transport in the rock block. In the analysis, only geological structures were modelled and only advection and dispersion in the structures were taken into consideration. As a result of the analysis, the 42 structures were selected as structures dominating groundwater flow and tracer transport, see Figure 6-31. The numerical model in which the main 42 structures were considered gave the same breakthrough curve as the model in which 1,370 structures were considered, see Figure 6-32.

Finally a solute migration analysis in which the 42 main geological structures and their surrounding rock matrix were modelled was conducted. In the analysis, diffusion and sorption in rock matrix as well as advection and dispersion in the geological structures were taken into consideration. As a result of the analysis, breakthrough curves of solutes with different ability to sorb could be obtained under a reference set of performance assessment time scales and boundary conditions, see Figure 6-33.

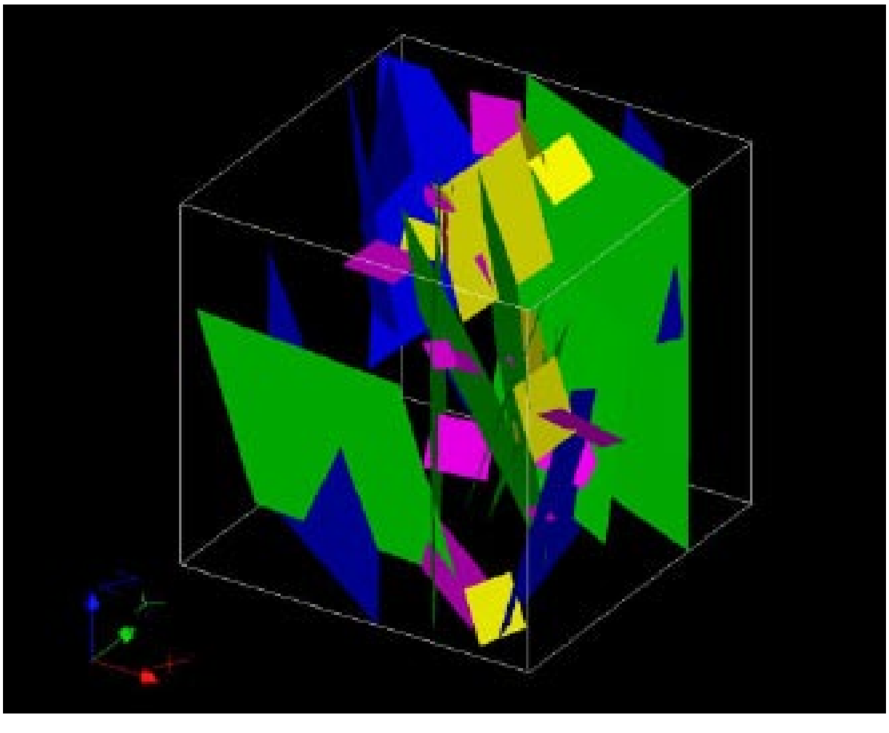


Figure 6-31. *Principal 42 geological structures extracted by preliminary analysis.*

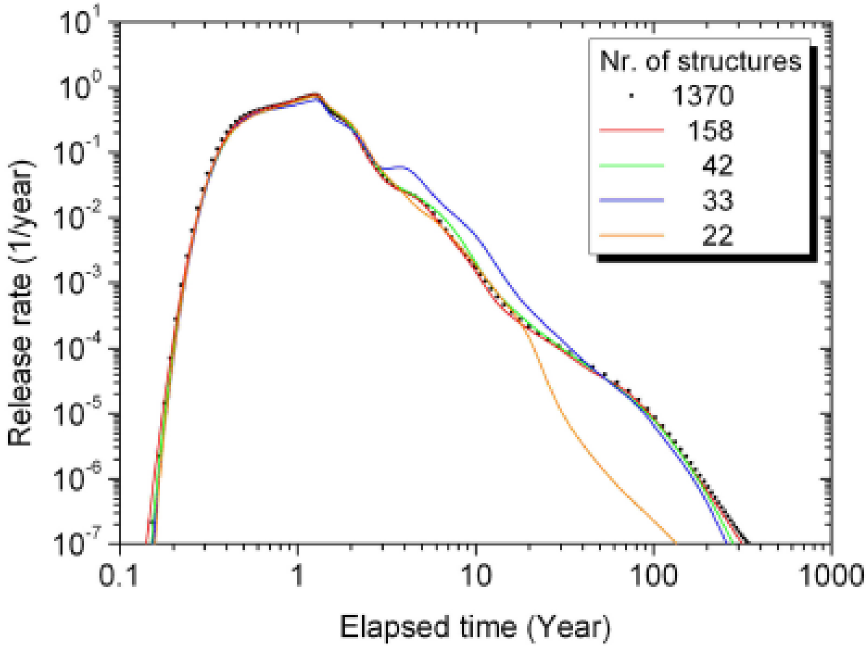


Figure 6-32. *Influence of number of modelled structures on solute migration.*

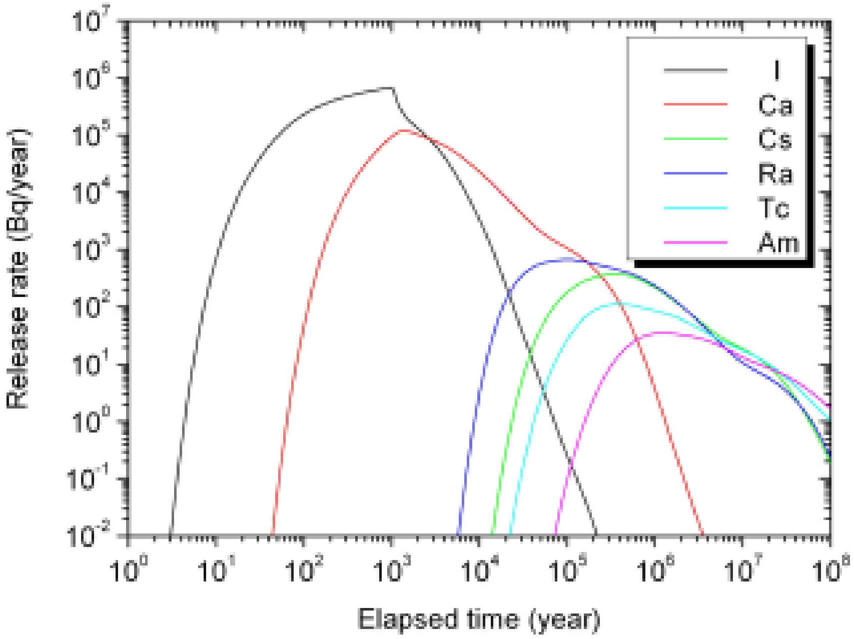


Figure 6-33. *Calculated breakthrough curves under PA boundary conditions.*

6.4.3 Voluntary project on impact of microbes on radionuclide retention

In order to evaluate the microbial impact on geochemistry of groundwater, CRIEPI has developed a groundwater circulation system in the experimental laboratory of CRIEPI, see Figure 6-34. In 2005, the pump for the circulation system was replaced by a gear pump to reduce the pulse flow which causes bubble cavitations. The groundwater reservoir was also replaced by the piston-type reservoir. The reservoir has been used to sample groundwater under in situ condition at Microbe –450 m site. Laboratory experiments using the system are presently being performed.

Figure 6-34. *Groundwater circulation system in the experimental laboratory.*

6.5 Japan Atomic Energy Agency – JAEA

JAEA, founded the 1st of October, 2005, is the successor to JNC (Japan Nuclear Cycle Development Institute), which has participated actively in the Äspö laboratory since it began. JAEA is currently constructing underground research laboratories at Horonobe and Mizunami, Japan. Both of these laboratories expect to benefit from research advances made at Äspö HRL.

JAEA research objectives at Äspö HRL during 2005 included the following:

a) Develop technologies applicable for site characterisation.

b) Improve understanding of flow and transport in fractured rock.

c) Improve understanding of the behaviour of engineered barriers and surrounding host rock.

d) Improve techniques for safety assessment by integration of site characterisation information.

e) Improve understanding of underground research laboratory experiments and priorities.

These objectives are designed to support high level waste repository siting, regulations and safety assessments.

6.5.1 Prototype Repository

During 2005, JAEA participated in Work packages on 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

The coupled THM analysis numerical code Thames was originally developed by Professor Ohnishi, Kyoto University /Ohnishi et al. 1985/. JAEA has validated the code Thames with the help of Hazama Corporation and Kyoto University. The code Thames was applied to the simulation of the coupled THM phenomena in and around the EBS in the second progress report on research and development for the geological disposal of HLW in Japan /JNC 2000/.

Objectives

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

Results

JAEA carried out the analysis of the Prototype Repository project for the prediction analysis A (two dimensional analysis) /Sugita et al. 2002/ and the prediction analysis B (three dimensional analysis) /SKB 2003/. In this report, the result of an additional analysis after the calibration of parameters is described.

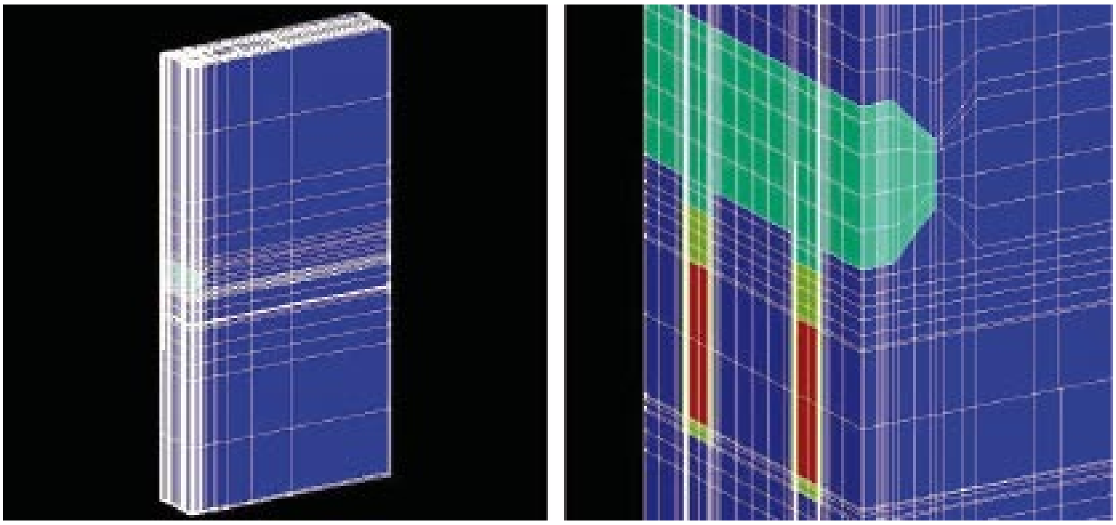
In the blind analysis, the thermal output from the canister was fixed at 1,800 W. However, predicted temperature in the bentonite is higher than the measured data. In the new analysis the output of canister is reduced 15%, in other word, output of canister in this simulation is 1,530 W. The permeability of the rock mass is 10^{-21} m^2 which is smaller than that of the buffer. The thermal vapour flow diffusivity is as follows:

$$D_T = D_{T0} \exp\left(\alpha \frac{T - T_0}{T_0}\right) \tag{6-1}$$

$$D_{T0} = 9.0\times10^{-12}\ \text{m}^2/\text{sK},\ \alpha = -0.4\ [-],\ T_0 = 10°\text{C} \tag{6-2}$$

where D_{T0} is reference thermal water diffusivity, T temperature, T_0 reference temperature and α is constant.

Figure 6-35 presents the finite element mesh which provides a correct geometry of a tunnel and pits. The input data of each material and the other conditions is the same as those used in the prediction analysis B (three dimensional analysis) /SKB 2003/. Figure 6-36 to Figure 6-38 show the results of the new analysis. Figure 6-36 shows the time history of temperature at the output points with the measurement points in deposition hole 3. The calculated temperatures at all points are almost the same as those of measurement. Figure 6-37 presents the time history of relative humidity at the output points with the measurement points in deposition hole 3. In spite of a decreasing tendency for the measured relative humidity near the heater, PXPWBU313 and PXPWBU319, the calculations show an increasing tendency. In order to decrease the relative humidity near the heater, a higher thermal vapour flow diffusivity than given in Equation (6-1) is needed. Figure 6-38 presents the relation of stress in deposition hole 3 between measurements and calculations. The measured value of the stress after 500 days is between 0 to 0.6 MPa, whereas the simulation result is between 0 to 0.4 MPa, i.e. a rather good agreement of the values.



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

***Figure 6-35.** Finite element mesh for analysis of the Prototype Repository.*

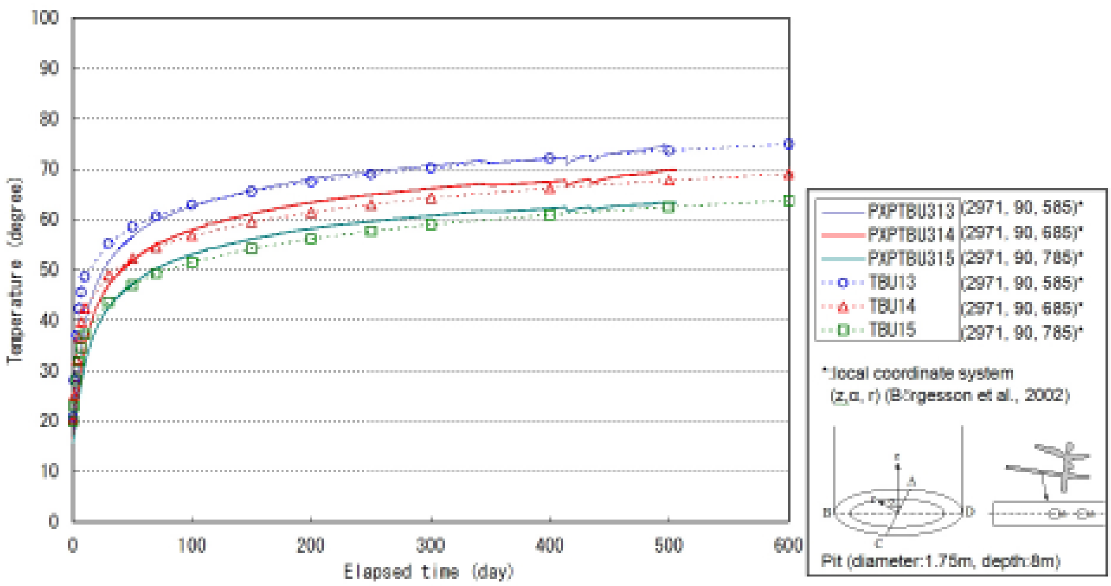


***Figure 6-36.** Time history of calculated and measured temperature in deposition hole 3.*

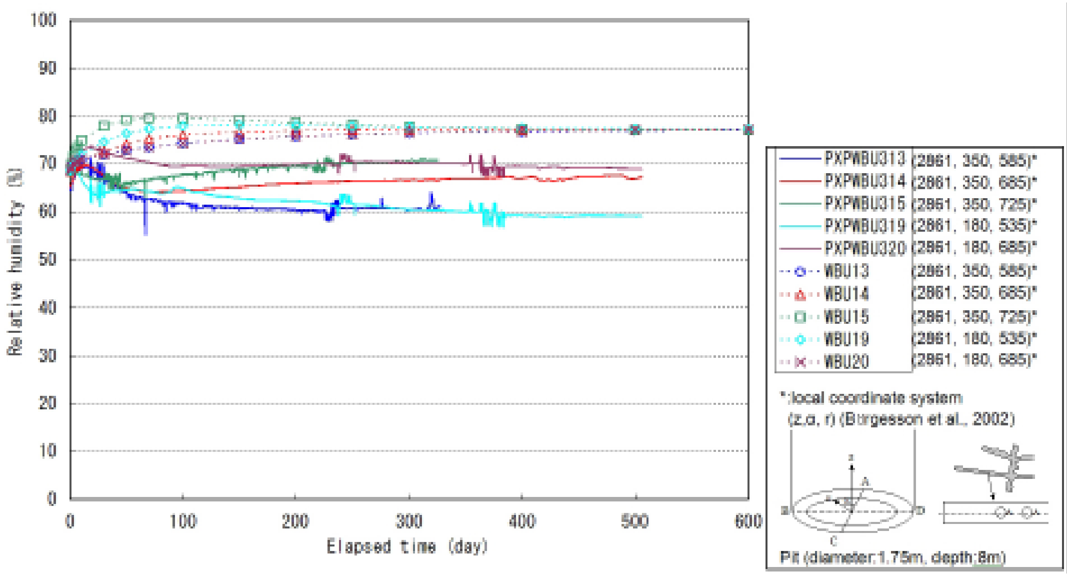


Figure 6-37. *Time history of calculated and measured relative humidity in deposition hole 3.*

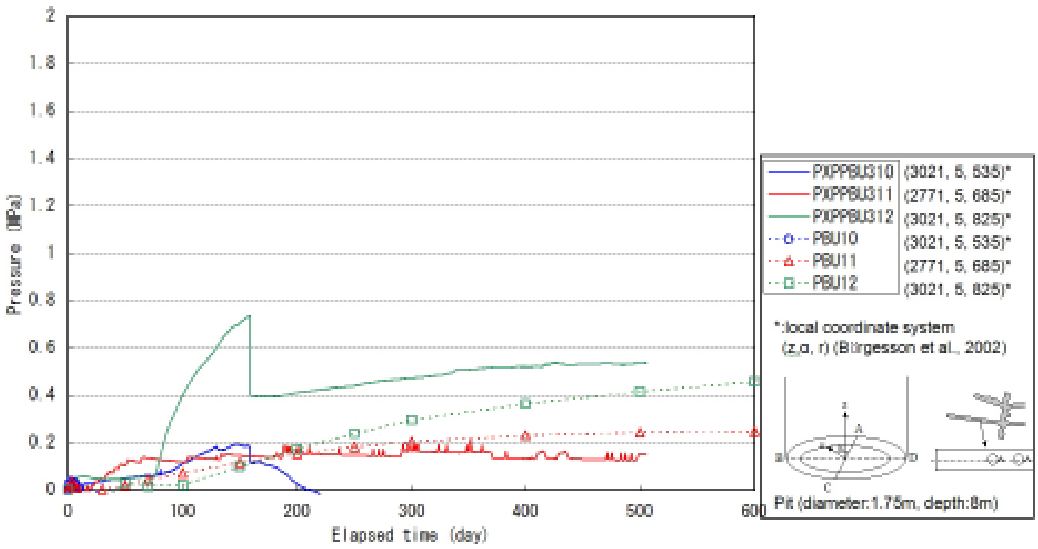


Figure 6-38. *Time history of calculated and measured stress in deposition hole 3.*

Chemical modelling of buffer, backfill and groundwater

Background

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 pore water. Since observation periods by laboratory and in situ experiments are very short and information by natural analogue studies is very limited, numerical calculations 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 an initial transient state. This 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 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 research on coupled THMC processes.

Objectives

The objectives with the Chemical modelling of buffer, backfill and groundwater are to:

- Predict near-field chemistry for overpack corrosion and radionuclide migration.
- Predict near field long-term integrity by chemical degradation.

Results

In order to perform a THMC coupled analysis of the processes in near field of the geological disposal system a coupling analysis code has been developed /Ito et al. 2003, Neyama et al. 2003/. The code is based on the coupling analysis code Couplys (Coupling analysis system) /Ohnishi et al. 1985/ including THMC-phenomena by existing analysis codes Thames, Dtransu-3D-EL and PHREEQC. The results in year 2005, are as follows:

1. In order to obtain a reliable resolution the Thames code was modified for 8 nodes element and each phenomenon was solved separately instead of full coupling.
2. In order to upgrade Dtransu-3D-EL model, gas diffusion has been introduced independent on aqueous element.
3. The geochemistry module has been adopted to take into account the dependence of the surface site density to the water conditions in the bentonite and the changes in CSH solid phase with changes in the ratio of C/S for cementitious material. The methodology of time mesh for kinetic model and separate method for pore water chemistry in the bentonite has been studied.

The evolution of THMC-modelling by JAEA is summarised in Figure 6-39.

6.5.2 True Block Scale Continuation

JAEA has participated in the True Block Scale project since 1997. During 2005, JAEA assisted in the final reporting for the True Block Scale Continuation project. This required a reassessment of each of the project hypothesis. Simulations were carried out to test hypotheses concerning the value of project microstructural and hydrostructural models. These simulations were all run as “forward models” of the True-BSC conservative and sorbing tracer experiments, implementing the derived hydrostructural and microstructural models, rather than as “inverse models” calibrated to tracer experiments.

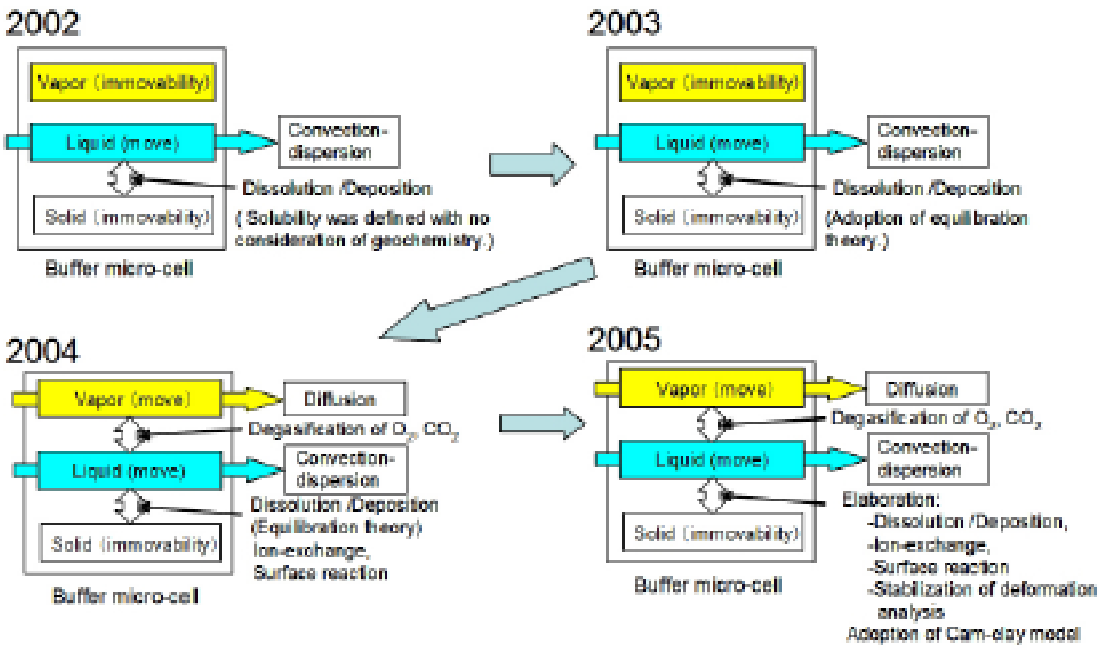


Figure 6-39. *Image of the evolution of THMC modelling by JAEA.*

The conclusions developed based on these analyses and simulations are as follows:

Hypothesis I a) Microstructural (i.e. detailed geological, mineralogical and geochemical) information can provide significant support for predicting transport of sorbing solutes at experimental time scales.

1. The prediction of many aspects of solute transport for the BS2b sorbing tracer experiment, based primarily on the True-Block Scale microstructural model demonstrates that it is valuable to have the available detailed microstructural model information for predicting solute transport.

2. Even with the detailed microstructural information, it was not possible to carry out a pure model prediction of solute transport due to the lack of definitive information concerning the geometry of the background fracture pathway.

3. The implementation of the microstructural model is also significant for the quality of predictions. In the predictive modelling by JAEA/Golder, the microstructural model did not consider the reduction in diffusion area due to channelling within the fracture plane. Much of the discrepancy between simulated and measured breakthrough was removed when this channelling effect was considered.

4. The hydrostructural model (i.e. identification of fracture geologic type, complexity, and geometry) is also important for defining the transport. In particular, the True-Block Scale hydrostructural model provided the geometry framework for the tracer pathways, and the assignment of microstructural models to different fractures.

5. In the predictive modelling, the implementation of identified complexity by proportionally increasing the area available for diffusion over-predicts retention and was therefore removed from the reconciliation modelling.

6. Reconciliation modelling over-predicted retention of strongly sorbing tracers. This is potentially due to the use of the full transport channel width for each of the immobile zones in parallel. This indicates that the microstructural model should consider additional reductions in the effective flow channel width for diffusive processes. Table 6-2 summarises transport simulations for the BS2b sorbing tracer transport experiments, with 10% of the fracture channel area assumed to be available for diffusion.

Hypothesis I b) Transport at experimental time scales is significantly different for faults (significant alteration, brecciation and fault gouge) and joints (with or without alteration), due to the indicated differences in microstructure and properties.

1. The solute transport in the Structure #19 pathway experienced a shorter advective travel time than the pathway involving the background fracture BG #1. This can be presumed to be a consequence of the differences between faults such as Structure #19 and no-fault fractures such as BG #1. This supports Hypothesis I b.
2. The project microstructural model for faults such as Structure #19 provides greater immobile zone retention than for small background fractures such as BG #1 and related pathways. A comparison of BS2b experimental results with modelling of sorbing tracers indicates that the background fracture immobile zone retention is even smaller than was assumed in the modelling. This indicates that immobile zone retention for faults is indeed significantly greater than for background fractures, at least at experimental time scales.

Table 6-2. BS2b Sorbing tracer transport breakthrough statistics assuming diffusion flow wetted surface availability limited to 10% of each immobile zone.

Critical time statistics for slow (#BG-1) flow path									
SKB						**10% of pipe perimeter model**			
	t5 hours	**t50 hours**	**t95 hours**	**% recovery**		**t5 hours**	**t50 hours**	**t95 hours**	**% recovery**
HTO	183	790	n/r	68%	HTO	176	313	613	100%
^{155}Eu	155	500	n/r	92%	^{155}Eu	162	315	659	100%
^{22}Na	300	1,490	n/r	72%	^{22}Na	697	1,275	2,455	100%
^{133}Ba	3,250	n/r	n/r	8%	^{133}Ba	n/r	n/r	n/r	< 1%
^{54}Mn	n/r	n/r	n/r	1%	^{54}Mn	n/r	n/r	n/r	< 1%
Total time	**hours**				(green)	Good match to measured data			
HTO	4,409				(yellow)	O.K. match to Measured data			
All others	4,577				(blue)	Poor match to measured data			
Critical time statistics for fast (#19) flow path									
SKB						**10% of pipe perimeter model**			
	t5 hours	**t50 hours**	**t95 hours**	**% recovery**		**t5 hours**	**t50 hours**	**t95 hours**	**% recovery**
$^{131}I^-$	14	62	n/r	80%	$^{131}I^-$	12.25	51	806	100%
^{160}Tb	14	63	4,075	87%	^{160}Tb	11	40	585	100%
^{85}Sr	19	107	4,327	86%	^{85}Sr	9.7	42	231	100%
^{86}Rb	51	490	n/r	56%	^{86}Rb	66.5	645	n/r	67%
^{137}Cs	555	n/r	n/r	28%	^{137}Cs	457	1,090	n/r	81%

Hypothesis I c) Longer distance pathways are dominated by fault rock zone behaviour, while shorter pathways (representative for fractures in the vicinity of a deposition hole) may be more likely to be dominated by joint fracture characteristics.

1. Both pathways in the BS2b sorbing tracer experiment have approximately the same Cartesian length (20 m), which makes it difficult to reach conclusions regarding this hypothesis.
2. However, the Structure #19 retention behaviour within the experiment is dominated by the immobile zone retention (principally gouge and fracture coating). Since Structure #19 extends for over 100 m, it is reasonable to conclude that the same fault rock zone behaviour would dominate at the larger scale.
3. Nevertheless, the BG #1 pathway, which was not dominated by fault rock behaviour, showed that it is possible to develop pathways of significant length (e.g. tortuous distances in excess of 50 m), made up of non-fault fractures. These non-fault fractures appear to have different advective transport behaviour, with lower advective velocities and lower retention. This evidence indicates that such networks of "background fractures" might also occur at larger scales.

Hypothesis I d) Fracture retention properties tend to be scale-dependent primarily due to differences in microstructure.

1. The dramatically longer advective travel time for the BG #1 pathway is not, strictly a microstructure issue, but rather an issue of the porosity and length of the advective pathway itself.
2. The difference in retention for the BG #1 and Structure #19 pathways could potentially be extrapolated as a "scale dependent" difference, because the Structure #19 has a much larger scale than BG #1. However, this extrapolation is not firmly based in the available data.

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

JAEA participation in the Äspö Task Force on Groundwater Flow and Transport of Solutes during 2005 included simulations for Task 6 – Performance assessment modelling using site characterisation data and for initiation of Task 7 – Onkalo site hydrogeologic modelling. During 2005, JAEA participation in Task 6 included:

- Reporting of sub-tasks 6A and 6B simulations which demonstrated the importance of microstructural models for performance assessment time scale calculations, due to their effect on matrix diffusion at both short and long scales.
- Fracture network solute transport sensitivity studies at site characterisation and safety assessment time scales (sub-tasks 6F and 6F2).
- Reporting of simulations and analyses for sub-tasks 6D, 6E, 6F and 6F2.

Sub-task 6F – Fracture network transport at performance assessment time scales

This sub-task was defined by the Äspö task force as a simple fracture network reference case under performance assessment boundary conditions, to provide a basis for comparison between different modelling groups of the task force. Although this case assumed flow and transport only in a limited number of assumed deterministic structures, the JAEA model work flow for this task required the inclusion of background fractures to provide a basis for meshing of pipes within the fractures (Figure 6-40). Background fractures and deterministic fractures are illustrated in Figure 6-41. Particle tracking simulations (Figure 6-42) demonstrate how the geometry of fracture pathways can result in asymmetric pathways, even through the assumed boundary conditions are symmetrical. This has important implications for both site characterisation and performance assessment modelling. In Figure 6-43 examples of breakthrough curves from this modelling are shown.

Sub-task 6F2 – Sensitivity studies of fracture network transport

Based on the results of sub-task 6F, it was decided that JAEA modelling for sub-task 6F2 would concentrate on the role of the pipe mesh generation assumptions on fracturing. Modelling assumptions and particularly mesh discretisation can be an important component of modelling uncertainty. Figure 6-44 shows an example of the variation of breakthrough results for different meshing assumptions for the simple Task 6F2 model. The variation is significant, but not as important as that previously identified as due to microstructural model assumptions.

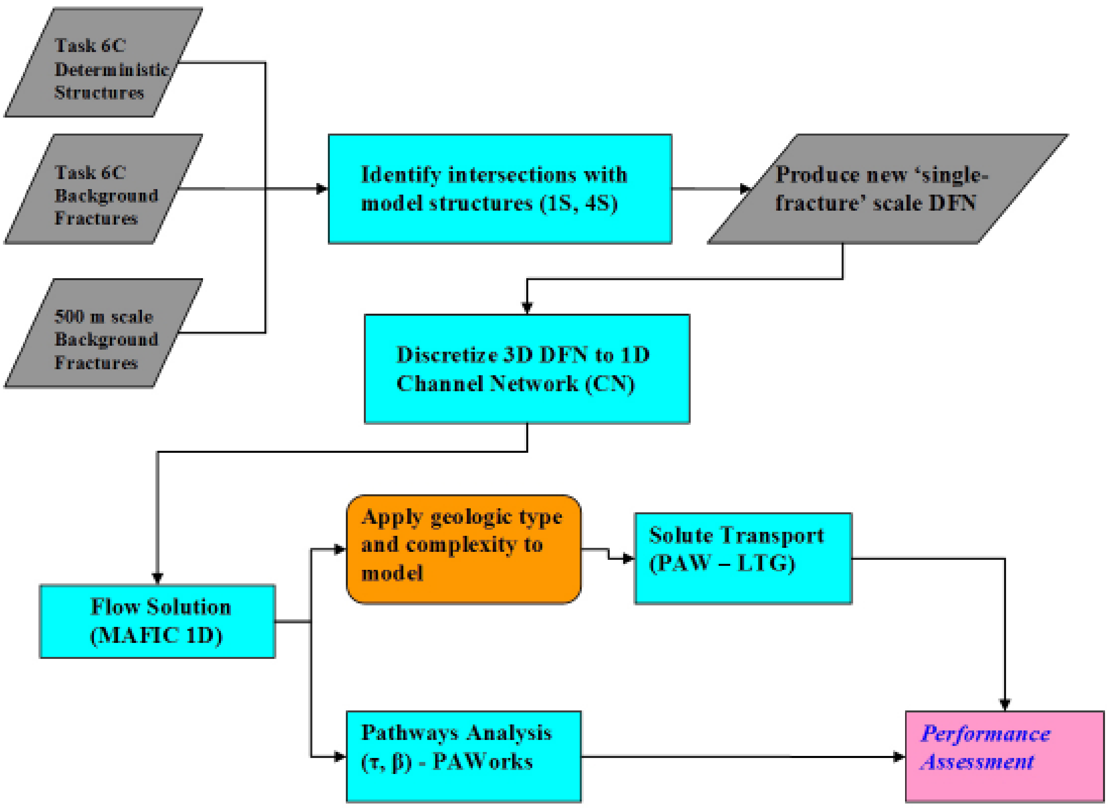


Figure 6-40. *JAEA modelling workflow for sub-tasks 6F and 6F2.*

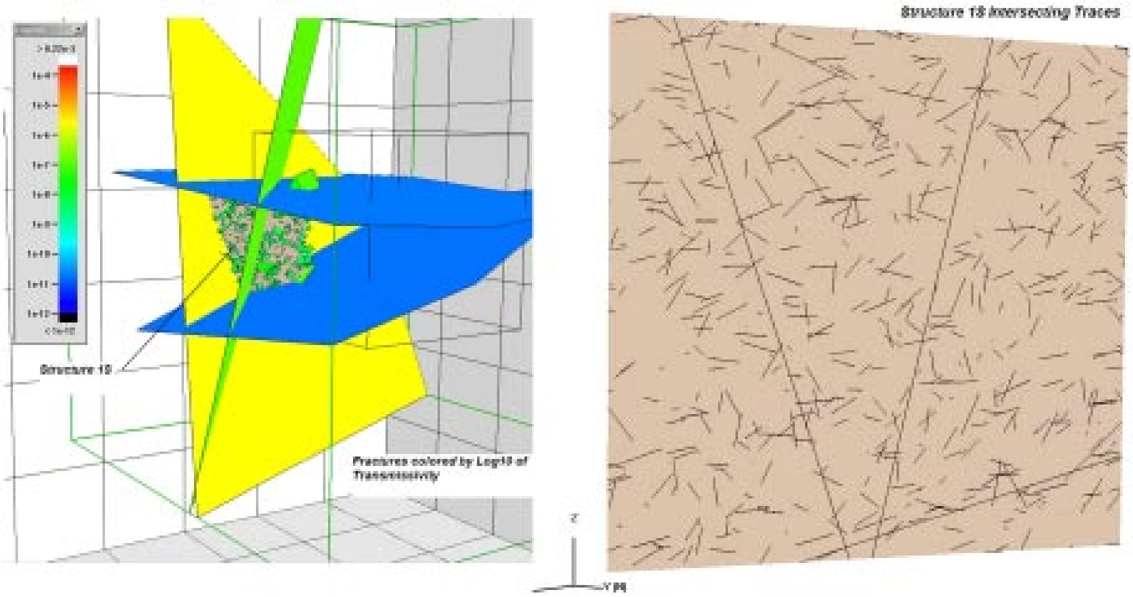


Figure 6-41. *Background fractures used to generate pipes for sub-task 6F, Case A.*

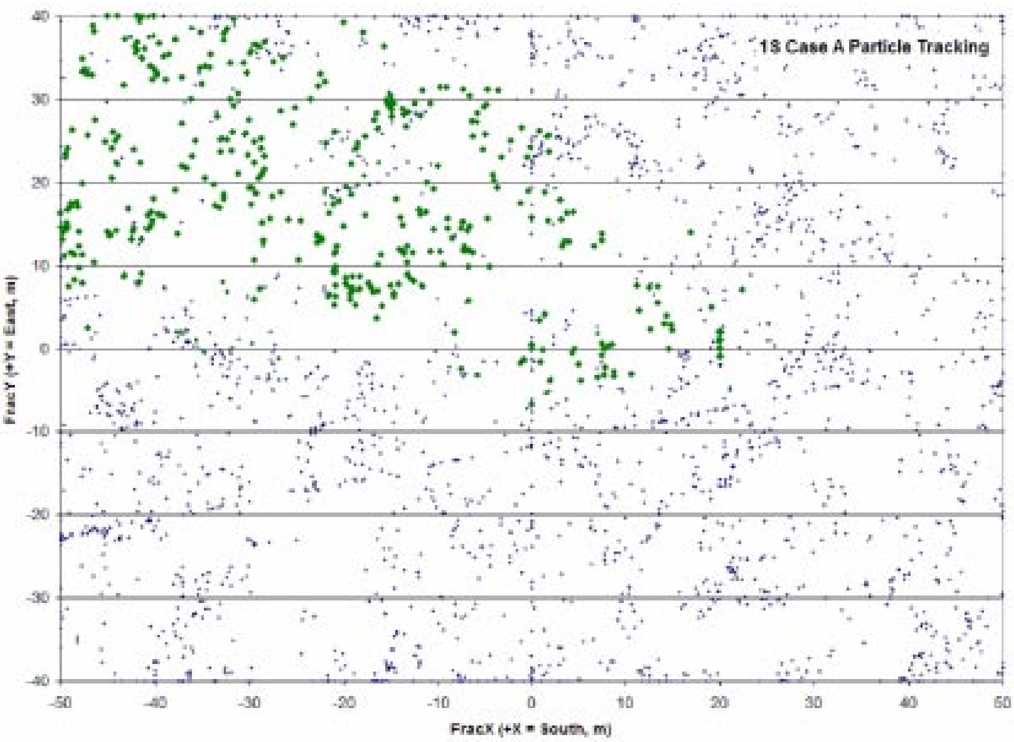


Figure 6-42. *Visualisation of particle tracks for sub-task 6F, Case A. Note that particle locations (green) are asymmetrical, even though the flow boundary conditions are symmetrical. This is due to the geometry of transport pathways defined by intersections with background fractures.*

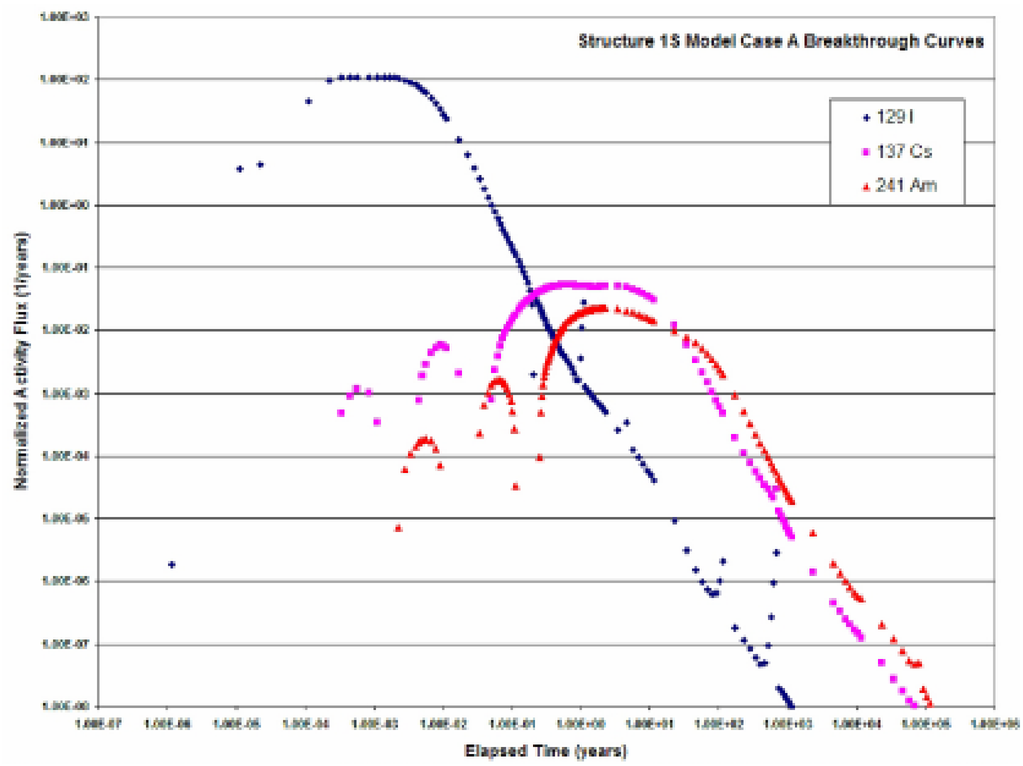


Figure 6-43. *Simulated breakthrough curves for sub-task 6F, Case A.*

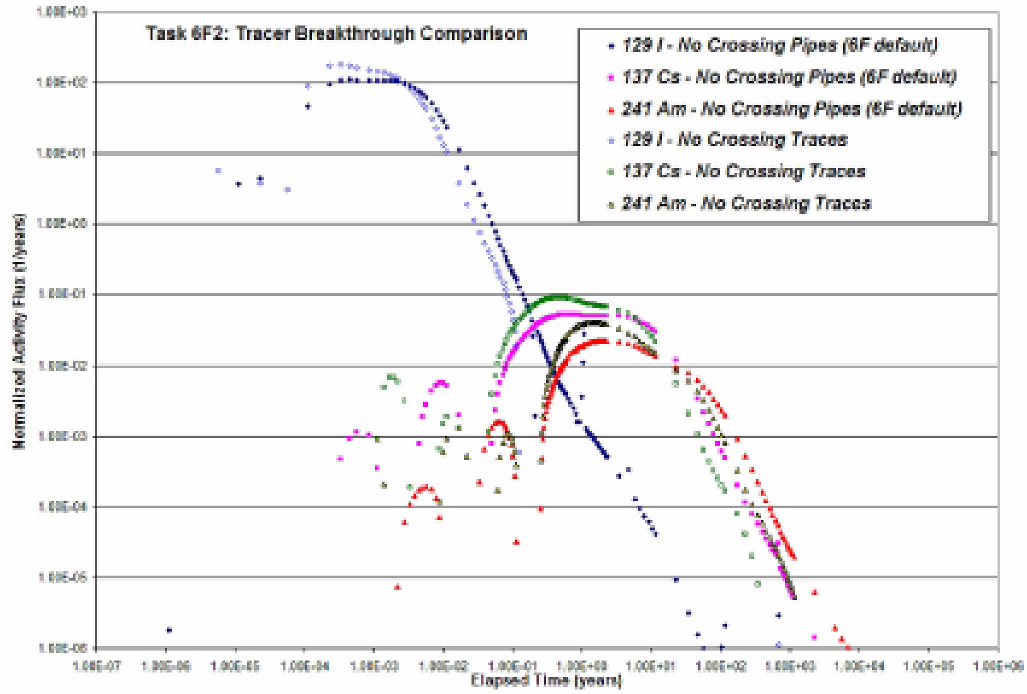


Figure 6-44. *Variability in breakthrough curves with alternative DFN pathway meshing assumptions used for sub-task 6F2.*

Task 7 – Onkalo site hydrogeologic modelling

During 2005, modelling for Task 7 was limited to initial sensitivity studies of the alternative approaches for modelling open-hole boundary conditions. These simulations were defined as "Test Cases" A, B, and C. JAEA simulation demonstrated the use of the powerful "Group Flux" boundary conditions, which was designed specifically to model this case, see Figure 6-45. Figure 6-46 shows the heads achieved with this model. Simulations with the "Group Flux" boundary conditions successfully represented the flows within the boreholes, and the flow patterns within and between the modelled structures.

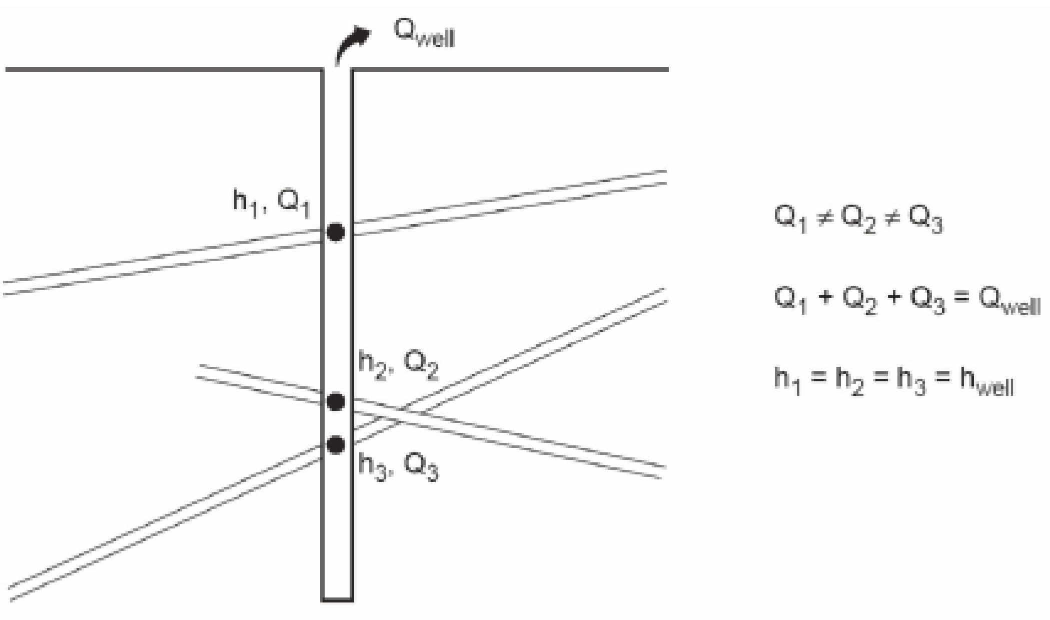


***Figure 6-45.** JAEA/Golder group flux boundary conditions for open boreholes.*

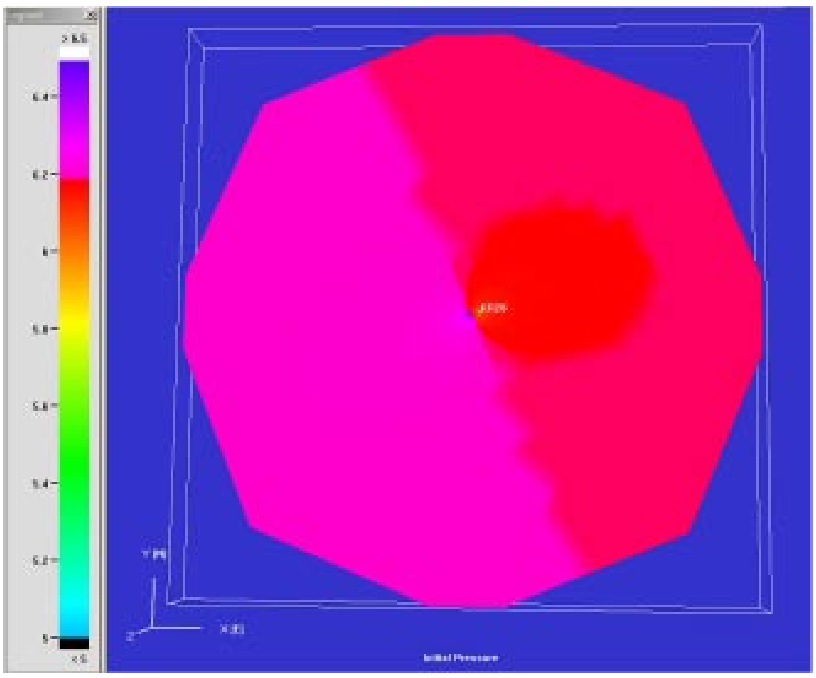


***Figure 6-46.** Head field in Structure #19 under "Case A" boundary conditions, using group flux boundary conditions for open boreholes.*

6.6 OPG

Ontario Power Generation (OPG) joined the Äspö HRL in 2004 for a five-year term. In 2005, work was performed on behalf of OPG by AECL, Université Laval and Intera Engineering. The results of this work are briefly described below.

6.6.1 Large Scale Gas Injection Test

OPG is contributing to the gas transport modelling component of Lasgit, and will provide an evaluation of both the test design and test results. Presently, the work (by Intera Engineering) is focussed on model preparation for the gas transport tests. In particular, the Tough2 code has been modified for Lasgit as follows:

- Pressure/stress dependent permeability modifications to simulate micro- and macro-fracturing of the bentonite due to the injection of helium gas from the canister.
- Pressure dependent capillary pressure modifications to simulate the dilation of fractures in the bentonite.
- Addition of helium properties to the EOS3 module of Tough2, which by default considers air as the gas component.

These code modifications were successfully verified using 1D and 3D test models, and by comparing model results to spreadsheet calculation and the nSights code, a hydraulic well-tested code that allows pressure-dependent permeability functions to be defined.

In addition to modifications to the Tough2 code itself, the paCalc code was further developed to provide a framework for inverse modelling and uncertainty analysis with the Tough2 code. Using a 3D Tough2 model, example uncertainty analysis and optimisation testing were successfully completed.

6.6.2 Task Force on Engineered Barrier Systems

OPG is represented by Atomic Energy of Canada Limited (AECL) in the Engineered Barrier Systems Task Force. The primary activity of the Task Force during 2005 was the conduct of a series of numerical modelling exercises that were intended to calibrate various numerical codes against a pair of benchmark tests referred to as the CEA and Ciemat mock-up tests. These mock-ups consisted of two cylindrical specimens of highly compacted bentonite that were exposed to known hydraulic and thermal gradients while the temperature, water content and stress conditions were monitored. The same material property information and experimental data generated by the mock-up tests were provided to each modelling team.

AECL used Code Bright to conduct numerical simulations of the Thermal-Hydro-Mechanical-gas (THMg) evolution of these systems.

AECL's numerical modelling of the CEA mock-up was conducted recognising that there were some limitations to the results of the physical simulations (water leakage, physical disturbance). An exact match between the simulation and physical test was not expected but general trends were reproduced.

The temperatures generated by the numerical simulation were within 4.5°C of the mock-up measurements (Figure 6-47). The difference between measured and simulated values is tentatively attributed to the thermal conductivity – saturation relationship that is currently incorporated in Code Bright.

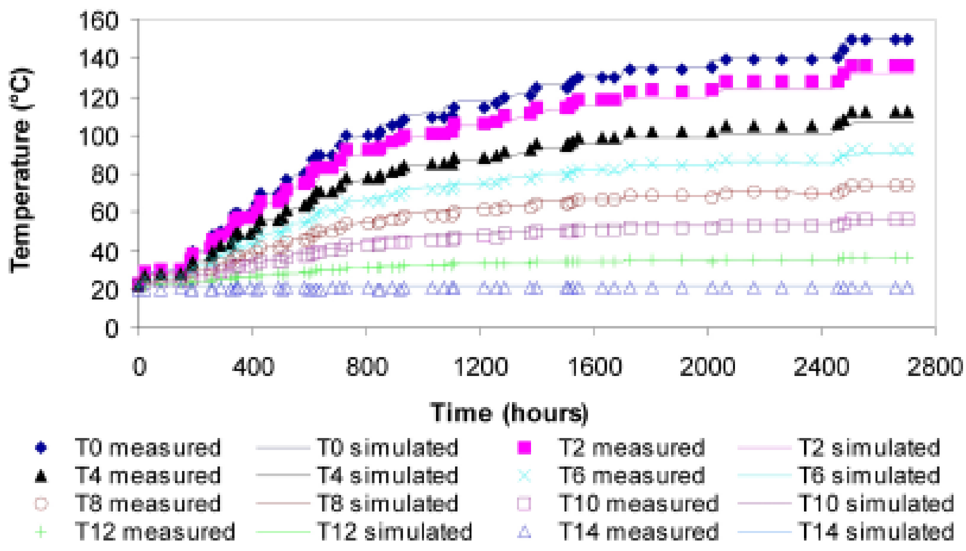


Figure 6-47. *Measured and simulated temperatures in CEA mock-up test during first phase (without water intake).*

The numerically simulated values for relative humidity were lower than the measured data although the trends were reproduced (Figure 6-48). The differences may be the result of the hydraulic parameters assumed for the bentonite. The formulae for the water retention curve needs to take the influence of temperature into greater consideration. Differences between the simulated and measured relative humidity also suggests that the actual gas boundary conditions may be different than was assumed in the mock-up.

The simulated and measured axial stresses were in reasonably good agreement in the first phase, but physical disturbance of the apparatus during the transition from the first phase to the second phase made simulation during the thermal phase problematic (Figure 6-49).

AECL's numerical simulation of the second (Ciemat) mock-up was also conducted using Code Bright. The measured water intake in the mock-up represented a volume much larger than the available pore space. This required careful evaluation of the thermal and hydraulic conditions within the specimen during numerical simulations. The results of the modelling were as follows.

The initial thermal hydraulic simulation predicted lower thermal gradients and higher relative humidities than were measured, although the trends observed in the mock-up were captured (Figure 6-50 and Figure 6-51).

In order to improve the fit of the simulation to the data, the thermal conductivity of the Teflon was decreased by a factor of 10 and the hydraulic conductivity of the bentonite was reduced to 1×10^{-14} m/s. The rationale for these modifications was possible vapour formation in the interface between the bentonite specimen and the Teflon cylinder, which could have influenced the pattern of the thermal transfer and the resultant water movement in the specimen. The result was an improved match in terms of both trend and magnitude to the mock-up (Figure 6-50 and Figure 6-51).

Based in part on these test results, it was suggested by AECL to the Task Force that incorporating the water retention curve as a function of temperature in Code Bright may be helpful in understanding the hydraulic evolution under thermal gradient conditions in unsaturated clay-based materials.

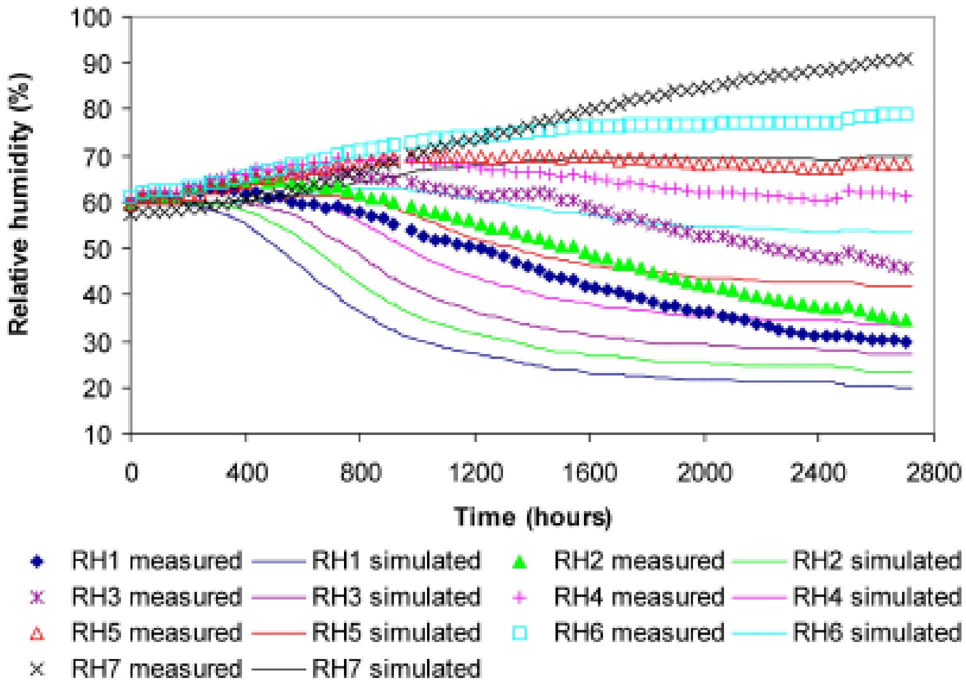


Figure 6-48. *Measured and simulated relative humidity during the first phase of the CEA mock-up test.*

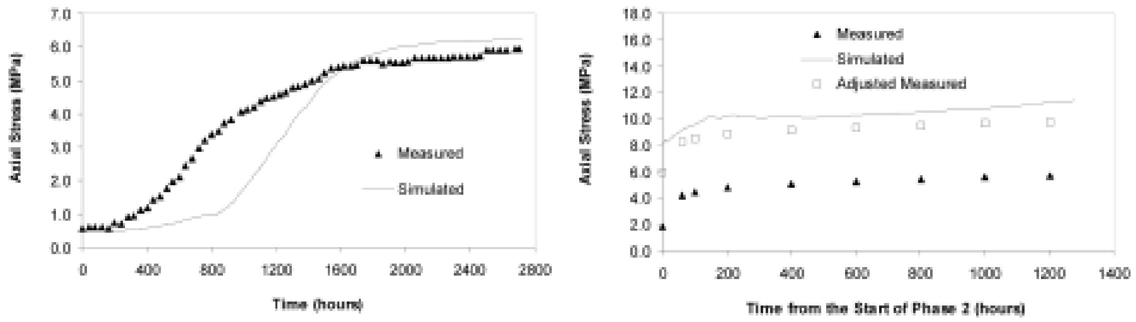


Figure 6-49. *Measured and simulated axial pressures during the first and second phases of the CEA mock-up test First phase without water intake (left) and second phase with constant temperature and with water uptake (right).*

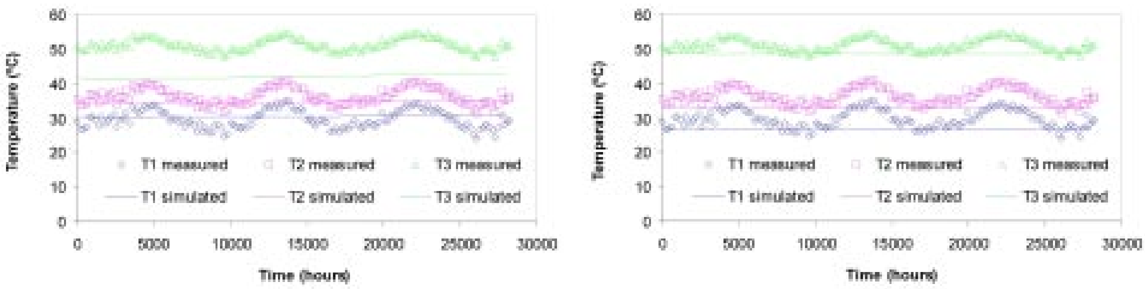


Figure 6-50. *Simulated and measured temperatures during the second phase of the Ciemat mock-up test, showing the influence of model parameter adjustment on the model results: Original simulation (left) and with adjusted materials parameters (right).*

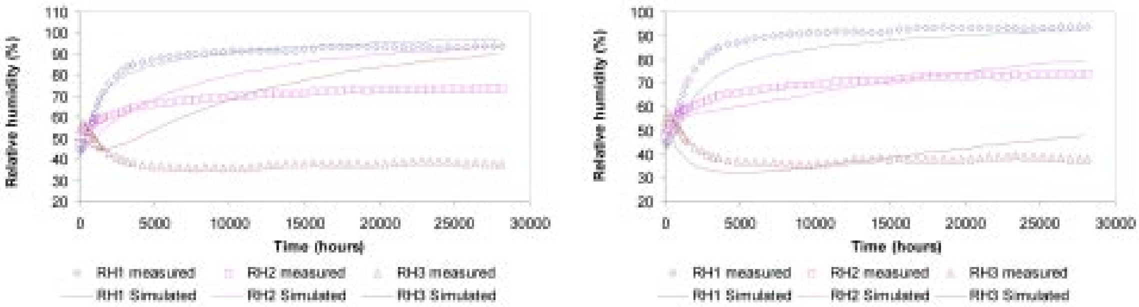


Figure 6-51. *Simulated and measured relative humidity during the second phase of the Ciemat mock-up test, showing the influence of model parameter adjustment on the model results: Original simulation (left) and with adjusted material parameters (right).*

The results of AECL's simulations of the CEA and Ciemat mock-ups were presented at the third meeting of the Task Force, organised by SKB and held in Barcelona, Spain in October 2005. Subsequent to this meeting, two reports that detailed the results of the numerical modelling efforts by AECL were submitted to the Task Force secretariat for inclusion in a task force report and to OPG for publication /Guo and Dixon 2005ab/.

At the Task Force meeting, the conduct of the next THM modelling activities were discussed. The intention is to extend the modelling exercises to try and reproduce the results observed in large-scale field simulations. OPG/AECL has offered the Isothermal Test and the Buffer/Container Experiment, both conducted at AECL's Underground Research Laboratory, as candidates for this next stage of modelling. Documents on both of these field simulations have been submitted to the EBS-TF secretariat for consideration.

6.6.3 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 instruments were returned after use in the test and were recalibrated in 2005.

The LVDTs were installed in one of two 1.8 m diameter and 6.4 m deep boreholes comprising the experiment, and were used to monitor the borehole wall displacement during the course of the experiment. The AECL supplied LVDTs had a 12 mm range and were paired with SKB-supplied LVDTs (GeoLVDTs), having a range of 40 mm. The ultimate temperature increase in the hole only reached about 15°C, so the deformation of the frame and instruments due to heating was small. Thus it was not included in the calculations for displacement in the pillar stability experiment.

During the test, heating of the rock did produce spalling of the borehole wall as anticipated. This was seen through direct observation and through acoustic emission monitoring. The LVDTs successfully recorded rock movement associated with the spalling. Some of the LVDTs were relocated to positions deeper in the borehole as the spalling advanced down the borehole wall with increasing temperature. The results of the LVDT measurements are to be reported by SKB.

6.6.4 Long Term Diffusion Experiment

In 2005, OPG funded laboratory diffusion cell and radial diffusion experiments in support of the Long Term Diffusion Experiment (LTDE) in Äspö HRL. Core samples of Äspö diorite from the LTDE borehole were supplied by SKB. The experiments, undertaken at AECL's Whiteshell Research Laboratories, provided laboratory-scale diffusion coefficients that can be compared to in situ derived values from the LTDE.

The main findings of the laboratory experiments were that diffusivity is not significantly reduced by alteration close to fracture surfaces, diffusivity is independent of direction with respect to rock fabric and iodide effective diffusion coefficients estimated by the diffusion cell experiments had a geometric mean of 1.7×10^{-13} m^2/s. The value is consistent with values estimated from mass fluxes and diffusion profiles analysed from the radial diffusion experiment. The geometric mean of tritium effective diffusion coefficients derived from diffusion cell experiments was 4.9×10^{-13} m^2/s.

6.6.5 Colloid Project

In 2005, OPG supported the development and initiation of a laboratory experimental program to support the Äspö Colloid Project. The laboratory-scale colloid transport experiments are being undertaken at AECL's Whiteshell Research Laboratory using a Quarried Block (QB) sample, a 1×1×0.7 m block of granite containing a single, complex, but well characterised, through-going, variable aperture fracture. This program includes migration experiments using both MX-80 bentonite and latex sphere colloids and is designed to evaluate the effects of varying flow velocities, solution compositions, and particle size on bentonite colloid transport. The laboratory experiments will contribute information that is useful in planning and interpreting field tests at Äspö and will provide complimentary information on bentonite colloid retention that cannot otherwise be obtained during the in situ experiments.

In preliminary laboratory work, MX-80 bentonite colloid suspensions were prepared and quantified with light scattering and their size distribution determined with an Ultrafine Particle size Analyzer. Initial, dipole-type transport experiments in the QB fracture confirmed that the bentonite and 100-nm latex sphere colloids showed similar transport behaviour and good mass recoveries (near 80% after 2 fracture volumes) under conditions of high flow and low ionic strength. In subsequent experiments, flow rate and ionic strength will be systematically altered in an effort to quantify their impact on bentonite colloid retention.

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

OPG is participating in the Äspö modelling task force's Task 7. The overall objective of Task 7 is to simulate hydraulic responses measured during the long-term OL-KR24 pumping test conducted in the fractured crystalline rock at the Onkalo site in Olkiluoto, Finland.

In 2005, the Task Force secretariat designed three preliminary test cases consisting of simplified, 3D representations of the interconnections between fracture zones and open boreholes at Onkalo. These test cases were simulated by the different modelling groups using their numerical tools, and results were presented at a workshop in September. The Université Laval, providing numerical modelling expertise for Task 7 on behalf of OPG, completed the simulation of the test cases with the FRAC3DVS model.

The results of the preliminary test cases confirmed that the FRAC3DVS model has the capability to incorporate the open boreholes and discrete fracture zones necessary to simulate fluid flow during the OL-KR24 test. The model can calculate volumetric fluid flow rates along the simulated open boreholes, which can then be compared to the actual Posiva Flow Log measurements. The FRAC3DVS simulations also demonstrated that the magnitude and direction of fluid flow into and out of the borehole-fracture connections show considerable sensitivity to the assumed boundary conditions and hydraulic properties of the fracture zones.

6.7 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 2005 as part of the joint projects with SKB and the multilateral projects at Äspö HRL. For example in the project Cleaning and Sealing of Investigation Boreholes the contribution of Posiva was mainly implemented on the Onkalo site. Posiva also participated in the Prototype Repository project.

6.7.1 Prototype Repository

The Posiva aims are to perform geochemical data-interpretation and modelling in collaboration with SKB. Data collection is the first step to geochemical understanding of the engineered barrier system. However, in order to understand the geochemical processes involved, the collected data needs to be evaluated and studied. The growing knowledge of geochemical processes is the gateway to more adaptive modelling attempts for the complete repository system.

A set of geochemical data was released at the end of 2005. However, certain technical difficulties have made the experiment more complex. There are problems with the electrically heated canisters of the experiment which cause problems in saturating the tunnel backfill material. As a result, the studied system appears heterogeneous in several respects. At the moment, the hydraulic flow through the system is an assortment of two-phase flow, where the proportion of gas phase varies.

Because of the complexities, the geochemical description and evaluation of the system is prioritised before any further detailed data-interpretation. Currently, the evaluation of the system and the description of possible processes is on-going. The aim is to find possibilities to utilise the geochemical data as correctly and effectively as possible.

6.7.2 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.

The experiment with parcel A2 was terminated in December 2005. The drilling, release and uptake of the parcel will take place in January 2006. During 2005 VTT has prepared air-tight transportation vessels for the bentonite samples to be studied in Finland. The vessels can be filled with nitrogen, in order to avoid oxygen contamination of the samples. Preparations have been done for on-line Eh and pH measurements in the bentonite and squeezing of the pore waters.

6.7.3 Cleaning and Sealing of Investigation Boreholes

Sealing of investigation boreholes has been studied in the joint project "Cleaning and Sealing of Investigation Boreholes" by SKB and Posiva. Phase 3 of the joint project started in 2005 and in this phase field studies of plugging of a deep borehole, OL-KR24 at Olkiluoto, was performed. The borehole is vertical (diameter 76 mm) and about 551 m deep. The borehole is situated inside the ventilation shaft profile. The upper part of the shaft is already excavated. The experiment was conducted from the platform constructed above the shaft.

The experiment included four main tasks:

1. Cleaning of the borehole.
2. Characterisation of the borehole.
3. Selective stabilisation of the borehole.
4. Emplacement of plugs.

Cleaning of the borehole included removal of all materials from the borehole, setting the casings in the borehole and flushing the borehole. The characterisation carried out in OL-KR24 included optical imaging, calliper-measurements and dummy-sonding. The selective stabilisation was done with local reaming and by filling the reamed section with cement-based material. Three potential borehole sections were located for stabilisation. After hardening time, the stabilised section was re-drilled.

Emplacement of plugs was carried out with a drill rig. Three types of plugs were used for sealing the hole:

- Clay plugs (jointed units of perforated copper tubes filled with highly compacted Na bentonite columns) that eliminate axial flow in the hole.
- Cement/quartz plugs (5 m) below and above the clay plug.
- Ordinary cement grout in the upper part of the hole.

The 10 m long clay plug was placed close to the bottom of the hole to allow sampling and lab testing of plug components from the shaft drift at –520 m level in a later stage when excavation of the ramp in Onkalo has been completed. The borehole KR24 was sealed in November 2005. The experiment will be reported in 2006.

6.7.4 KBS-3 Method with Horizontal Emplacement

In the KBS-3H project issues related to buffer experiments, groundwater control and design have in 2005 been performed within the second step of the Basic design study managed by SROY/Posiva. Posiva is also responsible for the sub-project KBS-3H Safety Case.

The focus in the Safety Case during 2005 has been on:

- Resolving and evaluation of critical issues identified for the evolution of the system, such as iron-bentonite interaction due to the steel components present.
- Compilation of a process report for KBS-3H.

- Compilation of a report on the evolution of the KBS-3H system after post-emplacement (emplacement of the first canister), including also an evaluation of the effects of potential deviations from the designed saturated state.
- Discrete Fracture Network (DFN) modelling in support of the KBS-3H process report and the evolution report.
- Setting up long-term Safety Case requirements and considerations for the KBS-3H buffer.

The overall goal is to perform a safety assessment of the KBS-3H concept, similar to the safety assessment of SR-Can, at the end of 2007 with Olkiluoto as a reference site.

The first step was to identify in what respect and how the behaviour in KBS -3H differs from KBS-3V, with vertical emplacement of the canisters. The comparison has been focussed on:

- Processes, which are fully identical in KBS-3H and KBS-3V.
- Processes, needing a slight effort to be modified from KBS-3V to KBS-3H.
- KBS-3H specific processes, for which the process description and treatment will be the main focus of the report.

An experimental study on the interaction between anaerobic corrosion of iron and bentonite has been performed in 2005 and will be finalised in early 2006. The consequences of the observations (reduction in cation exchange capacity and increase in hydraulic conductivity) will be evaluated after an overall mass balance modelling has been performed in spring 2006.

A first draft of the KBS-3H process report was available in the end of 2005. Issues discussed are e.g. redistribution of bentonite and possible impact on the saturated density of bentonite, along with the relevant time frame, such as:

- Redistribution of bentonite by displacement of distance blocks and Supercontainers.
- Redistribution of bentonite by piping/erosion.
- Redistribution of bentonite by erosion into fractures.
- Compaction of bentonite by formation of corrosion products.
- Impact of rock shear movements.

A draft report on the evolution of buffer until saturation and the overall long-term evolution of the system has been compiled. In addition to the description of the early evolution of the system, a number of the identified issues of importance for KBS-3H have been reported. The reported issues are; an evaluation of the effects of external loads on a KBS-3H repository including an evaluation of the possibility of damage of the canisters due to post-glacial faulting and the possibility of erosion of the buffer by flowing water following an increase in fracture transmissivity due to post-glacial earthquakes. The effects of potential deviations in the saturated state (e.g. variations in the bentonite density along the drift) on the long-term evolution of the disposal system and radionuclide release have also been studied. The process and evolution reports will be finalised in 2006.

A discrete fracture network (DFN) modelling study has been initiated to improve the understanding of the hydrodynamic evolution after waste emplacement. The report will be compiled in early 2006.

A technical note has been set up on the safety requirements and considerations for the buffer, which need to be considered both in the design and buffer studies as well as in the process and evolution reports. Considerations have been given to:

- Definition and purpose of the buffer with respect to long-term safety.
- Qualitative requirements on buffer properties.
- Quantitative requirements on buffer properties.
- Additional considerations to ensure that required properties will be achieved and maintained in the long-term.
- Additional requirements for the predictability of buffer performance.

A plan for the Safety Case reporting, SC-2007, will be set up in February 2006. The plan will include a description of necessary tasks still to be performed in order to fulfil the SC-2007 study and a listing of main reports to be included in the SC-2007.

The main activities of the second step in the Basic design study sub-project have been identified:

- Development of design basis.
- Development of reference bedrock model for design.
- Lay-out adaptation.
- Establishment of design parameters and resolving of the critical design issues.
- Design development (including the planning of tests to support the design).
- Groundwater control.
- Testing of most important design components at proper scales from laboratory up to full scale testing at Äspö in horizontal demonstration holes at –220 m level.
- Development of retrievability and delayed reversed operation.

Two design options are currently being developed in parallel: (a) Basic Design (BD) and (b) Drainage, Artificial Watering and air Evacuation (DAWE) design variant. The design work is based on a division of components, which have specific functions and requirements. Each component has a number of open design issues (e.g. the choice of whether or not to use bentonite pellets around the distance blocks in the case of BD and physical dimensions of some components). The objective is to reduce the number of open issues by evaluating the alternatives and to select the most appropriate.

A key consideration in the development of the present designs is to minimise the possibility of transient water flow (“piping”) along the interface between the distance blocks and the host rock. Piping can cause erosion and loss of bentonite mass (and thus inadequate density and swelling pressure) in some sections of a deposition hole and possibly an increase in mass in others. In the case of BD, piping and erosion are avoided essentially by avoiding emplacement in (and sealing off) sections intersected by more transmissive fractures that could generate high hydraulic pressure gradients sufficiently rapidly to give rise to piping and erosion. DAWE, on the other hand, uses artificial wetting to accelerate bentonite swelling and to seal the bentonite/host rock interface sufficiently tightly to prevent piping and erosion, before significant hydraulic pressure gradients develop.

The following critical design issues have been identified and should be resolved in order to produce proper designs:

- Humidity induced swelling of distance blocks.

- Erosion and transport of the buffer.
- Saturation and artificial wetting of distance blocks.
- Piping and sealing efficiency of distance blocks.
- Hydraulic pressure of distance blocks

There are also several parameters in the design, which may be regarded as critical issues and evidently may contain significant uncertainties and should be evaluated and confirmed. This is e.g. the length of distance blocks, the gap between distance blocks and the rock surface, salinity of groundwater, pressure increase rates and inflow rates. Solutions to evaluate the identified critical issues are being investigated and tested. It seems that the humidity induced swelling of distance block can be reduced by increasing the initial degree of saturation.

Two horizontal holes of diameter 1.85 m were bored at –220 m level at Äspö HRL to demonstrate the feasibility of horizontal blind boring. Posiva's representatives (from Saanio & Riekkola Oy) took part in the steering, follow-up, review and commenting of the work and related documents.

6.7.5 Large Scale Gas Injection Test

This project is jointly executed by SKB and Posiva and has a common steering group. The installation phase of the experiment was completed before the summer and the water saturation of the buffer was started thereafter.

Posiva's contribution to the project during 2005 has been in coordination and participation of following-up meetings as well as in quality assurance of project documentation.

6.7.6 Task Force on Engineered Barrier Systems

Äspö HRL International Join Committee has set up a Task Force on Engineered Barrier Systems (EBS) which objective is to develop effective tools for analysis of THM(C) behaviour of buffer and backfill. The objective of the year 2005 was to simulate the THM(C) behaviour of the EBS in the KBS-3V concept. The computer code FreeFEM++ was used in the simulations by Posiva.

The purpose of the work was to simulate two benchmark tests: (a) BMT 1.1 – THM mock-up experiments on MX-80 bentonite by CEA and (b) BMT 1.2 – the mock-up experiments on Febex bentonite by Ciemat.

BMT 1.1 consisted of two mock-up tests on vertical cylindrical samples of compacted bentonite. The tests were composed of two phases. In Phase 1 gradually increasing heat was applied to the bottom of the samples. The final temperature was 150°C. The top end was held at a temperature of 20°C. The Phase 2 started after thermal equilibrium was reached and involved gradual hydration of the sample by applying a constant water pressure of 1 MPa on the top end of the sample. The samples were held in constant volume.

BMT 1.2 also consisted of two mock-up tests but the samples were compacted Febex bentonite. One of the samples was held almost at room temperature and a constant water pressure of 1.2 MPa was applied on the top of it. In the other test the bottom of the sample was held at constant temperature of 100°C while the other end was cooled to a atmospheric temperature of 23°C. A constant water pressure of 1.2 MPa was applied at the cooled end.

Posiva's simulations of BMT 1.1 gave results, in accordance with measurements. However, there were some differences. Temperature of the hottest quarter in BMT 1.1 exceeded 100°C. Boiling water was visible in the measurement data when the moisture content was high (RH > 70%). When moisture content was lower, no signs of the boiling could be seen. However, the parameters used in this study were mostly determined at temperatures of 20°C to 80°C and this should affect the simulation results.

Leaking of the water through the instrument cables disturbed the measurements of Phase 2 in one of the cells. A comparison of them to simulations did therefore not give accurate information of the model performance.

In the model, suction was not used at all. It was calculated from the simulation results using retention curve. Sensors, which measure relative humidity, were not calibrated in bentonite but in free air, so it is possible that they did not behave according to retention curve measured with controlled ambient relative humidity. Therefore, the comparison of the simulation results and the measurements was difficult and sensitive to interpretation errors.

6.7.7 Äspö Pillar Stability Experiment

The large-scale pillar stability experiment called Apse (Äspö Pillar Stability Experiment) at Äspö HRL is focused on understanding and controlling the progressive rock failure in a pillar and damages caused by high stresses. The heating experiment including extensive monitoring took place in 2004. In 2005 data handling, interpretation of monitoring results and back calculations of temperatures have been performed. The pillar was also after the heating phase sawn out into pieces for further characterisation. It was estimated that the rock mass spalling strength is about 120 MPa, which is about 57% of the mean laboratory uniaxial compressive strength. This value is slightly above the onset of crack initiation (dilation) measured in laboratory samples.

Posiva's contribution in 2005 was to participate in the project follow-up and to comment on the project documentation. The work was carried out by Saanio & Riekkola Oy. The final project meeting was held in Äspö in June 2005 and the field work is now reported in final reports /Andersson and Eng 2005, Eng and Andersson 2004/.

6.7.8 True Block Scale Continuation

The True Block Scale Continuation project is an international project funded by Andra, Posiva, JNC and SKB. It is a continuation of the True Block Scale experiment and it utilises the same rock volume in Äspö HRL as its forerunner. 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 assessments.

During 2005, Posiva's group has evaluated and reported modelling of the BS2b tracer tests. Evaluation results indicate clear differences for the immobile zone retention properties of the two flow paths examined in the BS2b experiment. Results indicate that flow paths starting from the background fracture are characterised by the effective immobile zone properties of the background fractures, although the flow path may later go along larger structures.

Posiva's modelling group has also participated in the review meeting of the BS2b-experiment and in writing of the final report for the True Block Scale Continuation project.

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

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

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

During 2005, modelling of the sub-tasks 6E, 6F and 6F2 were finalised and a draft report of the sub-tasks 6D, 6E, 6F and 6F2 modelling was prepared. 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.

Sub-task 6F and 6F2 modelling indicates that the difference between fracture type features and more complex structures is basically the additional delay in breakthrough times for more complex features. This is caused by the larger volumes of high porosity immobile layers. Sub-task 6F2 modelling also shows that the coupling between the retention and flow field is very sensitive. For a system of two parallel fractures a difference in flow rates by a factor two leads to clear dominance of one of the flow paths in breakthrough curves.

6.8 Enresa

SKB and Empresa Nacional de Residuos Radioactivos, S.A. (Enresa) signed a project agreement in February 1997 covering the co-operation for technical work to be performed in the Äspö HRL. Both parties renewed the agreement in January, 2002. Due to the decision taken in the Spanish parliament in December 2004 to focus on a central interim storage of spent nuclear fuel before 2010, Enresa in 2004 chose not to renew this agreement and have now left the central and active core of participants.

Enresa is however still participating in the Temperature Buffer Test (TBT) in Äspö HRL and is co-ordinating the integrated EC project Esdred within the 6th Framework Programme. Some of the demonstration work of the integrated project Esdred is carried out in Äspö HRL.

6.9 Nagra

Nagra's agreement with SKB for participation in Äspö HRL (signed in 1994 and extended in 1998 to include mutual cooperation and participation in Äspö HRL and Grimsel Test Site projects for a period of five years) has expired. Discussions on its extension were initiated, with main focus on cooperation on the LOT experiment.

In 2005, Nagra joined the newly formed Task Force on Engineered Barrier System. In addition, Nagra is involved in other activities in Äspö HRL as part of 6th EU Framework Programme, namely Esdred and NF-Pro.

6.10 RAWRA

Radioactive Waste Repository Authority, RAWRA, was established in 1997. RAWRA's mission is to the ensure the safe disposal of existing and future radioactive waste in the Czech Republic and to guarantee fulfilment of the requirements for the protection of humans and the environment from the adverse impacts of such waste.

6.10.1 Task Force on Engineered Barrier Systems

The principal aims of the Czech Republic participation in the EBS project are to increase the understanding of gas and water transport in the engineered barrier system.

Commercial and/or special calculation tools have been prepared to evaluate selected THMC processes affecting the safety of a geological repository. Internally developed codes based on numerical methods have been used for the benchmark test 1.2 in Task 1 (THM processes in buffer materials). Currently used models are capable of describing e.g. heat and moisture transfer, heat conduction, vapour diffusion, absorbed water, latent heat and moisture redistribution. Cylindrical arrangement has been used to describe isothermal hydration, dry thermal gradient and thermal gradient dependent on hydration. The results showed sensitivity to constitutive relations, i.e. measurement versus simplified model and comparison of linear and non-linear model. Considering these conclusions, it is recommended to involve variable saturation conditions, mixing hot/cold water, gravity influence and horizontal heterogeneity. Alternative constitutive relations and numerical algorithms are currently compared to parallel codes developed by other institutions.

Two numerical models capable of predicting generation of hydrogen from anaerobic corrosion of carbon steel canisters and its transport through a layer of compacted bentonite are under preparation in the environment of the GoldSim Transport Code. The first one is aimed at the prediction of the impact of hydrogen from the carbon steel canisters surrounded by bentonite bricks in a granite host rock and the second one is focused on modelling the experimental results specified in the Benchmark 2.1 and 2.2 for Task 2 (Gas migration in buffer materials). The preliminary results of the first model suggest that under favourable conditions the diffusion of hydrogen in aqueous phase is sufficient for transport hydrogen away from the surface of canisters without exceeding surrounding hydrostatic pressure and bentonite swelling pressure. Advection driven transport has to be studied as an optional mechanism. Experimental equipment for studying generation of hydrogen from anaerobic corrosion of carbon steels and its transport through compacted bentonite is under development.

6.11 IAEA framework

SKB also takes part in work within the IAEA framework. Äspö HRL is part of the IAEA Network of Centres of Excellence for training in and demonstration of waste disposal technologies in underground research facilities.

7 Environmental research

7.1 General

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

7.2 Äspö Research School

7.2.1 Background and objectives

Kalmar University's Research School in Environmental Science at Äspö HRL, called Äspö Research School, 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.

7.2.2 Results

The research activities 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 the 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 during 2005 resulted in several scientific publications. In the Äspö HRL, however, the activities are as yet minor. In accordance with the agreement, the Äspö Research School was during autumn evaluated and the internal evaluation report was published in November.

The first Ph.D. dissertation took place in January 2005 after which the Ph.D. in June was appointed research assistant at the Äspö Research School. The research assistant works within several research projects and as assistant supervisor with special competence in urban geochemistry. In May 2005 a Ph.D. student was appointed focusing on hydrochemistry whereas in September another Ph.D. student requested study intermission. By the end of 2005, the scientific team consisted of a professor of Environmental geology, a research assistant, four assistant supervisors and five Ph.D. students.

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Technical documents

9 technical documents were produced during 2005.

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