Technical Report

TR-04-10

Äspö Hard Rock Laboratory

Annual Report 2003

Svensk Kärnbränslehantering AB

September 2004

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Abstract

The Äspö Hard Rock Laboratory (HRL) constitutes an important part of SKB's work to design and construct a deep geological repository for spent nuclear fuel and to develop and test methods for characterisation of a suitable site for a deep repository. One of the fundamental reasons behind SKB's decision to construct an underground laboratory was to create an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to repository depth. Äspö HRL has been in operation since 1995 and the associated research, development, and demonstration tasks, which are managed by the Repository Technology Unit within SKB, have so far attracted considerable international interest. A summary of work performed at Äspö HRL during 2003 is given below.

Technology

One of the goals for Äspö HRL is to demonstrate technology for and function of important parts of a deep repository. This implies translation of current scientific knowledge and state-of-the-art technology into engineering practice applicable in a real repository. It is important that development, testing and demonstration of methods and procedures, as well as testing and demonstration of repository system performance, are conducted under realistic conditions and at appropriate scale. A number of large-scale field experiments and supporting activities are therefore conducted at Äspö HRL.

The *Canister Retrieval Test*, located in the main test area at the –420 m level, is aiming at demonstrating the readiness for recovering of emplaced canisters also after the time when the bentonite is fully saturated. Bentonite blocks, bentonite pellets, and canisters with heaters have been installed in one vertically bored hole in full repository scale. The test has been running for a little more than three years and the bentonite in the cylinder along the canister is now saturated. The artificial water supply will continue during 2004 until the bentonite below and above the canister also reaches saturation. Wetting, temperature, tension and swelling has been measured and registered during the whole time. The actual retrieval test is scheduled for 2006.

The *Prototype Repository* is a demonstration of the integrated function of the repository barriers and provides a full-scale reference for test of predictive models concerning individual components as well as the complete repository system. It is also 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 inner section was installed and the plug cast in 2001. During 2003, the two canisters in the outer section were installed, the heaters were turned on, and the tunnel was backfilled and plugged. The instrument readings have started also in the outer section and will continue. Modelling teams have conducted predictive modelling and compared measured data and predictions.

The *Backfill and Plug Test* is a test of the evolution of the hydraulic and mechanical function of different backfill materials. It is also a demonstration of backfill emplacement methods and installation of a full-scale plug. The 28 m long test region is located in the Zedex tunnel. The inner part of the tunnel is backfilled with a mixture of bentonite and crushed rock and the outer part is filled with crushed rock. Wetting of the backfills from the rock and filter mats supplying artificial water have continued during the years 2000 to 2003

and data from transducers has been collected and reported. Flow testing in the backfills started during the autumn 2003, when the backfills were water saturated, and will continue until 2004 or 2005. Supplementary modelling will complement the flow testing and data collection.

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 meters. The parcels are left in the boreholes during one or five years and thereafter the parcels are extracted and the water distribution in the bentonite clay is determined and subsequent well-defined chemical and mineralogical analyses as well as physical tests are performed. Three parcels have been extracted and examined. The results from two of the parcels have been published whereas the report concerning the third parcel is in progress. The remaining four parcels have been functioning well during 2003 and water pressure, total pressure, temperature, and moisture content are continuously measured.

In the project *Cleaning and sealing of investigation boreholes* the best available techniques for this are to be identified and demonstrated. Surface based investigation boreholes are drilled during site investigations in order to obtain data on the properties of the rock. Tunnel based boreholes are drilled during repository construction work meaning that also horizontal and upward directed investigation holes are drilled. These boreholes must be cleaned and sealed, no later than at the closure of the deep repository. Cleaning of the boreholes means that instrumentation is removed. Sealing of the boreholes means that the conductivity in the borehole is no higher than that of the surrounding rock. In the first Phase of the project a state-of-the-art report summarising the developments of the techniques during the last 10–15 years was prepared. In November 2003 the decision was taken to continue with a second Phase. This Phase comprises the definition of a basic concept for cleaning and sealing of boreholes, laboratory studies on candidate sealing material, as well as characterisation and preparation of boreholes to be used in a field-tests with the aim to demonstrate and test different sealing techniques.

Using cementitious products in the repository may involve the use of low-pH products in order to get leachates with sufficiently low pH (≤ 11). A pre-study concerning this issue was carried out in 2001, followed by a feasibility study in 2002 – mid 2003. In the feasibility study a specific need for development of injection grouts both for larger and smaller fractures as well as testing them in field tests was identified. In June 2003 a joint project *Injection grout for deep repositories* between Posiva, SKB and NUMO was initiated. The project is divided into four sub projects: 1) Low-pH cementitious injection grout for larger fractures, 2) Non-cementitious low-pH injection grout for smaller fractures, 3) Field testing in Finland, and 4) Field testing in Sweden. The sub-project connected to Äspö HRL consists of field tests with silica sol, a gel of silica colloids in water. The sub-project start was December 2003 and the grouting is planned to be carried out during 2004.

Late 2001 SKB published an RD&D programme for the KBS-3 *method with horizontal emplacement* (KBS-3H). The programme, which is carried through by SKB and Posiva in co-operation, was divided into four phase: 1) Feasibility study, 2) Basic design, 3) Construction and testing at the Äspö HRL, and 4) Evaluation. The Feasibility study suggested in 2003 that the KBS-3H method is worth further development work, and the Basic design phase started with the technical development of the KBS-3H, preparations for a future demonstration of the method at Äspö HRL, and studies of the barrier performance.

During 2003 preparations for full scale demonstration at Äspö HRL was initiated, comprising preparation of a test niche at –220 m level, boring and characterisation of three exploratory boreholes. In addition, detailed design and manufacturing of deposition equipment and analyses of buffer and long-term safety issues have been made.

The aim of the *Large Scale Gas Injection Test* is to study gastransport in a full-scale KBS-3 deposition hole. The current understanding of the gas transport process through compacted bentonite indicates that the buffer would open for gas passage before any harmful pressures are reached. However, there are still large uncertainties around the gas migration process which have to be studied in large-scale experiments. The experiments will be performed in a bored full-size deposition hole with a full-scale canister without heaters, and a surrounding bentonite buffer. Water will be artificially supplied and the gas injection tests start when the buffer is fully saturated, which is expected to take two years. Planning of and preparations for the installation of the test were made during 2003. The artificial saturation of the buffer will start when the installation phase including testing of the gas injection system and other equipment is completed.

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, in order to be able to model this behaviour. The French organisation Andra is running this test in Äspö HRL in co-operation with SKB. Two heater probes are installed in one deposition hole in the same test area as the Canister Retrieval Test. One of the probes is surrounded by an ordinary bentonite buffer and the other has a ring of sand 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 and will continue during 2004. Monitoring and sampling of experimental data are continuously ongoing and a data link to Andra's head office in France has been established.

Geo-science

Geo-scientific research is a basic activity at Äspö HRL. Studies are ongoing with the major aims to increase the understanding of the rock mass properties and to increase the knowledge of methods that can be used in site investigations.

Rock stress measurements with different measuring techniques have during the years been performed as well as numerical modelling of the stress. To be able to make correct assessments of the *in situ* stress field from results from different types of measurements it is important to know the limitations and shortcomings of the different techniques. A co-operation with Posiva with the objective to quality-assure overcoring data has been initiated. The first phase has been completed which includes development of a numerical tool for isotropic and elastic conditions.

The objective with the *Rock Creep Project* is to develop better conceptual models for the evaluation of the influences of the rock damaged zone and rock creep on rock stability. A literature study and scooping numerical modelling with a three-dimensional coupled hydromechanical computer code (3DEC) have been performed during 2003. The literature study is under review and reporting of results from the modelling is in progress.

Äspö *Pillar Stability Experiment* was initiated to demonstrate the capability to predict spalling in a fractured rock mass and to demonstrate the effect of backfill (confining pressure) on the propagation of micro-cracks in the rock mass closest to the deposition hole. During 2003, a new tunnel was excavated to ensure that the experiment is carried out in a rock mass with a virgin stress field. The pillar between the holes is designed in such a way that spalling will occur when the pillar is heated. One of the two vertical holes that will be drilled for the experiment was completed in 2003 and the second one will be drilled next year. Geological characterisation of the tunnel and the deposition hole has been made and been used for the final update of the numerical models for the experiment. The heating of the pillar is planned to take place during 2004.

The project on *Heat transport* aims at decrease the uncertainties in the estimates of the temperature field in the repository. Less uncertain estimates of the temperature field around a repository makes it possible to optimise the distance between canisters in the repository layout. Three reports dealing with heat transport have been completed during 2003.

Natural barriers

In Äspö HRL experiments are performed at conditions that are expected to prevail at repository depth. The experiments are related to the rock, its properties, and *in situ* environmental conditions. The goals are to increase the scientific knowledge of the safety margins of the deep repository and to provide data for performance and safety assessment and thereby clearly present the role of the geosphere for the barrier functions: isolation, retardation and dilution. Tests of models for groundwater flow, radionuclide migration and chemical/biological processes are one of the main purposes of the Äspö HRL. The programme includes projects with the aim to evaluate the usefulness and reliability of different models and to develop and test methods for determination of parameters required as input to conceptual and numerical models.

A programme has been defined for tracer tests at different experimental scales, the so-called *Tracer Retention Understanding Experiments* (True). The overall objectives of the experiments are to increase the understanding of the processes which govern retention of radionuclides transported in crystalline rock, and to increase the credibility in models used for radionuclide transport calculations. During 2003, work has been performed within two projects; True Block Scale Continuation and True-1 Continuation. The objectives of the True Block Scale Continuation project are to improve the understanding of transport pathways at the block scale, including assessment of effects of geometry, macro-structure, and micro-structure. The passed year has been one of a multitude of activities. For example, modelling that pinpointed the area of interest for the subsequent *in situ* tests. This was followed by optimisation of the piezometer array and a sequence of pre-tests to test out the potential for tests with radioactive sorbing tracers as part of next phase. In the True-1 continuation project complementary cross-hole hydraulic interference tests combined with tracer dilution tests are planned. These tests are intended to shed light on the possible three-dimensional aspects of transport at the site. Principal activities during the year have been associated with preparatory characterisation work leading up to injection of epoxy resin in selected structures along the Äspö access tunnel. In addition, a comprehensive laboratory study on sorption characteristics of fracture rim zone and fault gouge material has been launched.

The *Long Term Diffusion Experiment* constitutes a complement to performed diffusion and sorption experiments in the laboratory, and is a natural extension of the experiments conducted as part of True. The difference is that the longer duration (approximately four years) of the experiment is expected to enable an improved understanding of diffusion and sorption in the vicinity of a natural fracture surface. The experiment will be performed in a core stub with a natural fracture surface isolated in the bottom of a large diameter telescoped borehole. The experimental set-up has been installed and during 2003 the installation-test and pre-test programmes were initiated which will be completed in 2004. The experimental set-up will be documented and failure mode effect analyses are planned to be carried out before the injection of radioactive tracers commence.

Radionuclide Retention Experiments are carried out with the aim to confirm result from laboratory experiments *in situ*, where conditions representative for the properties of groundwater at repository depth prevail. The experiments are carried out in special probes, Chemlab 1 and Chemlab 2, placed in boreholes in the rock. Radiolysis experiments, intended to investigate the influence of radiolysis on the migration of oxidised technetium, have been performed with the Chemlab 1 probe. The field experiment is finished, the collected data has been evaluated, and the final report is in progress. Migration of actinides in a natural rock fracture in a drill core is studied in the Chemlab 2 probe. The third actinide experiment was started at the end of 2002, but was expired due to several technical problems. The expired experiment provided, however, a few water samples that have been analysed and evaluated. The last field experiment will be initiated in 2004. This experiment will be performed similarly as previous ones and the radionuclides to be studied this time are uranium and technetium.

The *Colloid Project* comprises studies of the stability and mobility of colloids, measurements of the colloid concentration in the groundwater at Äspö, bentonite clay as a source for colloid generation, and the potential of colloids to enhance radionuclide transport. Borehole specific measurements, to determine the colloid generation properties of clay in contact with groundwater, were carried out during the first half of the year 2003. The compilation of the final report including these experiments as well as earlier performed laboratory experiments and background measurements are in progress. The initiation and planning of dipole colloid experiments started in August 2003. In the experiments the change in colloid content in the groundwater prior and after its transport through a natural fracture will be studied.

Microorganisms interact with their surroundings and in some cases they greatly modify the characteristics of their environment. Several such interactions may have a significant influence on the function of a future deep repository for spent fuel. There are presently four specific microbial process areas identified that are of importance for proper repository functions and that are studied in the *Microbe Project*. The process areas are: bio-mobilisation of radionuclides, bio-immobilisation of radionuclides, microbial effects on the chemical stability, and microbial corrosion of copper. The limitations of laboratory experiments have resulted in the construction and set-up of microbial investigations in the Äspö HRL tunnel. The main site is the Microbe laboratory at the –450 m level, but one more site (Bios) along the tunnel at 2,200 m tunnel length has been in use during 2003. Studies of bio-immobilisation of radionuclides on biological iron oxide systems are studied at the Bios site. At the main site, immobilisation of radionuclides on biofilms with circulating groundwater from a drilled borehole is under investigation. In two artificial channels at the Bios site the retention of naturally occurring trace elements in the groundwater by the Bios was investigated during 2003. Efforts have also been spent in the development of gas chromatography technology suitable for underground research. The gas composition in groundwater samples taken from the tunnel, in boreholes or directly from the circulations can now be immediately analysed in the Microbe laboratory. During spring 2003 the *in situ* copper corrosion experiments were decommissioned and analysed, and the results will be published.

The main objectives of the first phase of the *Matrix Fluid Chemistry* experiment were to understand the origin and age of matrix fluids, i.e. accessible pore water, in fissures and small-scale fractures and their possible influence on fluid chemistry in the bedrock. This phase of the project comprised a feasibility study carried out on drill core material, leaching and permeability experiments including crush/leach experiments, and a full-scale programme designed to sample and analyse matrix fluids from isolated borehole sections. The first phase of the Matrix Fluid Chemistry experiment, which was completed in 2003, increased the knowledge of matrix pore space fluids/groundwaters from crystalline rocks of low hydraulic conductivity, and this complemented the hydrogeochemical studies already conducted at Äspö. A second phase will commence in 2004 which focuses on the small-scale micro-fractures in the rock matrix, which facilitate the migration of matrix waters.

An important goal for the activities at Äspö HRL includes projects with the aim to evaluate the usefulness and reliability of different models and to develop and test methods for determination of parameters required as input to the models. An important part of this work is performed in the *Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes*. The work in the Task Force is closely tied to ongoing and planned experiments at the Äspö HRL. Specified tasks are defined where several modelling groups work on the same set of field data. The modelling results are then compared to the experimental outcome and evaluated by the Task Force delegates. The reporting of Task 5 was almost finalised in 2003 and the currently active task is performance assessment modelling using site characterisation data (Task 6). An external review process for Task 6 was initiated in 2003. The 17th International Task Force meeting was held in March in Thun, Switzerland. A workshop was held regarding Task 6 at Krägga Mansion in September 2003. At the workshop, the obtained results for the modelling sub-tasks were discussed, as well as the continuation of Task 6.

Padamot (Palaeohydrogeological Data Analysis and Model Testing) is an EC project that includes developments of analytical techniques and modelling tools to interpret data, but also focusing research to investigate specific processes that might link climate and groundwater in low permeability rocks. The term palaeohydrogeology is used as a common name for information from fracture minerals that is used for interpretations of past hydro-geochemical and hydrogeological systems. The EC project was initiated in the beginning of 2002 and is running to the end of 2004. The work on Swedish drill core material has continued during 2003 with sample preparation and analyses of calcite samples. The results form the second year of the Padamot project confirms largely the earlier given palaeohydro-geological interpretations and have provided extended confidence in the recognition of low temperature calcites by the use of several different methods.

Äspö facility

An important part of the activities at the Äspö facility is the administration, operation, and maintenance of instruments as well as development of investigation methods. The main goal for the operation is to provide a safe and environmentally correct facility for everybody working or visiting the Äspö HRL. This includes preventative and remedy maintenance in order to withhold high availability in all systems as drainage, electrical power, ventilation, alarm, and communications in the underground laboratory. During 2003 the operation of the facility has worked smoothly and the availability of service in the facility and the under-ground-related systems has been more than 98%. The rock and reinforcement programme has continued and work on increased fire safety underground has included an extension of the water distribution system. 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 measuring system has been working satisfactorily. However, in connection with the rocks works during the summer 2003 data from some measuring points in the tunnel were lost for one month. The annual water sampling campaign took place in September.

International co-operation

Seven organisations from six countries participated in the co-operation at Äspö HRL during 2003 in addition to SKB. Most of the organisations are interested in groundwater flow, radionuclide transport and rock characterisation. Several of the organisations are participating in the experimental work as well as in the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes.

SKB is through Repository Technology co-ordinating three EC contracts and takes part in several EC projects of which the representation in five projects is channelled through Repository Technology. SKB takes also part in work within the IAEA framework.

Environmental research

Äspö Environmental Research Foundation was founded 1996 on initiative of local and regional interested parties. The aim was to make the underground laboratory at Äspö and its resources available for national and international environmental research. SKB's economic engagement in the foundation was ended in 2003, and the activities are now instead concentrated on the Äspö Research School, which was founded in 2002. The objective is to provide conditions for today's and tomorrow's research concerning environmental issues at the school. During 2003 detailed plans for the activities were worked out. One professor – in Environmental Geology – has been employed and three PhD students begun their work during the fall. The research is carried out both in the Äspö HRL and in nearby surface environments. As far as projects in the Äspö HRL are concerned, these have just started and no results are thus as yet available.

Sammanfattning

Äspölaboratoriet är en viktig del i SKB:s arbete med utformning, byggande och drift av ett djupförvar för använt kärnbränsle samt för utveckling och testning av metoder för karakterisering av en lämplig plats för ett djupförvar. Ett av de grundläggande skälen till SKB:s beslut att anlägga ett underjordslaboratorium var att skapa förutsättningar för forskning, utveckling och demonstration i en realistisk och ostörd bergmiljö på förvarsdjup. Underjordslaboratoriet och forskningscentret på Äspö har varit i drift sedan 1995. Äspölaboratoriet och verksamheten där, vilka leds av avdelningen Förvarsteknik inom SKB, har hittills väckt stort internationellt intresse. En sammanfattning av det arbete som bedrivits vi Äspölaboratoriet under 2003 ges nedan.

Förvarsteknik

Ett av syftena med Äspölaboratoriet är att demonstrera teknologin för och funktionen hos djupförvarets olika delar. Detta innebär att omsätta dagens vetenskapliga och teknologiska kunskaper praktiskt genom att utveckla, testa och demonstrera de metoder och tillvägagångssätt som kommer att användas vid uppförandet av ett djupförvar under realistiska förhållanden. Det innebär också att möjlighet ges att testa och demonstrera hur förvarets delar kommer att utvecklas. Ett flertal projekt i full skala, liksom stödjande aktiviteter, pågår därför vid Äspölaboratoriet.

Återtagsförsöket, som ligger i försöksområdet på 420 meters djup, syftar till att prova teknik för att återta kapslar efter det att den omgivande bentonitbufferten har vattenmättats. En fullstor kapsel med elektriska värmare omgiven av bentonitblock och bentonitpellets har installerats i ett vertikalt deponeringshål. Försöket har varit i drift i lite mer än tre år och bentonitblocken som omger själva kapselröret är nu vattenmättade. Den konstgjorda bevätningen av bentoniten kommer att fortsätta under 2004 tills dess att även bentonitblocken under och över kapseln blir vattenmättade. Bevätningsgrad, temperatur, spänning och svällning har mätts och registrerats fortlöpande under hela försöket. Återtaget av kapseln beräknas äga rum under 2006.

Prototypförvaret är en demonstration av den integrerade funktionen hos djupförvarets barriärer och utgör dessutom en fullskalig referens för prediktiv modellering av utvecklingen av förvarets olika delar och hela förvarssystemet. Prototypförvaret är också en demonstration av tillgänglig teknik för inplaceringen av buffert, kapsel, återfyllning samt förslutning av en deponeringstunnel i full skala. Hela Prototypförvaret omfattar 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 och pluggen mellan de två sektionerna installerades under år 2001. De två kapslarna i den yttre sektionen installerades under 2003. Den yttre sektionen återfylldes och förslöts med en plugg samt värmarna i kapslarna slogs på. Mätning och registrering har startat också i den yttre sektionen och kommer att fortgå. Projektets modelleringsgrupper har gjort prediktiv modellering och jämfört sina resultat med uppmätta data.

I *Återfyllnads- och pluggningsförsöket* undersöker man den hydrauliska och mekaniska utvecklingen hos olika återfyllnadsmaterial. Försöket är också en demonstration av olika metoder för inplacering av återfyllnaderna och installation av en tunnelförslutning. Den 28 m långa testsektionen ligger i Zedextunneln. Den innersta sektionen är återfylld med en blandning av krossat berg och bentonit medan den yttre sektionen är återfylld med krossat berg. Under perioden 2000 till 2003 har bevätningen av återfyllnaden skett naturligt från berget och konstgjort via permeabla mattor. Under hela perioden har utvecklingen i återfyllnaderna registrerats och rapporterats. Under hösten 2003, när återfyllnaderna var vattenmättade, startades flödestesterna vilka kommer att fortsätta under 2004 och 2005. Flödestesterna kompletteras med modellering.

I *Lotförsöket* (Long Term Tests of Buffer Material) genomförs långtidsförsök av buffertmaterial som syftar till att validera modeller och hypoteser relaterade till buffertens fysikaliska egenskaper samt processer relaterade till mikrobiologi, radionuklidtransport, kopparkorrosion och gastransport i ett KBS-3 förvar. Lotförsöket innebär att paket som innehåller ett kopparrör med elektriskvärmare, kompakterad bentonit, instrumentering och kontrollutrustning placeras i 4 m djupa borrhåll med en diameter på 300 mm. Paketen ligger i borrhålen under ett eller fem år och därefter tas de upp och vattenmättnaden i bentonitleran bestäms, kemiska och mineralogiska analyser genomförs och fysikaliska tester utförs. Tre paket har tagits upp och undersökts. Resultaten från två av paketen har publicerats och rapporteringen för det tredje paketet pågår. De återstående fyra paketen har fungerat bra och vattentryck, total tryck, temperatur och fuktinnehåll mäts kontinuerligt.

I projektet för *rensning och förslutning av undersökningsborrhål* ska bästa möjliga tillgängliga teknik för detta identifieras och demonstreras. Undersökningshål borras från markytan under platsundersökningar för att data om berget ska kunna samlas in. Under byggskedet kommer horisontella eller uppåtriktade undersökningshål att borras från tunnlar i berget. Undersökningshålen måste rensas och förslutas senast vid tiden för förslutningen av djupförvaret. Rensning av borrhålen innebär att de instrument som suttit i borrhålen avlägsnas. Därefter försluts borrhålen vilket innebär att konduktiviteten i hålen inte får vara högre än den i det omgivande berget. Under projektets första fas har en statusrapport som sammanfattar teknikutvecklingen inom område under de senaste 10–15 åren sammanställts. I november 2003 fattades ett beslut att fortsätta med en andra fas. Denna fas innebär att referenskoncept för så väl rensning som förslutning av undersökningshål ska definieras, laboratoriestudier av kandidatmaterial för förslutningen ska genomföras, och befintliga borrhål ska karakteriseras och förberedas så att en demonstration ska kunna genomföras i fält.

Användning av cementprodukter i djupförvaret kan komma att innebära att produkter som ger lakvatten med tillräckligt låg pH (≤ 11) ska väljas. Två studier, avseende denna fråga, genomfördes under 2001 respektive 2002–2003. I den senare studien identifierades ett behov av att utveckla och prova injekteringsmaterial med lågt pH för tätning av både större och mindre sprickor i berget. I juni 2003 initierade SKB, Posiva och NUMO ett samarbetsprojekt med syfte att utveckla *injekteringsmaterial för användning i djupförvar*. Projektet består av fyra delprojekt: 1) cementbaserade injekteringsmaterial med lågt pH för tätning av större sprickor, 2) icke cementbaserade injekteringsmaterial med lågt pH för tätning av mindre sprickor, 3) fältförsök i Finland och 4) fältförsök i Sverige. Delprojektet – fältförsök i Sverige – innebär att Silicasol, en vattengel av kiselkolloider, kommer att injekteras i berget vid Äspölaboratoriet. Delprojektet startade i december 2003 och injekteringen planeras äga rum under 2004.

Under 2001 publicerade SKB ett forsknings-, utvecklings- och demonstrationsprogram för ett *KBS-3-förvar med horisontell deponering* (KBS-3H). Programmet, som genomförs som ett samarbetsprojekt mellan SKB och Posiva, är indelat i fyra delar: 1) förstudie av genomförbarheten, 2) konceptuell utformning, 3) tillverkning av utrustning samt demonstration vid Äspölaboratoriet och 4) utvärdering. I förstudien drogs slutsatsen att KBS-3H bör utvecklas vidare. Arbete i projektets tredje fas omfattar teknisk utveckling, förberedelser för en framtida demonstration vid Äspölaboratoriet och studier av barriärernas utveckling. Under 2003 påbörjades förberedelserna för demonstrationen i Äspölaboratoriet. Dessa har inneburit att en nisch på 220 meters djup har tillretts och tre undersökningsborrhål har borrats och karakteriserats. Dessutom har utredningar om bufferten och andra frågeställningar om långsiktigsäkerhet genomförts.

Syftet med ett *gasinjekterinsförsök i stor skala* (Large Scale Gas Injection Test) är att studera gastransport i ett fullstort deponeringshål (KBS-3). Nuvarande kunskap om gastransportprocessen visar på 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 storskaliga försök. Experimentet kommer att genomföras i ett fullstort deponeringshål med en kapsel utan värmare, och en omgivande bentonitbuffert. Bufferten väts på konstgjord väg och injektering av gas kommer att påbörjas när bufferten är vattenmättad, vilket beräknas ta cirka två år. Planering av och förberedelser för experimentet genomfördes under 2003. Bevätningen kommer att påbörjas när installationen, inklusive tester av systemet för gasinjektering och annan utrustning, är avslutad.

Syftet med *TBT-försöket* (Temperature Buffer Test) är att förbättra nuvarande förståelse av buffertens temiska-hydrologiska-mekaniska utveckling under vattenmättnadsfasen vid temperaturer runt eller högre än 100°C. En förbättrad förståelse innebär bland annat att buffertens utveckling under sådana förhållanden ska kunna modelleras. Den franska organisationen Andra ansvarar för experimentet vid Äspölaboratoriet vilket genomförs i samarbete med SKB. Två värmare har installerats i ett deponeringshål beläget bredvid återtagsförsöket. Den ena av värmarna är omgiven av en bentonitbuffert medan den andra är omgiven av en buffert bestående av sand närmast värmaren och bentonit utanför sanden. Sanden är tänkt att fungera som ett termisktskydd mellan värmaren och bentoniten. Experimentet kunde påbörjas i mars 2003 med uppvärmning och konstgjord bevätning av bufferten under tryck samt övervakning och mätning av temperatur, fuktighet, tryck och rörelser. Driftfasen beräknas pågå under hela 2004. Övervakningen och insamlingen av data sker kontinuerligt och data överförs direkt till Andras huvudkontor i Frankrike.

Geovetenskap

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

Mätning av bergspänningar har under årens lopp genomförts i fält med hjälp av olika mättekniker och bergspänningar har simulerats med numeriska modeller. För att kunna utvärdera fältmätningarna är det viktigt att ha god kunskap om de olika mätteknikernas begränsningar och brister. Ett samarbete har inletts mellan SKB och Posiva för att kvalitetssäkra data från en av mätteknikerna – överborrning. Första fasen, vilken omfattade utveckling av numeriska verktyg för isotropiska och elastiska förhållanden, har avslutats.

Målet med projektet om *krypрörelser i berget* (Rock Creep Project) är att utveckla en bättre konceptuell modell för utvärderingen av de effekter den störda zonen och bergkryp har på bergstabiliteten. En litteraturstudie och inledande modellering med en tredimensionell kopplad hydromekanisk datorkod (3DEC) har genomförts under 2003. En granskning av litteraturstudien pågår liksom rapporteringen av resultaten från modelleringen.

Syftet med *Pelarförsöket* (Aspo Pillar Stability Experimet) är att demonstrera möjligheterna att förutsäga spänningsinducerade bergbrott runt deponeringshål i sprickigt berg. Man vill även studera effekten av mottryck från återfyllnad på utbredningen av mikrosprickor närmast deponeringshålet. Under 2003 har en ny tunnel sprängts, för att säkerställa att experimentet genomförs i berg med jungfruliga spänningsfält. Pelaren mellan två deponeringshål har utformats så att spänningsinducerade bergbrott förväntas äga rum när pelaren värms upp. Ett av deponeringshålen borrades under 2003 medan det andra hålet kommer att borras under 2004. Den nya tunneln och deponeringshålet har karakteriserats geologiskt och informationen används för att uppdatera de numeriska simuleringarna av experimentet. Uppvärmningen av pelaren kommer att ske under 2004.

Projektet *värmetransport* i berg syftar till att minska osäkerheterna i de uppskattningar av temperaturfältet runt ett djupförvar som görs. Kan dessa osäkerheter reduceras innebär det att avstånden mellan kapselpositioner kan optimeras. Tre rapporter som behandlar värmetransport har färdigställts under 2003.

Naturliga barriärer

I Äspölaboratoriet genomförs experimenten vid förhållanden som likar de som förväntas i ett djupförvar. Experimenten kopplar till berget, dess egenskaper och *in situ* förhållanden. Målen med de pågående experimenten är att öka den vetenskapliga kunskapen om säkerhetsmarginalerna i djupförvaret och att ta fram data för funktions- och säkerhetsutvärderingar och därigenom tydligt förklara geosfärens roll 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 experimentskalor i *True-försöken*. Syftet är att öka förståelsen för de processer som styr fördröjningen av radionuklider i granitiskt berg samt att öka tillförlitligheten hos de modeller som används för beräkning av radionuklidtransport. Under 2003 har arbete bedrivits inom två delprojekt: ”True Block Scale Continuation” och ”True-1 Continuation”. Målet med ”True Block Scale Continuation” är att öka kunskapen of transportvägar i blockskala i berget med avseende på bland annat betydelsen av geometri, macro- respektive mikrostrukturer. Under det senaste året har ett flertal aktiviteter pågått, till exempel modellering för att välja ett område för kommande fältförsök. Därefter gjordes en optimering av placeringen av mätsonder (pietsometrar) och ett antal förtester genomfördes inför de planerade försöken med radioaktiva spårämnen i projektets nästa fas. I ”True-1 Continuation” planeras kompletterande hydrauliska interferenstester mellan två borrhål vilka kombineras med spårämnesutspädningsförsök. Dessa tester ska belysa den tredimensionella transporten av spåämnen på platsen. De huvudsakliga aktiviteterna det senaste året har varit förberedande karakterisering som resulterat i att en utvald struktur längs Äspötunneln har injicerats med epoxyharts. Dessutom har laboratorieförsök genomförts där sorptionsegenskaperna hos sprickfyllnadsmaterial och sprickytor har studerats.

LTDE-försöken (Long Term Diffusion Experiment) är ett komplement till de sorptions- och spårämnesförsök som genomförts i laboratoriet, det är också en utvidgning av de experiment som genomförts inom True-programmet. Experimentet pågår under längre tid (omkring 4 år) och förväntas därför ge en förbättrad förståelse av diffusion och sorption på och i närheten av naturliga sprickytor. Experimentet genomförs i en borrhålskärna i botten av ett teleskopformat borrhål. Under 2003 har utrustningen installerats i hålet och både installationstester och förförsök har kunnat genomföras. Innan huvudförsöket som omfattar injicering av radioaktiva spårämnen startar kommer utrustningen att dokumenteras och en risk- och sårbarhetsanalys att genomföras.

Fördröjning av radionuklider studeras i *RNR-försöket* (Radionuclide Retention Experiments). Syftet med experimenten är att bekräfta resultat från tidigare laboratorie-experiment som genomförts vid förhållanden som liknar de som råder på förvarsdjup. Experimenten genomförs i två specialutvecklade borrhålsutrusningar, Chemlab 1 och Chemlab 2. För att studera hur radiolysprodukter påverkar rörligheten hos teknetium i bentonit har två olika typer av experiment genomförts i Chemlab 1. Dessa experiment har nu avslutats, insamlade data har analyserats och rapporteringen pågår. Migration av aktinider i naturliga sprickor i borrkärnor studeras i Chemlab 2. Det tredje aktinidförsöket startades i slutet av 2002 och men avbröts under 2003 på grund av tekniska problem med borrhålsutrustningen. Några vattenprov samlades dock in innan försöket avbröts, dessa har analyserats och utvärderats. Ett sista fältexperiment planeras vilket ska påbörjas under 2004. Detta experiment kommer att genomföras på samma sätt som de tidigare och de spårämnen som ska studeras är uran och teknetium.

Kolloidprojektet omfattar studier av kolloiders stabilitet och rörlighet, mätning av kolloid-koncentrationen i grundvattnen på Äspö, studier av bentonitens betydelse som källa för bildandet av kolloider samt studier av risken för att radionuklider transporteras med kolloider. Mätningar i borrhål genomfördes under första halvåret 2003 för att studera bentonitlerans förmåga att bilda kolloider i kontakt med grundvatten. Sammanställningen och rapportering av dessa experiment samt tidigare genomförda laboratorieexperiment och mätningar av bakgrundshalter av kolloider i grundvattnet pågår. I augusti 2003 påbörjades planeringen av nästa kolloidexperiment, ett dipolförsök, där kolloidkoncentrationen i grundvatten ska studeras före respektive efter passage genom en naturlig spricka.

Mikroorganismer samverkar med sin omgivning och kan i vissa fall ge stor påverkan på förhållandena där. Sådan samverkan kan ge betydande påverkan på funktionen hos ett framtida djupförvar för använt kärnbränsle. För närvarande studeras fyra mikrobiella processer som har identifierats som viktiga för förvarets funktion i *Mikrobprojektet*. Processerna är: biotransport av radionuklider, biosorption av radionuklider, mikrobiella effekter på de kemiska förhållandena och biokorrosion av koppar. Begränsningar hos laboratorieexperiment har drivit på utvecklingen av utrustning för mikrobiella studier i Äspölaboratoriet. Huvuddelen av de mikrobiella studierna äger rum på 450-metersnivån men en plats (BIOS) som ligger på cirka 300 meters djup har också varit i drift under 2003. På denna plats studeras sorption på bilogiska järnoxider. På 450-metersnivån studeras sorption av radionuklider på biofilmer genom att grundvatten från ett djupt borrhål cirkuleras genom en biofilm. En gaskromatograf anpassad till forskning undermark har utvecklats. Gassammansättningen i grundvattenprover från Äspötunneln, borrhål eller direkt från cirkulationsutrustningen kan nu analyseras direkt på plats i tunneln. Under 2003 avslutades experimentet för att studera biokorrosion av koppar. Insamlad information har analyserats och kommer att publiceras.

Syftet med *Matrisförsökets* första fas har varit att bestämma ursprung och ålder på matris-vatten, det vill säga tillgängligt porvatten i små sprickor, och dess inverkan på vattenkemin i berget. Denna fas av projektet har omfattat en förstudie och ett fullskaleprogram. I för-studien genomfördes laknings- och permeabilitetsexperiment på material från en borrkärna liksom lakförsök på krossat material. Fullskaleprogrammet omfattade provtagning och analys av matrisvatten från en isolerad borrhålssektion. Den första fasen av projektet, vilken avslutades och avrapporterades under 2003, har givit ökad kunskap om matrisvattnet i kristallint berg med låg hydraulisk konduktivitet. Denna kunskap utgör ett viktigt komp-lement till tidigare hydrogeokemiska studier som genomförts vid Äspölaboratoriet. En andra fas av projektet kommer att påbörjas under 2004 vilken fokuserar på hur småskaliga mikrosprickor i berget bidrar till rörelsen av matrisvatten.

Ett viktigt mål med aktiviteterna vid Äspölaboratoriet är att ta fram dataunderlag till de projekt som syftar till att utvärdera användbarheten och tillförlitligheten hos olika beräkningsmodeller samt att utveckla och prova metoder för att bestämma de parametrar som krävs som indata till modellerna. En viktig del av detta arbete genomförs i ett internationellt samarbetsprojekt *"Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes"*. Arbetet i projektet har anknytning till pågående och planerade experiment vid Äspölaboratoriet. Flera modelleringsgrupper arbetar med definierade uppgifter och använder samma fältdata. Modelleringsresultaten utvärderas och jämförs med data från experimenten. Rapporteringen av "Task 5" slutfördes mer eller mindre under 2003 och för närvarande bedrivs det huvudsakliga arbetet inom "Task 6" som omfattar modellering av utvalda delar av True-1 försöket med de beräkningsmodeller som används för att göra säkerhetsanalyser respektive platskarakterisering. En extern granskningsprocess av "Task 6" initierades under 2003. I mars hölls det 17:e "Task Force-mötet" i Thun i Schweiz och i september genomfördes ett arbetsmöte rörande "Task 6" på Krägga herrgård. På arbetsmötet diskuterades erhållna resultat från de olika modelleringsgrupperna samt fortsättningen av "Task 6".

Projektet *Padamot* (Palaeohydrogeological Data Analysis and Model Testing) är ett EU-projekt som omfattar utveckling av analysteknik och modelleringsverktyg för att utvärdera palaeohydrogeologiska data. I projektet bedrivs dessutom forskning som syftar till att undersöka de specifika processer som beskriver kopplingen mellan klimat och grundvattenkemi i lågpermeabelt berg. Palaeohydrogeology är en benämning som används för att beskriva den information om förflutna hydrogeokemiska och hydrogeologiska system som erhålls vid utvärdering av sprickfyllnadsmaterial. EU-projektet initierades i början av 2002 och kommer att pågå fram till slutet av 2004. Arbetet med svenska borrkärnor har fortsatt under 2003 med provpreparering och analys av kalcit. Resultatet från det andra året av projektet stöder de tidigare gjorda palaeohydrogeologiska tolkningarna och har medfört ett ökat förtroende för bestämning av kalciter bildade vid låg temperatur genom användandet av flera olika metoder.

Äspöanläggningen

En viktig del av verksamheten vid Äspöanläggningen är administration, drift och underhåll av instrument samt utveckling av undersökningsmetoder. Målet med driften av Äspöanläggningen är att garantera säkerheten för alla som arbetar eller besöker anläggningen samt att driva anläggningen på ett miljömässigt korrekt sätt. Driften av anläggningen under 2003 har fungerat programenligt och tillgängligheten på servicerelaterade system i anläggningen och underjordslaboratoriet har varit mer än 98 %. Inom bergförstärkningsprogrammet har fortsatta arbeten utförts. En ombyggnad av vattendistributionssystemet för att öka dess kapacitet och därmed förbättra brandsäkerheten under jord har genomförts. Andra aktiviteter är underhåll av det stationära hydromonoteringssystemet (HMS) för att det ska vara kontinuerligt tillgängligt, att genomföra programmen för mätning av grundvattentryck och flöden samt programmet för grundvattenkemi. Mätsystemen har fungerat tillfredställande under året, men i samband med bergarbetena som genomfördes under sommaren förlorades mätdata från några mätpunkter i tunneln under en månad. Den årliga provtagningen av grundvattenkemin genomfördes under september.

Internationellt samarbete

Under 2003 har sju organisationer från sex länder deltagit i det internationella samarbetet vid Äspölaboratoriet förutom SKB. Flertalet av de deltagande organisationerna är intresserade av grundvattenströmning, radionuklidtransport och bergkaraktärisering. Flera av organisationerna deltar både i det experimentella arbetet vid Äspölaboratoriet och i modelleringsarbetet inom ”Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes”.

Enheten Djupförvarsteknik, inom SKB, koordinerar tre EU-kontrakt och deltar även i flera andra EU-projekt varav deltagandet i fem sker via enheten Djupförvarsteknik. SKB deltar även i arbete inom IAEA:s ramverk.

Miljöforskning

Äspö Miljöforskningsstiftelsen grundades 1996 på initiativ av lokala och regionala intressenter, med målsättningen att göra Äspölaboratoriet och dess resurser tillgängliga även för nationell och internationell miljöforskning.

SKB:s ekonomiska engagemang i Miljöforskningsstiftelsen avslutades under 2003 och ansträngningarna fokuseras nu i stället till Äspö forskarskola, vilken grundades år 2002. Målsättningen för skolans verksamhet är at ge förutsättningar för dagens och morgondagens miljöforskning. Detaljerade planer för den kommande verksamheten har utarbetats under 2003. En professor på Institutionen för biologi och miljövetenskap vid Högskolan i Kalmar har anställts och tre doktorander påbörjade under hösten sitt arbete. Forskning kommer att bedrivas både i Äspölaboratoriet och i angränsande omgivningar. Projekt som berör Äspölaboratoriet har precis kommit igång och inga resultat finns för närvarande tillgängliga.

Contents

1 General

1.1 Background

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

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

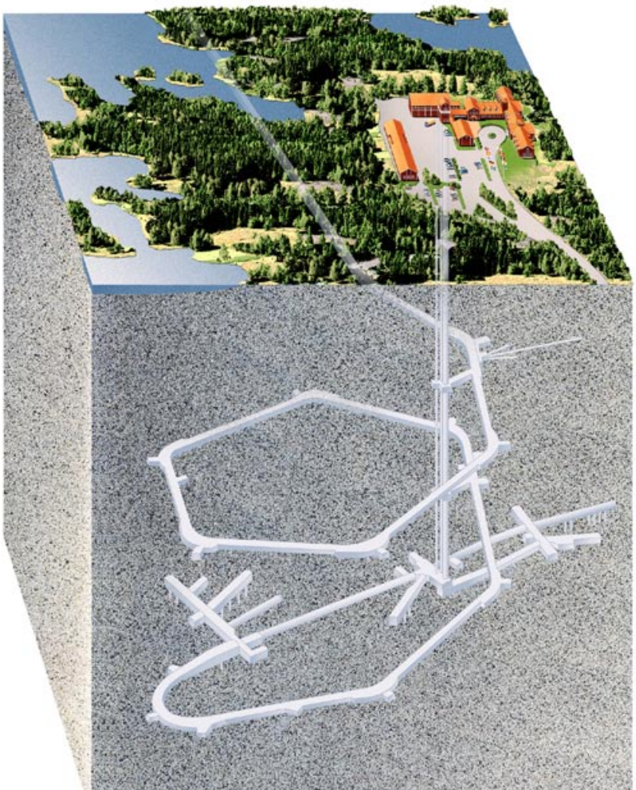


Figure 1-1. *Overview of the Äspö HRL facilities.*

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

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

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

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

1.2 Goals

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

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

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

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

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

- Provide experience and train personnel for various tasks in the deep repository.
- Provide information to the general public on technology and methods that are being developed for the deep repository.

1.3 Organisation

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

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

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

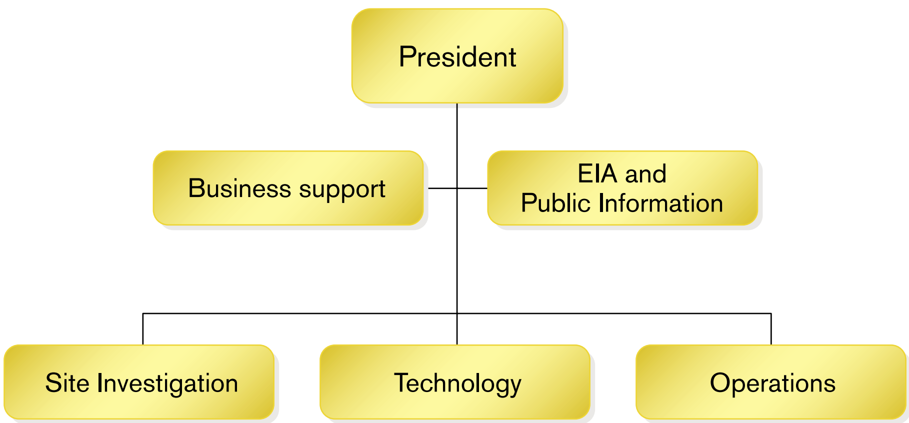


Figure 1-2. *SKB's organisation.*

1.3.1 Repository Technology

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

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

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

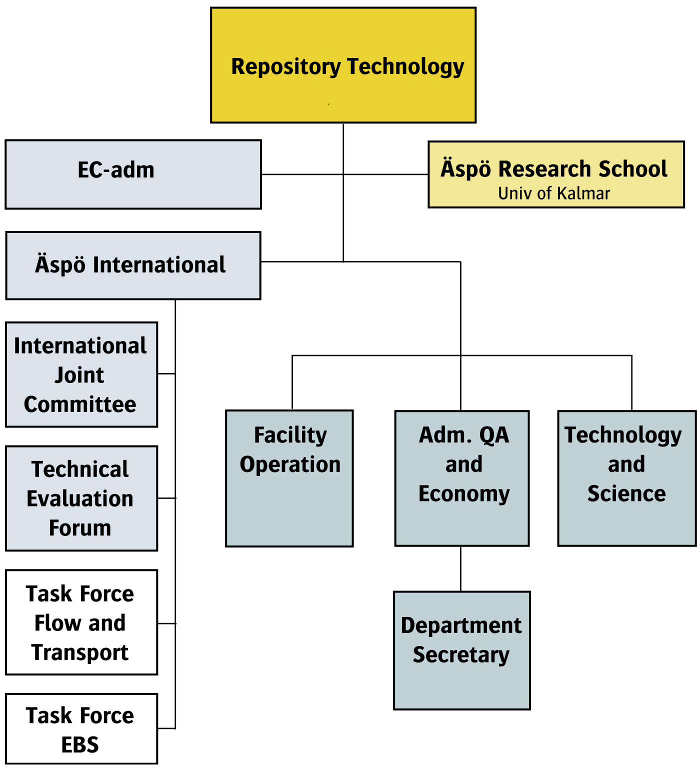


Figure 1-3. Organisation of Repository Technology and Äspö HRL.

1.3.2 International participation in Äspö HRL

The Äspö HRL has so far attracted considerable international interest. Seven organisations from six countries participated in the co-operation at Äspö HRL during 2003 in addition to SKB. The participating organisations were:

- Agence Nationale pour la Gestion des Déchets Radioactifs (Andra), France.
- Bundesministerium für Wirtschaft und Arbeit (BMWA), Germany.
- Central Research Institute of Electric Power Industry (CRIEPI), Japan.
- Empresa Nacional de Residuos Radiactivos (Enresa), Spain.
- Japan Nuclear Cycle Development Institute (JNC), Japan.
- Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (Nagra), Switzerland.
- Posiva Oy, Finland.

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

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

Some EC projects are co-ordinated by the Director of Repository Technology and administrated by the Repository Technology staff. Examples are EC projects concerning the Prototype Repository that has a direct coupling to the test set-up at Äspö and the CROP project that is coupled to experiments carried out in the Äspö HRL. Both those projects will be concluded in 2004.

1.4 Allocation of experimental sites

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

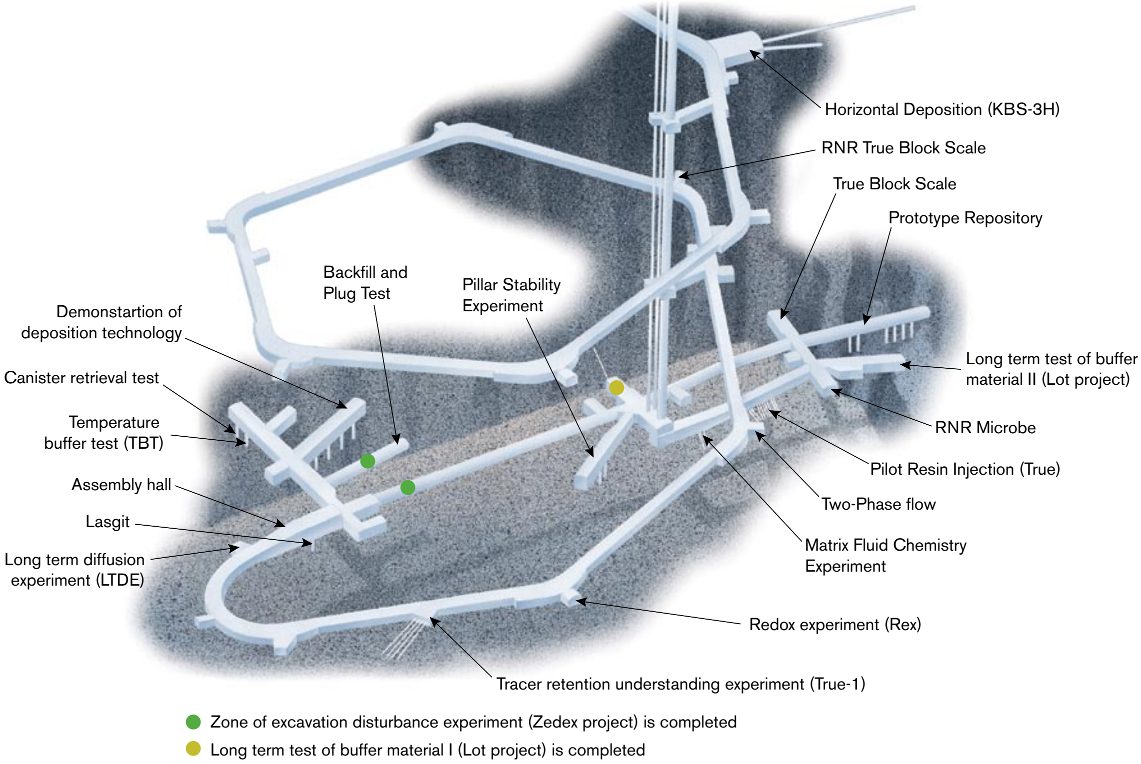


Figure 1-4. *Allocation of experimental sites from –220 m to –450 m level.*

1.5 Reporting

Äspö HRL is an important part of SKB's RD&D-Programme. The plans for research and development of technique during the period 2002–2007 are presented in SKB's RD&D-Programme 2001. The information given in the RD&D-Programme related to Äspö HRL is detailed in the Äspö HRL Planning Report, which is revised each 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 issued four times a year for internal distribution.

Joint international work at Äspö HRL as well as data and evaluations for specific experiments and tasks are reported in Äspö 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

1.6 Management system

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

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

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

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

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

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

Project Model

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

Environmental management

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

SKB also makes every effort to minimise the impact of ongoing operations and activities on the environment. This environmental work is goal-oriented and the progress versus goals is assessed each 3rd months. Key assessment parameters for the selection of suppliers include security, environmental aspects and quality.

1.7 Structure of this report

The work performed at Äspö HRL during 2003 is described in six chapters in this report:

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

2 Technology

2.1 General

To meet stage goal 4, to demonstrate technology for and function of important parts of the repository system, work is performed on translation of current scientific knowledge and state-of-the-art technology into engineering practice applicable in a real repository.

It is vital 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, buffer and 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 under way are:

- Canister Retrieval Test.
- Prototype Repository.
- Backfill and Plug Test.
- Long Term Test of Buffer Material.
- KBS-3 method with horizontal emplacement.
- Large Scale Gas Injection Test.
- Temperature Buffer Test.

2.2 Canister Retrieval 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 the deposition holes has been used for implementation of the Canister Retrieval Test.
- Saturation and swelling of the buffer under controlled conditions are monitored.
- Preparations for testing of canister retrieval.

Boring of full-scale deposition holes and geometrical/geotechnical characterisation of holes as well as emplacement of bentonite and canister with heaters were made within sub-projects that concern also other tests in the Äspö HRL. In addition to the retrieval testing the results of monitoring and manual excavation with laboratory testing of parts of the buffer will be used to increase the understanding of the THM processes in a deposition hole.

2.2.3 Experimental concept

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

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

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

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

The buffer was installed in the form of blocks of highly compacted Na-bentonite, with a full diameter of 1.65 m and a nominal height of 0.5 m. Instruments for measuring temperature, relative humidity, total pressure and pore pressure were installed in the bentonite in many of the blocks. When the stack of blocks was 6 m high the canister equipped with electrical heaters was lowered down in the centre. Cables to heaters, thermocouples in the rock and strain gauges in the rock were connected, and additional blocks were emplaced until the hole was filled up to 1 m from the tunnel floor. On top the hole was sealed with a plug made of concrete and a steel plate as cover. The plug was secured against heave caused by the swelling clay with 9 cables anchored to the rock. The tunnel will be left open for access and inspections of the plug support. The experimental set-up is shown in Figure 2-1.

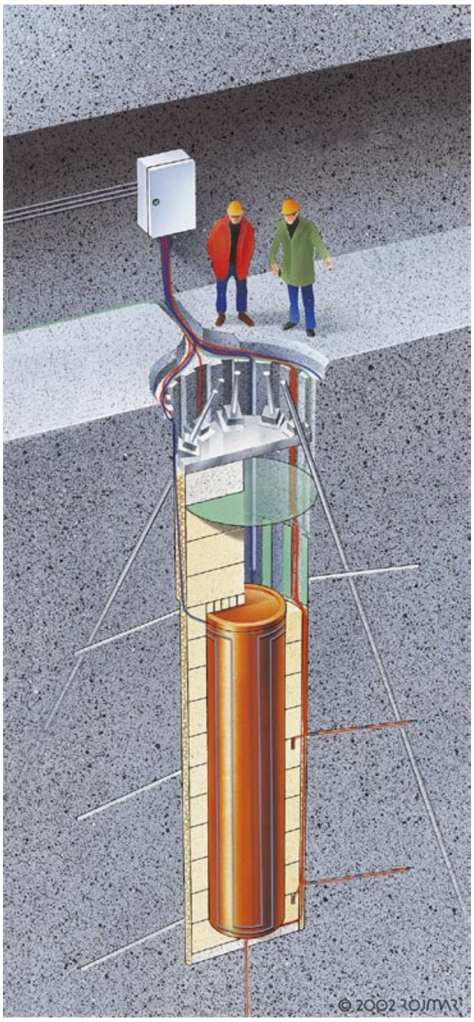


Figure 2-1. Illustration of the experimental set-up of the Canister Retrieval Test.

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

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

2.2.4 Results

The Canister Retrieval Test was installed during year 2000 and the heaters were started on October 26 with a constant power of 1,700 W. The power was increased to the final thermal load, 2,600 W, when the temperature had reached approximately 65 degrees on the canister surface on February 13, 2001.

At the end of 2001 two of the 36 electrical heaters failed due to short circuit to earth. The remaining heaters have worked well during 2002 and 2003 until November 2, 2003, when a new failure occurred. The power in the heaters have been reduced two times, in order to lower the temperature in the canister and in this way increase the resistance to earth in the heater elements. The power was reduced from 2,600 W to 2,100 W on September 9, 2002 and to 1,600 W on November 4, 2003.

The mats for artificial wetting were flushed and the water pressure was increased from 50 kPa to 850 kPa in September and October 2002. The water pressure was temporarily reduced to 100 kPa during the period 5/12 2002 – 9/1 2003 and to 400 kPa during the period 9/1 2003 – 23/1 2003. The mats have been flushed regularly during 2003.

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 2003-05-01 /Goudarzi et al. 2003/ and the period up to 2003-11-01 /Goudarzi et al. 2003a/ have been released. Table 2-1 shows the parameters that are measured. Selected characteristic values from 2000-10-26 until 2003-12-30 are shown in Figure 2-2 to Figure 2-4. The evolution of the total pressure in the buffer and the temperatures in the buffer and rock along one line at mid-height heater are shown Figure 2-2 and Figure 2-3. The evolution of tensile forces in the rock anchors retaining the plug is shown in Figure 2-4.

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

Table 2-1. Measurements in Canister Retrieval Test.

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

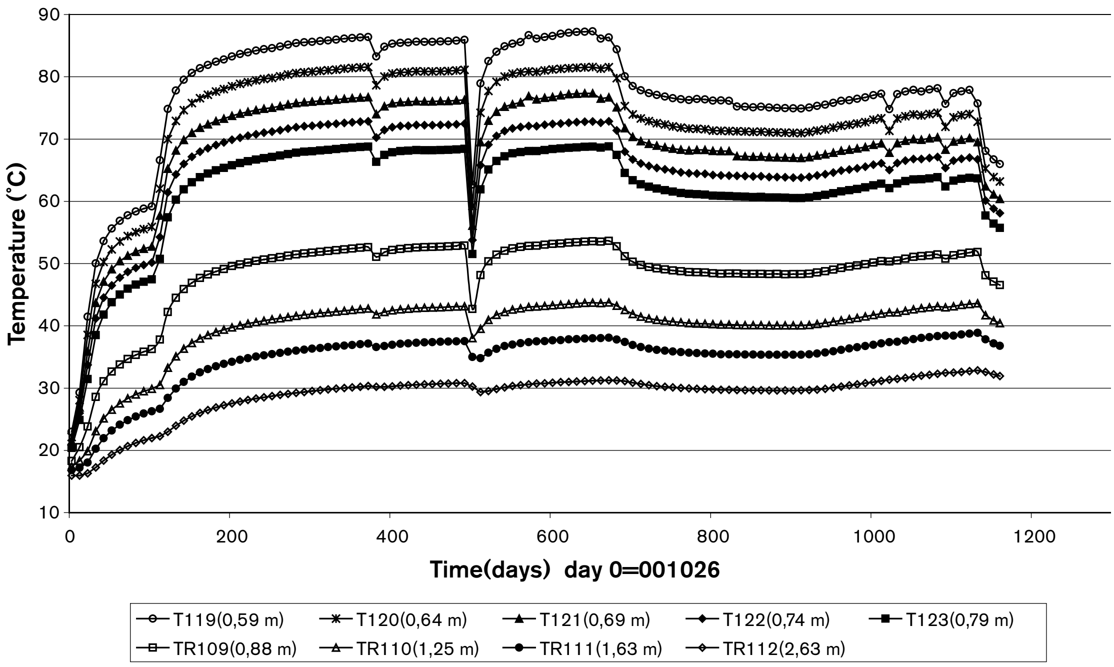


Figure 2-2. *Temperature in the buffer and rock as a function of the time from start. The sensors are located at mid height canister along the same radial line, with the distance from the canister centre line noted in the table of signs (canister surface at 0.53 m; rock surface at 0.88 m).*

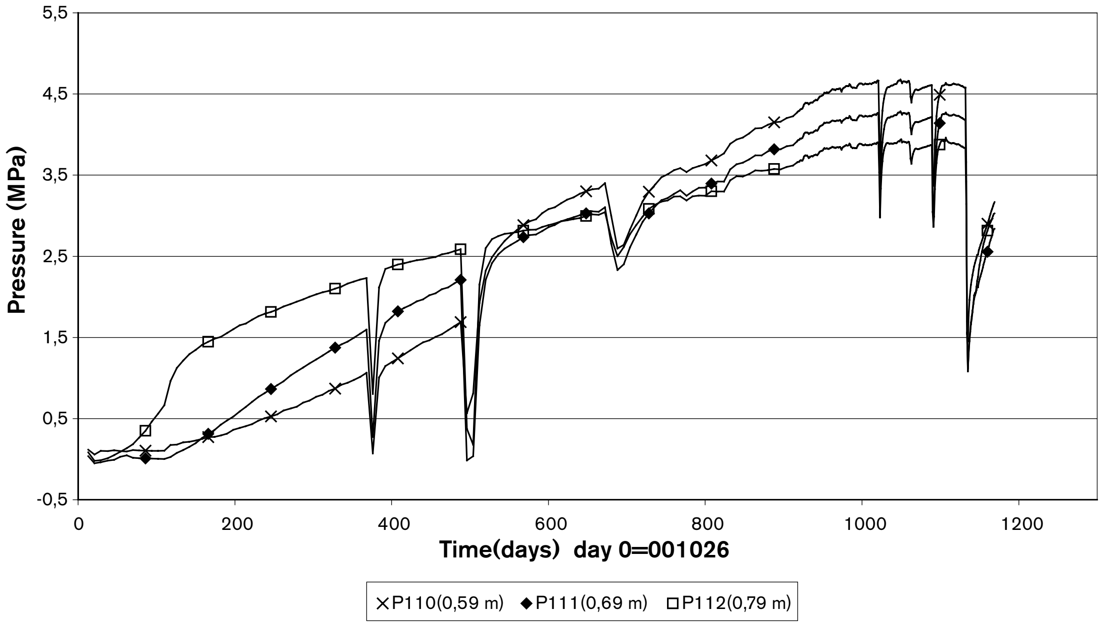


Figure 2-3. *Total pressure in buffer as a function of the time from start. The sensors are located mid height canister along the same radial line, with the distance from the canister centre line noted in the table of signs (canister surface at 0.53 m; rock surface at 0.88 m). The first two dips are caused by heat shut down and the third dip is caused by the first power decrease. The final dip, which has not yet recovered, is caused by heater failure and the subsequent latest decrease in power.*

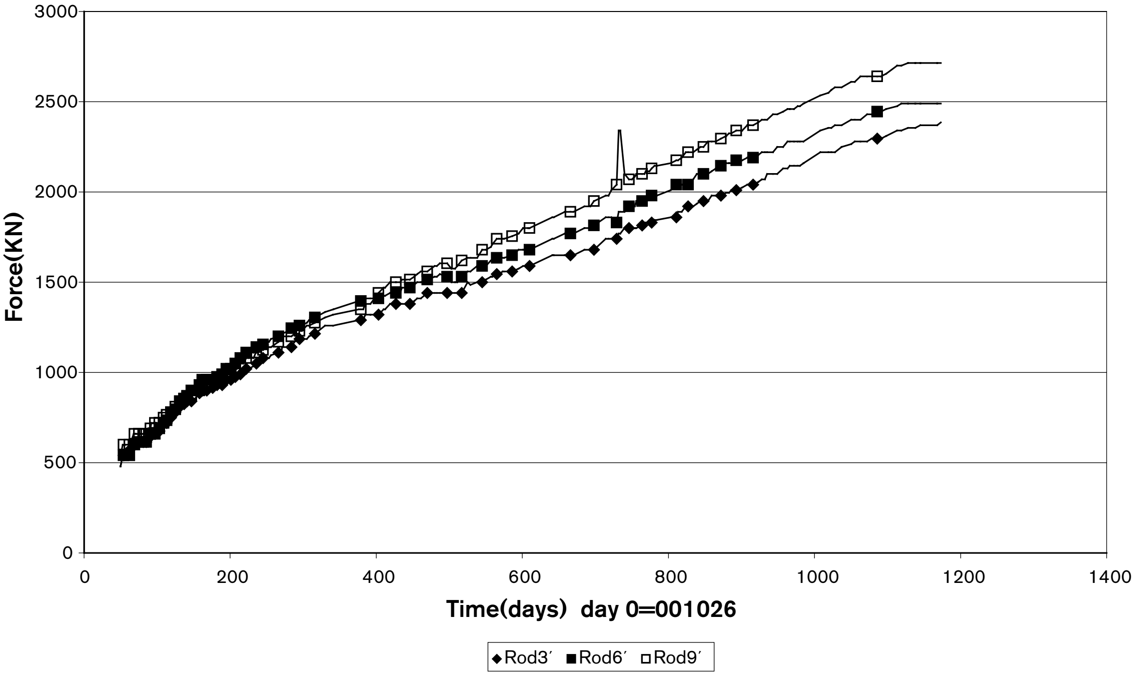


Figure 2-4. Tensile forces in rock anchors for the retaining plug as a function of the time from start. The force is multiplied with 3 in order to illustrate the total force (only 3 out of 9 anchors were measured after 40 days).

2.3 Prototype Repository

2.3.1 Background

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

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

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

2.3.2 Objectives

The main objectives for the Prototype Repository are:

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

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

2.3.3 Experimental concept

The test location chosen is the innermost section of the TBM-tunnel at the –450 m level. The layout involves altogether six deposition holes, four in an inner section and two in an outer, see Figure 2-5. The tunnels are backfilled with a mixture of bentonite and crushed rock (30/70). A massive concrete plug designed to withstand full water and swelling pressures separate the test area from the open tunnel system and a second plug separate the two sections. This layout will in practice provide two more or less independent test sections. Canisters with dimension and weight according to the current plans for the deep repository and with heaters to simulate the thermal energy output from the waste are positioned in the holes and surrounded by bentonite buffer (MX-80). The deposition holes are with a centre distance of 6 m. This distance is evaluated considering the thermal diffusivity of the rock mass and the fact that maximum acceptable surface temperature of the canister is 100°C.

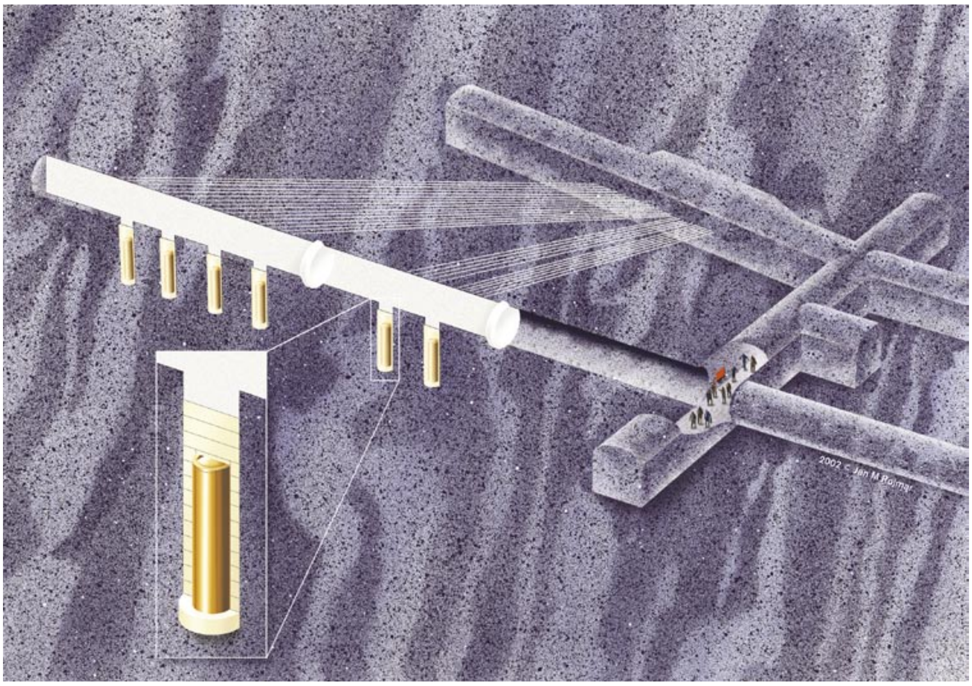


Figure 2-5. Schematic view of the layout of the Prototype Repository (not to scale).

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. 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 was restarted with Section II (the outer section) in early 2003, when the cause of the malfunction of the electrical system to the heaters inside the canisters became known and an adjusted design of the cables from the heaters to the power grid in the adjacent tunnel (G tunnel) had been done. This was a 10 months delay in relation to the original time plan. The heater in Hole 5 was turned on by May 8th and the heater in Hole 6 (the outer hole) by May 23rd. The outer plug was cast in September 2003. The installation applied the same techniques as in Section I, and the result was as predicted and expected. Only minor events occurred with no influence on the future monitoring of the above mentioned processes. Reading of the newly installed instruments started immediately. The ongoing reading of the instruments in Section I went on in parallel.

The text below summarises the instruments installed in Section II and provides the results during the year on comparisons between predicted developments of processes with the observed data.

Measurement of THM processes in buffer and backfill

Measurements in the buffer are performed in the two deposition holes in Section II and in two (Hole 1 and 3) of the four deposition holes in Section I. The reason being to have two deposition holes yielding results with absolutely no doubt about the influence instrumentation may have on the development of THM processes in the buffer, like cables leading the way for water and thereby supporting flow, while transport is expected to be a diffusion-related process. Hole 5 is instrumented in the same way as Hole 1 and 3, i.e. the instruments are placed in four vertical sections according to Figure 2-6. Hole 6 has, however, been instrumented according to another strategy, see Figure 2-7, implying that the instruments are placed in eight directions (four directions in each instrumented block) with the intention to avoid influence of instruments radially located between the measurement point and the rock.

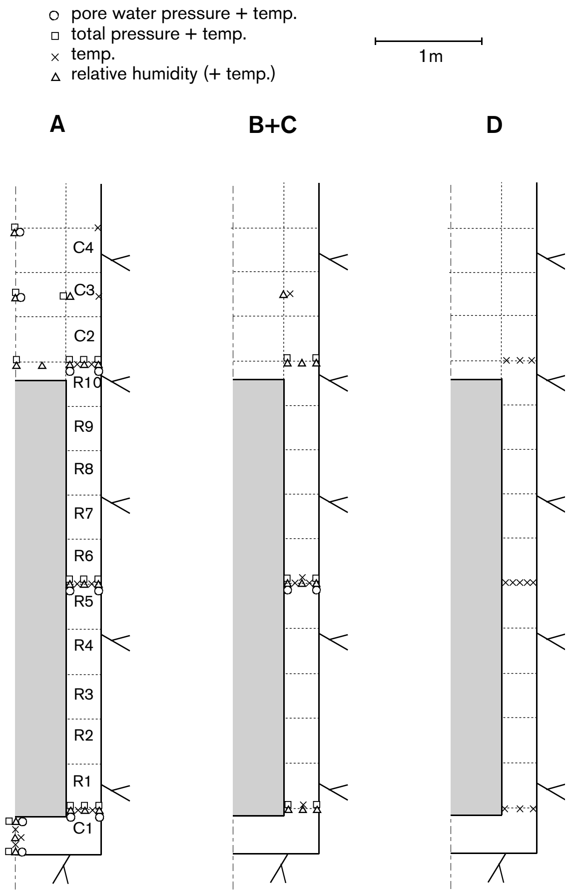


Figure 2-6. *Schematic view of the instruments in four vertical sections and the block designation. This strategy of positioning the sensors is used in deposition Hole 5 as well as in Holes 1 and 3.*

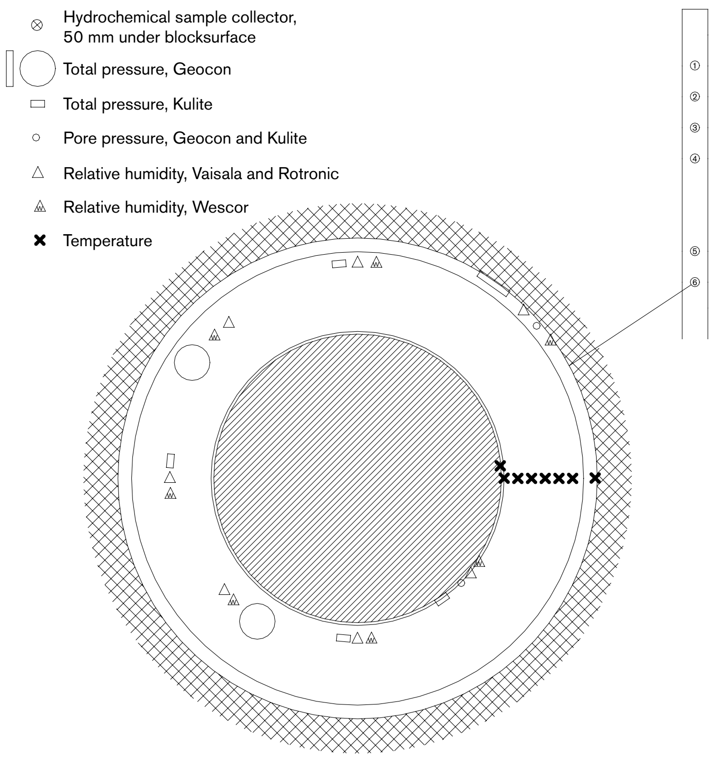


Figure 2-7. *Schematic view of the instrument positions in Hole 6.*

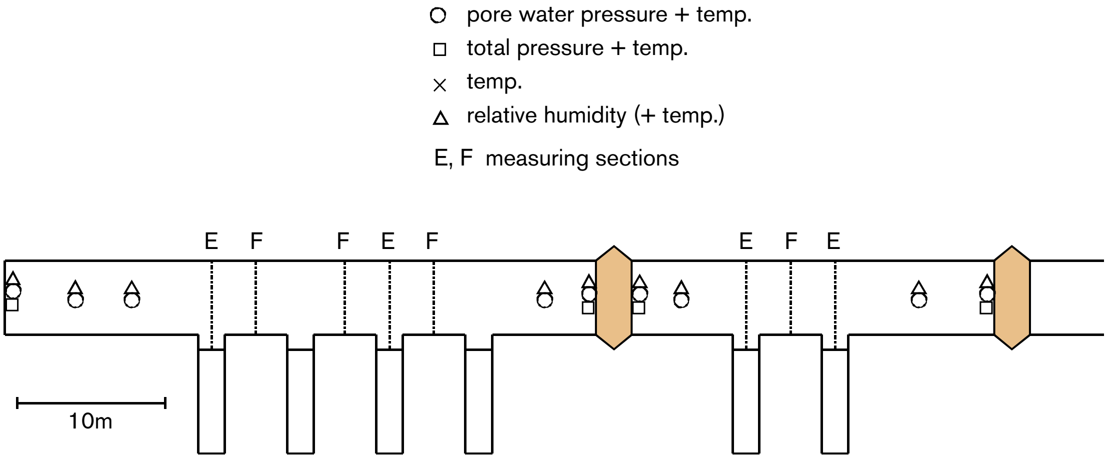


Figure 2-8. *Schematic view of the instrumentation of the backfill.*

Measurements are performed of THM processes in the backfill. The backfill has mainly been instrumented in vertical sections (E and F) straight above and between the holes, see Figure 2-8.

An aim when choosing instruments for the project was to have two different measuring principles for each measured variable. This was basically carried through, as Table 2-2 shows. All instruments are of the same type in both the buffer and the backfill. However, since the temperature in the backfill is much lower than in the buffer it was decided to use stainless steel for the sensor housing instead of titanium. The cables from the sensors were led in polyamide tubes into the lead-throughs and further to the adjacent G tunnel, where connections to power and computers are arranged.

Table 2-2. Principles for THM measurements in the buffer and in the backfill.

Measuring quantity	Measuring principle	Remarks
Temperature	Thermocouple	
	Resistive temperature sensor	Built-in to capacitive humidity sensors and to Geokon pressure cells
	Fibre optics	Only on canisters. Placed as a loop on the canister's surface
Total pressure	Vibrating wire	
	Piezo-resistive	
Porewater pressure	Vibrating wire	
	Piezo-resistive	
Water content	Capacative sensors	Only installed in the buffer
	Psychrometer	

Measurement of hydraulic regime in the rock

A large number of boreholes have been drilled to characterise the rock mass. These boreholes are used for the long-time monitoring of the development of processes in the rock. Packers, 1–5 in each borehole, have been installed to facilitate monitoring of the water pressure and water chemistry in borehole sections. Temperature and deformation sensors have been installed in some of the boreholes sections. Tubes and cables from the borehole sections are lead to the nearby G tunnel, where the pressure, deformation and temperature are measured and the water is sampled. Hydraulic tests are also planned to be performed from the G tunnel by flowing of borehole sections (one by one) and measuring the pressure responses.

An overview of the instrumentation is given in Table 2-3 and the boreholes with hydro-monitoring sections in the two Prototype Repository sections are shown in Figure 2-9.

Table 2-3. Overview of instrumentation in the Prototype Repository.

Instrumentation	Number
Section I	
Bentonite packers (1–2 m long, 2–5 packers in each 8–50 m borehole)	49
Mechanical packers (one in each 2 m borehole, stainless)	16
Pressure measurement sections	65
Circulation sections (two tubes)	5
Flow sections (one-two tube-s)	7
Hydrochemical sections	6
HM sections	0
Temperature	37
Section II	
Inflatable packers (1 m long, 1–5 in each 3–30 m borehole)	46
Mechanical packers (one in each 2 m borehole, stainless)	6
Pressure measurement sections	52
Circulation sections	10
Flow (one tube)	3
Hydrochemical sections	0
HM sections (Deformation+temperature. Same as circulation sections)	10
G tunnel+borehole KA3510A01	
Inflatable packers (1 m long, 5 in each 49–150 m borehole)	15
Pressure measurements sections (5 in each borehole)	15
Circulation sections (holes from G-tunnel)	2
Flow (one tube, KA3510A01)	1
Hydrochemical sections (holes from G tunnel)	2
HM sections (reference in G tunnel, the north tunnel wall)	1

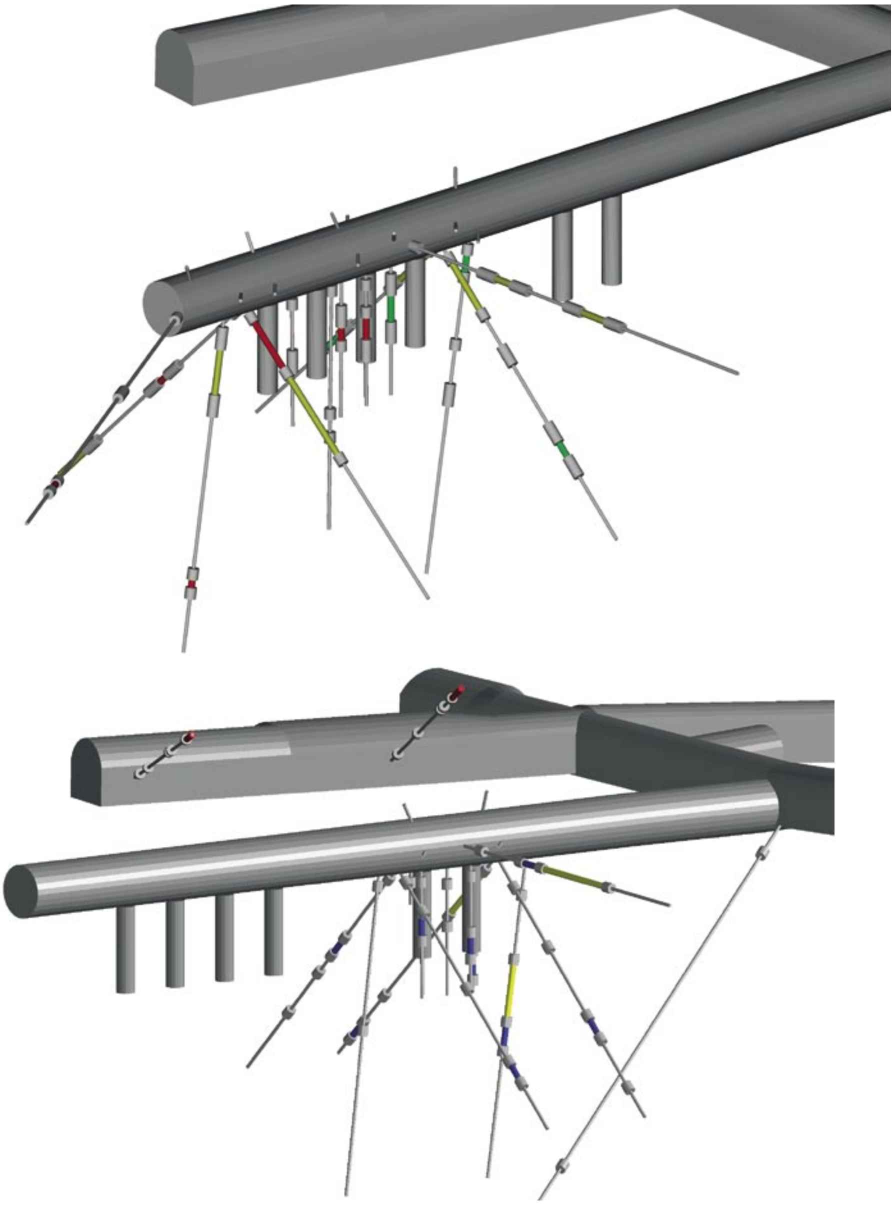


Figure 2-9. *Boreholes with hydro monitoring sections in Section I (upper) and Section II (lower). The colours along the boreholes indicate a packer or the type of measurement section (Grey – wide cylinder packer, No colour – pressure section (P), Red – hydrochemical section (HC) + P, Yellow – flow section (F) + P, Green – circulation section (C) + P, Blue – hydro mechanical section (HM) +C+P.*

Measurement of mechanical conditions in the rock

The major objective of the rock mechanical studies is to verify rock mechanical processes in the construction and operation phases of a future Deep Repository. Only Section II has been used for these studies. Instruments have been installed for measurement of the stress redistribution due to excavation and temperature increase in the host rock around the holes. Monitoring of strain and deformations takes place within intact rock as well as single fractures and fractures zones. Since the intention was to minimise disturbance during the operation, the test arrangement was such that artificial disturbances of the engineered barriers and the interaction with surrounding rock were kept to a minimum.

The instruments for monitoring rock mechanical response were installed in two stages. The instruments used to monitor the drilling phase of the deposition holes were installed within vertically drilled boreholes located 0.3 m from the periphery of the deposition hole. Following drilling of the deposition holes, complementary instruments were then installed in boreholes drilled from within the deposition holes.

In Table 2-4 the number and types of instruments selected for installation to allow monitoring of stresses and strains within the host rock surrounding the holes in Section II are given and in Figure 2-10 the location of primary instruments is shown.

Table 2-4. Summary of primary and complementary instruments.

Parameter measured	Instrument type	Total number installed
Primary instruments		
Compressive stress change in intact rock	Biaxial stress meter	8
Compressive and tensile stress change in intact rock	Soft stress cell	8
Vertical movements in intact rock, over single fractures and within fracture zones	Deformation meter	17
Vertical strain measurements in intact rock and over single fractures	Strain gauge	7
Complementary instruments		
Horizontal deformation perpendicular to the axis of the deposition hole	Displacement transducer	32
Vertical strains beneath the deposition hole	Strain gauge	8

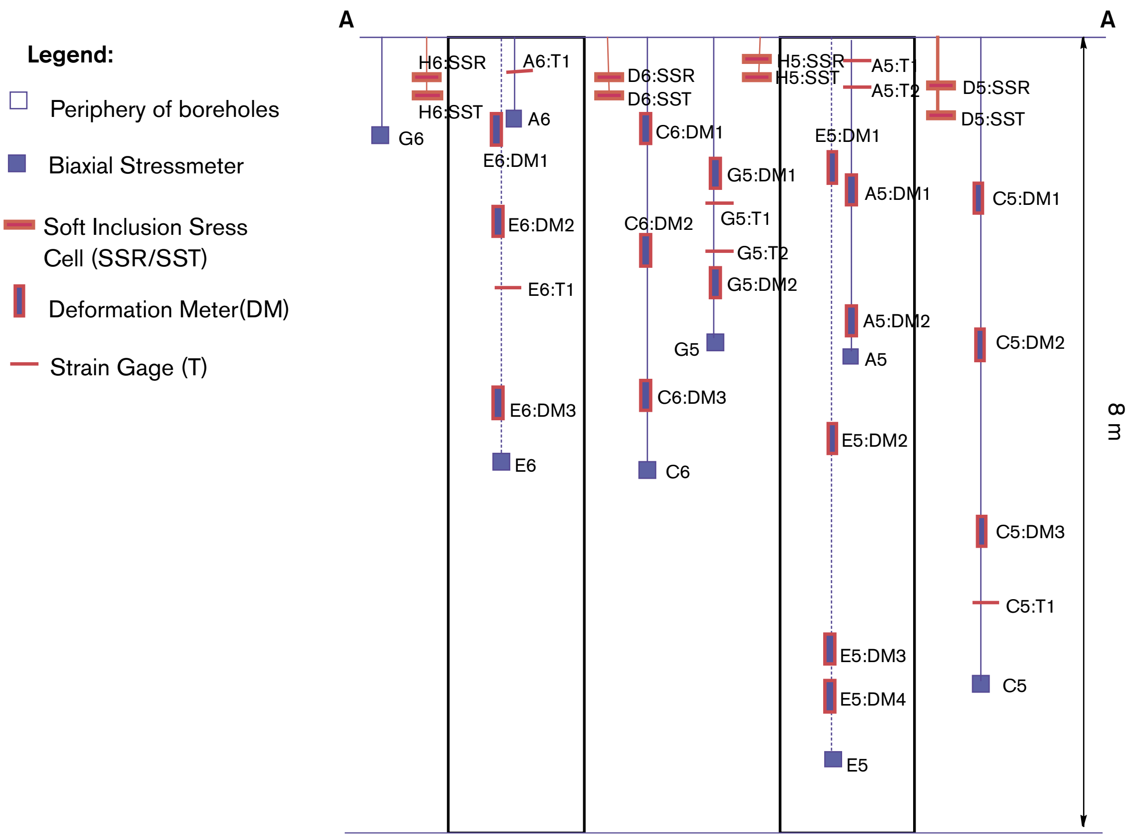


Figure 2-10. Primary instrument locations in elevation view. Hole 5 is to the left.

Geochemistry, gas and biology of buffer and backfill

Two types of collectors for gas and water sampling have been installed. Twelve sample collectors have been placed in the bentonite in each of the Holes 5 and 6 (as well as 12 in Hole 1). The sample collectors consist of a titanium cup, on which a titanium filter is placed on the top. Pore water from the bentonite flows after saturation of the buffer through the filter and into the cup. When the test is over and the excavation of the bentonite has started, the cups will be located and the water will be analysed. Fifteen additional sample collectors were also installed, two on top of deposition Holes 5 and 6 respectively, one on top of Holes 1 and 3 respectively, and nine in the backfill.

Resistivity measurements

GRS, Germany, carries out research on measurements of electrical resistivity to monitor water uptake in the tunnel backfill, the bentonite buffer, and saturation changes in the rock between Holes 5 and 6, see Figure 2-11. The method takes advantage of the relation between electric resistivity and water (solution) content, and the electrical resistivity in the buffer is determined by use of multi-electrode chains. The resistivity distribution in the areas between the chains is determined by means of tomographic dipole-dipole measurements.

A double cross array consisting of 36 single electrodes each with a spacing of 0.5 m has been installed on a 35° inclined backfill ramp above Hole 6 in Section II and above Hole 3 in Section I. These arrays monitor the resistivity distribution in the backfill.

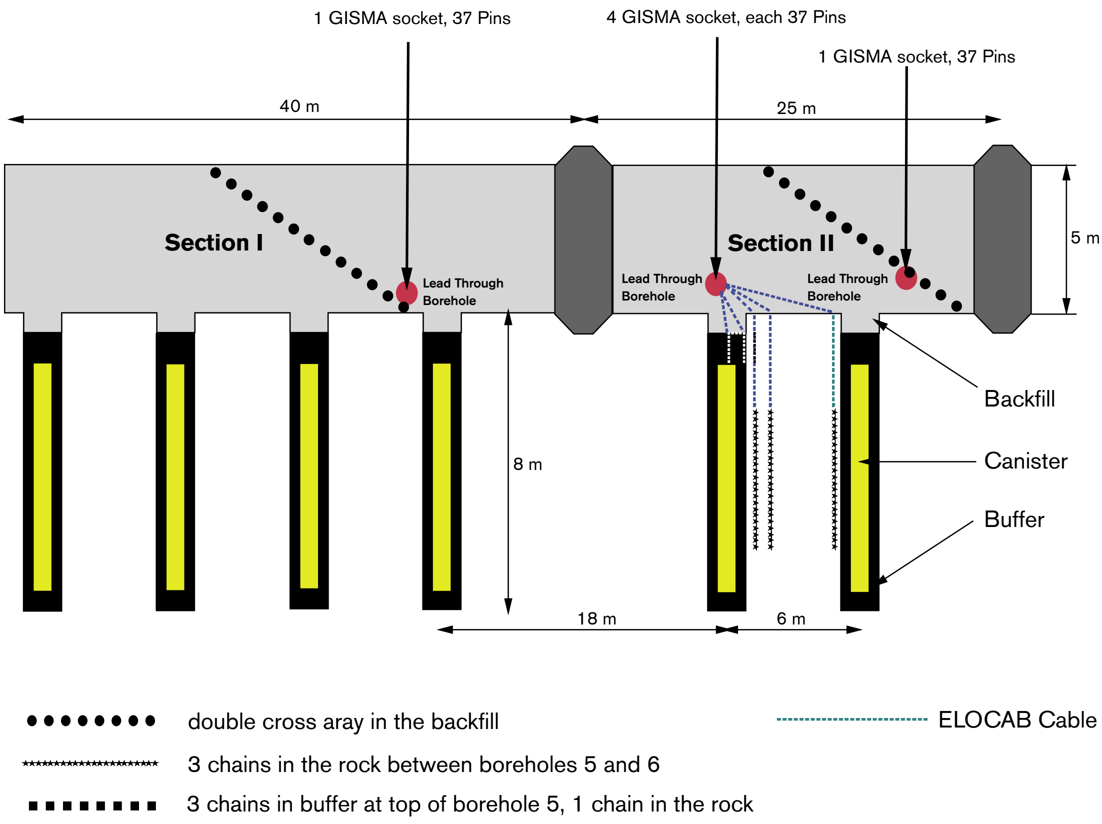


Figure 2-11. *Overview of electrode arrangements.*

The resistivity in the buffer at top of deposition Hole 5 is determined by dipole-dipole measurements between one horizontal electrode chain at the surface of the buffer and three vertical chains installed in the centre of the buffer, about 10 cm from the deposition hole wall and outside of the hole in the rock at 30 cm distance from the deposition hole wall. The electrode spacing is 0.1 m for the horizontal chain and 0.15 m for the vertical chains, respectively. The resistivity distribution is determined in the plane enclosed by the buffer electrodes.

The resistivity distribution in the rock in the immediate vicinity of Holes 5 and 6 is monitored with electrode chains installed in three vertical holes in the rock between the two deposition holes.

Displacement of canisters

One important aspect within the repository performance is the displacement that canisters will probably undergo along the duration of the monitoring period. The main goal of this part of the project is to track this displacement both on its vertical and horizontal component, including as well the tilting. Such system for tracking the heaters displacement has been applied in Hole 6 in Section II and in Hole 3 in Section I by Aitemin, Spain. The location of the sensors in the two deposition holes is shown in Figure 2-12.

The selected sensors are fibre optics based. They comprise no electronics inside, but a Thin Film Fizeau Interferometer, that receives a broadband white light and returns a wavelength modulated light. Hence, it is assured that no electromagnetic interference will affect the readings. Besides, the use of fibre optics based sensors incorporates an innovative aspect into the project in relation with the displacement sensors conventionally used so far. Because of the harsh working conditions for the sensors, they were constructed in Incoloy 825, assuring water tightness and corrosion resistance.

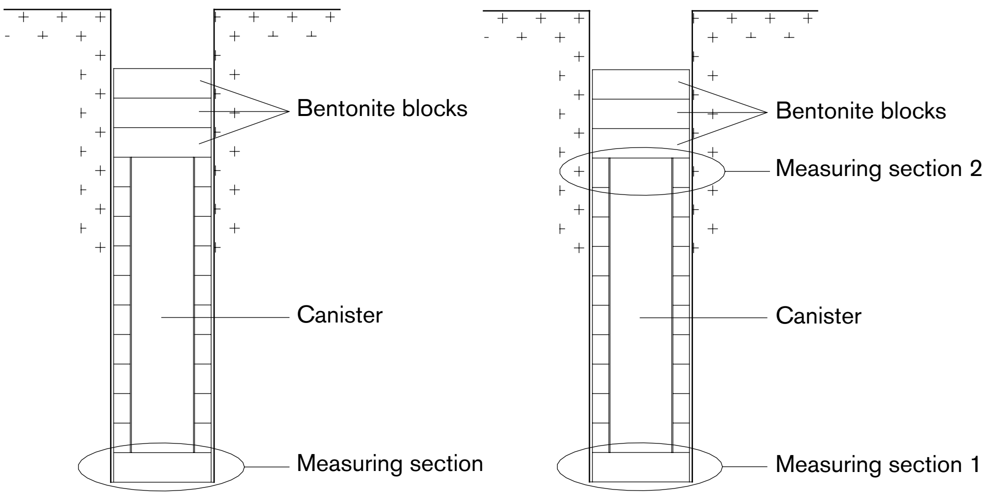


Figure 2-12. *Location of measuring sections for Hole 3 (left) and Hole 6 (right).*

Modelling of THM processes

The models 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 Liedtke, BGR).
- Thames – (Y Sugita, JNC).
- ABAQUS – (L Börgesson, Clay Technology AB, SKB).

Recording of THM processes

Temperature at mid-height canister in the wettest hole (Hole 1)

In early 2004 the temperature was still rising after more than 2 years testing time. It reached about 72°C in the clay adjacent to the canister surface and around 60°C at the rock after 700 days as shown by Figure 2-13. The average temperature gradient is about 0.034 centigrades per millimetre radial distance. Almost the same temperature figures were also given by the Vaisala RH meters. The power has been about 1,800 W.

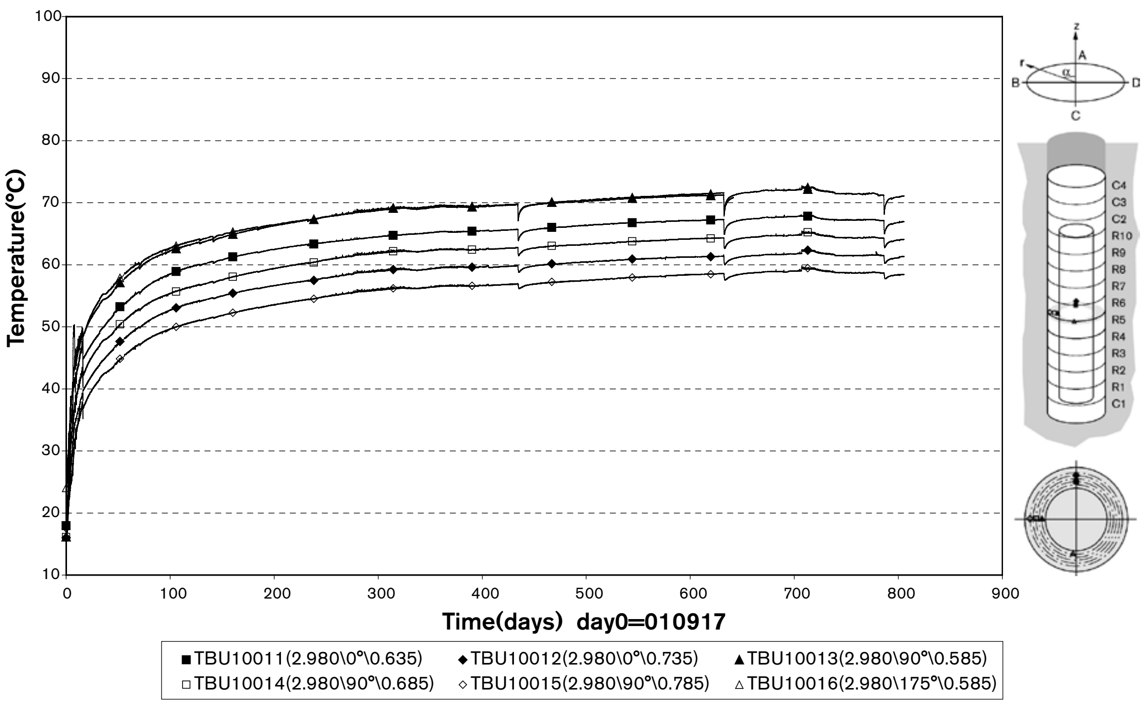


Figure 2-13. *Temperature at mid-height of the canister in the wettest hole (Hole 1). The legend denotes which instrument and where it is located; example TBU10011 (2.980\0°0.635) where TBU is gauge type (here temperature sensor), 10011 is the gauge number, 2.980 is the distance from the hole bottom, 0° is the coordinate angle from the drift axis (see top figure at right), and 0.635 is the distance from the hole centre.*

Hydration at mid-height canister in the wettest hole (Hole 1)

The hydration process has been interpreted from the output of the Vaisala RH meters (an example is given in Figure 2-14). The results indicate that the clay between the canister and the rock in Hole 1 had reached RH values of 92–94% after about one year.

Total pressure at mid-height canister in the wettest hole (Hole 1)

The total pressure was measured by two types of gauges of which the Geokon sensors appeared to be the most accurate. The homogeneous distribution of water according to the RH measurements would correspond to a uniform distribution also of the pressure but the obvious variations in Figure 2-15 indicate that full maturation of the buffer had not taken place within 2–2.5 years. One reason may be that the degree of water saturation varies more than indicated by the RH measurements and another that complete, homogeneous embedment of the pressure cells requires rather long time for the involved creep, expansion, consolidation and moisture redistribution. It may also be that the cables connecting the Vaisala gauges to the recording units served as water conductors and caused local wetting and too early saturation at the spots where the gauges are. This may explain the slight drop of RH after reaching a maximum value for one of the gauges, cf Figure 2-14.

It is estimated that nearly complete homogeneity will require several years a main cause being that complete hydration is slower than expected.

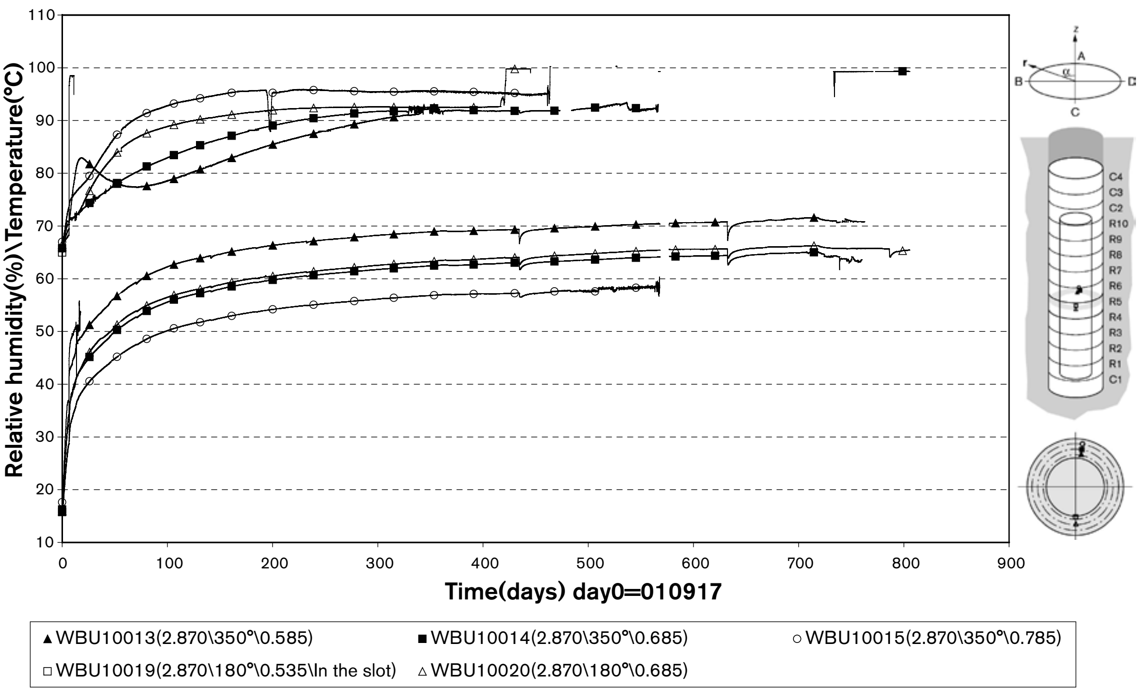


Figure 2-14. *RH distribution in the buffer in the wettest hole (Hole 1). The legend is explained under Figure 2-13, WBU denotes relative humidity sensors. The data can be approximately taken as the degree of water saturation. The upper curve set shows the RH readings and the lower set gives the temperature.*

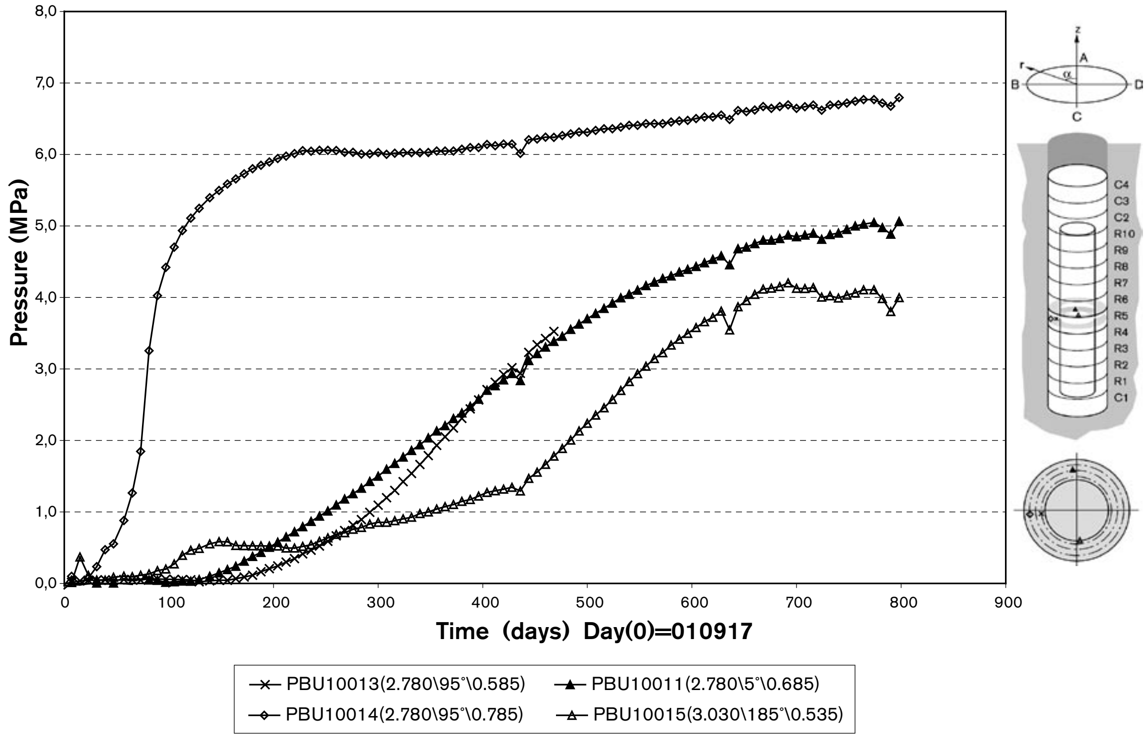


Figure 2-15. Evolution of total pressure at mid-height of the buffer in the wettest hole. The legend is explained under Figure 2-13, PBU denotes total pressure sensors. The highest pressure, about 6.7 MPa, was reached after about 2 years while the lowest (4 MPa) was signalled from a cell close to the canister.

Comparison between predictions and recordings

The predicted and actual temperatures at the rock and the canister surface at mid-height canister level of the canister in "wet rock" represented by Hole 1 are shown in Table 2-5. One finds that two of the models give adequate data while one (Thames) somewhat exaggerates the temperature. For the BGR modelling the canister temperature was selected to be 100°C, which hence controlled the heat evolution of the entire buffer. For ABAQUS the boundary conditions were set to yield maximum 83°C in the canister and the results not coupled to the wetting, which explains the high gradient in the buffer.

Table 2-5. Actual and expected temperature in centigrades at the canister and rock surfaces at mid-height canister in the wettest hole after 1 and 2 years from start.

Location	Recorded	Compass (UWC)	Code Bright (CIMNE, Enresa)	Rockflow (BGR)	Thames (JNC)	ABAQUS (ClayTech, SKB)
Canister	1 y=69	1 y=70	1 y=70	1 y=100 [1)]	1 y=87	1 y=67 [3)]
	2 y=72	2 y=72	2 y=72	2 y=100 [1)]	2 y=92	2 y=70 [3)]
Rock	1 y=56	1 y=56	1 y=57	1 y=92 [2)]	1 y=71	1 y=44
	2 y=60	2 y=59	2 y=60	2 y=96 [2)]	2 y=76	2 y=47

[1)] Set by modeller, [2)] Controlled by set canister temperature by modeller, [3)] No real prediction. Boundary conditions set to yield maximum 83° in canister and results not coupled to the wetting.

The predicted and actual degrees of saturation are difficult to compare since the uncertainty in the "measured" degree of saturation is large. It should be noted that all the models gave quicker saturation than the "measured", which could be due to that the actual rock conditions deviate from the assumption of unlimited access to water. Still, all the models appear to exaggerate the rate of wetting, see Table 2-6, which relates to the true conditions of a wet boundary.

Table 2-7 shows the predicted total pressure which deviates significantly from the actual data in some cases. ABAQUS predicts too rapid pressure build-up at the canister while the predicted and measured pressures at the rock agree well. Compass predicts too slow pressure growth.

The development of the temperature regime is captured well and the results illustrate that the temperature regime is well understood and represented in the system. It is clear, however, that the three-dimensional configuration of the six holes in the experiment is essential to correctly capture the variation in the thermal response in each of the various holes.

The simulated hydration rates in the buffer for the wettest hole (Hole 1) show reasonable agreement with the experimental results although some over-prediction of drying in the initial stages, (first 100 days), of the test is found. For the "dry" hole (Hole 3) it was found that the simulated hydration rates throughout the buffer also showed reasonable agreement with the experimental results measured by certain humidity sensors. The hydration is more difficult to predict than the temperature since the boundary conditions are poorly defined. Variations related to condensation and evaporation of pore water can be seen near the heater by close examination of recordings while such phenomena can not be simulated because of the difficulty to combine water diffusivity and thermal diffusivity.

Table 2-6. Actual and expected degree of saturation in percent at the canister and rock surfaces at mid-height canister in the wettest hole after 1 and 2 years from start.

Location	Recorded	Compass (UWC)	Code Bright (CIMNE, Enresa)	Rockflow (BGR)	Thames (JNC)	ABAQUS (ClayTech, SKB)
Canister	1 y=90–100	1 y=96	1 y=95	1 y=76	1 y=79	1 y=75
	2 y=90–100	2 y=100	2 y=97	2 y=84	2 y=99	2 y=100
Rock	1 y=90–100	1 y=98	1 y=99	1 y=95	1 y=94	1 y=100
	2 y=90–100	2 y=100	2 y=99	2 y=98	2 y=100	2 y=100

Table 2-7. Actual and expected pressure in MPa at the canister and rock surfaces at mid-height canister in the wettest hole after 1 and 2 years from start.

Location	Recorded	Compass (UWC)	Code Bright (CIMNE, Enresa)	Rockflow (BGR)	Thames (JNC)	ABAQUS (ClayTech, SKB)
Canister	1 y=1.0	1 y=0.8	1 y=3.0	1 y=3.5	1 y=4.7	1 y=5.3
	2 y=4.0	2 y=3.2	2 y=5.1	2 y=4.8	2 y=6.2	2 y=6.8
Rock	1 y=6.0	1 y=2.8	1 y=5.0	1 y=3.5	1 y=6.4	1 y=5.3
	2 y=6.7	2 y=3.9	2 y=7.2	2 y=4.8	2 y=7.2	2 y=6.8

One of the simulations of the mechanical behaviour of the buffer in Hole 1 captured the key features of the observed development of swelling pressures. Peak pressures close to the rock are under-predicted possibly due to an over-estimation of the compressibility of the pellet region. In Hole 3 there is very little swelling pressure developed in both the simulated and measured results due to the slow rate of hydration experienced in this hole. It is believed that a problem is caused by neglecting the gaps between the buffer blocks. For some models the initial stress in the simulation is therefore too large compared with the measured data.

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 is partly a preparation for the Prototype Repository.

2.4.2 Objectives

The main objectives of the Backfill and Plug Test are to:

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

2.4.3 Experimental concept

The test region for the Backfill and Plug Test is located in the old part of the Zedex tunnel. Figure 2-16 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 (30/70) of bentonite and crushed rock (six sections).
- The outer part filled with crushed rock (0/100) and bentonite blocks and pellets at the roof (four sections).
- The concrete plug.

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

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

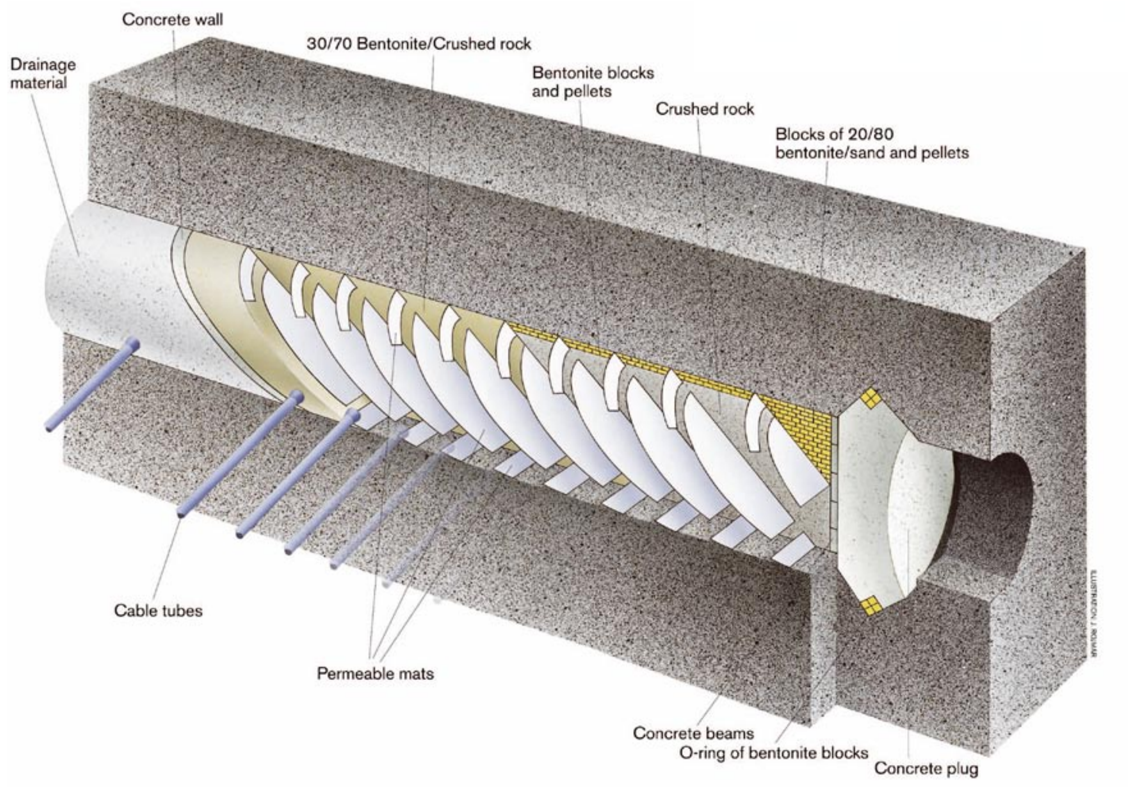


Figure 2-16. *Illustration of the experimental set-up of the Backfill and Plug Test.*

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.

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

The flow testing in the backfill started after completed water saturation, when steady state flow and pressure had been reached.

2.4.4 Results

Since the backfill is judged to be completely water saturated the wetting system has been rebuilt and adapted to flow testing. The water pressure in all mats has been kept at the water pressure 500 kPa during the whole year until the start of the flow testing in October. The flow testing is done by decreasing the water pressure in the permeable mats sections (one by one) to 400 kPa and measuring the flow between the mat sections, starting with the filter at the plug. The results received so far have not yet been fully evaluated. Puls tests were performed with the local permeability sensors in March 2003. Results of these tests and adherent modelling work are given in Section 6.4.2.

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

Logging of measured results from all sensors have continued during 2003 except for the relative humidity sensors, which were disconnected since all those sensors showed full water saturation. Data are reported in sensors data reports /Goudarzi et al. 2003b/. Figure 2-18 shows an example of measured results. The water pressure in the rock measured in the short boreholes about 30 cm below the floor of the tunnel is plotted. Laboratory tests have been made to characterise the backfill material and to analyse the salt effect on HM properties, see Section 6.4.2.

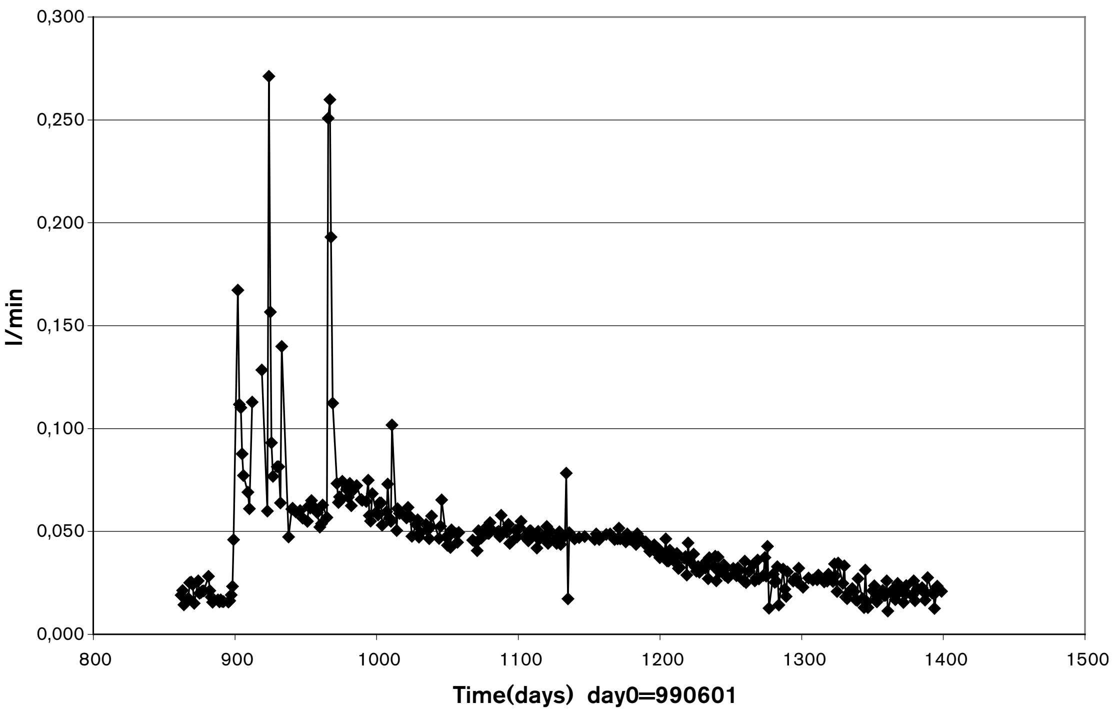


Figure 2-17. *Water flow through the plug and its surroundings. 500 kPa water pressure has been kept inside the plug from day 965 to day ~ 1,320, when the water pressure was reduced to 400 kPa.*

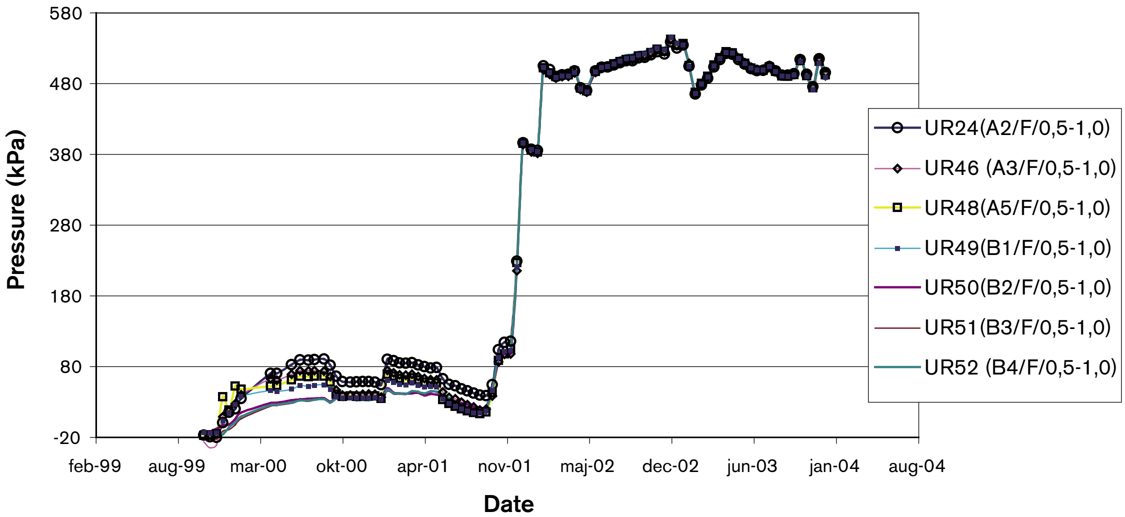


Figure 2-18. *Water pressure measured in boreholes in the floor 30 cm below the rock surface. UR24, 46, 48 and 49 are placed in the 30/70 sections and the rest in the 0/100 sections.*

2.5 Long Term Test of Buffer Material

2.5.1 Background

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

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

2.5.2 Objectives

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

- Collect data for validation of models concerning buffer performance under quasi-steady state conditions after water saturation, e.g. swelling pressure, cation exchange capacity and hydraulic conductivity.

- Check of existing models on buffer-degrading processes, e.g. illitization and salt enrichment.
- Gather 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 data concerning gas penetration pressure and gas transport capacity.
- Gather information which may facilitate the realisation of the full scale test series with respect to clay preparation, instrumentation, data handling and evaluation.

2.5.3 Experimental concept

The testing principle for all tests is to emplace parcels containing heater, central tube, pre-compacted clay buffer, instruments, and parameter controlling equipment in vertical boreholes with a diameter of 300 mm and a depth of around 4 m, see Figure 2-19. The test series (Table 2-8) concern realistic repository conditions except for the scale and the controlled adverse conditions in three tests. Adverse conditions in this context refers to high temperatures, high temperature gradients over the buffer, and additional accessory minerals leading to i.e. high pH and high potassium concentration in clay pore water. The central copper tubes are equipped with heaters in order to simulate the decay power from spent nuclear fuel. The heater effect are regulated or kept constant at values calculated to give a maximum clay temperature of 90°C in the standard tests and in the range of 120 to 150°C in the adverse condition tests.

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

Table 2-8. Layout of the Long Term Test series.

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

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

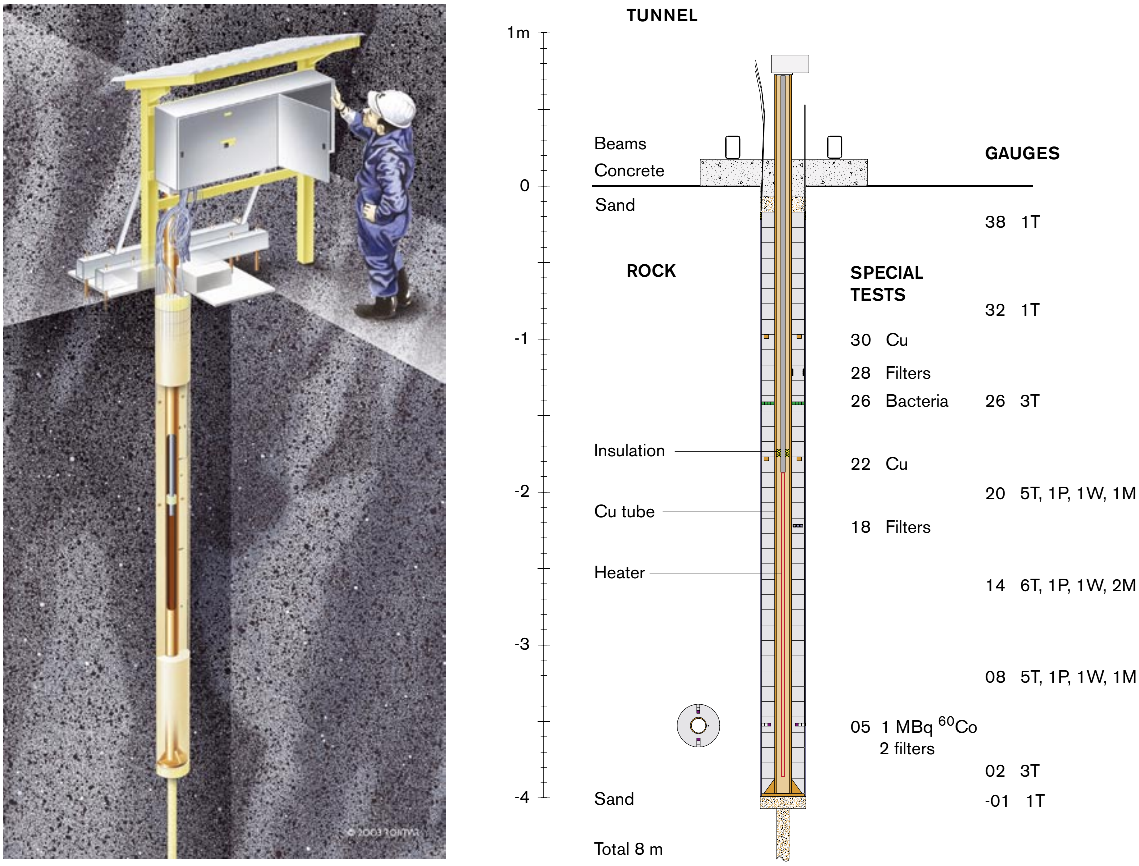


Figure 2-19. *Illustration of the experimental set-up in the Long Term Test of Buffer material (left) and a cross-section view of an S-type parcel (right). The first figures in the column denote block number and second figures denote the number of sensors. T denotes thermocouple, P total pressure sensor, W water pressure sensor, and M moisture sensor.*

2.5.4 Results

The analyse results from the extracted A0 parcel are used for modelling the chemical and mineralogical evolution in the buffer by Enviros, Barcelona. The modelling is made by use of a transport code coupled with a geochemical code (PHAST) and is aimed at improving previous modelling by taking the prevailing temperature gradient into account.

Corrosion of embedded copper rods have been measured *in situ*, and shows an average corrosion rate of around 2 µm per year, which is close to what was found for the retrieved coupons in parcels S1 and A0. The remaining ongoing four long term test parcels have functioned satisfactory, and temperature, total pressure, water pressure and water content have been continuously measured and registered every hour. The bentonite swelling pressure is still increasing in several positions, showing that water uptake is still ongoing, although the tests have been running for almost four years. Temperature gradients are decreasing, likely as a consequent of the ongoing water saturation (Figure 2-20).

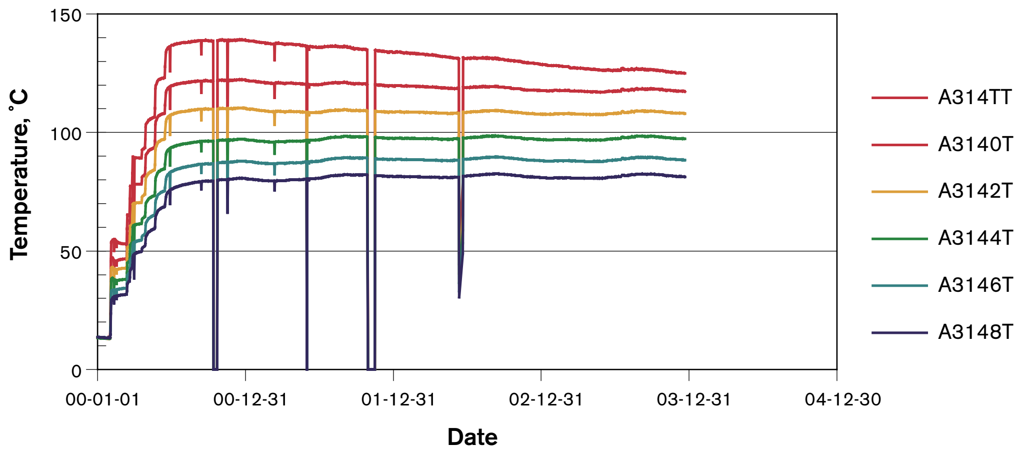


Figure 2-20. Measured temperatures from test start in the warmest section in parcel A3. Uppermost curve represent copper tube surface temperature, and the next curve shows the temperature 2 cm outwards into the bentonite, etc. The lowest curve shows the temperature at the interface with rock.

The incoming data from the four ongoing parcels are automatically monitored, and all recorded data are followed up monthly. Supply and minor function tests will be made during 2004. Online measurements of the corrosion rate of embedded copper rods will be made in parcel A2. Results from temperature and moisture measurements of the A0 parcel will be made for modelling by use of the THM-code Code Bright. Geochemical modelling is ongoing, and mineralogical analyses/modelling will be made by use of Rietweld analysing technique. Detailed planning for the uptake of the 5-years parcels will start during the fall 2004. The uptake is preliminary planned to start in March 2005.

2.6 Cleaning and sealing of investigation boreholes

2.6.1 Background

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

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

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

2.6.2 Objectives

The main objective of this project is to identify and to demonstrate the best available techniques for cleaning and sealing of investigation boreholes. The project comprises two phases. Phase 1 is mainly an inventory of available techniques, and Phase 2 aims to develop a complete cleaning and sealing concept and to demonstrate it. Phase 1 of the project was finalised in the end of 2003 and the project has now come to Phase 2.

2.6.3 Experimental concept

In Phase 2 the work is divided in the four main areas described below:

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

2.6.4 Results

The first Phase of this project is completed. A state of the art report summarising the developments of the sealing and cleaning techniques during the last 10–15 years has been published as an internal report (TD) titled “Borehole plugging – State of art”. The major conclusions were that smectite clay has been used successfully for borehole plugging and is recommended as main candidate material in the forthcoming work. Cement is concluded to serve less good, primarily because of questionable chemical stability.

In November 2003 the decision was taken to continue with Phase 2 of the project. During 2003 efforts have been spent on detailed planning of the second phase of the project and planning of laboratory test to be performed on candidate materials (e.g. bentonite and cement mixtures). Studies on techniques for manufacturing perforated copper pipes that can host precompacted clay blocks have also been made. Investigations of different techniques to be used for stabilising the upper 50 meters of the boreholes that can withstand the pressure from potential ice loads have also been initiated.

2.7 Injection grout for deep repositories

2.7.1 Background

Use of common construction materials, as steel and concrete, are foreseen in the deep repository. With respect to the repository long-term safety a suitable chemical environment is vital. The use of low-pH products is necessary in order to get leachates with a sufficiently low pH (≤ 11).

A pre-study in 2001 was followed by a feasibility study in 2002 – mid 2003. The current project aims at achieving some well quantified, tested and approved low-pH injection grouts to be used from the start of the construction of the underground rock characterisation facility ONAKO. The project is a joint project between SKB, Posiva and NUMO. The project is divided into four sub projects:

SP1 Low-pH cementitious injection grout for large fractures.

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

SP3 Field testing in Finland.

SP4 Field testing in Sweden.

The work to be carried out at the Äspö HRL is part of sub project 4, Field testing in Sweden, and started in December 2003.

2.7.2 Objectives

The objective of the field test in Äspö HRL is to investigate if it is possible to estimate/predict the penetration of silica sol based on transmissivity and hydraulic aperture, resulting from hydraulic tests.

The evaluation will increase the knowledge concerning the behaviour of silica sol, which will be useful for predictions and selection of grouting strategies.

2.7.3 Experimental concept

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

2.7.4 Results

Plans and programme for the field-test at Äspö HRL are being written and resources booked. The actual field-test and evaluation of results will be performed during 2004.

2.8 KBS-3 method with horizontal emplacement

2.8.1 Background

The KBS-3 method based on the multi-barrier principle is accepted by the Swedish authorities and the government as base for the planning of the final disposal of the spent nuclear fuel. The possibility to modify the reference method and make serial deposition of canisters in long horizontal holes (KBS-3H) instead of vertical emplacement of single canisters in the deposition hole (KBS-3V) has been considered since early nineties, see Figure 2-21. The deposition process in KBS-3H requires that each copper canister and its buffer material are assembled into a prefabricated waste package, hereafter called super container, see Figure 2-22.

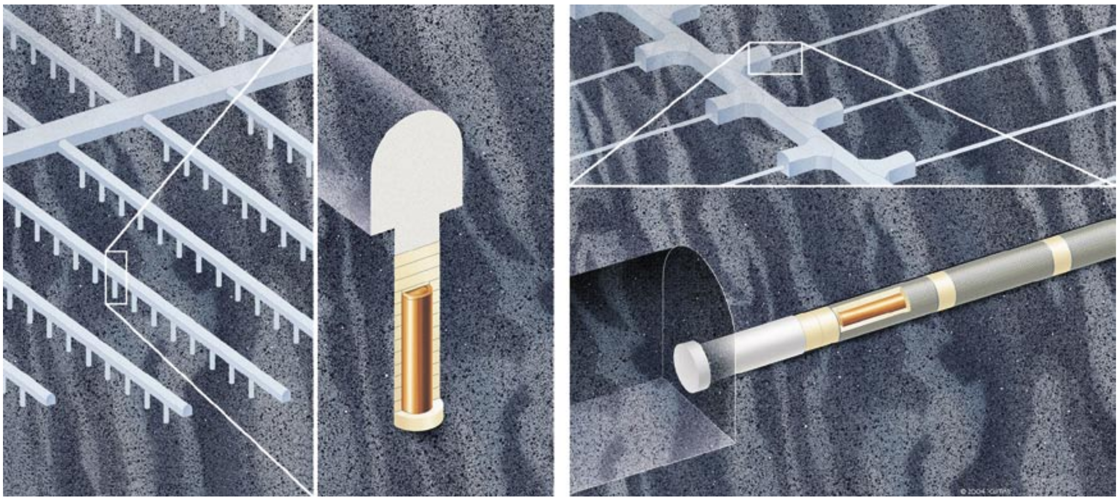


Figure 2-21. *Schematic illustrations of variants of the KBS-3 method.*

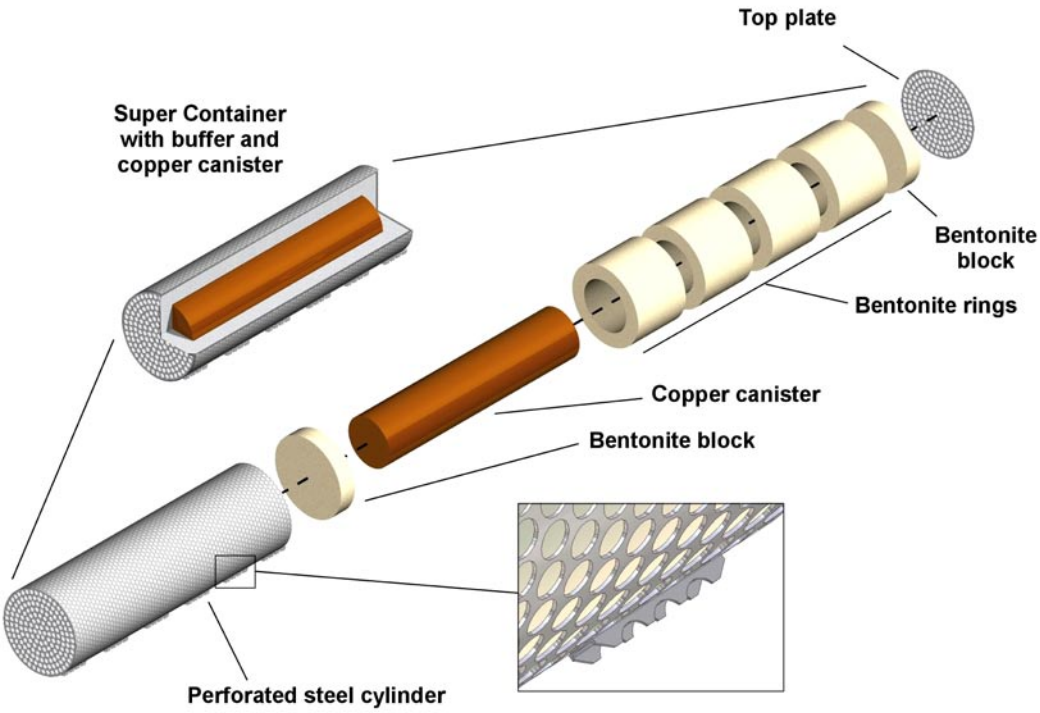


Figure 2-22. *Super container consisting of one copper canister, buffer material and a perforated steel shell.*

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 out by SKB in co-operation with Posiva.

2.8.2 Objectives

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

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

Before KBS-3H can be considered as a realistic alternative to KBS-3V the investigations have to show positive results regarding a number of questions for instance emplacement technology, the design of the buffer.

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 deposition tunnels, the deposition technique and the function of the buffer.

2.8.3 Results

During 2003 work within the Basic Design phase has been focused on three subtasks; Technical development of the equipment necessary for construction and operation of a KBS-3H repository, Preparations for a future full scale demonstration at Äspö HRL, and studies of the barrier performance of the KBS-3H concept. The Basic Design phase will be reported during the third quarter 2004.

Basic design work on the deposition equipment necessary for the KBS-3H concept has been made. An important part of the design work was full scale tests of transport cushions with both water and air as the carrying media. The results showed that water was the most efficient media. The next step, detailed design and manufacturing of deposition equipment, will be based on this experience.

A number of experiments regarding the buffer behaviour in the KBS-3H concept have been finalised, for instance the 1:10 scale experiment in which the interaction between the bentonite and the perforated super container was studied, see Figure 2-23. The results of the experiment were positive.

Preparations for a future full scale demonstration at Äspö HRL

In the beginning of 2003 it was decided that the future demonstration of the KBS-3H concept will take place at the –220 m level in the existing niche NASA 1623A. The dimensions of the niche was not large enough and therefore the niche was enlarged to the present dimensions about 25×15×7.5 (l×w×h) meters. Exploration drilling for the horizontal deposition holes has been made and grouting through the core holes was carried out during the first part of 2004.

Figure 2-23. *Photo from 1:10 scale experiment with a perforated container containing bentonite buffer.*

Studies of the barrier performance of the KBS-3H concept

During 2003 three independent nuclear waste management organisations (Numo, Enresa and Nagra) have reviewed the preliminary safety assessment of the KBS-3H concept. Overall, the KBS-3H concept was considered as a feasible alternative to KBS-3V. However, significant issues and demonstration work that should be addressed were identified. A number of critical issues related to the long term safety of the concept have been identified during 2003, for instance thermal analyses and effects of iron-bentonite interaction, see Section 6.8.4.

2.9 Large Scale Gas Injection Test

2.9.1 Background

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

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

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

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

2.9.2 Objectives

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

2.9.3 Experimental concept

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

The installation phase consists of the design, construction and emplacement of the experiment and it includes:

- Characterisation of the deposition hole and hydraulic measurements of the wall of the deposition hole (major fractures and EDZ properties).
- Development of a technique for the manufacturing of buffer blocks with exceptional high water content. Manufacturing of a set of blocks for one deposition hole. Preliminary modelling of the hydration of the buffer.
- Preparation of a full-scale canister with gas injection equipment.
- Design and construction of a lid, which will seal the deposition hole and simulate the tunnel backfill.
- Instrumentation of the wall of the deposition hole.
- Design and construction of a gas injection and measurement field laboratory and installation of the laboratory at the site.
- Testing of the equipment before deposition of the canister.
- Preparatory works in and around the deposition hole.
- Installation of canister and buffer in the deposition hole.
- Installation of the lid and sealing of the deposition hole.

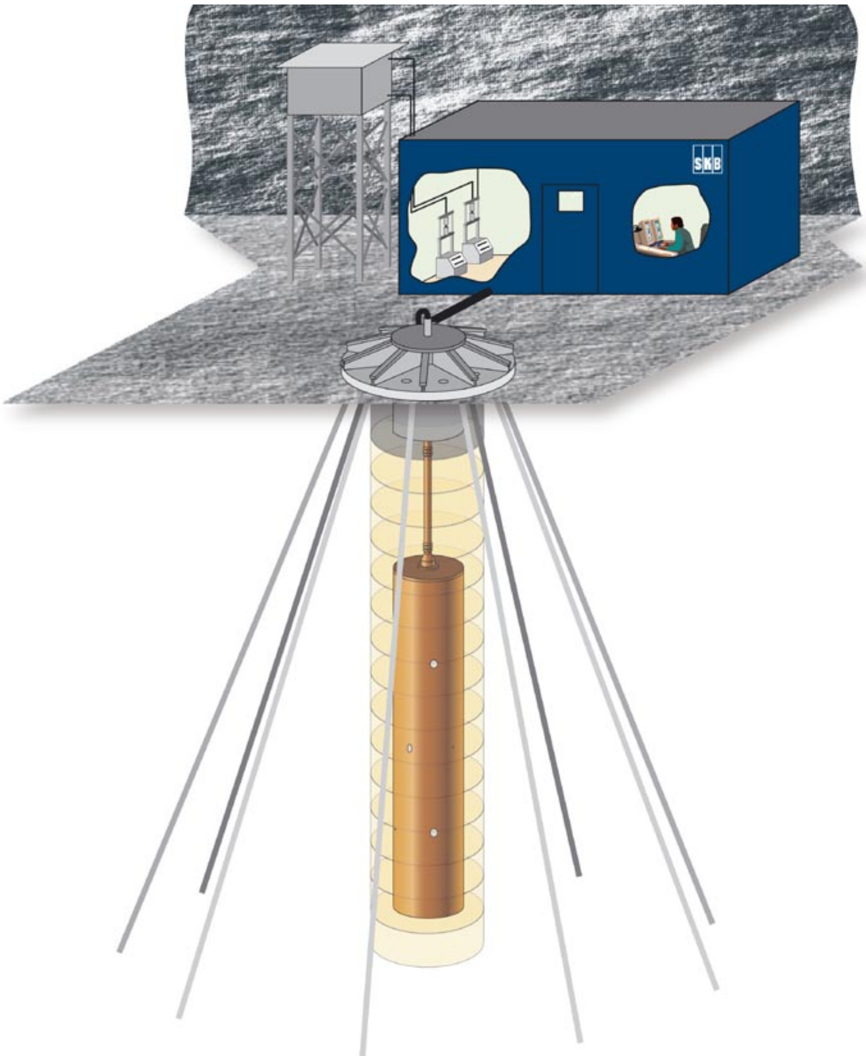


***Figure 2-24.** Illustration of experimental set-up of the Large Scale Injection Test.*

The aim with the hydration phase is to fully saturate and equilibrate the buffer. This will be done by:

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

The saturation will be monitored by measuring pore pressure, total pressure and suction at both the buffer/rock interface and key locations within individual clay blocks. The hydration phase will provide an additional set of data for (T)HM modelling of water uptake in a bentonite buffer. However, no such modelling is planned within the project at this stage.

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

2.9.4 Results

Planning of and preparations for the installation of the test have been made during 2003. The test will take place in an existing deposition hole (DA3147G01) in the TBM tunnel. The information available on the hole is sufficient and no new characterisation is planned.

The bentonite blocks used in the test are manufactured in a hydrostatic well press (30,000 tonnes). The goal was to achieve a water saturation degree of 95% in the rings (surrounding the canister) and 98% in the cheeses (emplaced above and below the canister). The pressing was successful and resulted in 1% higher water saturation degree in all blocks. A full-scale canister with gas injection equipment and instrumentation has been manufactured.

The measurement field laboratory hosted in a blue container is designed and constructed by BGS Nottingham.

A lid for the upper part of the deposition hole, very similar to the one used in the Temperature Buffer Test, has been designed and constructed.

Testing of equipment and preparatory works in and around the deposition hole and the installation of the test are in progress. The artificial water saturation of the buffer is expected to start in the end of 2004.

2.10 Temperature Buffer Test

2.10.1 Background

The aim of the Temperature Buffer Test (TBT) is to evaluate the benefits of extending the current understanding of the behaviour of bentonite buffer to include high temperatures (above 100°C). The French organisation Andra is running the test in Äspö HRL in co-operation with SKB.

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

2.10.2 Objectives

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

2.10.3 Experimental concept

TBT is located in the same test area as the Canister Retrieval Test (CRT) at the –420 m level. Two identical heater probes, each 3 m long and 0.6 m in diameter, are stacked in a vertical 1.8 m diameter deposition hole. The principle design of the test and the experimental set-up are shown in Figure 2-25.

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

Two buffer arrangements are being investigated:

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

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

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 that 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.

2.10.4 Results

During 2002, TBT design modelling, procurement of instruments, fabrication of bentonite blocks have been carried out by Clay Technology and heater probes built by Aitemin. Early 2003, the experiment was installed in Äspö HRL. The operation phase started late March 2003. Artificial water pressure and heater power have been set according to plan. Monitoring and sampling of experimental data are continuously ongoing during the operation phase. A data link to Andra's head office in France has been established.

The initial thermal shock has produced its effect showing local desaturation of the bentonite in place where temperature exceeded 100°C. No fluid pressure was measured in the sand of the composite buffer.

A modelling group, formed with Swedish, Spanish and French teams, has issued a preliminary predictive modelling report mid 2003. Predictions were compared with the first experimental results and presented in November 2003 at Sitges /Hökmark, 2003/.

Experimental activities

The experiment has generated data since the start in March 2003. The results include measurements of temperatures, relative humidities, stresses, total pressures, pore pressures and cable forces in the anchoring system. The inflow into the sand filter surrounding the experiment is also recorded. The data are reported in sensor data reports /Goudarzi et al. 2003c/. The experimental findings include the following:

- The temperature at the surface of the lower heater is around 140°C. For the upper heater the surface temperature is higher, around 160°C, because of the insulating sand shield.
- The saturation of the bentonite is now in general progress. Around the lower heater there is a 0.15 m annular zone that shows clear signs of drying. Also this dehydrated zone is now slowly being resaturated.
- The inflow into the sand filter takes place under an elevated pressure. The pressure is needed to overcome a flow resistance that may be a result of clogging of the filters attached to the tips of the inflow pipes, or a result of sand filter compression and simultaneous bentonite intrusion.

Modelling activities

A predictive modelling phase has been completed. Blind predictions were made by a number of teams, organised by Andra, Enresa and SKB prior to releasing the first sets of experimental results. The modelling was based on a case definition given in a specific predictive modelling program. Comparisons between the different predictions and between predictions and experimental results have been compiled in a paper, presented at the workshop on large-scale field tests in granite, Sitges, Spain, in November 2003 /Hökmark, 2003/. The focus of the modelling work has largely been on the horizontal sections at the mid-height of the two heaters (Figure 2-26). These sections are particularly densely instrumented /Sandén et al. 2003/ and provide convenient test grounds for conceptual and numerical models of interest to high temperature aspects on THM processes in bentonite. Predictions were made of temperature, relative humidity, degree of saturation, stresses and pressures. Examples of predicted and measured values of the relative humidity are found in Figure 2-27 and Figure 2-28 for the two horizontal scan-lines, respectively. Figure 2-29 shows temperatures, measured and predicted, at a vertical scan-line located 0.2 m from the heater surfaces.

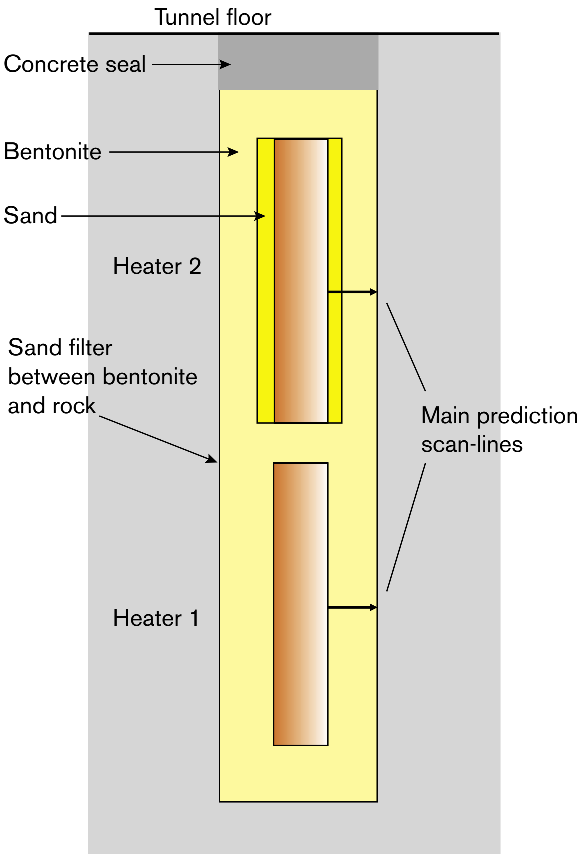


Figure 2-26. *Schematic view of the experiment and location of the most important scan-lines.*

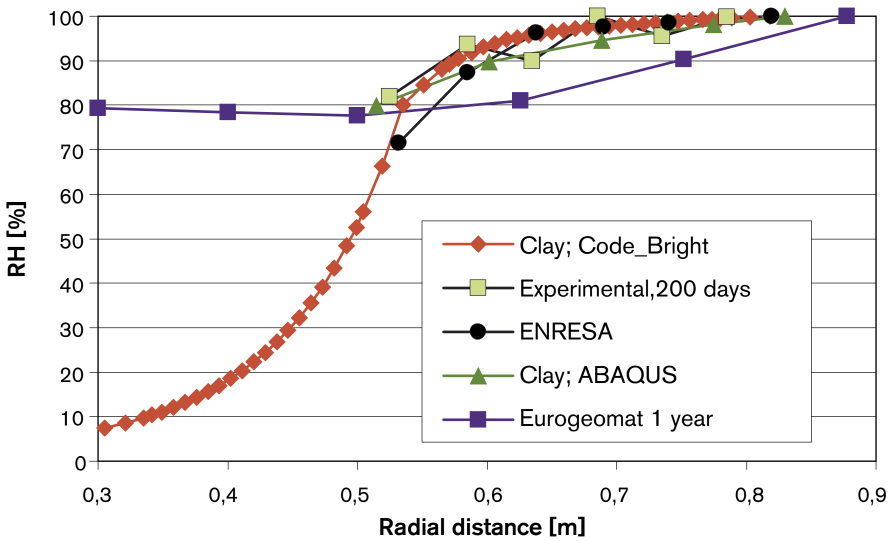


Figure 2-27. *Predicted and measured values of the relative humidity on radial scan line at mid-height of the upper heater after 270 days.*

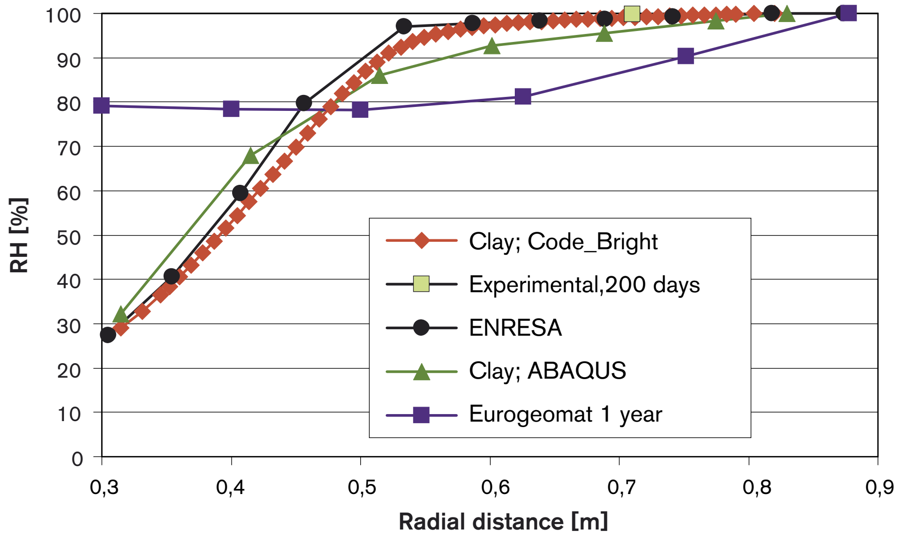


***Figure 2-28.** Predicted and measured values of the relative humidity on radial scan line at mid-height of the lower heater after 270 days.*

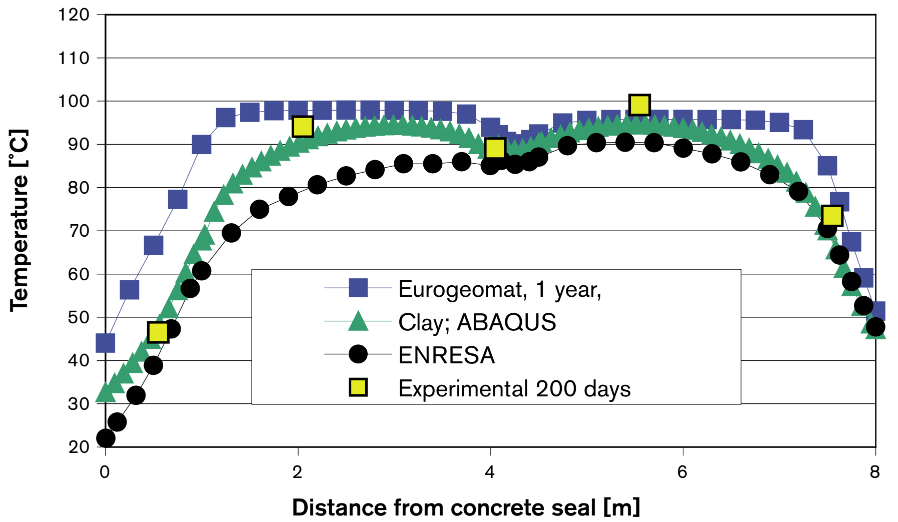


***Figure 2-29.** Predicted and measured values of the temperature on vertical scan-line 0.2 m from the heater surfaces after 270 days.*

2.11 New experimental sites

2.11.1 Background and objectives

The major aims of this project have been to find new experimental sites at Äspö HRL for three large-scale experiments: Äspö Pillar Stability Experiment (Apse), Testing of low-pH grout, and KBS-3 method with horizontal emplacement (KBS-3H) and to carry through the necessary rock work for providing the tests with large enough openings. Another objective is to identify possible sites for two to three full scale deposition holes, which can be bored in conjunction with the boring of the two holes in the Apse project. No needs for these holes are presently identified, and the aim is to prepare for the future needs as new excavation will be prohibited for several years because of the impact this has on projects related to Natural barriers.

The use of explosives is known to cause disturbance in the hydraulic regime in the whole Äspö rock mass. However, the disturbances have been permanent only in very few cases. Another conflict with other experiments is that a penetration of a water-carrying fracture may change the hydraulic head in a large region around the place where the intersection takes place.

2.11.2 Results

Experimental sites were selected for Apse and the KBS-3H experiment during the first quarter 2003. The Apse site is located at the –450 m level and the KBS-3H site is located in a niche at the –220 m level. Testing of low-pH grout can be made in existing tunnels or niches in Äspö HRL.

Most excavation work took place during the second quarter and the excavation work was finalised in July. During the excavation experiments dependent on a stable hydraulic environment were stopped and held on stand-by. An approximately 70 m long tunnel is excavated for Apse and a niche with an average height of 8 m and a bottom area of about 15×15 m is excavated for KBS-3H. From the niche exploratory boreholes with a total length of 160 m has been drilled.

The location of two extra deposition holes has also been decided, one at the entrance of the Apse tunnel and one at the –420 m level close to the TBT site. The deposition hole in the entrance of the Apse tunnel was bored as a training hole before boring the Apse holes. The hole at –420 m level will be made in 2004.

2.12 Learning from experiences

2.12.1 Background and objectives

Several large-scale experiments have during the years been installed in Äspö HRL and methods and machines used have provided experiences for refinement and evaluation of limits of the methods applied. Emplacement of buffer and canisters, and backfilling of tunnels have been experienced in Canister Retrieval Test, Prototype Repository and Backfill and Plug Test. In this project these experiences are documented and analysed with respect to possible improvements as well as limitations in methods and techniques.

The aim is to identify techniques by:

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

2.12.2 Results

Each experiment has been reported in installation reports. A draft report that describes the large series of experiments related to engineered barrier systems that have been conducted in SKB's underground laboratories and construction sites during the time period 1981 to 2003 has been compiled and will be finalised and published as an IPR report in Äspö's report series in 2004.

In addition, a major programme is run on development of backfill material and means of backfilling deposition tunnels. Field tests may be needed in the future.

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 the Prototype Repository project, and the Task Force was put in a stand-by position. As the European Commission funding of the Prototype Repository project will cease in February 2004 it is 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 issue of establishing a Task Force on EBS was revisited during this year's Äspö International Joint Committee meeting. The issue was also raised during this year's ISCO meeting (Grimsel Test Site – annual scientific meeting). The indication in both those fora was that there is a need for a co-ordination of similar activities, like conducting modelling work that uses data from experiments in both Äspö HRL and Grimsel Test Site. The IJC meeting recommended SKB to make a proposal, for consideration by the Äspö HRL participants in the first place, with the goal of fulfilling integration needs as well as being activated in early 2004. A proposal is planned to be submitted to the 2004 year IJC meeting.

3 Geo-science

3.1 General

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

- Establish and maintain geo-scientific models of the Äspö HRL rock mass.
- Establish and develop the understanding of the Äspö HRL rock mass material properties as well as the knowledge of measurements that can be used in site investigations.
- Determine the rock mechanics characteristics at potential repository depths at candidate sites.
- Develop methods for numerical modelling of stress and strain evolution, and methods for *in situ* stress measurements.

3.2 GeoMod Project

3.2.1 Background and objectives

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

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

The objectives of the GeoMod Project are to:

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

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

3.2.2 Results

The models of Äspö within each geo-scientific discipline have been assessed and results from the different projects conducted at Äspö has been utilised to modify or update the models. The improved models will be used e.g. to facilitate future selection of experimental sites in the Äspö HRL. The reporting of the different geo-scientific disciplines has been made and the draft reports will after review be issued as IPR reports in the Äspö series in 2004.

3.3 Rock stress measurements

3.3.1 Background and objectives

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

3.3.2 Results

A co-operation with Posiva with the objective to quality-assure overcoring data has been initiated. The first phase has been completed which includes development of a numerical tool for predictions of isotropic and elastic conditions in rock. SKB has contributed with seven articles to the special issue of the International Journal of Rock Mechanics and Mining Sciences /IJRMMS, 2003/ where ISRM's suggested strategy for rock stress measurements is presented.

3.4 Rock creep

3.4.1 Background and objectives

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

3.4.2 Results

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

3.5 Äspö Pillar Stability Experiment

3.5.1 Background

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

A Pillar Stability Experiment is therefore initiated at Äspö HRL as a complement to an earlier study at URL performed by AECL in Canada. AECL's experiment was carried out during 1993–1996 in an almost un-fractured rock mass with high *in situ* stresses. The combination of high stresses and low fracturing gives the rock mass a brittle behaviour. The major geological difference between Äspö HRL and the URL is that the rock mass at Äspö is fractured and the *in situ* stresses significantly lower which gives an elastic rock mass response to loading. The conditions at Äspö HRL therefore make it appropriate to test a fractured rock mass's response when loaded through the transitional zone.

3.5.2 Objectives

The Äspö Pillar Stability experiment can be summarised in the following three main objectives:

- Demonstrate our current capability to predict spalling in a fractured rock mass.
- Demonstrate the effect of backfill (confining pressure) on the rock mass response to loading.
- Comparison of 2D and 3D mechanical and thermal predicting capabilities.

3.5.3 Experimental concept

To achieve the objectives a new tunnel (Figure 3-1) has been excavated in Äspö HRL to ensure that the experiment is carried out in a rock mass with a virgin stress field. The experimental tunnel has a rounded floor in order to concentrate the stresses to the centre of the tunnel. The tunnel is shown in Figure 3-2.

In the new tunnel a 1 m thick vertical pillar is constructed in the floor between two large boreholes, each with a diameter of 1.8 m. The pillar is designed in such a way that minor spalling will occur in the walls of the boreholes during the excavation. The spalling will then be propagated by heating of the pillar and hence applying a thermal load. The spalling that takes place during the heating phase will be monitored by LVDTs for displacement measurements, thermocouples and an Acoustic Emission, AE, system.

The two large vertical holes will be drilled in the floor of the tunnel so that the distance between the holes is 1 m. To simulate a 0.8 MPa confining pressure in the backfill the first hole excavated will be subjected to an internal water pressure via a liner. Convergence measurements, LVDTs, thermistors and an acoustic emission system will be used to monitor the experiment.

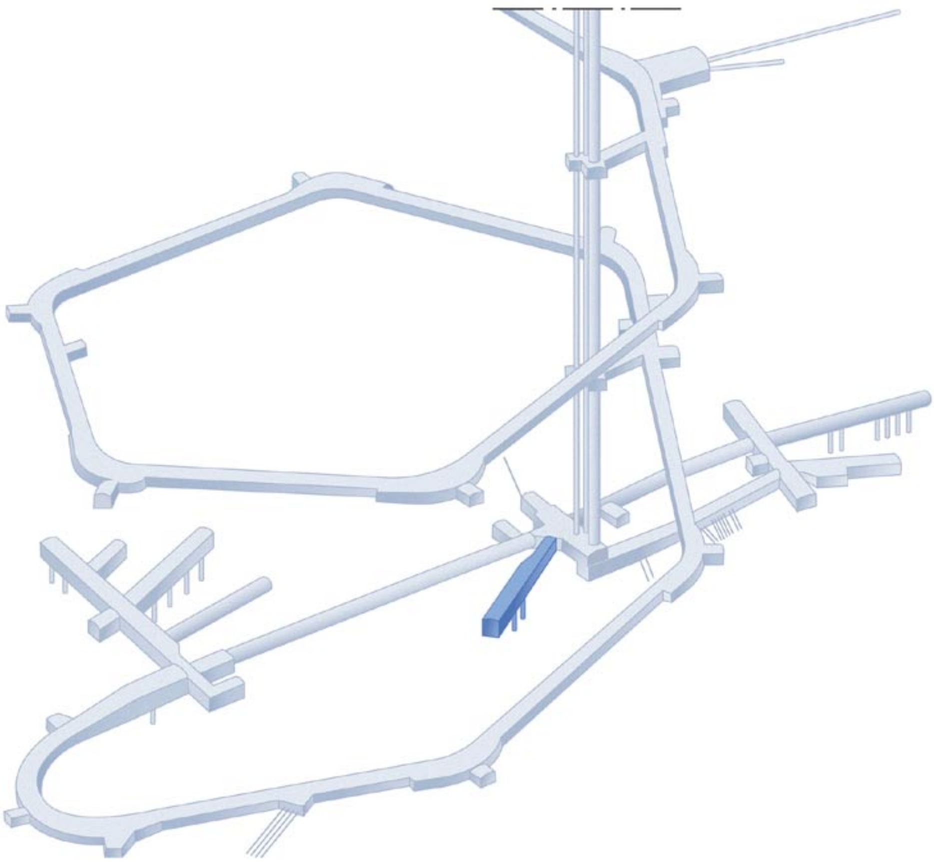


Figure 3-1. *The location of the Äspö Pillar stability experiment (dark blue).*

Figure 3-2. *The experimental TASQ tunnel shortly after the excavation.*

3.5.4 Results

The project work has proceeded well during 2003. The major achievements are presented below giving a short description of the projects status.

Rock excavations

During the late spring and summer 2003 the experimental tunnel, TASQ, was excavated by drill and blasting technique. The tunnel has a total height of 7.5 m and has an arched floor to nicely concentrate the stresses at the centre of it. The excavation was made in two steps. First a pilot tunnel with a height of 5.5 m was excavated followed by the excavation of the arched floor. The floor was excavated as a separate bench to minimise the excavation damaged zone in the floor region. The strategy worked well and the extent of the damaged zone is preliminary estimated to be100–200 mm. Extensive vibration measurements were performed during the blasting. The results will be evaluated and among other things the damping in different directions will be further investigated.

One of the two deposition holes that will be drilled for the experiment was completed during 2003. The second one is scheduled to be drilled in early 2004.

Geological characterisation

After the completion of the excavations the tunnel and the first deposition hole were geologically mapped and 14 vertical core boreholes drilled in the target area for the pillar. Extensive laboratory testing on core pieces from the vertical boreholes gave input data on rock strength, thermal properties and fracture properties of the rock close to the pillar. These site specific data were used as input data for the final update of the numerical models of the experiment.

During the excavation of the pilot tunnel convergence measurements were performed giving an excellent data series. The data was back analysed giving updated information of the actual *in situ* stress field and Young's modulus of the rock mass close to the experimental volume.

A detailed 3D-model of the fractures in the experimental volume was made using the data from the tunnel and core mapping.

Numerical modelling

Numerical modelling using the codes Examine3D, FLAC3D, PFC2D, FRACOD and JobFem were completed with the site specific input data derived from the characterisation programme performed. The new input data were similar to what earlier was assessed resulting in that the new predictions from the numerical modelling was very similar to the ones made on preliminary data.

Monitoring

The acoustic emission system that is one of the monitoring systems used in the experiment was installed prior the drilling of the first deposition hole. The system was enabled at night time when no work was made in the tunnel. The monitoring gave high quality data. The acoustic emissions were concentrated parallel to the tunnel indicating that the major principal stress is perpendicular to the tunnel direction. This validated the previous assessed direction of the major principal stress.

The thermocouples have been installed in the first deposition hole and in the adjacent core boreholes. In the beginning of 2004 they will be connected to the data sampling unit so that the background temperature is well defined before the heating starts.

3.6 Heat transport

3.6.1 Background and objectives

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

The aim of the heat transport project is to develop a strategy for site descriptive thermal modelling to decrease the uncertainties in the estimates of the temperature field in a repository. Less uncertain estimates of the temperature field make it possible to optimise the distance between canisters in the repository layout. The work includes measurements of thermal properties of the rock, examination of the distribution of the thermal conductivities, and analyses of the thermal properties at different scales.

3.6.2 Results

Comparison of thermal properties measured by different methods

In the strategy for thermal site descriptive models different kinds of uncertainties exist. Some of these uncertainties are related to the potential errors in the methods used for determining thermal properties of rock. Therefore a comparable study has been conducted and reported in /Sundberg et al. 2003/. In two earlier investigations /Sundberg and Gabrielsson, 1999; Sundberg, 2002/ thermal conductivity and thermal diffusivity of rock samples were analysed according to the TPS method (transient plane source). For a comparison, the same samples have been measured at the Geological Survey of Finland (GSF). In this later investigation, the thermal conductivity was determined using the divided-bar method and the specific heat capacity using a calorimetric method.

Comparable studies of measurements with different methods are rare. In this study, 17 samples were measured using the TPS method and the results were compared with results from the divided bar method and a calorimetric method. The mean differences between the results of the different methods are relatively low but the results of individual samples show large variations.

Conclusions:

- Thermal conductivity measured by the divided bar method gives for most samples slightly higher values, in average 3.4%, than the TPS method. The difference between individual samples ranges between –8.9% to +10.6%. See also Figure 3-3.
- The specific heat capacity measured by the calorimetric method gives for most samples slightly lower values, in average 2.4%, than the calculated specific heat based on the results of the TPS method. The difference between individual samples ranges between –13.2% to +6.1%.

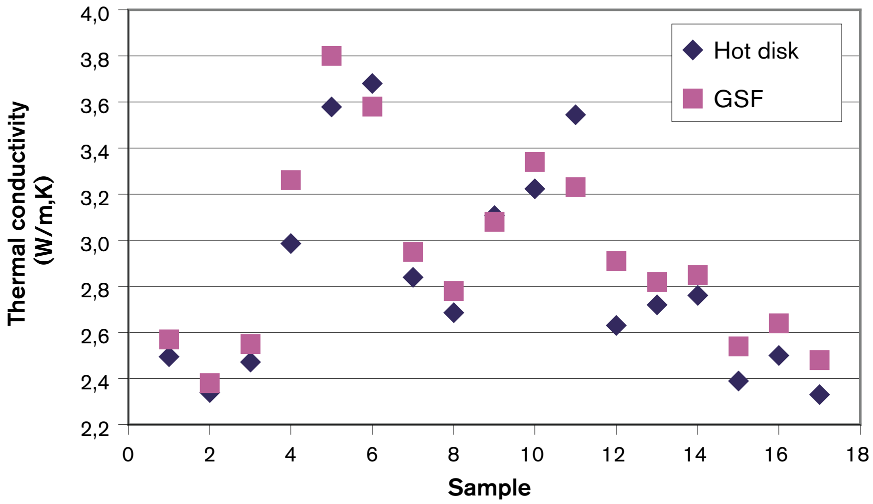


Figure 3-3. Thermal conductivity determined according to the TPS method (Hot Disk) and the divided bar method (GSF).

- Consequently, the thermal diffusivity evaluated from the divided bar and the calorimetric methods, is in average 5.7% higher than the thermal diffusivity measured by the TPS method. The difference between individual samples ranges between –2.9% to +15.1%.

The reasons for the differences in the results are mainly dependent on differences between the samples, errors in the temperature dependence of specific heat, and in the transformation from volumetric to specific heat. The TPS measurements are performed using two pieces (sub-samples) of rock. Only one of these two sub-samples were sent to the GSF and measured using the divided bar method and the calorimetric method. Further, sample preparation involved changes in the size of some of the samples. The differences between the methods are for most samples within the margins of error reported by the measuring laboratories. However, systematic errors in one or both methods cannot be excluded.

Recommendations:

- A set of thermal conductivity standard materials should be selected for testing using the different methods of the laboratories.
- Because of large obtained individual variations in the results, comparisons of different methods should continue and include measurements of temperature dependence of thermal properties, especially specific heat.

Analysis of distribution and scale factors

Thermal conductivities of the rock at Äspö HRL have been modelled from reference values of thermal conductivity of different minerals and from the mineral composition of all Äspö samples in the Sicada database /Sundberg, 2003/. The produced thermal conductivity database, including measured values, has been analysed according to different rock types. The analyse give values of 2.6 (std: 0.17) W/(m·K) for Äspö diorite and 3.05 (std: 0.32) W/(m·K) for Ävrö granite. However, there are uncertainties in the base material of rock classification, mainly due to problem to distinguish between Äspö diorite and Ävrö granite, but also because of different classification systems.

There is a relationship between thermal conductivity and density for the rock types at Äspö /Sundberg, 2002/. Equations of the relationship have been developed based on measurements of thermal conductivity, heat capacity and density /Sundberg, 2003/. The equations have been tested on two boreholes at Äspö with promising results, see Figure 3-4. It may be possible to evaluate the spatial distribution of the thermal properties from density loggings. However, more work is needed to develop a complete model including the handling of high and low density zones. The use of the relationship between density and thermal properties must be restricted to investigated rock types and density intervals. The relationship is probably related to the content of dark minerals.

There is an insufficient knowledge in the variation of thermal properties at different scales. If the whole variation within a rock type is in the cm-m scale the thermal influence on the canister is small. This is due to the fact that the small-scale variation in thermal properties is mainly averaged out in the 5–10 m scale. If the main variation within rock types is in the 5–10 m scale there is probably a significant effect on the canister temperature. However, it is likely that the observed variation occurs in both these scales.

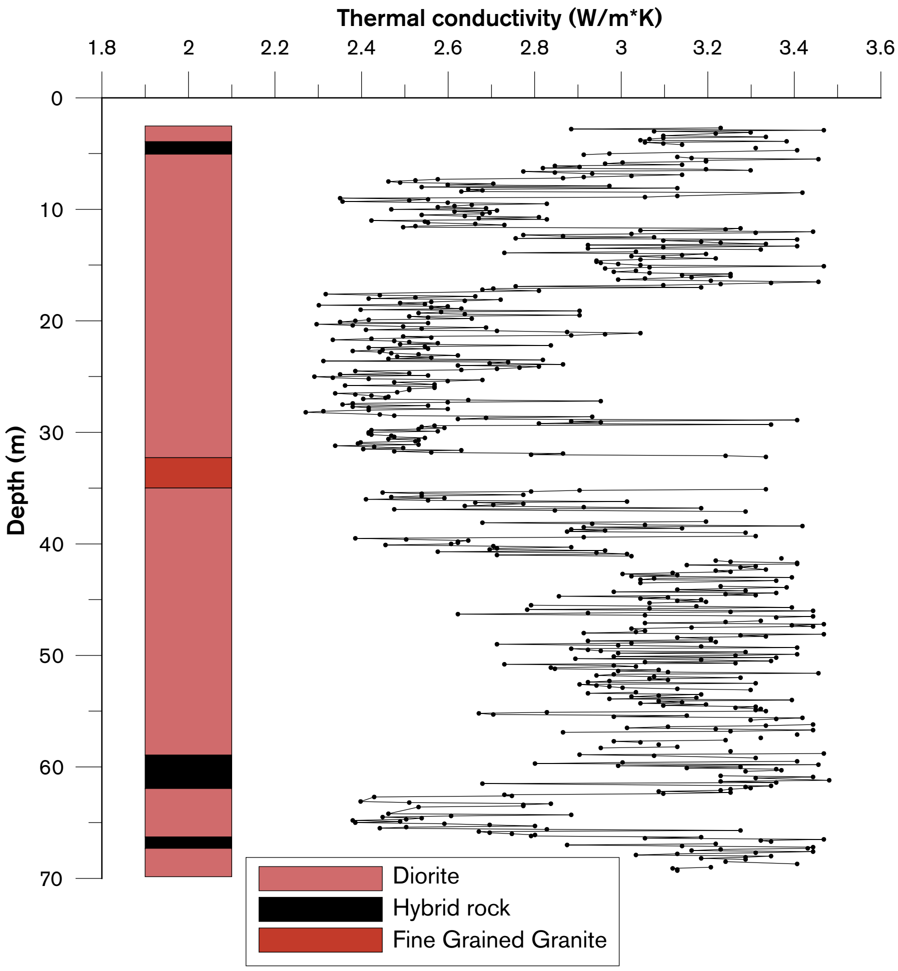


***Figure 3-4.** Thermal conductivity vs. depth for borehole KF0069A01. Example of thermal conductivity calculated from density loggings.*

Simulation has been performed of the sensitivity in canister temperature for variations in thermal properties within one rock type and between different rock types /Sundberg, 2003/. The results show that the canister temperature is quite sensitive to the thermal conductivity within an area ($6 \times 40\ m^2$) around the canister. The influence is obviously largest closest to the canister. With well defined thermal properties in the tunnel area there is still a large influence on the canister temperature, if low conductive rock is present outside the tunnel.

Conclusions:

- Density logging seems to be a promising method to evaluate the spatial distribution, scale factors and the variations in thermal properties of the rock mass. A model has to be developed in order to get a better understanding of the relationship and to handle different rock types.
- The knowledge is presently only basic about scale effects on thermal properties due to the measurement process and the actual thermal process in canister-tunnel scale. Measurements of thermal properties in different scales are needed.

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.

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

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

The overall purposes are to:

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

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

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

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

The ongoing or planned experiments and projects 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.
- The EC project Padamot (Palaeohydrogeological Data Analysis and Model Testing).

4.2 Tracer Retention Understanding Experiments

The primary objective of the True family of experiments is to improve the understanding of transport and retention processes in crystalline rock. The work done covers a variety of different scales, from laboratory experimentation for sorption and diffusion experimentation on decimetre sized drill core samples to *in situ* experiments in fracture systems on length scales of about 100 metres, see Figure 4-1. The work include basic characterisation of the rock mass to obtain the parameters of importance and subsequent cross-hole *in situ* tracer experiments performed over periods of months to years. The evaluation comprises integration of the collected information to descriptive models of the investigated fracture systems as well as descriptive models of the microstructure of investigated fractures and fracture zones. These models have formed the base for applying various approaches to numerical and analytical modelling of radionuclide transport and retention. The project has reported two major undertakings so far, the First True Stage (True-1), /Winberg et al. 2000/ focused on an interpreted single fracture on a length scale < 10 m, and the True Block Scale Project, focussed on a network of fractures on a length scale < 100 m /Andersson et al. 2002a,b; Poteri et al. 2002; Winberg et al. 2002/. The above two projects are presently followed by two continuation projects; True-1 Continuation and True Block Scale Continuation, both of which should be regarded as mutually supporting. True-1 Continuation focuses on improving description and understanding of the altered wall rock (fracture rim zone) and fracture infillings (fine-grained fault gouge) and its sorption characteristics. The True Block Scale Continuation applies the knowledge base obtained so far for making use of geological information for the purpose of prediction of reactive transport in fractured media. In this context, it is noted that the knowledge base from the True Block Scale rock volume was used to devise an integrated semi-synthetic hydrostructural model /Dershowitz et al. 2003/. This model is employed in the analysis of Task 6D and 6E as part of the Äspö Task Force work, cf Section 4.8.

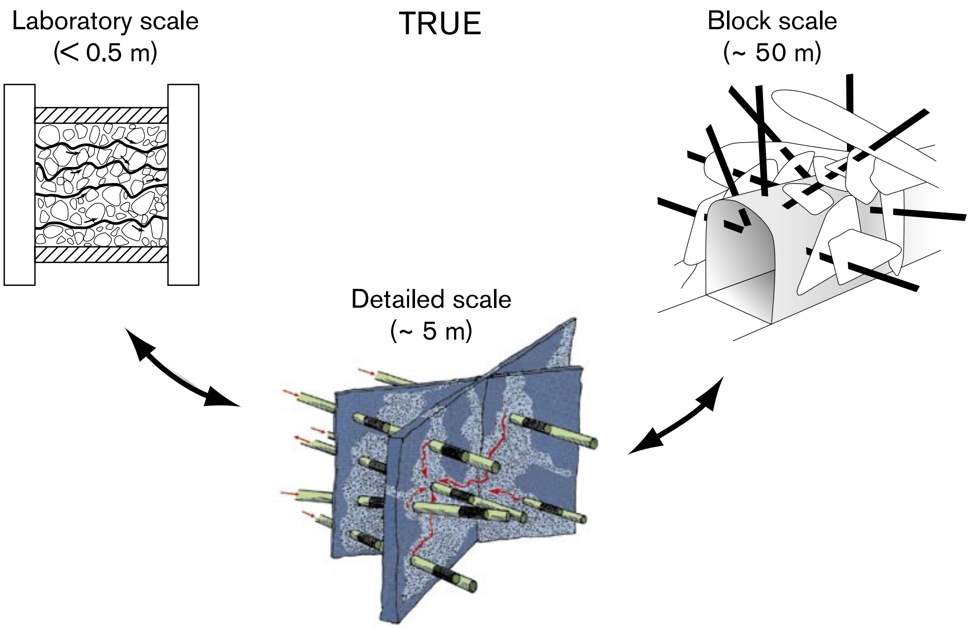


Figure 4-1. *Schematic representation of transport scales addressed in the True programme.*

4.2.1 True Block Scale Continuation

Background

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

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

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.

Results

The passed year has been one of a multitude of activities. For example, modelling in support of *in situ* tests (Phase BS2a), that pinpointed the area of interest for the subsequent *in situ* tests. This was followed by optimisation of the piezometer array and a sequence of pre-tests to test out the potential for tests with radioactive sorbing tracers as part of Phase BS2b.

Results of BS2a

The principle results of Phase BS2a are related to various types of modelling activities in support of the future *in situ* tests and their subsequent interpretation. The JNC-Golder team carried out extensive modelling to map out the parts of the True Block Scale rock volume which were feasible for *in situ* tests. In addition, the modelling explored the need for additional sampling points (new boreholes). The results showed that even tests with non-sorbing tracers in a complicated fracture network would be prohibitive from pure perspective of time. Instead, focus was shifted to Structure #19, located in the interior or the block, which could offer a) variable length scales and b) potential source sections for tracer experiments in background fractures.

The Andra-Itasca team /Darcel, 2003/ explicitly explored the possibility to make use of background fractures as source sections for the planned BS2b tests. In doing so they applied a concept whereby all structural information available at various scales were integrated to one unified description employing a power-law distribution of fracture length, see Figure 4-2. The analysis showed that the studied network is self-similar, implying that the distribution of small and large fracture lengths is the same at all scales considered. The analysis further showed that transport to a large extent is governed by the knowledge on the deterministic structures in which (or close to which) the planned tracer tests are to be performed.

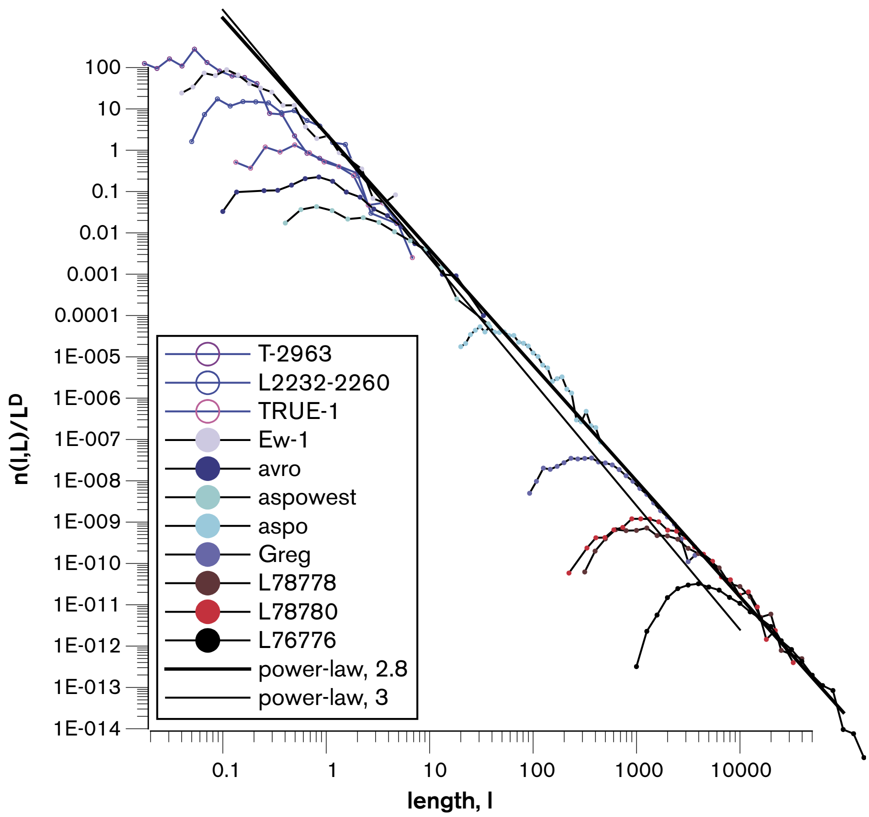


Figure 4-2. *Results of multi-scale analysis of structural data with a representation as a function of length of the number of fractures of a given length normalised by the characteristic size of the studied system.*

The Posiva-VTT team /Poteri, 2003/ explored the ability to distinguish various types of heterogeneity along a conceived transport path and its relative effect of transport of sorbing tracers. The analysis addressed both variations in material properties and variations in the flow field properties. Analysis of lateral (sideways) and longitudinal (along the flow path) heterogeneity showed that retention only depend on the effective quantity of the different properties, not on their spatial distribution. It was further noted that non-sorbing tracers with documented pore diffusivities will be especially useful for determining the effects of heterogeneity. In addition, the non-sorbing tracers will provide information on the diffusion-controlled retention (and heterogeneity) that is associated with a limited capacity of the available pore spaces. The heterogeneity associated with limited capacity can also be addressed by applying variable pumping rates. Saturation of the available immobile pore space is indicated when the tail of the breakthrough curve deviates from the power-law when the flow rate is decreased.

The significance of diffusion limitations and rim zone heterogeneity was also explored by the SKB-WRE team /Cvetkovic, 2003/. The impact of diffusion limitations cannot be observed when the injection pulse is finite or tail-off. It is noted that a rim zone of 10 mm will make observation of diffusion limitations impossible for Cs, difficult for Ba and possible for HTO.

Results of BS2b

A review of the needs to facilitate focus on Structure #19 and its environs showed that only Boreholes KI0025F02 and KI0025F03 required reinstrumentation. Apart from focussing on Structure #19 a series of focused short-time interference tests were made with new piezometer array in KI0025F03 to verify the connectivity of i.a Structure #25 (background fracture) and to guide packer positioning in KI0025F02. The test sections were at the new interpreted Structure #25 at 1–140 m borehole length and at two minor interpreted background fractures at 164–169 m and at 170–175 m borehole length. Unfortunately, no pressure responses were observed. However, the planned instrumentation with isolation of Structure #25 in KI0025F02 was carried out.

Subsequently a series of pre-tests (CPT1 through CPT3) were performed to identify a suitable sink in Structure #19 and also, through combined analysis of drawdown and tracer dilution anomalies, to identify suitable source sections for subsequent tracer experiments. The following sinks (maximum flow rate) were employed:

- KI0025F:R2 (Q≈3.4 l/min).
- KI0025F02:R3 (Q≈1.6 l/min).
- KI0025F03:R3 (Q≈2.8 l/min).

The sinks used in CPT-2 and CPT-3 gave good flow responses in all sections intersected by Structure #19. Structures #13, #21 and #25 only show minor responses in all three tests. Preliminary analysis of the pressure responses shows similar drawdown (about 1,800 kPa) in both sink sections during CPT-2 and CPT-3. However, the source sections show somewhat larger drawdown in test CPT-3.

Based on the results described above the following test geometries were proposed for the tracer tests with non-sorbing tracers (CPT-4) using KI0025F03:R3 (#19) as sink section, cf Figure 4-3 and Table 4-1. This selection primarily based on a good flow rate and pressure responses, its central location and suitable distances to source proposed locations.

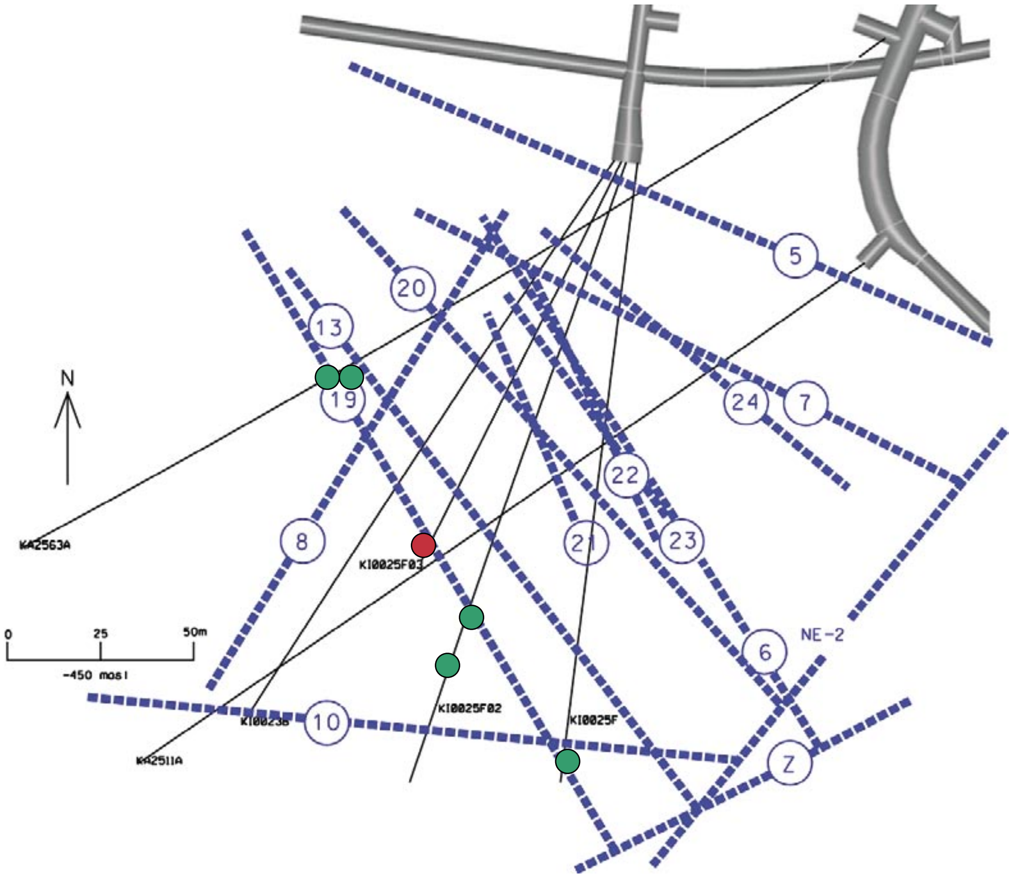


Figure 4-3. Overview of source sections (green) and sink section (red) used in CPT-4 tracer test with non-sorbing tracers.

Table 4-1. Overview of test layout for tracer tests with non-sorbing tracers (CPT-4, Phases A and B).

Source	Borehole section	Distance (m)	Tracer	Comment
A1	KI0025F02:R3 (#19)	20	RdWT	Short path, expected high mass recovery
A2	KI0023B:P2 (#19)	27	Amino G	Relatively short path, expected high mass recovery
A3	KI0025F:R2 (#19)	69	Uranine	Long path, good flow response
B4	KA2563A:S1 (#19)	49	Uranine	Long path, dual intercept, mixing with source B5
B5	KA2563A:S2 (#19)	49	RdWT	Long path, mixing with source B4
B6	KI0025F02:R3 (#25)	22	Amino G	Relatively short path, background fracture, recovery unknown

The test was divided in two batches, the first (CPT-4a) including sources A1–A3 and the second (CPT-4b) including sources B4–B6. Sources 1–5 was injected using a decaying pulse, while source 6 was injected with an excess pressure through the pressure line as this section has no flow lines.

Figure 4-4 and Figure 4-5 show the observed breakthrough curves for the two batches. Obvious are the clear and well-defined breakthroughs for the injections in the central parts of Structure #19. The mass recovery are > 80, > 70 > 40%, respectively. This implies that the two short flow paths can meet the requirements of an 80% recovery stipulated by SSI. However, the mass injected at KI0025F is partly lost, probably due to Structure Z south of the KI0025F intercept.

A fortunate result is the noted high mass recovery breakthrough (> 80%) for the injection in Structure #25 in KI0025F02, c.f. Figure 4-4. However, the other injections show mass recoveries of > 50% and > 2%, respectively and an increase in mass recovery is not expected.

Based on the data available early January 2004 only three flow paths are possibly suited for tracer tests with sorbing tracers (injection points in KI0023B:P2 (#19, L=27 m), in KI0025F02:R3 (#19, L=20 m) and in KI0025F02:R2 (#25, L=22 m). Because of radiation safety considerations it was decided to administer the tracer as fast as possible into the fracture using a weak dipole configuration. Therefore, the re-run tests were using a weak dipole to verify the mass recovery > 80% stipulated in the permit from SSI.

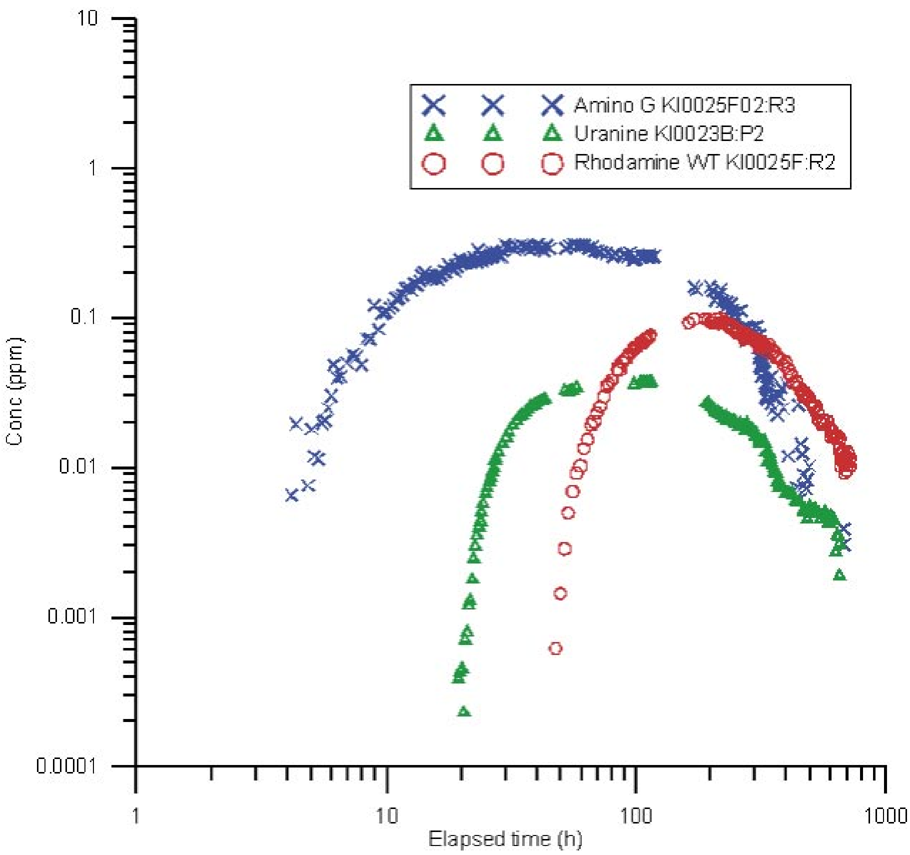


Figure 4-4. *Breakthrough curves for CPT-4a injections. Pumping in KI0025F02:R3 (Structure #19).*

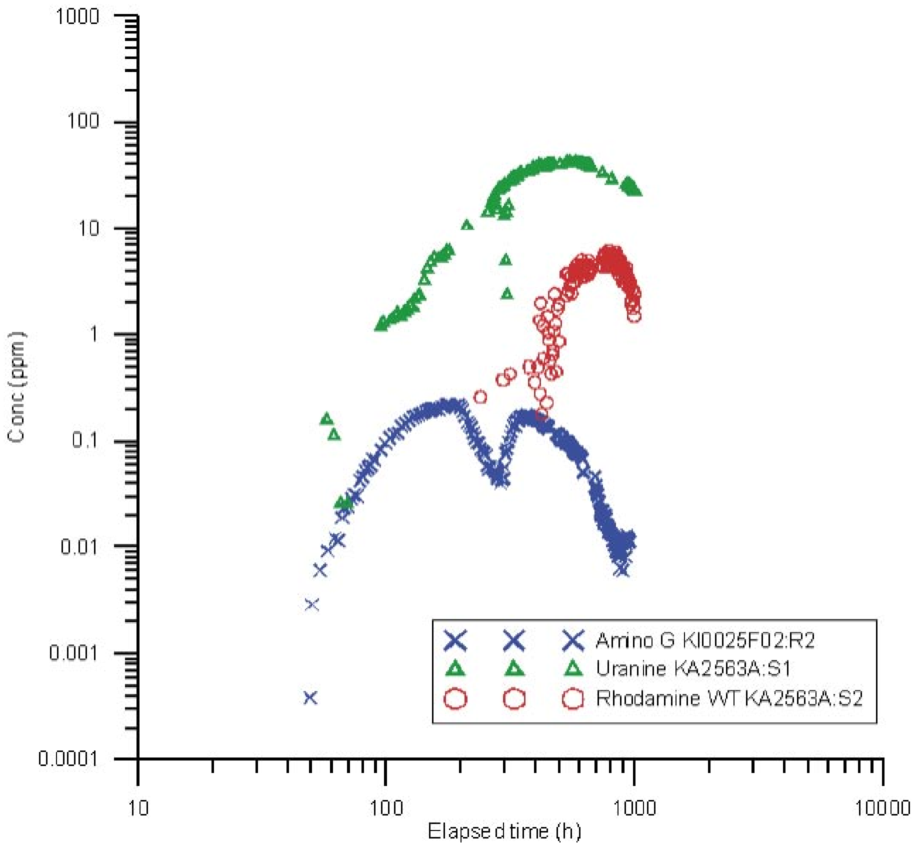


Figure 4-5. *Breakthrough curves for CPT-4b injections. Pumping in KI0025F02:R3 (Structure #19).*

4.2.2 True-1 Continuation

Background

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

A complication for the scheduling of planned future work lies in the fact that the True-1 and LTDE sites are hydraulically connected. Because LTDE requires undisturbed hydraulic conditions, LTDE has been given priority by SKB. Consequently, the resin impregnation at the True-1 site will be postponed until vital parts of LTDE have been accomplished. According to the present plans resin injection will be possible 2006 at the True-1 site.

Complementary works include detailed studies of fault rock zones and laboratory sorption experiments on fault gouge and fracture rim zone materials.

Objectives

The objectives of True-1 Continuation are:

- To obtain insight into the internal structure of the investigated Feature A, in order to allow evaluation of the pore space providing the observed retention in the experiments performed.
- To provide an improved understanding of the constitution, characteristics and properties of fault rock zones (including fault breccia and fault gouge).
- To provide insight into the three-dimensionality of the rock block studied as part of the First True Stage such that the role and effects of the fracture network connected to Feature A on the performed tracer tests can be assessed.
- To test a methodology to estimate fracture aperture from radon concentration in groundwater and radon flux from geological materials.
- 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 identified remaining field and laboratory activities related to the True-1 site includes:

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

Results

Principal activities during the year have been associated with preparatory characterisation work leading up to injection of epoxy resin in selected structures along the Äspö access tunnel. In addition, a comprehensive laboratory study on sorption characteristics of fracture rim zone and fault gouge material has been launched. Due to resources conflicts, only minor work has been put on realising two scientific papers on the True-1 work /Winberg et al. 2000/. Similarly no work has been put on assessment of fracture apertures using radon data.

Fault Rock Zones Characterisation

Principal achievements during the year included drilling of a total 16 triple tubed cored boreholes (diameter 76 mm) on four different structures of variable complexity /Stigsson et al. 2003/. The four structures which all intercept the tunnel, are located at approximately 1/596 m, 2/169 m, 2/430 m and at 2/545 m, range from discrete fractures to a full-fledged fracture zone (NE-2) with large amounts of fracture infillings. The outcome of the exploratory drilling including a tentative description of the identified structures is given by /Mærsk Hansen et al. 2003/. The boreholes were supplied with mechanical packer systems which isolated the interior of the borehole including the primary target zone for resin impregnation. The test section was equipped with two lines, one at the packer and one in the bottom of the hole to allow circulation. Measures were taken to reduce the volume of the test section by fitting a solid 74 mm polyethene cylinder to the packer filling the remainder of the hole. Subsequent hydraulic characterisation (injection tests, pressure monitoring) identified seven boreholes as being suitable for injection of resin. These were characterised by inflows of 0.001<W<1 l/min and stable natural formation pressures < 30 bars. The inspection of the drill cores revealed that the structure at 2/245 m was of minor or no importance to the project because of its lack of fault gouge and complex nature.

Drilling for supply of suitable material for injection tests in the laboratory was performed late 2002. The subsequent epoxy impregnation tests performed at the Swedish Cement and Concrete Research Institute (CBI) employed two resins (Epotech 301 and Barricade/Hesselberg) administered at two temperatures (12 and 35 degrees centigrade) under the influence of vacuum (110–130 mbar) and during a 30 min time period. Penetration depths of up to about 70 mm were noted and fractures of about 0.02 mm were completely impregnated. No significant differences in penetration or width filling ability associated with the temperature of the resin were noted.

Prior to injection a fluorescent dye (EpoDye) was added to the resin (Epotec 301). Hardener was added to the resin with a ratio of 1:4. Prior to injection the water in the fractures were exchanged by circulation isopropanol. Injections were normally made at pressures below 5 bars above ambient and over period of some 10 hours at the most (0.2–0.3 l/min). During the injection the pressure and the injection flow rate were monitored at regular intervals. Injections were performed successfully in seven of the 16 original exploration boreholes, three at 2/169 m, two at 1/596 m, one at 2/430 m and one at 2/545 m. The consumption of resin varied between about 0.1 litre at 1/596 m and about 1 litre at 2/169 m.

Planned work for 2004 includes overcoring with a 300 mm drill bit producing 277 mm cores. These cores will be used to verify and improve the macrostructural modelling. Careful sectioning of the drill cores will be used to image and reconstruct the microstructure of the connected pore spaces. Furthermore, the collected core materials will be subject to additional mineralogical, geochemical and petrophysical investigations.

Laboratory sorption experiments

This study was originally planned to be part of the True Block Scale Continuation but has been transferred to True-1 Continuation.

Specific objectives of the study are to:

- Provide sorption data for the interaction of this material with the type of sorbing tracers that so far has been used in the True program (Mainly tracers sorbing with cation exchange as the major mechanism)
- Make sorption studies addressing geologic material from the True Block Scale Structures #13, #19, #20 and #22 in the True Block Scale experiment. Structures #13, #20 and #22 are presumed to have been involved in the different flow paths in the True Block Scale Phase C experiment /Andersson et al. 2002b/. Structure #19 is the primary target structure for the True Block Scale Continuation experiment, se above section. In addition, material associated with the Fault Rock Zones structure at 1/596 and 2/169 m, see section above.

- Provide the cation exchange characteristics of the material, i.e. estimation of the cation exchange capacity, the fractional occupancies and the selectivity coefficients. This is performed in order to evaluate the validity of the predictions of sorption properties of fault gouge materials made by /Andersson et al. 2002a/. Corroboration of the employed estimation technique for intact wall rock and cataclasite materials was presented by /Dershowitz et al. 2003/.
- Perform desorption experiment with varying strength of desorption agents (different concentrations of the cation exchange competitor ammonium acetate, different concentrations of the complexing agent EDTA). This will be performed as a test to evaluate the sorption strength of naturally occurring cationic tracers (e.g. lanthanides, thorium and uranium) and to be the basis for a coming *in situ* sorption experiment.
- A test of the possibility of determining sorption coefficients using low levels of α-emitting isotopes (proposed for ^{241}Am and ^{226}Ra) within the laboratory experiment strategy document for the SKB Site Investigation Program /Widestrand et al. 2003/.

Preliminary results to be employed in the numerical model predictions will be provided early April 2004.

4.3 Long Term Diffusion Experiment

4.3.1 Background

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

Matrix diffusion studies using radionuclides have been performed in several laboratory- and *in situ* experiments. Some experimental conditions such as pressure and natural groundwater composition are however difficult to simulate with good stability in long-term laboratory experiments. Investigations of rock matrix diffusion in laboratory scale imply that 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 the 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/, which will be subject to a separate report to be presented.

4.3.2 Objectives

The objectives of the Long Term Diffusion Experiment project are:

- To investigate diffusion into matrix rock from a natural fracture *in situ* under natural rock stress conditions, natural hydraulic pressure and 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 are circulated in the test section for a period of approximately 4 years after which the core stub is over-cored, and analysed for tracer content and tracer fixation, see Figure 4-6.

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 away 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.

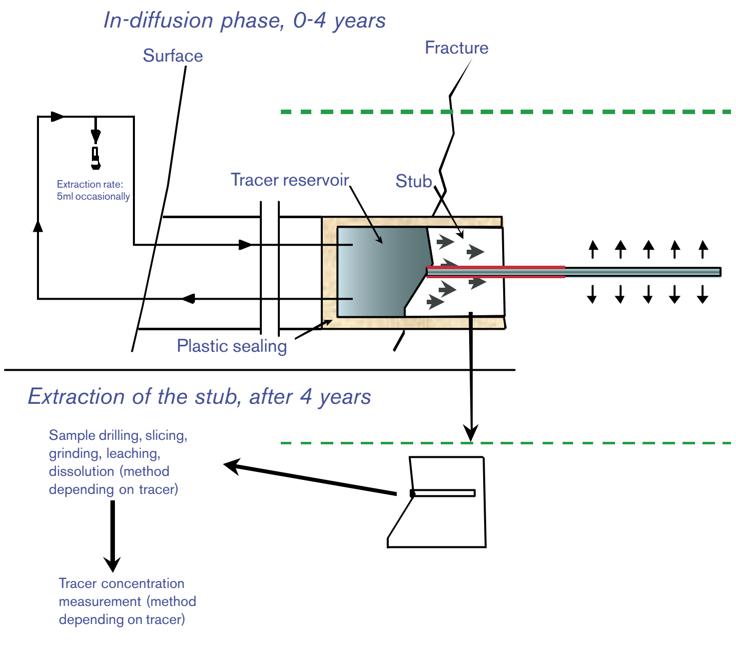


Figure 4-6. *LTDE experimental concept including injection borehole in contact with a fracture surface.*

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

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

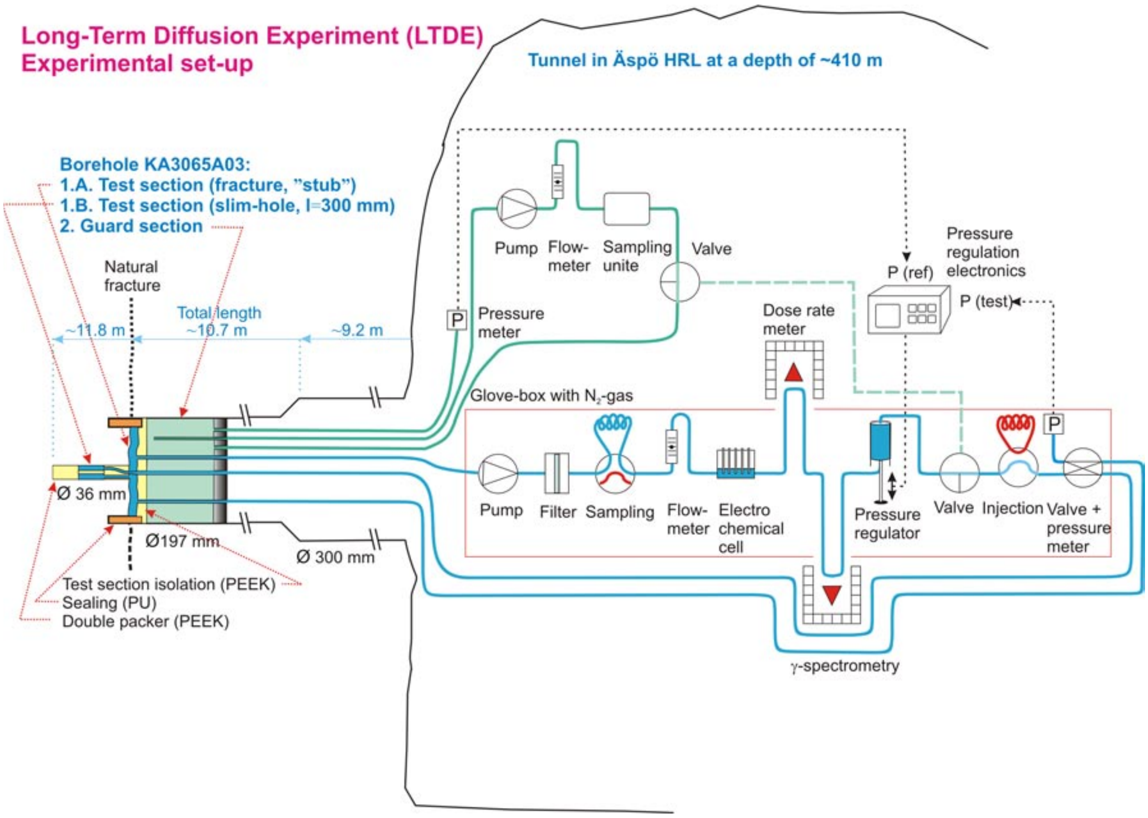


Figure 4-7. LTDE experimental set-up in the experimental borehole including the water circulation system to the test-section and the hydraulic pressure control system.

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.

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

The following topics have been carried out during 2003:

- Instrumentation of the LTDE test-site.
- Start of an installation-test programme focused on system function control and simulation of extreme experimental conditions.
- Start of a pre-test programme in order to evaluate the hydrological conditions in the vicinity of the experimental borehole KA3065A03 and to study possible hydrological interferences from other activities in Äspö HRL.
- Chemical and microbial analyses of water samples from the LTDE site.

In Figure 4-8 photographs on the installations at the LTDE site are shown.

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 of the laboratory studies *in situ*, where the natural contents of colloids, of organic matter, of bacteria etc are present in the groundwater used in the experiments. Special borehole probes, Chemlab 1 and Chemlab 2, have been designed for different kinds of *in situ* experiments where data can be obtained representative for the properties of groundwater at repository depth.

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

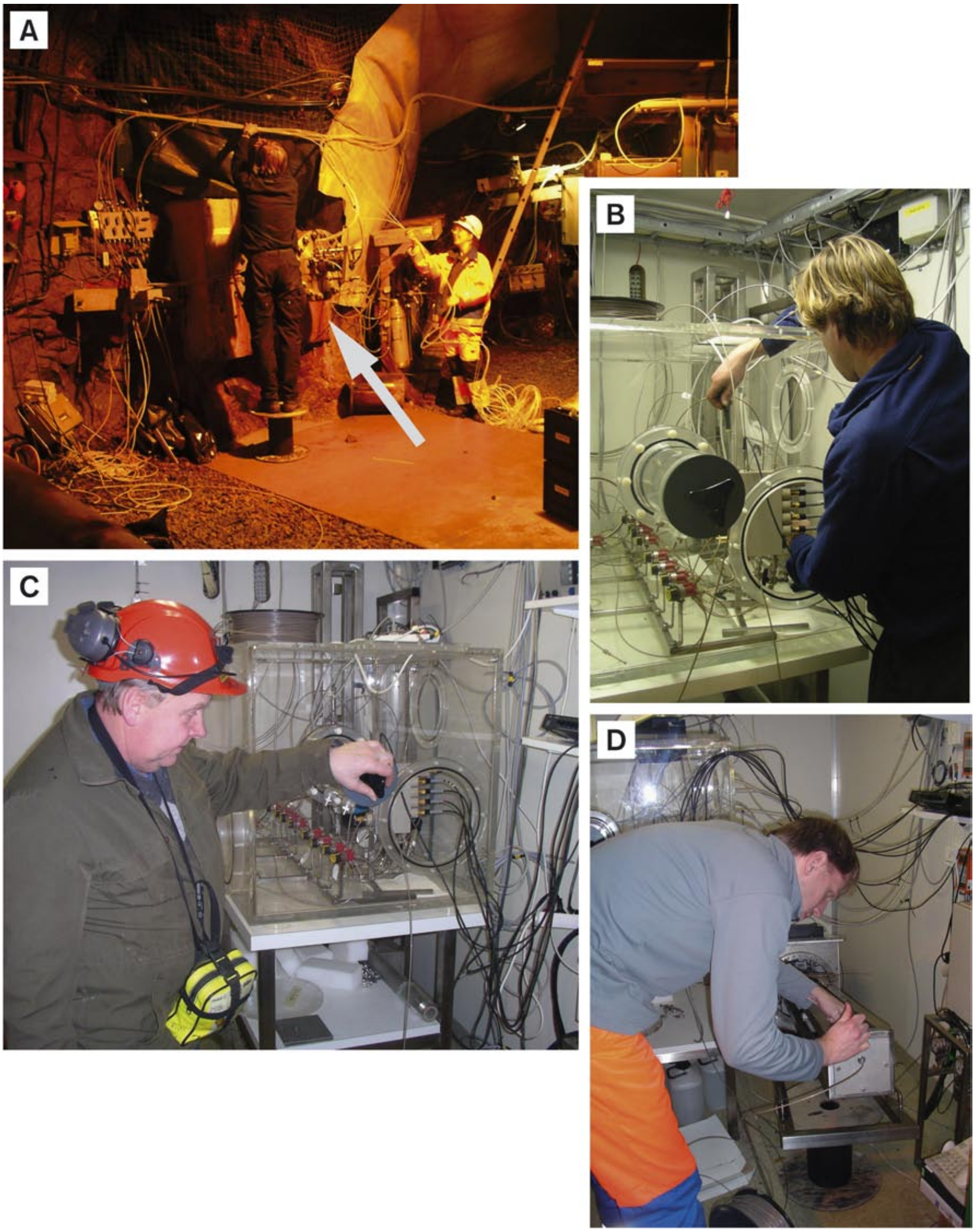


Figure 4-8. *Installation at the LTDE site. a) Installation of tubes for circulation of water and pressure registration. The KA3065A03 borehole casing is marked with an arrow in the picture. b) Mounting of experimental equipment within a glove box. c) Installation tests of the electro-chemical cell for pH and redox measurements. d) Mounting of the pressure regulator, prior installation in a separate Plexiglas box.*

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 given.

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

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

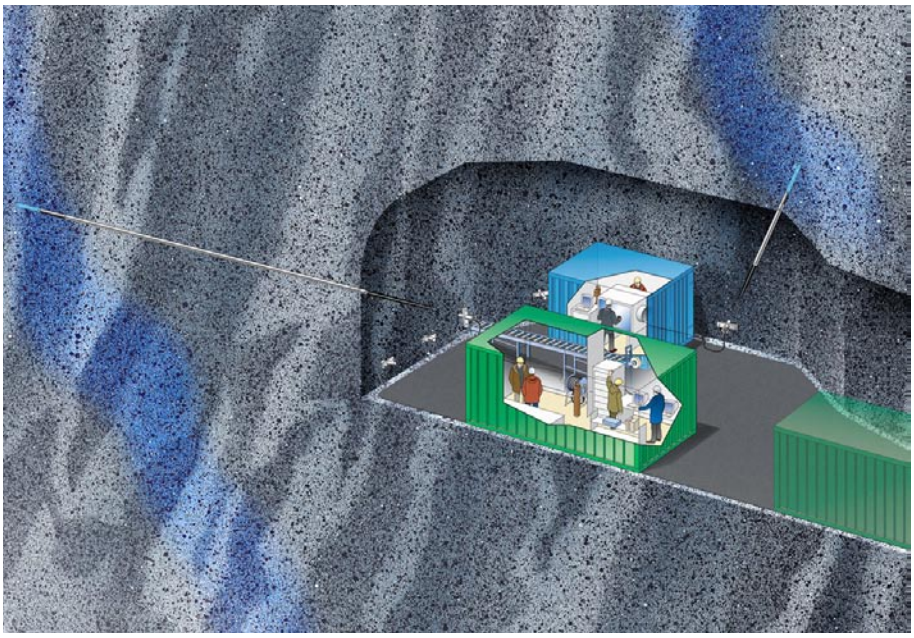


Figure 4-9. *Illustration of the experimental set-up of the Radionuclide Retention Experiments.*

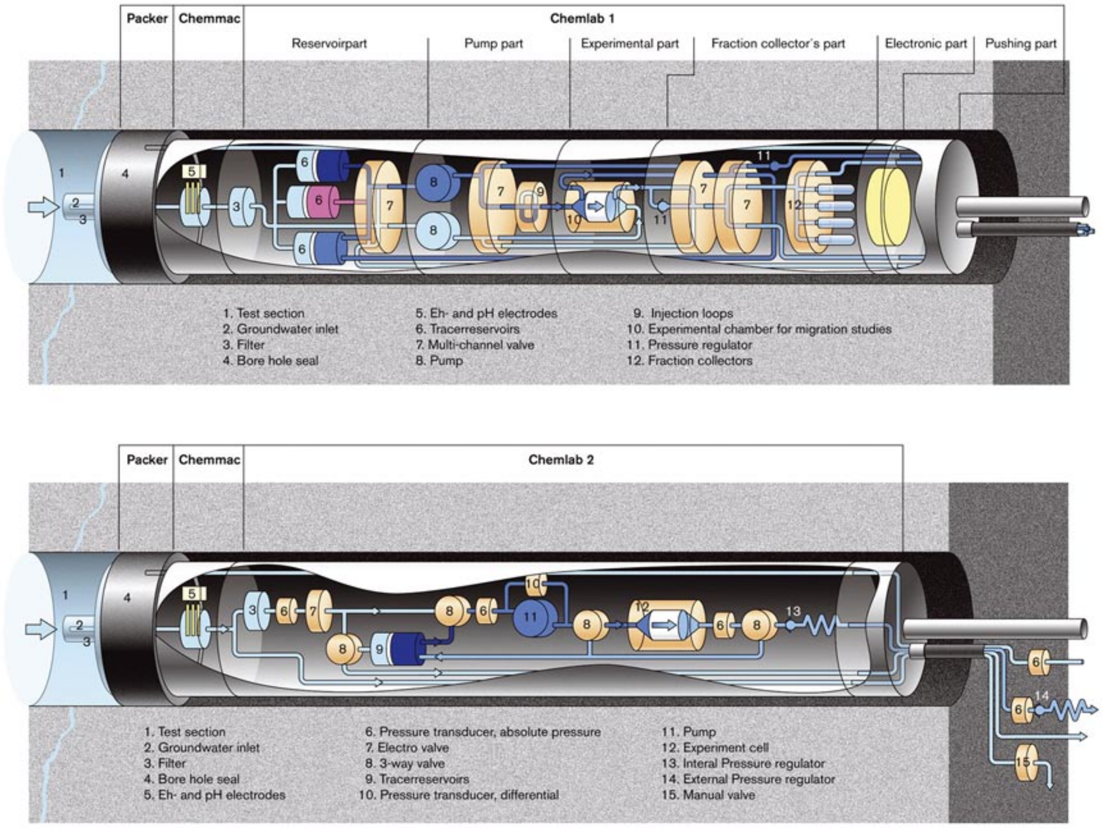


Figure 4-10. *Schematic illustration of Chemlab 1 and 2 borehole laboratories.*

4.4.4 Results

Radiolysis experiments

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

The experiments have been analysed and the major conclusions are that technetium was to some extent oxidised in the direct radiolysis experiment and had started to diffuse whereas in the indirect radiolysis experiment technetium was only found in its reduced form. The so far obtained results bring about a need for additional analysis, e.g. the distribution of technetium in bentonite probes not influenced by radiolysis. The final evaluation of data and the preparation of a final report are in progress and will be finished during 2004.

Migration of actinides

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

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

The first experiment comprised migration of the actinides americium, neptunium, and plutonium. The second experiment was carried out in the beginning of 2002 and the results has been evaluated and published /Kienzler et al. 2003a/. The third actinide experiment in Äspö HRL was started at the end of 2002. This experiment was expired due to several technical problems e.g. corrosion in the probe. The expired experiment provided, however, few water samples that have been analysed and evaluated by FZK/INE. The results from the third field experiment are reported in a technical report from Forschungszentrum, Karlsruhe /Kienzler et al. 2003b/, see Section 6.3.2. The last *in situ* experiment (in borehole KJ0044F01) is planned to start during 2004. The laboratory reservoir containing the tracer cocktail will be prepared by FZK/INE. According to present plans the experiment will be ran with radioactive isotopes (uranium and technetium).

4.5 Colloid Project

4.5.1 Background

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

It has been argued that e.g. plutonium is immobile owing to its low solubility in 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 FZK/INE in Germany. 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, 2002a; Vuorinen, 2002; Gurban, 2002; Wold and Eriksen, 2002b; Mattsén 2002; Rantanen and Mäntynen, 2002; Pedersen, 2002b/.

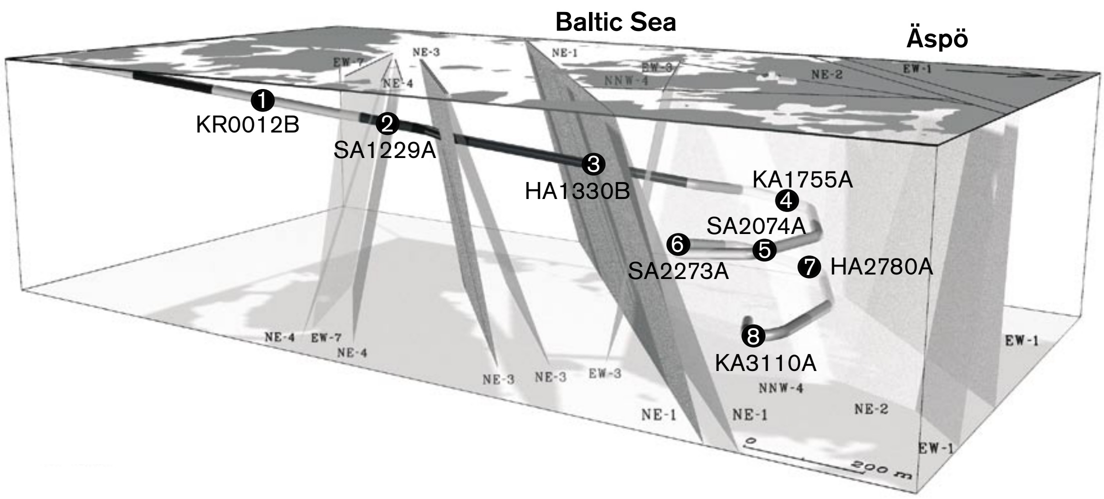


***Figure 4-11.** The eight boreholes sampled for colloids along the Äspö tunnel.*

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 was in contact with the bentonite clay adapted in a container/packer equipment in the borehole and the colloid content was measured prior and after contact with the bentonite clay. The bentonite reactor is 50 cm long and installed in boreholes with a diameter of 36 mm, see Figure 4-12. The colloid content was measured by using conventional filtering and ultra filtration at different flow conditions. The results indicate that the colloid release from the bentonite clay at prevailing groundwater conditions is small and the increased flow did not increase the colloid release from the bentonite reactor.

Dipole colloid experiments

The dipole colloid experiment is a fracture specific experiment planned to be performed within the Colloid Project during the time period 2003–2006. According to present plans two nearby boreholes intersecting the same fracture having the same basic geological properties will be selected for the dipole colloid experiment at Äspö HRL. One of the boreholes will be used as an injection borehole and the downstream borehole will be used for monitoring. After assessing the natural colloid content in the groundwater, bentonite clay will be dissolved in ultra pure water to form colloidal particles. The colloids are labelled with e.g. a lanthanide and the fluid is labelled with a water conservative tracer.

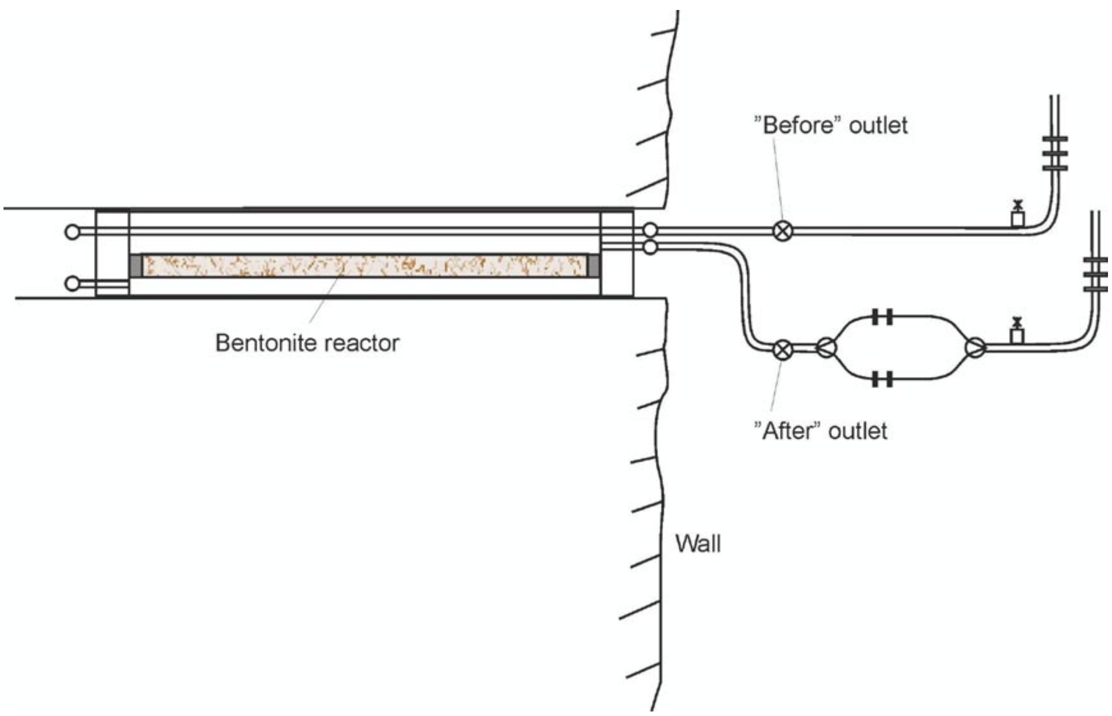


Figure 4-12. The natural groundwater is in contact with the bentonite clay surrounded by a filter textile. The water flowing by the reactor is sampled and analysed. A bypass allows colloid determination of the natural groundwater. The aim is to determine the colloid generation potential from the bentonite in contact with the water.

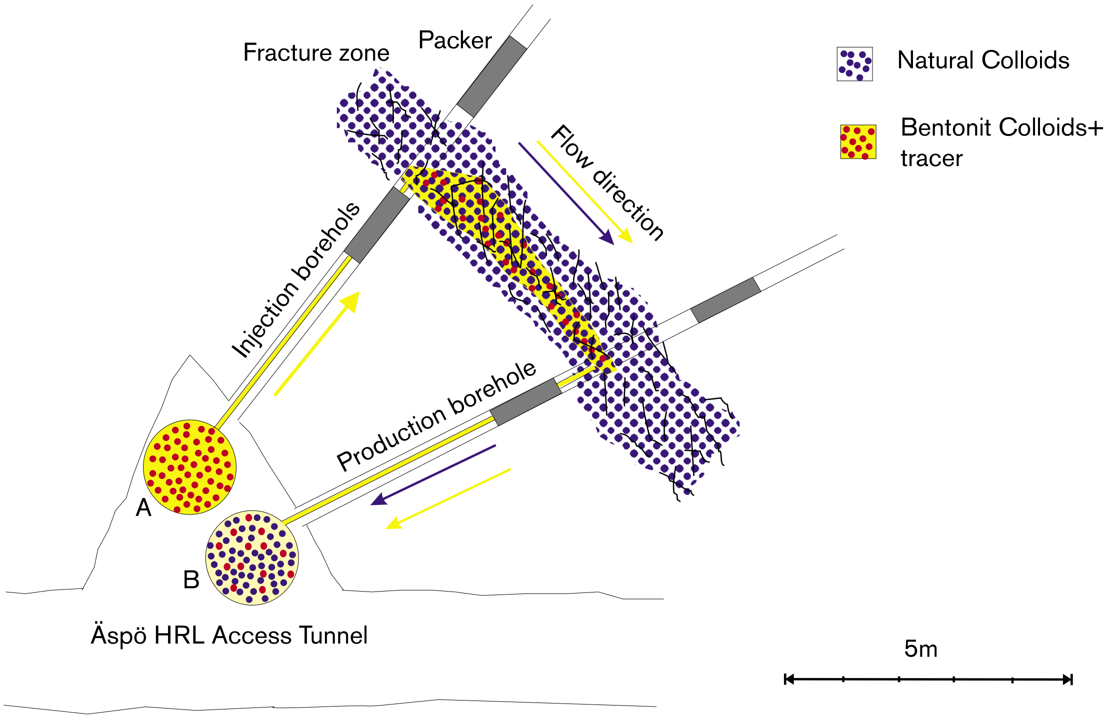


Figure 4-13. *Dipole colloid experiments – injection of bentonite colloids and monitoring of the injected and natural colloids in the production borehole.*

The mixture will be injected into the injection borehole, see Figure 4-13. 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

A status report including the results from the laboratory experiments and background measurements was printed in March /Laaksoharju, 2003/. The borehole specific measurements were carried out during the first half of the year 2003. The compilation of the final report including laboratory experiments, background measurements and borehole specific measurements is in progress and will be ready in June 2004. The initiation and planning of the fracture specific measurement started in August 2003.

4.6 Microbe Project

4.6.1 Background and objectives

Microorganisms interact with their surroundings and in some cases they greatly modify the characteristics of their environment. Several such interactions may have a significant influence on the function of a future deep repository for spent fuel /Pedersen, 2002a/. The study of microbial processes in the laboratory gives valuable contributions to our knowledge about microbial processes in repository environments. However, the concepts suggested by laboratory studies must be tested in a repository like environment. The reasons are several. Firstly, at repository depth, the hydrostatic pressure reaches close to

50 bars, a setting that is very difficult to reproduce in the microbiology laboratory. The high pressure will influence chemical equilibria and the content of dissolved gases. Secondly, the geochemical environment of deep groundwater, on which microbial life depends, is complex. Dissolved salts and trace elements, and particularly the redox chemistry and the carbonate system are characteristics that are very difficult to mimic in a university laboratory. Thirdly, natural ecosystems, such as those in deep groundwater, are composed of a large number of different species in various mixes /Pedersen, 2001/. The university laboratory is best suited for studies on pure cultures and, therefore, the effect from consortia of many participating species in natural ecosystems cannot easily be investigated there.

The limitations of university laboratory investigations arrayed above have resulted in the construction and set-up of sites for microbiological investigations in the Äspö HRL tunnel. The main site is the Microbe laboratory at the –450 m level, but one more site along the tunnel have been in use during 2003, i.e. at 2,200A m tunnel length.

The major objectives for the Microbe sites are:

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

Overview of studied microbial processes

Microbial processes can significantly alter the mobility of radionuclides in the environment. Multi-disciplinary research at the Microbe sites combines microbial physiology, ecology and molecular biology with nuclear chemistry, geochemistry and geology in the exploration of how microbial processes may influence the repository and migration of radionuclides.

Table 4-2 and Figure 4-14 summarise microbial processes that can influence radionuclide speciation and thereby their migration behaviour. Microbial processes will act immobilising or mobilising, depending on the type of process and the state of the microbes. Microbes in biofilms will, with exception for those who produce complexing agents, be immobilising. Planktonic cells, that bio-sorb or bio-accumulate radionuclides, will act mobilising on radionuclides. The processes can have a direct or indirect action on radionuclide transport in the geosphere. A direct action involves contact between a microbe and the radionuclide with a resulting change in its speciation. Indirect action is caused by changes in the environment generated by microbial metabolism, which in turn influences radionuclide behaviour. Finally, all microbial processes except bio-sorption 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 in Table 4-2 are investigated, or will be investigated in various details at Microbe. The emphasis is on their importance for understanding geosphere retention phenomena in the safety assessments of radioactive waste disposal. During 2003, the research at Microbe has been focussed on a selection of processes in Table 4-2. They are briefly introduced below.

Table 4-2. Microbial processes can influence retention of radionuclides directly or indirectly in several different ways. The most important variables for such processes are the state of attachment, if the microbes are attached or unattached, and whether the microbes are active with a metabolism that turns over energy, or dormant and inactive.

Microbial processes that influence radionuclide migration	Microbes in this process are in the following state(s):		This 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						
Bio-sorption		X	X			X
Bio-accumulation		X	X		X	
Bio-transformation	X	X	X		X	
Bio-mineralisation	X	X		X	X	
Metabolic redox reactions	X	X		X	X	
Mobilisation processes						
Bio-sorption	X		X			X
Bio-accumulation	X		X		X	
Production of complexing agents	X	X	X		X	

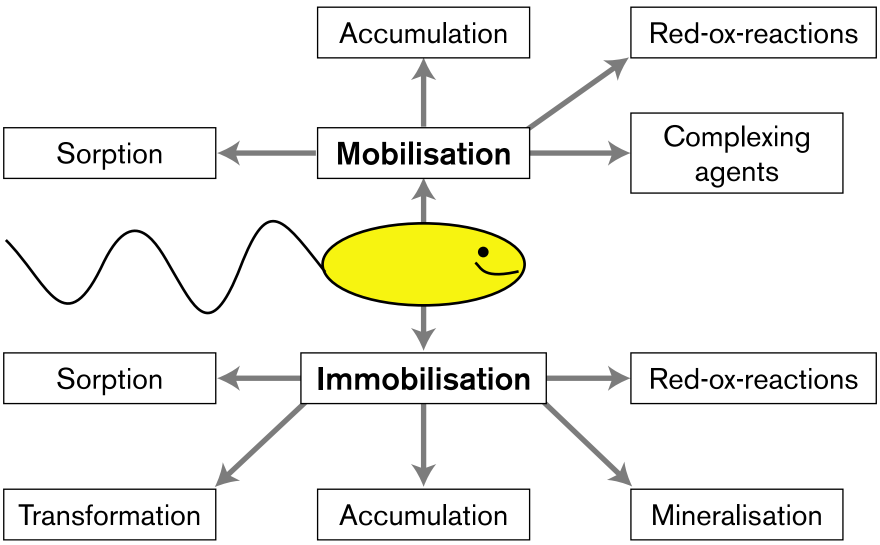


Figure 4-14. *Schematic representation of microbial processes that may influence radionuclide migration.*

Bio-mobilisation of radionuclides (I)

Microbes need metals for their metabolism, just as all multi-cellular living organisms. Both bacteria and microscopic fungi have this demand. Such metals are often available only in small quantities or, as in the case of 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. In the process of capturing the metal-ligand complex, microbes sort toxic metals from essential ones and expel the toxic elements back to the environment. The potential for mobilisation of radionuclides from repository environments by bacterially produced ligands is unknown and, therefore, a concerning possibility in the safety analysis that should be explored. This process has been investigated using microorganisms isolated from the deep groundwaters of Äspö HRL. Fungi have the ability to produce large amounts of complexing agents, e.g. via fermentation processes. The presence of fungi in deep groundwaters has been noted in earlier work. A detailed survey of fungi in Äspö groundwaters has been performed and published during 2003 /Ekendahl et al. 2003/.

Immobilisation of radionuclides by bio-sorption (II)

The term bio-sorption (Table 4-2) is used to describe the metabolism-independent sorption of heavy metals and radionuclides to biomass, i.e. microbial cells. Bio-sorption 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 bio-sorption and ligands involved in metal binding include carboxyl, amine, hydroxyl, phosphate and sulfhydryl reactive groups on the cell wall. Microbes in biofilms are different compared to planctonic microbes. They have been reported to reach 10^{11} cells m^2 in Fennoscandian shield rock groundwater /Pedersen, 2001/. Biofilm microorganisms commonly excrete extra-cellular material supporting attachment and this material also create a three dimensional shape of a growing biofilm. As this extra-cellular material is organic in its nature, it will add a bio-sorption capacity to the cell's surfaces. In conclusion, bio-sorption to attached microbes in biofilms will act immobilising on radionuclides (Table 4-2). Up to date, no, or very little *in situ* experimental data existed on the importance of bio-sorption biofilm processes for understanding geosphere retention phenomena in the safety assessments of radioactive waste disposal. New experiments at the Microbe site have generated new information during 2003.

Immobilisation of radionuclides by bio-accumulation and bio-mineralisation (II)

A large group of microbes catalyse the formation of iron oxides from dissolved ferrous iron in groundwater that reaches an oxidising environment /Ferris et al. 1999, 2000/. Such biological iron oxide systems (Bios) will have a retardation effect on many radionuclides. Typically, microbes form stalks and sheaths that increase the volume of the iron oxides from densely packed inorganic oxides to a fluffy, rust-like material with water contents of up to 99%. The microbes contribute to the exposure of a large oxide area to trace elements flowing by with the groundwater and the organic biological material adds a strong retention capacity in addition to iron oxides. The retention effect from Bios (bioaccumulation and mineralisation, Table 4-2) has been studied at the Microbe 2,200 m site.

Microbial effects on the chemical stability of deep groundwater environments (III)

Microorganisms can have an important influence on the chemical situation in groundwater /Haveman and Pedersen, 2002/. Especially, they may execute reactions that stabilise the redox potential in groundwater at a low and, therefore, beneficial level for the repository. It is hypothesised that hydrogen from deep geological processes contributes to the redox stability of deep groundwater via microbial turnover of this gas. Hydrogen, and possibly also carbon monoxide and methane energy metabolisms will generate secondary metabolites such as ferrous iron, sulphide and organic carbon. These species buffer towards a low redox potential and they will act reducing on possibly introduced oxygen. A circulation system, and analytical instrumentation for dissolved gas in groundwater have been used during 2003 and microbial biofilms have been grown under *in situ* conditions at the Microbe –450 m site.

Microbial energy metabolism requires a reduced electron and energy donor and an oxidised electron acceptor (Table 4-3). The energy donor can be an organic or an inorganic compound. The electron acceptor is generally an inorganic compound, with exception for fermentation, where the electron donor and electron acceptor is 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 from microbial harvesting of energy from redox couples is an oxidised donor and a reduced acceptor. Important to notice here is that microbial metabolism generally lowers the redox potential in the environment.

Microbial corrosion of copper (IV)

Bio-corrosion of the copper canisters, if any, can be the result of microbial sulphide production. Two important questions have been identified and studied: Can sulphide-producing microbes survive and produce sulphide in the bentonite surrounding the canisters? Can microbial sulphide production in the surrounding rock exceed a performance safety limit? A series of laboratory and field experiments have indicated that this is not the case /Pedersen et al. 2000a,b/. However, the results have been criticised for not accounting for natural conditions such as high pressure and the natural population of sulphate reducing bacteria in deep groundwater. This issue has been addressed at the Microbe –450 m site during 2002. The data is presently in preparation for publication during 2004.

Table 4-3. The most common energy and electron donors and electron acceptors in microbial metabolism. The respective atom that donates or accepts one or several electrons is underlined.

Organic energy sources and electron donors		Inorganic energy sources and electron donors		Electron acceptors	
Reduced	**Oxidised**	**Reduced**	**Oxidised**	**Oxidised**	**Reduced**
Carbohydrates	$\underline{C}O_2$			$\underline{O_2}$	$H_2\underline{O}$
Amino acids	$\underline{C}O_2$	$\underline{N}H_4^+$	$\underline{N}O_3$	$\underline{N}O_3$	$\underline{N_2}$
Organic acids	$\underline{C}O_2$	$\underline{Mn}^{2+}$	$\underline{Mn}^{4+}$	$\underline{Mn}^{4+}$	$\underline{Mn}^{2+}$
Fat	$\underline{C}O_2$	$\underline{Fe}^{2+}$	$\underline{Fe}^{3+}$	$\underline{Fe}^{3+}$	$\underline{Fe}^{2+}$
		$H_2\underline{S}$	$\underline{S}O_4^{2-}$	$\underline{S}O_4^{2-}$	$H_2\underline{S}$
		$\underline{C}H_4$	$\underline{C}O_2$	$\underline{S}^0$	$H_2\underline{S}$
		$\underline{C}O$	$\underline{C}O_2$	$\underline{U}^{6+}$	$\underline{U}^{4+}$
		$\underline{H_2}$	$\underline{H_2}O$	$\underline{C}O_2$	$\underline{C}H_4$

4.6.2 Experimental concept

The Microbe –450 m site

The main Microbe site is on the –450 m level in the F-tunnel (Figure 4-15). 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 (Figure 4-15) that allow controlled circulation of groundwater via respective fracture /Pedersen, 2000/. Each borehole has been equipped with a circulation system offering a total of 500 cm^2 of test surface in each circulation for biofilm formation at *in situ* pressure, temperature and chemistry conditions. The systems operate at the pressures 24, 32 and 24 bars in KJ0050F01, KJ0052F01 and KJ0052F03, respectively. The flow through the flow cells is adjusted to about 15–20 ml per minute, which corresponds to a flow rate over the surfaces of 0.5 mm per second. Temperature is controlled and kept close to the *in situ* temperature at around 15–16°C. Remote alarms have been installed for high/low pressure, flow rate and temperature.

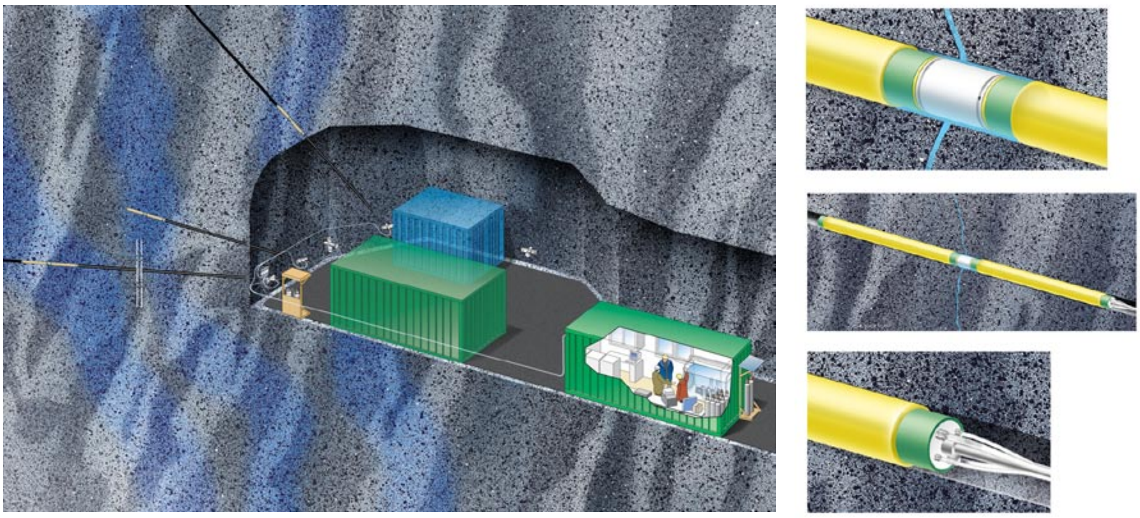


Figure 4-15. *The artists view of the Microbe 450 m site and the metal free packer configuration. The laboratory is situated in a steel container and connected to three discrete fractures in the rock matrix. Peek tubing connects the systems in the lab with the groundwater (See text for details).*

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 Oxide Systems). Bios can be found everywhere along the Äspö HRL tunnel system. This Bios is mainly produced by the stalk-forming bacterium *Gallionella ferruginea* /Hallbeck and Pedersen 1990, 1991, 1995; Hallbeck et al. 1993/. One particularly good site for investigations has been identified at tunnel length 2,200 m, on the A side. A vault is reaching about 10 m into the host rock perpendicular to the tunnel and it has a borehole in the front that delivers groundwater rich in ferrous iron and iron oxidising bacteria. The borehole has been connected to two 200×30×20 cm artificial channels that mimic ditches in the tunnel. The channels have rock and artificial plastic support that stimulate Bios formation (Figure 4-16). 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/.

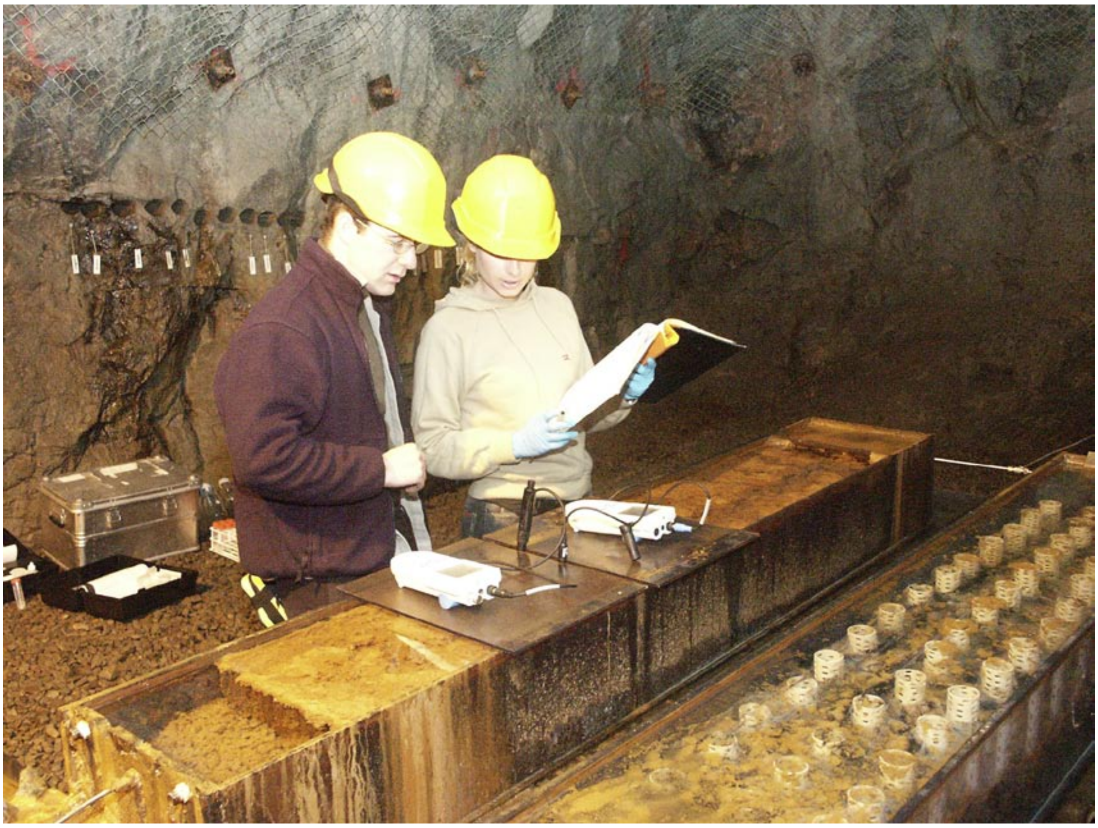


Figure 4-16. *Microbiologists working at the Bios site, taking redox and oxygen measurements along the flow line.*

4.6.3 Results

Bio-mobilisation of radionuclides

Three bacterial species (*Shewanella putrefaciens*, *Pseudomonas fluorescens* and *Pseudomonas stutzeri*), isolated from deep groundwater at Äspö HRL, and four radionuclides ($^{59}Fe(III)$, $^{147}Pm(III)$, $^{234}Th(IV)$ and $^{241}Am(III)$) were selected for a laboratory study. The microbes were cultured in the laboratory, separated from dissolved compounds that were produced by the microbes and expelled into solution. The separation was performed by centrifugation, and the supernatants were collected. The supernatants were mixed with radionuclide and solid phase (TiO_2 or SiO_2). All three bacterial species produced ligands that were able to complex the radionuclides at various degrees in competition with the solid phase (Figure 4-17). Those experiments were performed under aerobic conditions. New experiments are planned at Microbe that will analyse the potential of *in situ* production of complexing agents under anaerobic conditions in the installed circulations.

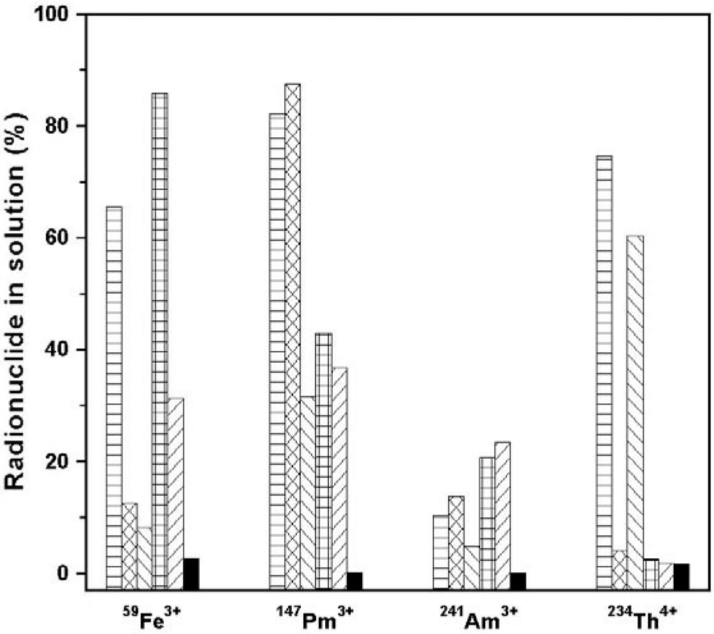


Figure 4-17. *Mobilisation of radionuclides by three different mixes of dissolved compounds that were produced by the microbes and expelled into solution, and two known chelating compounds (Hydroxamate and Catechol) in competition with solid phase SiO_2 at around neutral pH. Bars are, from left to right:* Pseudomonas fluorescens*,* Pseudomonas stuzeri*,* Shewanella putrefaciens*, Hydroxamat, Catechol, and Culturing medium.*

Immobilisation of radionuclides by bio-accumulation and bio-mineralisation

The results were published during 2003 /Anderson and Pedersen, 2003/. A summary of this work follows below.

Gallionella ferruginea is an iron-oxidising chemolithotrophic microorganism that lives in low-oxygen conditions (0.1–1.5 mg/l saturation). It produces a stalk structure from the concave side of the cell depending on population development, pH and redox conditions. After *Gallionella* oxidises ferrous iron, bacteriogenic iron oxides (Bios) precipitate on the stalk material and over time the stalks and/or the precipitated Bios attenuate trace metals from surrounding groundwater. *Gallionella ferruginea* biofilms were cultured *in situ* in an artificial channel (2,000×300×250 mm) using groundwater sourced from a borehole 297 m below sea level in the Äspö HRL in southern Sweden (Figure 4-16). The pH of the groundwater in the channels was always between 7.4 and 7.7 with oxygen saturation below 1.5 mg/l and Eh between 100 and 200 mV. Oxygen eventually declined to < 0.3 mg/l, terminating prolific biofilm growth.

Biofilms formed within 2 weeks and were sampled every 2 weeks over 3 months. Cell number, stalk length and ferric iron concentration were measured for each sample and trace metal concentration was measured by inductively coupled plasma mass spectrometry (ICP-MS). Results from well-developed *in situ* biofilms suggest that *Gallionella* could concentrate metals at levels up to $1 \cdot 10^3$-fold higher than found within the host rock and more than $1 \cdot 10^6$ times the levels found in the groundwater. These new experiments were used to support the results from the well-developed biofilms and to relate biofilm development and population characteristics to metal attenuation. After 3 months, rare earth element (REE) plots indicated that Bios can accumulate metals at levels up to $1 \cdot 10^4$-fold higher than found in the groundwater and fractionate heavy rare earth elements (HREEs) over light rare earth elements (LREEs). Generally the presence of the organic phase promotes the adsorption of all lanthanides and actinides that are not adsorbed by the inorganic phase. The iron oxides are directly correlated with stalk length ($R^2 = 0.96$) indicating that rapid REE and actinide adsorption requires both iron oxides and a nucleating biological structure for the iron oxides (Table 4-4).

Table 4-4. Multiple regression coefficients and upper and lower 95% confidence limits for lanthanides (represented by La) and uranium (U) and thorium (Th) plotted against precipitated iron (Fe), stalk length and cell numbers. The concentration of either La or U or Th was set as the dependent variable while Fe^{3+}, stalk length and the cell numbers were set as independent variables. Negative coefficients indicate that that factor has negative influence and vice versa. Stalk length has the strongest influence in this system. Confidence intervals that include zero indicate data is insignificant.

Dependent variable	Independent variables	Coefficients	95% Lower	95% Upper
La	Fe^{3+}	– 1.38	– 2.46	– 0.30
$R^2 = 0.973$	Stalk length	2.27	1.24	3.30
	Cell number	0.13	0.04	0.23
U	Fe^{3+}	– 0.84	– 2.62	0.92
$R^2 = 0.923$	Stalk length	1.82	0.13	3.51
	Cell number	$-3.20 \cdot 10^{-3}$	– 0.16	0.15
Th	Fe^{3+}	– 2.56	– 7.94	2.82
$R^2 = 0.565$	Stalk length	3.42	– 1.74	8.57
	Cell number	$8.72 \cdot 10^{-2}$	– 0.39	0.56

Immobilisation of radionuclides by bio-sorption

Flow cells were installed in the circulation from the borehole KJ0052F03 in June 2002. Microbes were allowed to attached and grow on glass surfaces in flow cells (Figure 4-18) for about 15 months. *In situ* pressure and groundwater chemistry prevailed. The flow cells with biofilms on glass were sampled in intervals during fall 2003 and transported rapidly to the laboratory at Nuclear Chemistry in Göteborg. They were opened in an anaerobic box with inert N_2 atmosphere. The slides were subsequently immersed in various solutions containing radioactive isotopes with different charge. The results show that the biofilms increased immobilisation of the tested elements (Figure 4-19). The results are prepared for publication during 2004.

Figure 4-18. *The flow cell that was used to grow biofilms. Glass slides were exposed to circulating groundwater from borehole KJ0052F03 for about 15 months.*

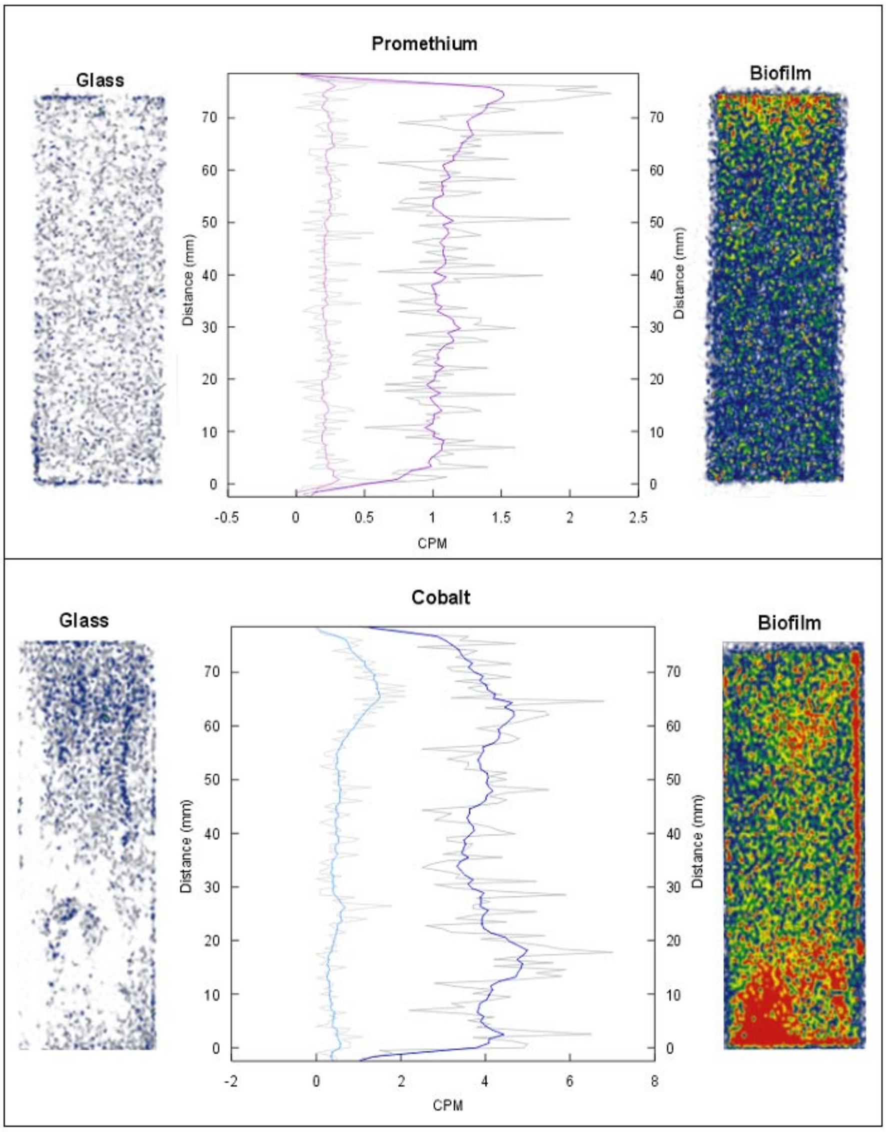


Figure 4-19. *Bio-immobilisation of the radioactive isotopes ^{147}Pm and ^{60}Co on biofilms (right) that have grown on glass surfaces (left). The radioactivity is higher on the slides with biofilm (right) compared to the naked glass (left).*

Microbial effects on the chemical stability of deep groundwater environments

A case of special importance is the reduction of oxygen in microbial metabolism. Oxygen is the preferred electron acceptor by many microorganisms, because the free energy available in oxidation of an electron/energy donor is largest when oxygen is used, compared to other acceptors (Table 4-3). Several of the energy donors in Table 4-3 are gases. Therefore, efforts have been invested in the development of gas chromatography technology suitable for underground research. We can now extract and analyse hydrogen, carbon monoxide, methane carbon dioxide, ethane and propane directly in the Microbe container (Figure 4-15). Samples can be taken in the tunnel, from boreholes or directly from the circulations for immediate analysis. Figure 4-20 shows typical results. Drilling of new boreholes next to the Microbe site during fall 2002 (F0066A01 and KF0069A01) seems to have permanently changed the gas composition in KJ0052F01. In particular, hydrogen increased significantly in concentration.

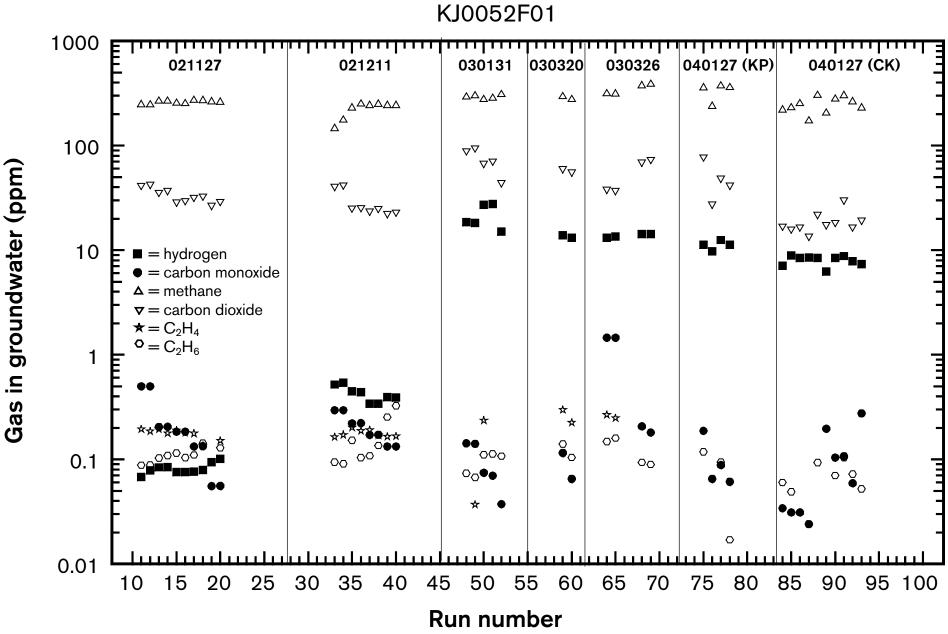


Figure 4-20. Multiple runs and analysis of gas concentrations over time in groundwater from borehole KJ0052F01.

Yeasts isolated from Äspö HRL

The results were published during 2003 /Ekendahl et al. 2003/. A summary of this work follows below.

The diversity of procaryotes in the groundwater at the Äspö HRL (HRL) in southeast Sweden is well documented. In addition, there is some evidence that eukaryotes, too, are present in the deep groundwater at this site, although their origins are uncertain. To extend the knowledge of eukaryotic life in this environment, 5 yeast, 3 yeast-like and 17 mould strains were isolated from Äspö HRL groundwater between 201 and 444 m below sea level. Phenotypic testing and phylogenetic analysis of ^{18}S rDNA sequences of the five yeast isolates revealed their relationships to Rhodotorula minuta and Cryptococcus spp. Scanning (Figure 4-21) and transmission electron microscopy demonstrated that the strains possessed morphological characteristics typical for yeast, although they were relatively small, with an average length of 3 µm. Enumeration through direct counting and most probable number methods showed low numbers of fungi, between 0.01 and 1 cells per ml, at some sites. Five of the strains were characterised physiologically to determine whether they were adapted to life in the deep biosphere. These studies revealed that the strains grew within a pH range of 4–10, between temperatures of 4°C and 25–30°C, and in NaCl concentrations from 0 to 70 g/l. These growth parameters suggest a degree of adaptation to the groundwater at Äspö HRL. Despite the fact that these eukaryotic microorganisms may be transient members of the deep biosphere microbial community, many of the observations of this study suggest that they are capable of growing in this extreme environment. The isolates can be used for controlled investigations of the potential for production of complexing agents by fungi.

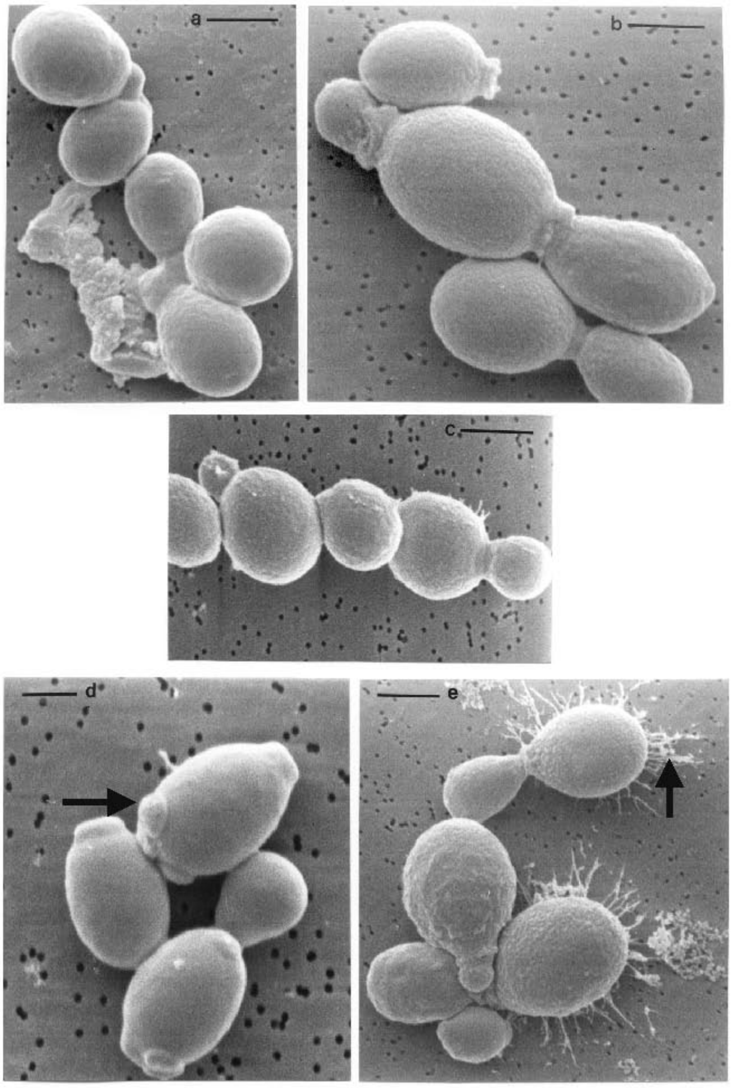


Figure 4-21. *Scanning electron microscopy photographs of yeast strains isolated from Äspö HRL. The strains shown are: a) 8,000:1, bar = 2 µm, b) 9,000:1, bar = 2 µm, c) 8,000:1, bar = 2 µm, d) 9,000:1, bar = 1 µm, arrow shows typical bud scar, e) 6,750:1, bar = 2 µm, arrow shows exopolymeric material.*

4.7 Matrix Fluid Chemistry

4.7.1 Background

The planning of a repository for the deep geological disposal of radioactive wastes will try and ensure that disposal will be in a low permeable bedrock environment. Under such conditions interaction with circulating groundwater is limited or essentially does not occur at all. Long residence times therefore are characteristic and the composition of the groundwaters is more likely influenced to varying degrees by the rock matrix pore fluid chemistry. Matrix pore fluids can be highly saline in composition and, if accessible, their effect on the near-field groundwater chemistry may pose a threat to the integrity of the multi-barrier disposal system over repository timescales.

The term “matrix pore fluid” as used in this study includes all fluid types: a) the water in the pore space of a rock that is only accessible by diffusion, b) the water residing in dead-end pores, and c) the fluid enclosed in mineral fluid inclusions. The term ‘matrix pore water’ is used when referring to the water in the connected pore space of the rock matrix that is accessible for interaction with groundwaters circulating in nearby microfractures.

The Matrix Fluid Chemistry Experiment (MFE), initiated to study these matrix pore fluids/waters, commenced in 1998 and was completed in March 2003; the results were published in early 2004 /Smellie et al. 2003/.

4.7.2 Objectives

The MFE set out to determine the composition and evolution of matrix pore fluids/waters in low permeable rock located at repository depths in the Äspö HRL. In addition to the *in situ* sampling and analysis of accumulated matrix pore waters from isolated borehole sections, the extracted drillcore was studied with respect to both the accessible and inaccessible matrix pore fluids. This involved crush/leach and out-diffusion laboratory studies, fluid inclusion characterisation and porosity measurements together with detailed mineralogy, petrology and geochemistry.

The MFE aimed at initially characterising the “matrix pore fluid” using various laboratory methods and approaches cited. The final goal of the investigations was to characterise the *in situ* “matrix pore water”.

4.7.3 Experimental concept

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

Special equipment, see Figure 4-22, was designed for sampling purposes 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 water (and gases) under pressure, and g) convenient sample holder to facilitate rapid transport to the laboratory for analysis.

4.7.4 Results

Whilst time-consuming, pore waters were successfully collected from the rock matrix. Relating the rate of *in situ* pore water accumulation during sampling to the measured rock porosity indicated a hydraulic conductivity of 10^{-14}–10^{-13} m/s for the rock matrix. This was in accordance with earlier estimated predictions. The brackish nature of the pore water, not too dissimilar from the surrounding more highly permeable fractured bedrock, mostly represent older palaeogroundwater mixtures preserved in the rock matrix and dating back to at least the last glaciation. A component of “matrix pore fluid” is also present. One borehole section suggests a younger groundwater component which has accessed the rock matrix during the experiment. There is little evidence that the salinity of the matrix pore waters has

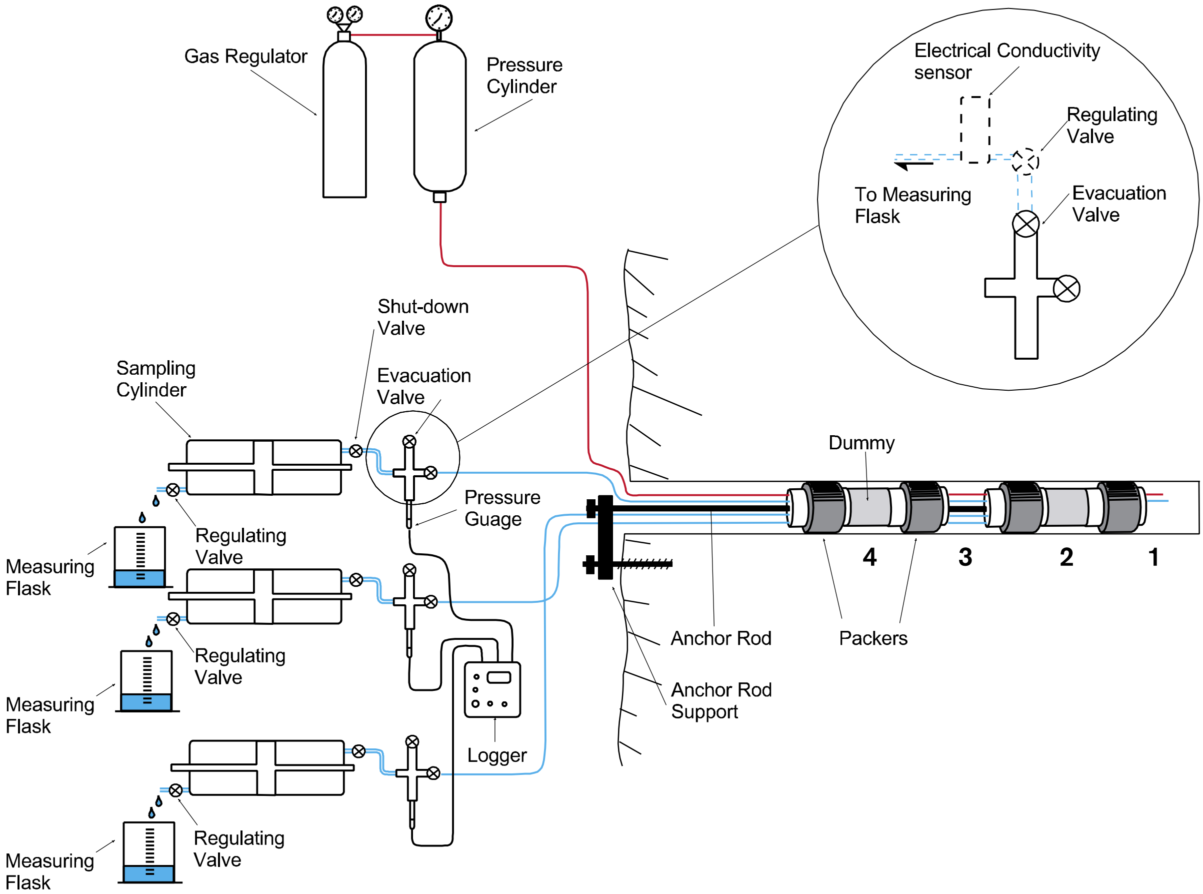


Figure 4-22. *Matrix Fluid Chemistry experimental set-up. Borehole Sections 2 and 4 were selected to collect matrix pore water; Sections 1–4 were continuously monitored for pressure.*

been influenced significantly by fluid inclusion populations hosted by quartz. Crush/leach, cation exchange, pore water diffusion and pore water displacement laboratory experiments were carried out to compare extracted/calculated matrix pore fluids/waters with *in situ* sampling. Of these the pore water diffusion experiments appear to be the most promising approach and a recommended site characterisation protocol has been formulated.

The main conclusions from the Matrix Fluid Chemistry Experiment are:

- Groundwater movement within the bedrock hosting the experimental site has been enhanced by increased hydraulic gradients generated by the presence of the tunnel, and to a much lesser extent by the borehole itself.
- Over experimental timescales (~ 4 years) solute transport through the rock matrix is mainly by small-scale advection via an interconnected microfracture network and by diffusion.
- Over repository timescales (thousands to hundreds of thousands of years) diffusion of pore fluid/water from the rock matrix to the adjacent microfracture groundwaters will become more important depending on the nature of existing chemical gradients.
- At Äspö, permeable bedrock at all scales has facilitated the continuous removal and replacement of the interconnected pore space waters over relatively short periods of geological time, probably hundreds to a few thousands of years.

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

4.8.1 Background

The work within Äspö Task Force constitutes an important part of the international co-operation within the Äspö HRL. The group was initiated by SKB in 1992 and is a forum for the organisations to interact in the area of conceptual and numerical modelling of groundwater flow and transport. A Task Force delegate represents each participating organisation and the modelling work is performed by modelling groups. The Task Force meets regularly about once to twice a year.

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

Task 1 Long term pumping and tracer experiments (LPT-2). Completed.

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

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

Task 4 The Tracer Retention and Understanding Experiment, 1st stage. Completed.

Task 5 Coupling between hydrochemistry and hydrogeology. Completed.

Task 6 Performance Assessment Modelling Using Site Characterisation Data. On-going.

4.8.2 Objectives

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

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

4.8.3 Results

Mainly, the Tasks 1 to 5 are already completed and the main results can be found in previous Äspö HRL Annual Reports /SKB, 2003/. During 2003, the report of the Overall Evaluation of the modelling conducted in Task 4 /Marschall and Elert, 2003/, the Task 5 Summary report /Rhén and Smellie, 2003/, and Task 5 Reviewers report /Bath and Jackson, 2003/ have been published. An external review process for Task 6 has been initiated. Here, mainly ongoing activities and results are presented for Task 6, which was initiated in 2001. The objectives of this task are to:

- Assess simplifications used is performance assessment (PA) models.
- Assess the constraining power of tracer (and flow) experiments for PA models.

- Provide input for site characterisation programs from a PA perspective (i.e. provide support for site characterisation programme design and execution aimed at delivering needed data for PA).
- Understand the site-specific flow and transport behaviour at different scales using site characterisation models.

Five sub-tasks have been defined within Task 6:

Sub-task 6A	Model and reproduce selected True-1 tests with a PA model and/or a SC model to provide a common reference.
Sub-task 6B	Model selected PA cases at the True-1 site with new PA relevant (long term/ base case) boundary conditions and temporal scales to understand the differences between the use of PA and SC models. In a variant denoted task 6B2, a line source was used instead of a point source for the injection of solutes.
Sub-task 6C	Develop semi-synthetic, fractured granite hydrostructural models.
Sub-task 6D	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.
Sub-task 6E	This modelling task extends the sub-task 6D transport calculations to a reference set of PA time scales and boundary conditions. In sub-task 6A, it is attempted to model and reproduce selected True-1 tests with a performance assessment model and/or a site characterisation model in order to provide a common reference.

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 the results were presented at the 16th Task Force Meeting at Äspö HRL in June 2002. Drafts of the modelling reports regarding Task 6A, 6B and 6B2 have been sent to the reviewers.

In sub-task 6C, a 50–100 m block scale synthesised structural model is developed using data from the Prototype Repository, True Block Scale, True-1, and FCC (Fracture Characterisation and Classification). The developed model is to be used as input data to sub-task 6D. The Task 6C report has been printed /Dershowitz et al. 2003/.

The 17th International Task Force meeting, hosted by Nagra was held March 11–13, 2003 in Thun, Switzerland. 27 attendees from seven countries participated in the meeting. A summary of the final report for the Overall Evaluation of Task 4 was presented. The modelling groups presented final results of Task 6A, 6B and 6B2 and preliminary results for Task 6D. Proceedings of the 17th International Task Force have been published on the Task Force web site at SKB.

A workshop was held regarding Task 6 at Krägga Mansion, September 2003. At the workshop, the obtained results for sub-tasks 6A and 6B were discussed, as well as how to continue the task by performing sub-tasks 6D and 6E. Specifications of sub-task 6E have been sent out to the Task Force members.

4.9 Padamot

4.9.1 Background

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

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

4.9.2 Objectives

The objectives for the Padamot project include:

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

The Swedish part of the Padamot project concentrates on the two work packages WP2 (palaeohydrogeological characterisation of sites) involving applications of several analytical techniques on fracture filling calcites dominantly from KLX01, and WP5, which deals with performance assessment applications of palaeohydrogeological data and modelling.

4.9.3 Results

The results form the second year of the Padamot projects confirms largely the earlier given palaeohydrogeological interpretations and have provided extended confidence in the recognition of low temperature calcites by the use of several different methods together, $\delta^{18}O$, $\delta^{13}C$, $^{87}Sr/^{86}Sr$, calcite morphology and trace element composition.

A four-folded subdivision from palaeohydrogeological perspective has been constructed /Tullborg, 2003/:

I (0–100 m). A near surface zone of calcite dissolution and precipitation (almost no old hydrothermal calcites are left in the open fractures in this section). Redox conditions have probably varied over time.

II (100–500 m). Low temperature calcites of varying compositions have been precipitated. Zoning of calcites are common. Biogenic input is significant. The redox conditions have probably remained reducing during the latest 1 Ma /Tullborg et al. 2003/.

III (500–1,000 m). Low temperature carbonates are present although less common. The biogenic input is less significant.

IV (> 1,000 m). Very few samples are available from depth larger than 1,000 m but the present indication is that calcite precipitates are over all less frequent and the calcite found is dominantly not of low temperature origin.

The new results have revealed possible Quaternary low-temperature freshwater carbonates at depth of 800 to 950 m in the KLX01 borehole and there is an overall tendency of meteoric water carbonates to larger depth in KLX01 than at Äspö and Simpevarp, based on $\delta^{13}C$ and $\delta^{18}O$. It is therefore possible that the depths of the different zones I–IV are different between Laxemar and Äspö, but the observations are still too few.

Cathodoluminescence (CL) and fluid inclusion microthermometric analysis of a suite of samples from the KLX01 borehole have been carried out at BGS. The CL imaging has allowed the recognition of five calcite generations which show evidence for significant fracture rejuvenation, reworking, brecciation, replacement and cementation by later calcite generations. These generations are consistent with those recognised during earlier work. Fluid inclusion microthermometric data has been acquired from all the generations.

The fluids are shown to have variable chemistries, with low-salinity (fresh water, typically < 2 wt% $CaCl_2$ equiv.) inclusions occurring in close proximity to very saline solutions (up to 24 wt% $CaCl_2$ equiv.), even within the same calcite generation. The higher salinity inclusions are $NaCl$-$CaCl_2$-H_2O brines, with high $CaCl_2$ / ($NaCl$+$CaCl_2$) ratios inferred for the highest salinity inclusions. The chemical species present in the low salinity inclusions are unknown.

The presence of high salinity fluids even at shallow depths in the borehole (well within the present day freshwater zone that extents down to approximately 1,000 m), indicates that the transition zone between the fresh and saline fluids was closer to ground level at some time during precipitation of these cements. Fresh water inclusions extend at least down to 840 m, but did probably not extend deeper than 1,000 m.

5 Äspö facility

5.1 General

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

5.2 Facility operation

5.2.1 Background

The main goal for the operation is to provide a 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 plant supervision system has considerably increased the possibility of running the facility in a safe and economic way. The availability of the underground-related systems has been more than 98% during 2003.

An automatic registration and object-monitoring system with the aims of increasing personnel safety underground was taken into operation for testing during December 2003. It was, however, discovered that the delivered system did not meet the requirements and that the contractor would not be capable of fulfilling the major requirements of the contract, consequently the contract was terminated by SKB.

The control inspection of the lift wire of the underground elevator indicated wear and the wire was exchanged just before the year-end.

The long term rock control and reinforcement programme has been continued to ensure safe and reliable rock conditions. Work on increased fire safety was also of concern during 2003 and safety-related education and fire fighting training was held in co-operation with the local fire brigade. The installation of a pipe from –340 to –440 m level, which will supply water to the ramp for fire protection and water to the experiments, has been started.

Excavation work has been performed underground for the Äspö pillar stability experiment (Apse) and for the site for demonstration of the KBS-3 method with vertical emplacement (KBS-3H). This work forced a re-routing of electricity cables, drainage and water supply pipes on the –450 m level. This routing has improved the infrastructure, which is now less exposed to mechanical damages.

Energy consumption at the facility has increased by approximately 10% compared to 2002 mainly due to the increase in additional office space and work with rock excavation at the –450 m level (Apse) and the –220 m level (KBS-3H), as well as the start of operations in the outer section of the Prototype Repository and the start of the Temperature Buffer Test.

5.3 Hydro Monitoring System

5.3.1 Background

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

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

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

5.3.2 Measuring system

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

5.3.3 Results

The measuring system has been working satisfactorily. However, in connection with the rock works during the summer 2003, data were lost for about one month from some of the measuring points in the tunnel. Improvements, new installations and other measures carried out during 2003 are:

- Calibration of the weirs and the sensors measuring electrical conductivity in the tunnel.
- Maintenance of the hydraulic multiplexer at 1,645 m position in the tunnel.
- Instrumentation of new boreholes in the outer part of the Prototype Repository tunnel.

5.4 Programme for monitoring of groundwater head and flow

5.4.1 Background

The network for the monitoring of groundwater head and flow includes boreholes on the islands of Äspö, Ävrö, Mjälen, Bockholmen and some boreholes on the mainland at Laxemar.

The monitoring of water level in surface based 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 was completed during 1995. The tunnel excavation began to affect the groundwater level in many surface based boreholes during the spring 1991.The first pressure measurements from tunnel drilled boreholes were included in the HMS in March 1992.

To date the monitoring program comprises a total of 149 boreholes (52 surface based boreholes and 97 tunnel based boreholes). Besides computerised monitoring is manual levelling obtained from the surface based boreholes on a regular basis (once a month). Water seeping through the tunnel walls is diverted to trenches and further to 22 weirs where the flow is measured.

5.4.2 Objectives

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

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

5.4.3 Results

The Hydro Monitoring System has continued to provide basic information on the influence of the tunnel drainage on the surrounding environment by recording the evolution of groundwater head and flow, and salinity of the groundwater.

The HMS data have been used in different ways, in addition to complying with the water rights court they have provided the means to continuously control the groundwater head in the rock volume where tracer experiments have been conducted. The head distribution in the block was to remain constant throughout the experiment since it forms an initial condition to the problem. Alteration in head gradients during the experiment might complicate the analysis.

The number of information points in the end of 2003 is shown in Table 5-1.

Table 5-1. Type of measurement and number of measurement points in 2003.

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

5.5 Programme for monitoring of groundwater chemistry

5.5.1 Background

During the 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.

5.5.2 Objectives

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

5.5.3 Results

Groundwater samples were taken at one occasion during 2003, in September. Sampling and analyses were performed according to SKB's routines. The analyses included in SKB Chemistry Class 4 (extensive sampling and complete chemical characterisation) and SKB Chemistry Class 5 (extensive sampling, complete chemical characterisation and special analyses) are shown in Table 5-2. The results from the sampling period will be presented in a Technical Document in the beginning of 2004.

Table 5-2. SKB Chemistry classes 4 and 5.

Class no	Analyses	Optional
4	Electric conductivity, pH Cl, HCO_3, SO_4, Br, F^- (500 ml), Fe (total, ferrous) (500 ml), NH_4 (100 ml), HS^- (600 ml), Uranine*, DOC (250 ml), major cations** SO_4 as Sulphur on ICP-AES (100 ml) ^2H, ^3H, ^{18}O (3,100 ml) Freeze stored back-up sample, preserved and non-preserved (500 ml)	NO_2, NO_3 and/or NO_2+NO_3, PO_4 (250 ml), I^- (100 ml)
5	Electric conductivity, pH Cl, HCO_3, SO_4, Br, F^- (500 ml), Fe (total, ferrous) (500 ml), NH_4 (100 ml), HS^- (600 ml), Uranine*, DOC (250 ml), major cations** SO_4 as Sulphur on ICP-AES (100 ml) ^2H, ^3H, ^{18}O (3,100 ml) NO_2, NO_3 and/or NO_2+NO_3, PO_4 (250 ml), I^- (100 ml) Freeze stored back-up sample, preserved and non-preserved (500 ml)	TOC (250 ml) ^{13}C, PMC (200 ml) U, Th (elements and/or isotopes) (100 ml), ^{34}S (1,000 ml), ^{37}Cl, ^{87}Sr (100 ml), ^{10}B (100 ml) Environmental metals, lantanoids and other trace elements (ICP-MS)*** ^{226}Ra, ^{228}Ra, ^{222}Rn (500 ml) Or Your decision

* Analysed when used as tracer in drilling water.

** Cations: Na, K, Ca, Mg, Fe, Mn, Li, Sr+Si.

*** Environmental metals are Al, Ba, Cd, Co, Cr, Cu, Hg, Mo, Ni, P, Pb, V, Zn.
Lantanoids and other trace elements are Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, La, Sc, Rb, Y, Zr, Sb, Cs, Hf, Tl, U, Th.

6 International co-operation

6.1 General

Seven organisations from six countries participated in the co-operation at Äspö HRL during 2003. Most of the organisations are interested in groundwater flow, radionuclide transport and rock characterisation. Several organisations are participating in the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes, which is a forum for co-operation in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock.

The international organisations are taking part in the projects and experiments described in Chapters 2, 3 and 4. The co-operation is based on separate agreements between SKB and the organisations in question. The participation by JNC and CRIEPI is regulated by one agreement. The participation of each organisation is given in Table 6-1. In the following sections the main work performed by the different organisations during 2003 is presented.

Table 6-1. International participation in the Äspö HRL projects during 2003.

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

SKB is through Repository Technology co-ordinating three EC contracts and takes part in several EC projects of which the representation in five projects is channelled through Repository Technology. SKB takes also part in work within the IAEA framework.

6.2 Andra

During 2003, within the frame of the co-operation agreed with SKB, Andra contributed to research on the following topics in the fields of Engineered and Natural barriers:

- Research on Engineered Barrier Systems mainly through the new Temperature Buffer Test, which focuses on the behaviour of bentonite buffer subjected to high temperature.
- Modelling tasks related to site characterisation with True Block Scale and related to an approach to performance assessment with the Task force on Groundwater Flow and Transport of Solutes.

6.2.1 Temperature Buffer Test

In co-operation with SKB, Andra is conducting the Temperature Buffer Test (TBT) dealing with the thermo-hydro-mechanical behaviour of a buffer under temperatures exceeding 100°C. One of its main objectives is to identify the temperature limit for a bentonite buffer, i.e. the highest temperature the buffer can withstand without alteration of its hydraulic properties, see Section 2.10.

Early in 2003, teams from SKB, Clay Technology and Aitemin carried out the field work required to implement the test. Heaters were switched on March 26 and a thermal shock was observed during in the first months of heating. It caused some desaturation in the hottest part of the bentonite.

Concurrently, predictive modelling studies of the buffer behaviour were carried out by Clay Technology, Electricité de France, Eurogéomat, and a Spanish team supported by Enresa, UPC & DM Iberia. A comparison of modelling results and early experimental findings, and the causes of the differences, were presented at the Sitgès Workshop in November 2003. An evaluation of the modelling programme will follow during 2004.

6.2.2 True Block Scale Continuation

During the True Block Scale Project, several tracer tests were performed over distances ranging from 15 to ~ 100 m, with all the source and sink points located in the relatively high-conductive structures identified in the hydrostructural model. Therefore, the tracer tests mainly sampled the network of highly conductive structures at the scale of interest.

One of the aims of the True Block Scale Continuation (BS2) is to assess the feasibility of tracer tests through the less conductive background fracture network, which may participate significantly in the retention processes. If the tests are feasible, they will be carried out.

For Andra and Itasca, 2003 was the year for reflection the representation and modelling of background fractures in the context of tracer test to be performed during the next BS2b stage.

Fracture length distribution

Classical models for fracture length distributions are exponential, lognormal or power-law. Itasca performed a review of earlier statistical analyses of the fracture system at Äspö at various scales. The presence of fractures over a large range of scales and also the absence of any obvious characteristic length scale were considered to be arguments in favour of the use of the power law model for fracture network modelling.

The simplest power-law model predicts the number of elements n(l), of length l, comprised between l and l+dl such that :

$n(l)dl \propto l^{-a}dl$

The power-law model is thus characterised by its scaling exponent, a, and the minimum and maximum fracture lengths below which and above which there are no fractures. Represented in a log-log diagram, the power-law distribution corresponds to a straight line with –a slope.

A combination of a power-law size distribution of fractures with a fractal scaling of the fracture spatial density can be expressed using the model as:

$n(l,L)dl \propto l^{-a}L^{D}dl$

Where D is the fractal dimension and L the characteristic linear size of the system (for instance the edge length of a cube) at which the fracture system is observed. The fractal dimension D expresses the way the fracture network fills the space.

Statistical analysis

A multi-scale analysis of Äspö fracturation data has been performed by representing in a log-log diagram the variations of the number of fractures of a given length, normalised by the system characteristic size, as a function of the length, see Figure 4-2.

Itasca states that, although a precise determination of exponents remains difficult due to artefacts present in the available data, the fracture system in 2D is well fitted by the fracture density length model outlined above. In addition the qualitative similarity of the fracture patterns through all scales speaks in favour of the power law model, with parameters a_{2d} and D_{2d} such that $a_{2d}=D_{2d}+1$. If $a_{2d}<D_{2d}+1$, an increase in the proportion of large fractures with increasing observation scale would be implied and conversely if $a_{2d}>D_{2d}+1$, a decrease in the proportion of large fractures with increasing observation scale is implied. Only when $a_{2d}=D_{2d}+1$ does the proportion remain scale invariant, as is observed on maps of Äspö fracture data.

The derivation of 3D parameters using stereological principles yields two pairs of parameters that could explain the data at hand: either a power-law exponent a_{3d} of 3.8 combined with a fractal dimension D_{3d} of 2.8, or an exponent a_{3d} of 4 combined with a fractal dimension D_{3d} of 3.

The scarcity of small scale fracture length samples with a high resolution make it impossible to fully assure the validity of the statistical model below a fracture size of about 10 m.

Tracer test simulations

Analysis of transport at the Block Scale is very much governed by knowledge of the deterministic structures, in which (or close to which) BS2b tracer tests will be performed. In particular, the properties of these structures such as positions and transmissivity are directly introduced in the model. The rest of the fracture network (stochastic) has been generated considering several fracture distribution models including the one above (power-law and lognormal, varying a3d, varying smallest length cut-off).

The configuration simulated corresponds to a pumping point at borehole KI0025F03 in Structure #19. Several injection points have been simulated, located along Structure #19, and in the new background Structure #25. Conservative tracer tests were simulated to provide predictions of the travel times through the fracture network partly including the secondary flowing network.

The simulations carried out show how the relative behaviour of a background fracture network varies when considering a lognormal or a power law fracture radius distribution (with the specific parameters corresponding to Äspö conditions). For the BS2 program, however, the differences resulting from the stochastic assumptions of the model are not of great concern, because the main structures are known and strongly control the advective flow.

Conclusion

This work includes an attempt to develop a view of the Äspö fracture system that encompasses all scales in a unified conceptual framework. Such a view, taking into account data at several scales, is likely to provide a robust description of the fracture network and can help filling voids in observation scales for sizes that are difficult to assess from field work. This work may provide new insights in several directions, beyond the framework of True Continuation.

In order to increase confidence in the multi-scale view, the following requirements have been identified:

- Detailed unbiased mapping at the smaller scale (metres to tens of metres) to improve the predictive capacities of the models at the geologic barrier close to the canisters. This is where properties of the smaller scale fractures become essential. This data would also help to confirm, or invalidate, the relevance of the power law model.
- More theoretical studies of the connectivity of such networks, using the fact that they show self-similarity, would yield estimates of the size of possible unconnected clusters within the network, and of the conductive/non conductive proportion of the fracture system.
- More theoretical work on the correlation of size/transmissivity/connectivity properties of fractures would improve the robustness of the models for varying hydraulic conditions.

Conclusions from the study concerning the practical work in BS2b, are that the tracer tests in the volume surrounding Structure #19 are feasible provided that injections in background fractures, if any, are carried out close to the Structure #19. After this necessary first step of advective transport modelling, it will have to be dealt with how reactive transport is affected.

The multi-scale study and related modelling results have been published /Darcel, 2003/.

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

The final results of Task 6A and 6B (single fracture models) were presented and discussed. An internal preliminary evaluation was made and conclusions were drawn. The major issue was to understand the large differences between the results produced by the different modelling groups. Andra's modelling work focused on the following objectives:

- Impact of the matrix heterogeneity on the transport and retention of tracers, iodine, strontium, cobalt, technetium and americium (Team from CEA).
- Demonstration of tracer tests, HTO and strontium, constraining power (Team from Golder).
- Transition between site characterisation and performance assessment modelling – simplification of the PA model (Team from Itasca).

Difference in the predicted performance cannot clearly be attributed to differences in the modelling approaches applied. There is a need to understand these discrepancies between the performance assessment modelling results. Andra suggested the development of reference case, to be compared with previous simulations, with the aim of understanding how the different conceptual models influence the results.

At the Workshop held in September, the Task Force attempted to identify differences in modelling approaches. Two external reviewers (John Black and David Hodgkinson) were nominated by the Task Force to carry out an evaluation of Task 6 Modelling reports. The reviewers will go through the reports and have an interview with each modelling group.

Task 6D, the fractured bloc modelling, is aimed to simulate the C2 tracer test. The modelling groups have not yet incorporated the complexity factor, which accounts for a combination of faults and joints. A discussion took place about the need to use this factor and how. The final modelling results are expected at the next Task Force meeting to be held early in 2004.

The Task6E is dedicated to transport in the fractured block within the performance assessment time scale. Specifications for PA modelling were discussed and defined. Suggestions about how the sensitivity analysis will be performed were made by various organisations.

6.3 BMWA

The co-operation agreement between BMWA (Bundesministerium für Wirtschaft und Arbeit) and SKB was signed in 1995. The agreement was extended in 2003 for a period of six years. Five research institutes are performing the work on behalf of and funded by BMWA: BGR, DBETec, FZK, FZR, and GRS.

The purpose of the Äspö HRL co-operation is to complement knowledge about potential host rocks for radioactive waste repositories in Germany. The items of special interest are:

- Characterisation of fracture zones in the rock mass and disturbed zones surrounding underground openings.
- *In situ* measurement of groundwater flow in fractured rock and in the rock matrix.

- Geochemical investigations of the migration behaviour of radionuclides, especially actinides, under near field and far field conditions.
- Geochemical modelling of individual processes controlling migration.
- Thermodynamic data bases for radionuclides relevant for long-term safety.

The work carried out in 2003 is described below.

6.3.1 Prototype Repository

Geoelectric monitoring

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

The *in situ* measuring programme agreed by SKB and GRS includes the monitoring of two electrode arrays in the backfilled tunnel above deposition Holes 3 and 6, three electrode chains at top of Hole 5 and three electrode chains in the rock between deposition Holes 5 and 6 (see Figure 2-11).

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

Results and interpretation

The array in the backfill in inner Section I was the first one to be installed. Measurements started in October 2001. Figure 6-1 (left) shows the resistivity distribution of the first measurement. The initial resistivity of the backfill ranges around 10 to 14%, corresponding to a water content of 13 to 14 Ωm. In the lower part of the backfill the resistivity is somewhat higher, which is due to a lower density of the backfill near the floor (a consequence of the installation and compaction procedure).

The resistivity of the backfill has been steadily decreasing, starting near the walls of the tunnel and continuing to the centre. The right side of Figure 6-1 shows the resistivity distribution at the end of November 2003. In November 2003, a very homogeneous resistivity distribution with a value of 3 to 5 Ωm, which corresponds to a water content around 20%, was reached. There has, however, also been a slight temperature rise in the tunnel (maximum 32°C) which may cause an additional resistivity decrease. This is limited, however, to less than 1 Ωm, which means water content may be lower by 0.5 to maximal 1%.

The water uptake from the tunnel walls and the lower saturation in the center is also confirmed by suction measurements performed by Clay Technology /Goudarzi and Börgesson, 2003/.

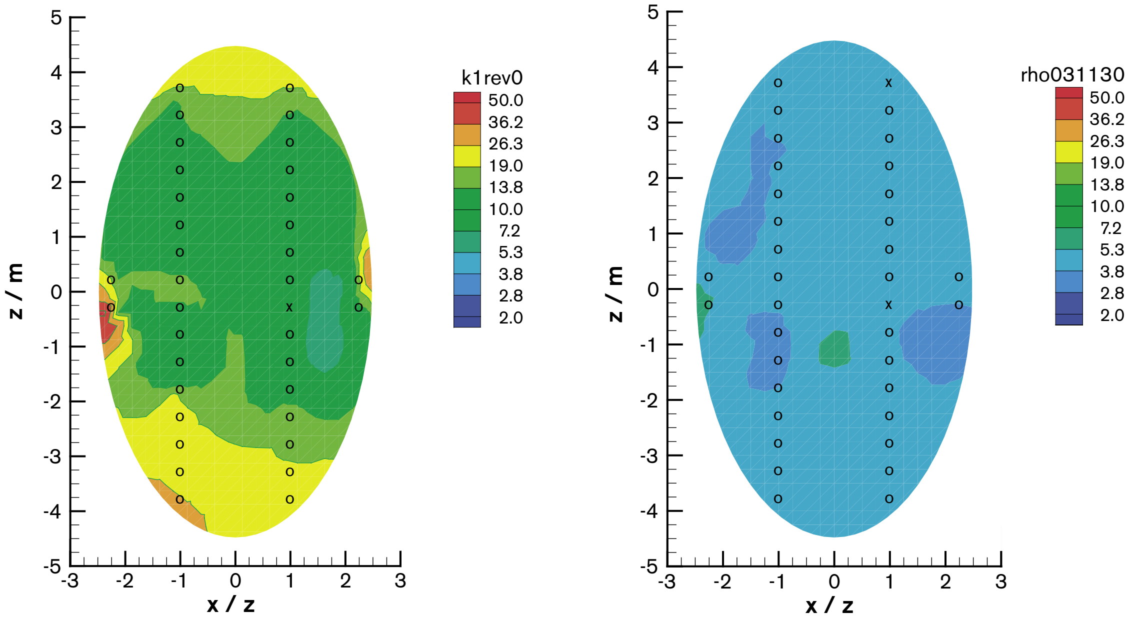


Figure 6-1. Resistivity distribution in backfill Section I, October 2001 (left) and November 2003 (right).

The array in the backfill in the outer Section II was installed in June 2003. The results of the first measurement (Figure 6-2, left) show a much lower resistivity than the early measurements in Section I. Obviously, the backfill had considerably higher water content already during installation. This observation was also made during instrumentation. Resistivity is decreasing further from the tunnel walls (Figure 6-2, right). Close to the walls it ranges below 3 Ωm; the backfill is therefore not far from full saturation. In the centre, the resistivity has decreased to between 5 and 8 Ωm corresponding to a water content of about 15 to 18%.

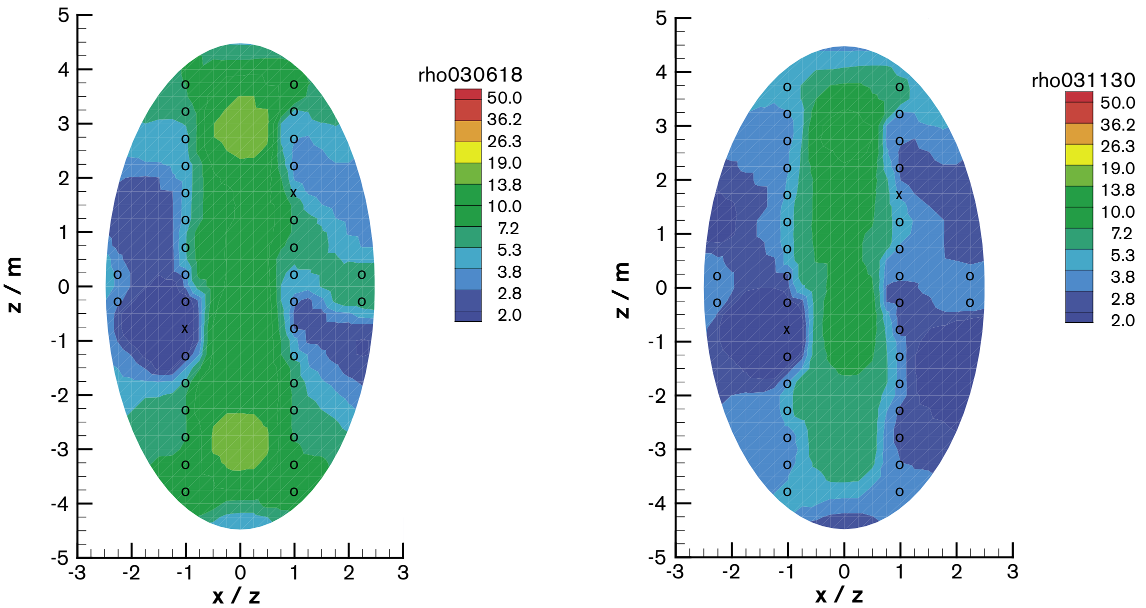


Figure 6-2. Resistivity distribution in backfill Section II, June 2003 (left) and November 2003 (right).

The results of the first measurement in the buffer taken in May 2003 (Figure 6-3, left) show the high resistivity (above 1,000 Ωm) of the rock on the right side and the low resistivity of the buffer (below 80 Ωm) on the left. The picture is somewhat distorted by the fact that near the electrode chains the resistivity is higher than in the undisturbed buffer. This finding can be attributed to the refilling of the electrode boreholes with bentonite powder produced during borehole drilling. It is, however, expected that the difference will diminish with time, especially if the buffer takes up water. This becomes particularly clear in the tomogram from November 30, 2003. It can be seen that the resistivity near the electrode chains is no longer higher than in the surrounding buffer. While the overall behaviour is rather clear, it is difficult to determine the water content from the buffer resistivity. Near the electrode chain in the centre of the buffer (left of the tomograms) the resistivity ranges between 4 and 24 Ωm.

The resistivity distributions along the three electrode chains in the rock are quite similar to each other and show no significant variation in time until April 2003. 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 increases to between 2,000 and 7,000 Ωm which is characteristic for granite. Figure 6-4 (left) shows as an example the resistivity distribution around the chain KA 3550 G04 in the rock near deposition Hole 5. From April 2003 on, there is a slight decrease in the resistivity of the rock near deposition Hole 5 (Figure 6-4, centre and right side). This coincides with installation of the buffer which also stopped the pumping of water from the open deposition hole. Apparently, this had caused a slight de-saturation of the rock which has now recovered. Near to deposition Hole 6, no such effect was detected.

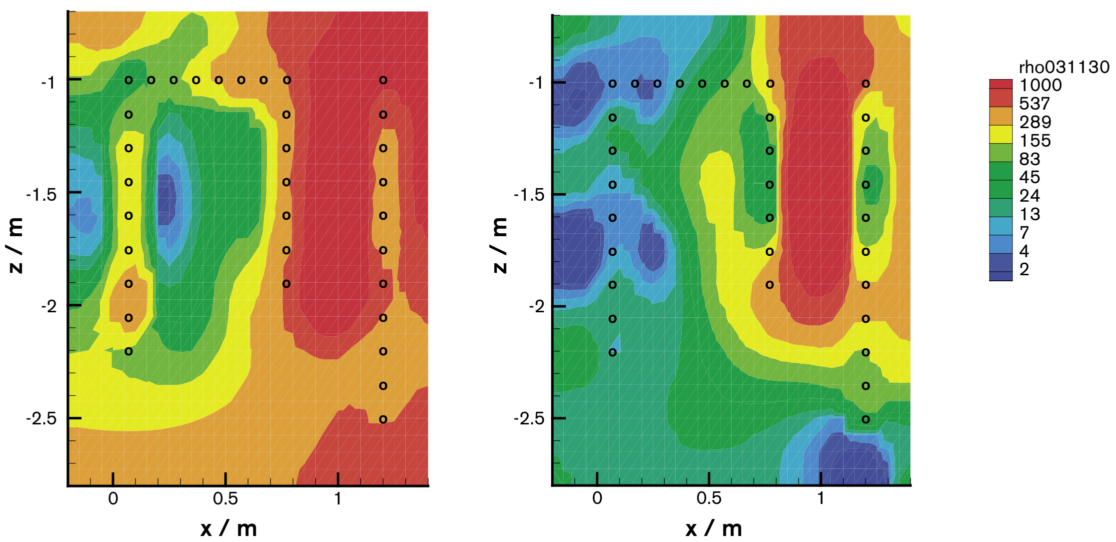


Figure 6-3. *Resistivity distribution in the buffer at the top of deposition Hole 5, May 2003 (left) and November 2003 (right).*

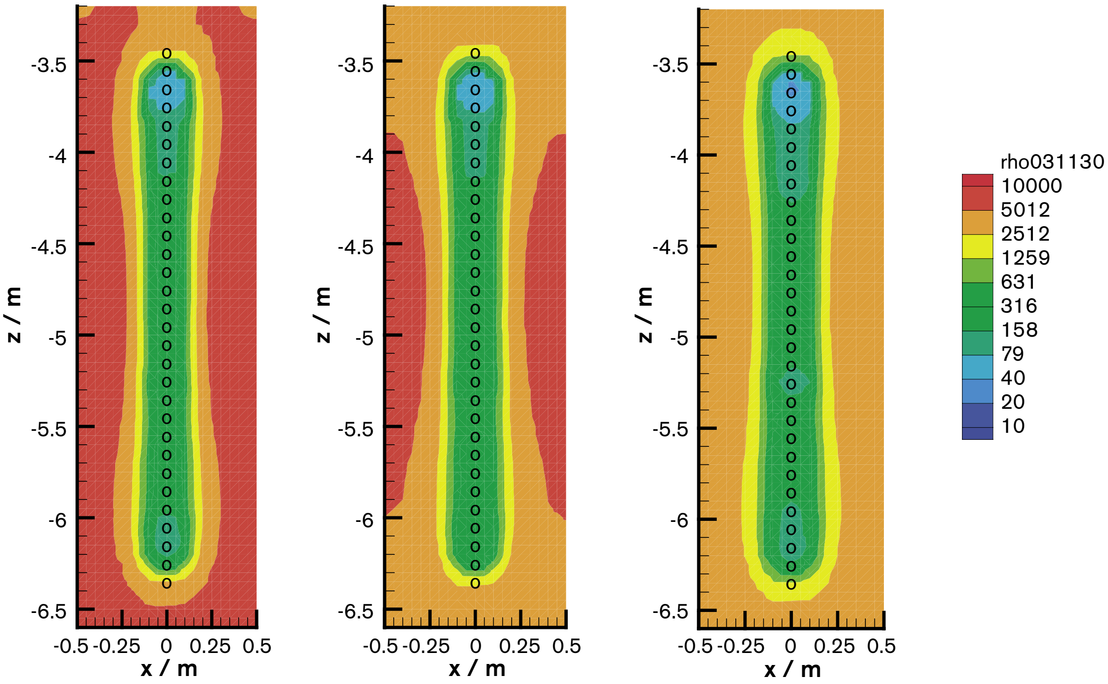


Figure 6-4. *Resistivity distribution along electrode chain KA 3550 G04 in the rock near deposition Hole 5, August 2002 (left), April 2003 (centre), and November 2003 (right).*

Modelling the resaturation of bentonite

The aim of the work which has been carried out as part of the participation in the working group modelling the Prototype Repository is to develop a simplified model for simulating re-saturation, with regard to long-term safety assessment for final repositories /Kröhn, 2004/.

To create a date base for the testing of numerical models describing the re-saturation of bentonite, laboratory experiments were performed at the geotechnical laboratory of GRS in Braunschweig, Germany. They showed for the first time the dynamics of the re-saturation process in high spatial as well as high time-dependent resolution. Re-saturation of MX-80 bentonite with Äspö solution was investigated at room temperature and under atmospheric pressure. The set up of the experiment was simple (see Figure 6-5a). The results were highly reproducible.

Although re-saturation with Äspö solution came closest to a re-saturation scenario, it was not possible to distinguish whether water transport takes place via the liquid phase, via the gaseous phase, or via the two phases at the same time. An additional experiment with water vapour instead of liquid water (see Figure 6-5b) allowed investigation of vapour transport without the interference of liquid water transport. The experimental results allowed not only a proper model test but also, by comparison with the results of the model calculations, allowed conclusions to be drawn regarding the relevance of the different transport processes.

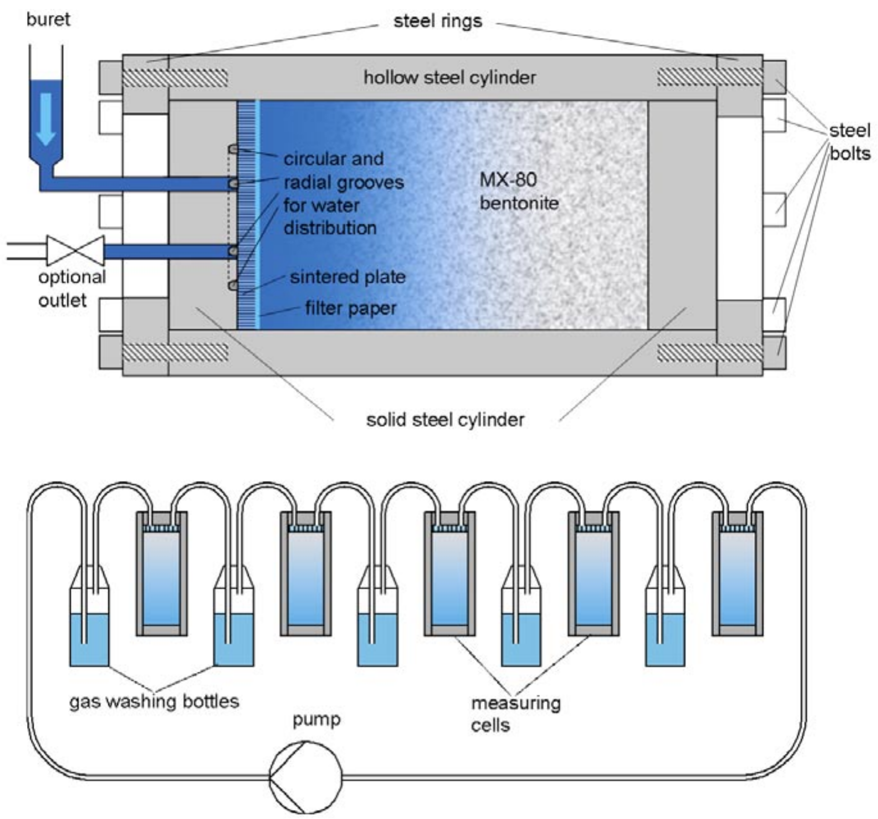


Figure 6-5. *a) Cross-sectional view of a measuring cell; experiment with liquid water.*
b) Connection diagram of the measuring cells for the water vapour uptake tests.

In addition, the water uptake rate of un-compacted bentonite samples in a vapour-saturated atmosphere was determined. The aim of these experiments was to quantify the hydration rate as a function of the water content. This allowed determination of the reference hydration rate, which was needed for modelling purposes and had so far been unknown. All these experiments in conjunction with the numerical modelling allow an in-depth insight into the dynamics of the hydraulic processes which occur during re-saturation, especially since mechanical and thermal influences are largely excluded.

The model calculations presented in the remainder of this section are based on the vapour diffusion model which has been developed in an earlier project phase. It simulates re-saturation via water vapour, taking into account only binary gas diffusion and hydration, including the subsequent pore volume changes. Figure 6-6 shows a selection of the measured time-dependent moisture distributions for the uptake of water vapour along with the corresponding modelling results. The figure demonstrates that the development of the vapour distribution could be reproduced fairly well with the vapour diffusion model. The amount of hydrated water as well as the trend of the distributions coincides well with the measured data. However, there are some discrepancies in the uptake dynamics. Considering that the vapour diffusion model at the present stage incorporates several simplifications the agreement is satisfying.

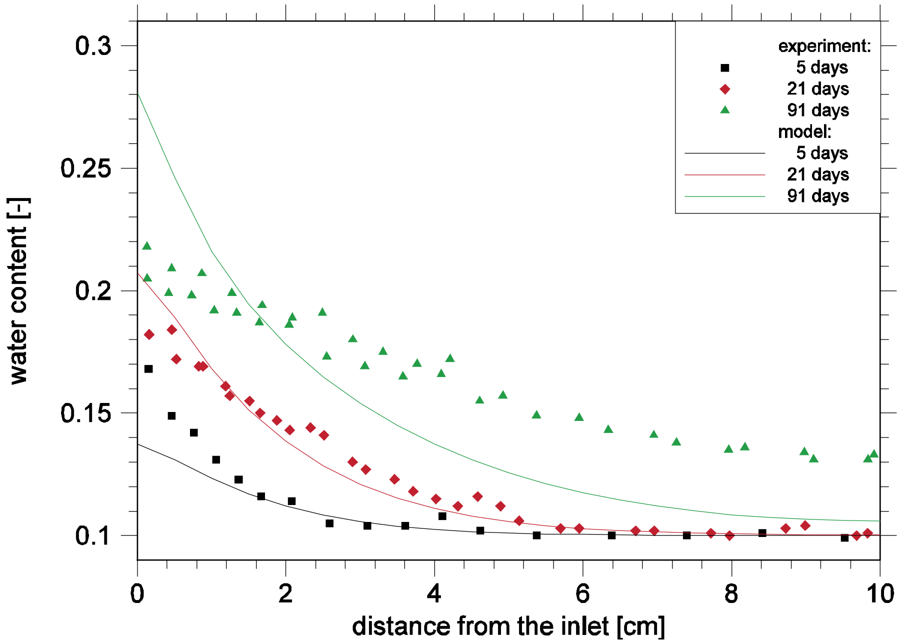


Figure 6-6. *Water content as a function of penetration depth; re-saturation experiment with water vapour and results from the vapour diffusion model.*

Interesting conclusions can be drawn from a comparison of the results of the vapour diffusion model with the data from the uptake experiment with liquid water as illustrated in Figure 6-7. It shows that about one half of the hydrated water can be explained by means of binary gas diffusion. This means that transport of a considerable part of the water taken up occurs by vapour diffusion. Assuming that vapour diffusion changes to Knudsen-diffusion in an advanced stage of saturation, it could even be possible to explain the bentonite saturation exclusively by vapour flow due to an increasing diffusion coefficient. If this is the case, the uptake of liquid water may be limited to the wetted bentonite surface.

The most important result is that the process of hydration via water vapour is highly relevant for the re-saturation of bentonite. Without further experimental evidence it has to be conceded that it could even be the dominant process. This would have severe consequences. Two-phase flow would be relevant only for a very short time period after the first contact with the liquid water and then possibly at a very late stage of re-saturation again. Therefore, the hydraulic part of any of the presently used resaturation models is questionable, because all these models are based on the assumption of unsaturated or two-phase flow /Kröhn, 2003/.

In the light of the new experimental results the actual relevant process of pore water transport is not clear, even under simple conditions such as room temperature and atmospheric pressure. Clarification in this respect, revision of the conceptual model of bentonite re-saturation and confirmation by investigations at elevated temperature and increased pressure are therefore highly advisable in order to re-establish confidence in the performance of resaturation models.

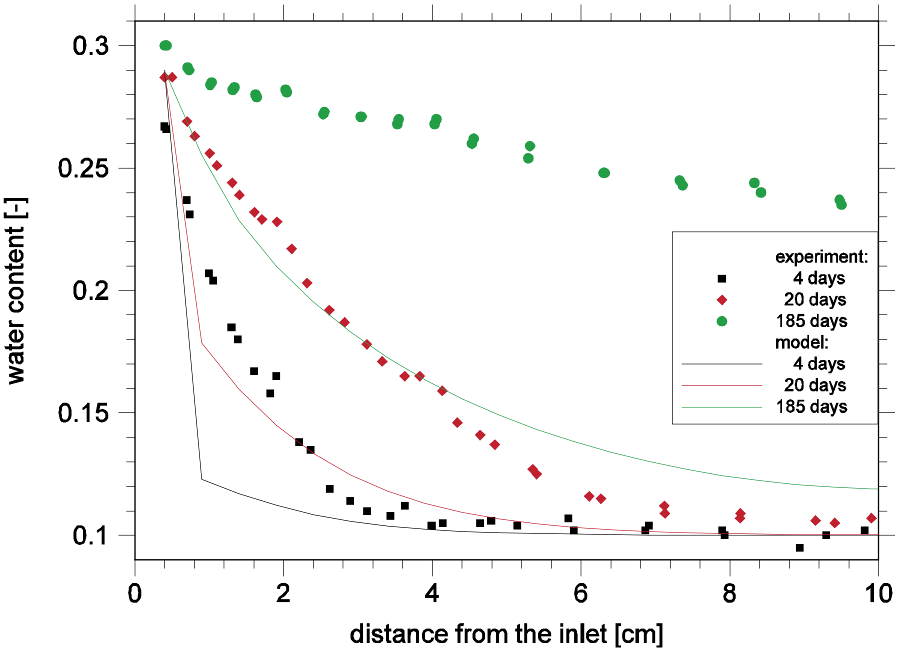


Figure 6-7. *Water content as a function of penetration depth; re-saturation experiment with liquid water and results from the vapour diffusion model.*

6.3.2 Radionuclide Retention Experiments

Objectives

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

Experiments and Results

An *in situ* migration experiment was started with the Chemlab 2 probe in November 2002. The same experimental setup was applied as in previous experiments. The flow path properties and the breakthrough of inert HTO tracer had been investigated previously in the laboratory. The actinides Am, Np and Pu are used as tracers. The results of the experimental investigations have been reported /Kienzler et al. 2003b/. After evaluation of the last experiment, the findings of the laboratory and *in situ* experiments were compared with respect to breakthrough, sorption patterns in the cores, and sorption mechanisms.

Breakthrough curves

Laboratory migration experiments using Core #1 were run with pulse injections at flow rates between 3 and 0.06 ml/h. In successive actinide migration experiments with Core #1, the radionuclide concentrations in the eluate were determined by both α-spectroscopy and ICP-MS measurement. The migration of Np was retarded compared to the migration of HTO. Recoveries for ^{237}Np were between 5 and 40%. The results showed that the bulk of Np was retained, especially at low flow rates. With Core #4, three subsequent actinide experiments were performed in the laboratory injecting 14 ml of actinide cocktail at constant flow rate of 0.3 ml/h. Only in the first experiment with Core #4 was a breakthrough of Np observed. In the following tests Np was found in concentrations close to the detection limit. Am and Pu concentrations in the eluate were below detection limit.

The same injection scheme was applied in Chemlab 2 with Core #2. In both experiments the breakthrough of Np followed the tendency of the HTO curve. In laboratory experiments as well as in the *in situ* experiment breakthrough of Np was observed to be unretarded compared to the inert HTO tracer. Recovery of Np in the Core #4 experiment was about 26%, whereas in the Chemlab experiment 40% of Np was recovered. At the peak of the breakthrough of the Chemlab 2 experiment, the speciation of Np was analysed by absorption spectroscopy. The spectrum showed only one absorption band, that of the free NpO_2^+ ion.

Actinide distribution patterns

Cores #1 and #5 showed an open fracture with an average aperture of 0.8 mm. The other cores showed partly open fractures. Structures which could be seen in the scans of Cores #2 and #4 slices were attributed to a healed fracture system. After impregnation of the fractures with a fluorescent resin and cutting, volumes and inner surfaces of the fractures were determined by scanning and pixel counting of the slices.

The open fracture of Core #1 varied between 38 and 87 mm^2 and the circumferences of the fracture at top and bottom of each slice were determined to be between 72 and 96 mm (mean value 80 mm). In the case of Core #5 the average cross section of the fracture for 30 slices is 46.3 ± 24.8 mm^2. α-autoradiography showed a strong correlation of the sorbed radioactivity with the surfaces of the fracture especially for Cores #1 and #5 with open fractures.

Because three different experiments were performed on Core #4, a greater quantity of actinides was injected. The Np content was determined by different methods. The distribution of Np in Core #4 showed the highest values at the site of the injection, a first peak at a distance between 30 and 40 mm and a third less pronounced peak between 104 and 118 mm. All these peaks were indicated by several measurements of abraded material as well as by γ-counting of ^{233}Pa (daughter of ^{237}Np). In Chemlab 2 with Core #2, a broad Np distribution between 50 and 112 mm was recorded. The spatial patterns obtained by α-autoradiography were not necessarily correlated with fracture filling material, which could be discriminated from granite by its colour.

From the Core #4 experiments, a lower limit for the retardation factors for Am and Pu can be estimated. By comparing the open volume of the fracture to the total groundwater volume eluted during the 3 consecutive experiments, a retardation coefficient of 135 was obtained.

In Core #5, both ^{237}Np and ^{243}Am distributions show the maximum count rate at a distance between 51 and 56 mm from injection. The maximum of Np was verified by both detection methods. However, the maximum for Am is characterised only by very few data points showing a wide scatter. ^{242}Pu could not be detected by ICP-MS. From the Core #5 experiments, a lower limit for the retardation factors for Np and Am is estimated by comparing the location of the Np peak with the total groundwater volume eluted. A retardation coefficient of 69 is obtained, which is a factor of 2 below the retardation coefficient determined from Core #4. The difference may be attributed to the fact that in Core #5 an open fracture system existed and therefore the specific surface area per migrated distance was significantly lower than in the almost clogged Core #4.

Sorption mechanisms

The time dependence of the sorption process within the period under investigation was investigated for Np, Pu and U. Np shows fast sorption onto altered material and retarded sorption onto granite. By using a factor to account for the form of the surface areas, which can be obtained from geometrical properties, results of batch sorption experiments can be applied to actinide migration in fractures.

Information on the retention mechanism was obtained from the investigations. The actinides were present as Am(III), Pu(IV) and Np(V) in the cocktail injected into the cores. Comparisons between the actinides showed that in Cores #4 and #5, Np and Am were retained at the same locations.

Two independent methods were applied to determine the Np redox state. From slices of Core #4, Np was dissolved with HCl, and by TTA extraction Np(IV) was separated. As a result, it was found that more than 60% of Np was bound to the slices in the form of Np(IV). Np(V) in solutions even at negative Eh remained as Np(V) for many months as long as no solids were present. This indicates that solid granite and/or fracture filling material catalyses reductive processes. Potential sites for reduction processes might be pyrite and Fe(II) containing clay minerals which are detected in the Äspö granite.

X-ray photoemission spectrometry (XPS) was applied as another method for identification of chemical valence states of Np and iron. Analyses at various areas on the samples (from batch experiments) indicated correlation of Np(IV) with the presence of Fe(II). More than 80% of Np could be assigned to the tetravalent state, which is agrees with the information from the TTA extraction method.

The next Chemlab experiment is planned with Core #7 using U and Tc as tracers.

6.3.3 Colloid Project

Objectives

After the measurement campaign to determine the concentrations and size distributions of colloids in natural groundwaters (background experiment), it was decided to prepare an *in situ* colloid migration experiment at Äspö HRL. The experiment is designed so that it can be performed in a dipole of a well-characterised fracture, for example in a True I feature. One pre-requisite of such an experiment is the knowledge about the behaviour of the tracer colloids under the prevailing groundwater conditions.

Experiments and results

Colloids originating from backfill bentonite have to be labelled by REE for an *in situ* colloid migration experiment. To prepare these smectite colloids, their stability in specific granite groundwater (Äspö) was estimated. The methodology was developed and tested within the framework of the CRR (Colloid Radionuclide Retardation) project.

Smectite colloid stability strongly depends on both the permanent charge induced by isomorphous substitutions of tetrahedral or octahedral sites and the pH dependent edge charge (silanol/aluminol groups). This edge charge is not easily determinable by classical zeta potential measurements, which measure the bulk surface charge dominated by the permanent layer charge. In the colloid stability measurements made in the laboratory /Geckeis et al. submitted; Möri et al. 2003; Schäfer et al. submitted/, this problem was approached by carrying out smectite independent measurements of purified γ-alumina and quartz colloids under variation of the ionic strength (1:1 electrolyte NaCl) and pH. From the Al/Si ratio which can be derived from the structural formula for the Febex bentonite used in this study $((Si_{7.66}Al_{0.34})(Al_{2.68}Fe_{0.34}Mg_{0.91})X_{0.81}O_{20}(OH)_4$ given by /Villar et al. 1998/) it was possible to estimate the smectite edge charge for ionic strength 0.001M to 0.1M.

The zeta potential measurements revealed that in the pH range 7 to 8, which is typical for Äspö groundwater, the bulk potential was ~ 40 mV (ionic strength 0.001M). However, the calculated edge zeta potential is significantly lower; –5 to –15 mV (ionic strength 0.001M) and 0 to –2 mV (ionic strength 0.1M). Furthermore stability ratio (W) measurements of natural Febex colloids under variation of the ionic strength (1:1 electrolyte NaCl and 1:2 electrolyte $CaCl_2$) at pH 9.6 revealed a critical coagulation concentration (W=1) of I = 0.1M (NaCl) and ionic strength 0.01M ($CaCl_2$). These results indicate clearly that pure smectite colloids will aggregate under most hydrogeochemical conditions found in Äspö groundwater.

However, additional spectromicroscopic investigations on natural Febex smectite colloids /Geckeis et al. submitted/ and natural smectite colloids in dissolved organic carbon (DOC) containing groundwater /Schäfer et al. 2003a,b/ revealed that edge charges might not be dominated by silanol/aluminol group, but by sorbed organic functional groups. The DOC concentrations of 1 to 16.1 mg/l found in Äspö groundwater might therefore be sufficient to significantly increase the negative edge charge and therefore stabilise smectite colloids. Further investigations are in progress to elucidate this effect.

6.3.4 Microbe Project

Introduction

Sulfate-reducing bacteria (SRB) are widely distributed in the deep granitic rock aquifers at the Äspö HRL. The work focussed on the SRB strain *Desulfovibrio äspöensis* DSM 10631T recovered from a depth of 600 m at Äspö. Very little is known about the interactions of Cm(III) with *D äspöensis* bacteria and with bacteria in general in comparison to what is known about uranium.

Experimental

The Gram-negative strain *D äspöensis* was grown to the mid-exponential phase. The collected biomass was 0.8 g dry weight/l. The molecular analysis of the *D äspöensis* cultures was performed using enzyme analyses (Ardrea). The time-resolved laser-induced fluorescence spectra were recorded at 25°C using a flash lamp pumped Ti:sapphire laser (Elight, Titania). Details on the experimental set-up are summarised in /Moll et al. 2003a,b/.

Results and discussion

Figure 6-8 shows emission spectra of $3{\cdot}10^{-7}$ mol/l Cm(III) in aqueous solution in presence of *D äspöensis* at various pH. The spectra of Cm(III) in solution at pH 3.00 and at pH 7.55 in absence of bacteria are also shown. At pH 3 only the emission band of the aqueous Cm^{3+} ion with a peak maximum at 593.8 nm was detected. At pH 7.55 a red shoulder is visible in the spectrum of Cm(III) indicating the formation of the first hydrolysis complex $Cm(OH)^{2+}$. This is in agreement with studies of /Fanghänel et al. 1994/ confirming that the first hydrolysis complex $Cm(OH)^{2+}$ is formed at pH > 6 in carbonate-free solutions. Speciation calculations, using the formation constants for the Cm(III) hydrolysis species published by /Fanghänel et al. 1994/, show that 18% of the Cm(III) exist as $Cm(OH)^{2+}$ at pH 7.55. In all samples with cells at pH < 3.35 the emission band of the aqueous Cm(III) ion dominates the emission spectra. Starting at pH 3.35 the intensity of the 593.8 nm peak decreases with increasing pH and a second peak appears with a peak maximum at 600.1 nm. From the pH-dependent emission data of Cm(III) in presence of bacteria (Figure 6-8) it was concluded that hydrolysis plays no role in the reaction mechanism. When hydrolysis occurs, all of the Cm(III) is already sorbed onto the cell envelope of the bacteria. 0.093 mg Cm(III) are bound to the biomass per g dry weight at pH 7.55.

The factor analysis technique was applied to calculate the contributions of the pure components to the measured composite spectra. The spectra of the single components derived by deconvolution of the mixed spectra (Figure 6-8) are shown in Figure 6-9.

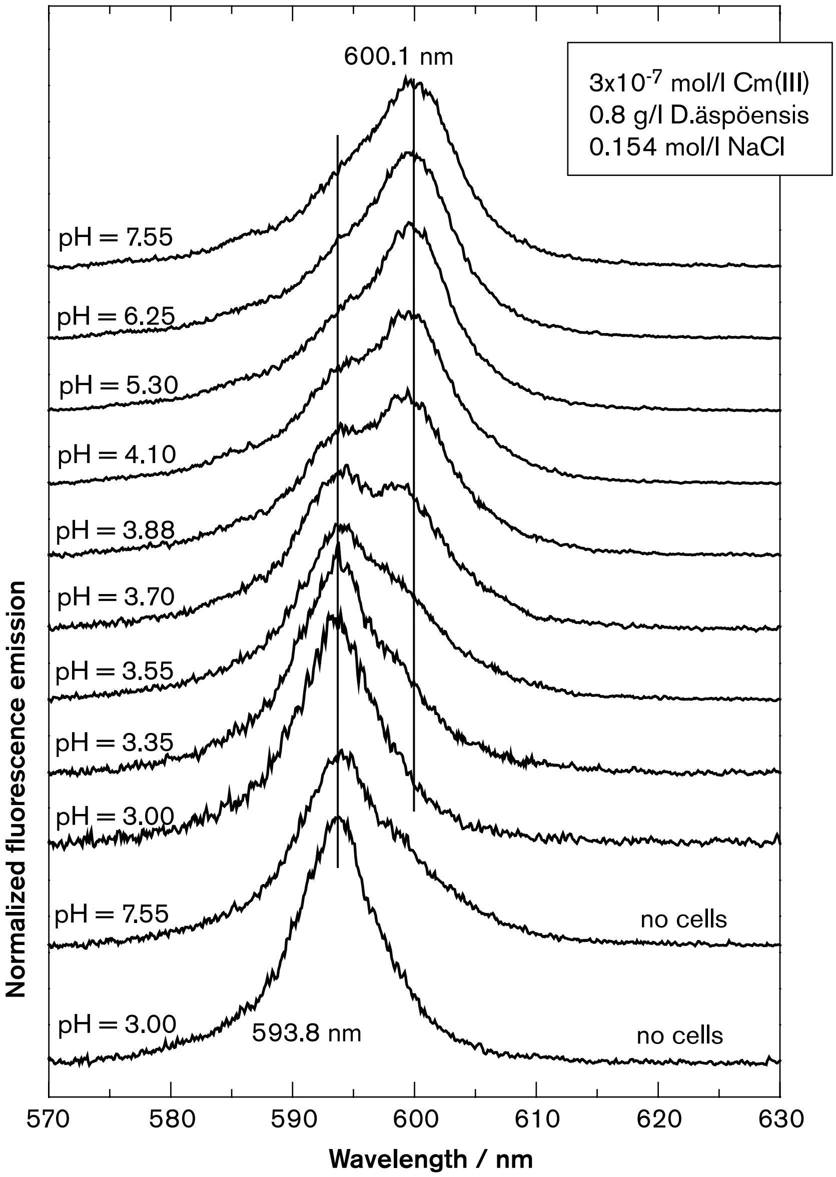


Figure 6-8. *Fluorescence emission spectra of Cm(III) in a suspension of* D äspöensis *at different pH.*

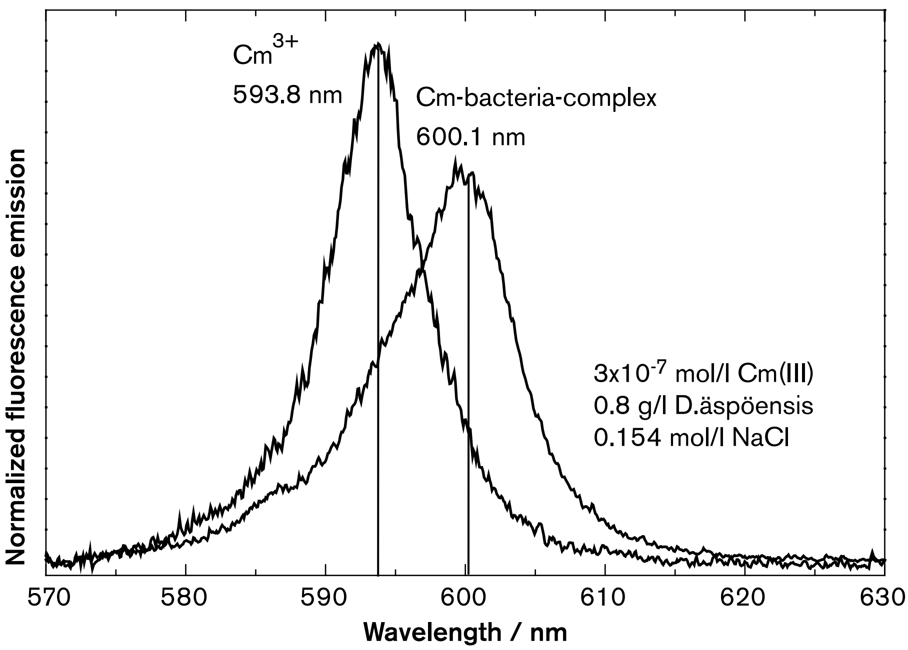


Figure 6-9. *Spectra of the single components of Cm(III) in suspensions of* D äspöensis.

Desorption experiments were performed to check the reversibility of the biosorption of Cm(III) onto functional groups of the *D äspöensis* cell envelope. $HClO_4$ was added to a Cm/bacteria containing sample at pH 6 to get pH 3. After a few minutes, a TRLFS measurements confirmed that the emission band of the Cm(III) surface complex moved from 600.1 nm to 593.8 nm. The detection of the aqueous Cm(III) ion indicates the reversibility of the sorption reaction.

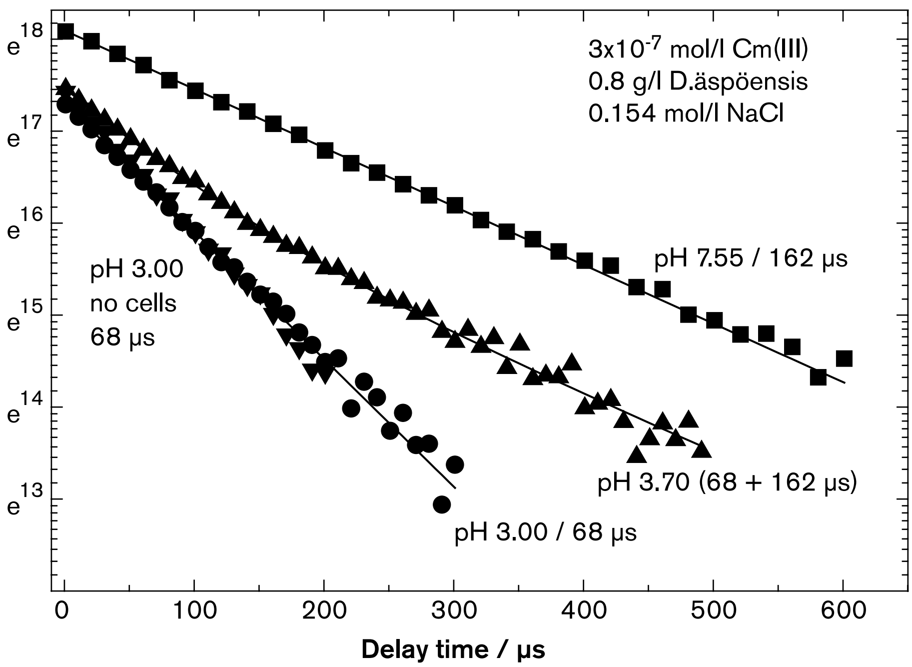


Figure 6-10. *Fluorescence lifetimes in the system Cm(III) –* D äspöensis*; mono- and bi-exponential decay behaviour.*

Fluorescence emission lifetimes of 68 µs were measured for the aqueous Cm^{3+} on, whereas the Cm-*D äspöensis*-surface complex is characterised by a long fluorescence emission life-time of 162 +/– 5 µs (Figure 6-10). According to the Kimura and Choppin equation a life-time of 68 µs corresponds to nine water molecules in the first Cm(III) coordination sphere and a lifetime of 162 µs corresponds to three water molecules in the actinide first hydration shell /Kimura et al. 1994/. The dehydration of Cm(III) by sorption onto the bacteria can be explained by the interaction process of Cm(III) and the cell envelope of *D äspöensis*. These findings and other investigations of Gram-negative bacteria with actinides may indicate an interaction of Cm(III) with organic phosphato-groups of the cell envelope. No indication of uptake of Cm(III) inside the cells was found.

6.3.5 Two-phase flow

A project has been performed to further improve the numerical tools for calculating gas-water flow in fractured and porous media. Methods for describing two-phase flow processes in single fractures and for upscaling the constitutive relations from microscale to macroscale were further developed. Data from the HRL were used to generate geostatistical models. In 2003, the models that have been developed were finalised and the project was concluded. The final report is being printed.

6.4 Enresa

Within the frame of the collaboration agreement signed with SKB, Enresa has continued working during 2003 with three of the Äspö HRL experiments related to the performance of the engineered barrier system: Prototype Repository, Backfill and Plug Test, and Temperature Buffer Test. Most of the work performed had to do with the interpretation and modelling of experimental results, although some installation of sensors, collection of monitoring data and laboratory support work was also accomplished.

6.4.1 Prototype Repository

Instrumentation and monitoring work

In the Äspö HRL Planning Report 2003, the installation of six displacement sensors for the deposition Hole 6 was scheduled for the month of March. However, some problems were detected in three of the sensors during the routine checking prior to the installation. The sensors had to be sent back to the manufacturer for repair work, which made it impossible to install the displacement system according to the schedule. Therefore, a modification was made to the installation plan. On March 18, the three operative transducers were installed as vertical sensors in the bottom bentonite block (Figure 6-11). Once repaired, the other three sensors were installed in the upper bentonite ring, on top of the canister, as horizontal sensors. This work concluded in late April with the connection of the sensors. Since that date, the data generated by the canister displacement systems installed by Aitemin in deposition Holes 3 and 6 is forwarded to Clay Technology on a quarterly basis.

Figure 6-11. *Photos showing the installation of vertical displacement sensors.*

Supporting laboratory tests

The laboratory work performed in support of the modelling task during 2003 was a continuation of the program initiated in 2001:

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

A detailed description of the tests performed, including the methodology used by CIEMAT for characterising the MX-80 buffer clay can be found in a previous annual report /Villar, 2002/.

Retention curve at laboratory temperature

The retention curves reported in the previous annual reports /Villar, 2002, 2003/ were determined following a methodology developed specifically for this project – the method of the block and the sensor. In order to check the performance of this new methodology a retention curve at 20°C has been determined in non-deformable cells /Villar, 2002/. With this aim, a wetting path for dry density 1.60 Mg/m^3 and an initial water content of 9 percent (approximate suction of 110 MPa) has been followed. The results obtained (Figure 6-12), show a good correlation between both methods. The advantage of the block and sensor method is that it is much easier and faster for getting results. It has the drawback that in its present configuration, it is not applicable to suction below 20 MPa.

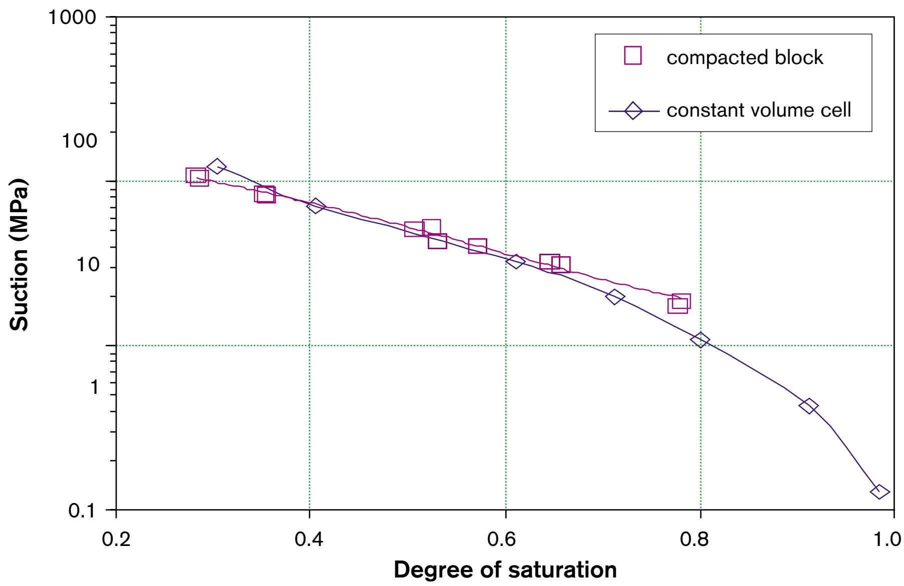


Figure 6-12. *Retention curves at 20°C determined with two different methods for MX-80 clay compacted at dry density 1.60 Mg/m^3.*

Retention curve at 60°C

The determination of the retention curves at 60°C started in December 2001 and is still undergoing. The testing paths followed were chosen taking into account the possible evolution of the clay in the barrier:

- Wetting paths for dry density 1.79 and 1.37 Mg/m^3, from initial water content of 17% (approximate suction of 40 MPa).
- Drying/wetting paths for dry densities 1.79 and 1.60 Mg/m^3, from an initial water content of 17% (approximate suction of 40 MPa).
- Wetting paths for dry density 1.30 Mg/m^3, from an initial water content of 9% (approximate suction of 110 MPa).

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

The results obtained up to now are presented in Figure 6-13. Two points show an anomalous degree of saturation (larger than one) the reason being that the density of the water considered for the computation was 1 g/cm^3 (free water) while the density of the water adsorbed in the bentonite is larger than 1. The retention curves barely show hysteresis, and the trends in the wetting, wetting after drying and drying paths are rather similar.

The comparison of the curves obtained at 60 and 20°C (Figure 6-14) shows that for a given dry density the retention capacity increases with temperature, at least for suctions above 30 MPa.

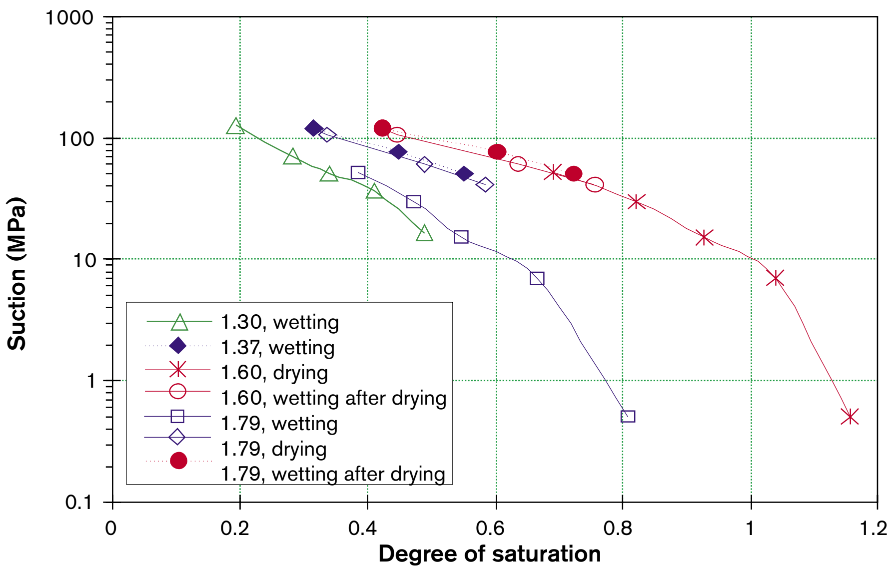


***Figure 6-13.** Retention curves at constant volume and at 60°C for MX-80 clay (dry densities in Mg/m^3).*

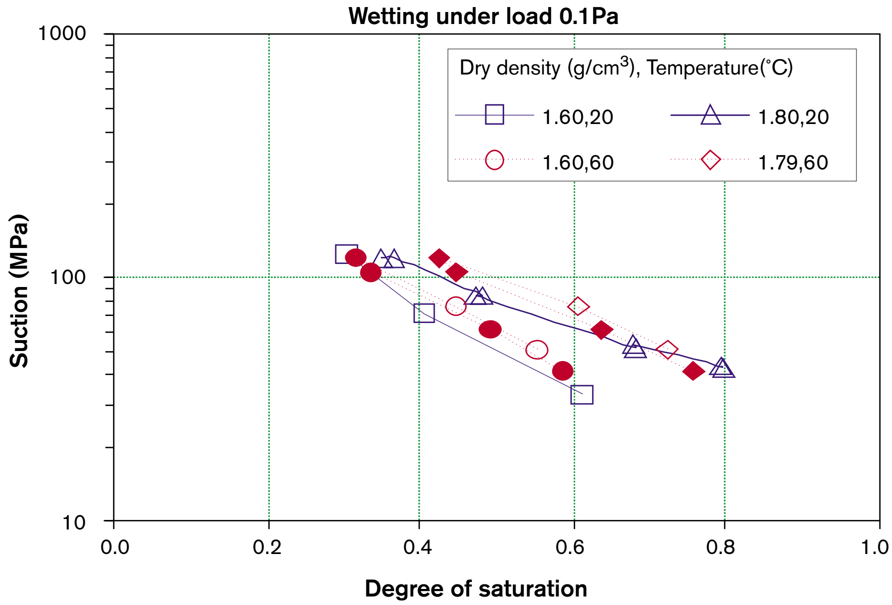


Figure 6-14. *Retention curves for MX-80 clay at 20 and 60°C.*

Suction controlled oedometer tests

Of the suction controlled oedometer tests proposed /Villar, 2003/, only those performed in nitrogen cells have been completed. In the tests performed in sulphuric acid cells, the time required for stabilisation of each suction step is very long, more than one year and, therefore, the duration of each test is very long. Of these tests, only the initial wetting under a low vertical load has been completed.

The results obtained in the initial wetting of the four oedometric tests are shown in Figure 6-15. A good agreement is found between the two methods of suction control, which indicates that, as in the case of the retention curves /Villar, 2002/, osmotic suction has little effect on the behaviour of the clay. The huge swelling developed at lower suctions attenuates the initial difference in void ratio of the specimens. A strange behaviour has been observed in the test performed in nitrogen oedometer for dry density 1.79 Mg/m^3.

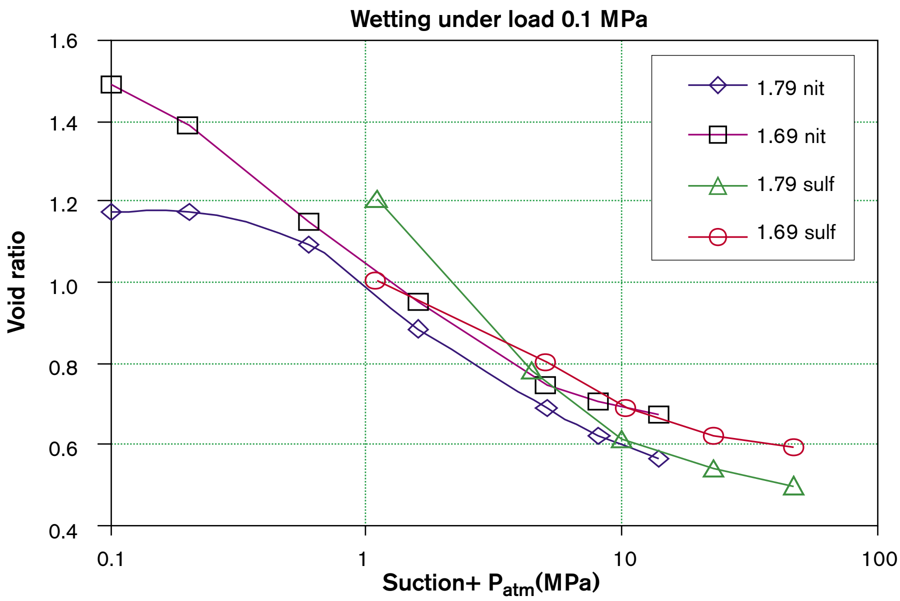


Figure 6-15. *Void ratio evolution as a function of suction in the oedometric tests. MX-80 clay compacted to two densities (expressed in g/cm*^{3}*). Suction control by nitrogen pressure: nit, suction control by solutions: sulf.*

THM analyses

During 2003, an important objective has been the THM simulation of the operational phase of the experiment. In particular, deposition holes number 1 and 3 in Section I have been simulated using the "in-house computer code" Code Bright. The measurements provided during this year have been used for comparison. The comparison made possible the improvement of some of the parameters involved as well as calibration of the models. This aspect has been very important in the development of the numerical simulations there is still no available experimental information on material properties i.e. mechanical parameters for the MX-80 bentonite.

Preliminary analyses performed during 2002 and the beginning of 2003 showed a reasonable agreement between measured and computed variables. Thus consistent set of parameters, models and constitutive laws could be defined and assumed to be quite realistic with respect to the actual experiments. Temperature, degree of saturation and displacements were mainly considered in the comparisons. Despite that general agreement, it was noticed that the simulation of the stress history could be improved. It is well known that measuring of stresses in the field is quite difficult and that the reliability of the total pressure cells is lower than that of other type of instruments. The gaps between heater and bentonite, and between bentonite and rock (including pellets) lead to a much more difficult short-term analysis of the stress measurements, because they depend on the contact conditions. That problem was also considered in 2002, but now a more sophisticated procedure to simulate gap reduction has been adopted.

One important observation in the development of the test is the different behaviour between deposition Holes 1 and 3. Whereas hole number 1 was already "wet" in the initiation of the experiment, Hole 3 is still quite "dry". This is due to the fact that Hole 1 includes a conductive fracture that provides water to the whole system. In the analyses both holes have been characterised using different rock hydraulic conductivity values, in order to reproduce measurements in a global manner. It is worth noting that this different behaviour found in the experiment might also happen in a future repository. Therefore, it is important to consider both deposition holes in the simulation using the same set of parameters except for the initial conditions and the rock permeability.

Different geometries were studied in the analyses, including 1D and 3D grids. It was concluded that for practical purposes, a quasi-3D geometry was adequate (2D axy-symmetric). Only some typical results for Hole 1 are presented here. Figure 6-16 shows the evolution of the degree of saturation as a function of time for some points of the buffer mid plane in Hole 1. Measurements corresponding to this variable are also included. The agreement is reasonable, taking into account the complexity of the processes involved. It is worth to point out that the cycle observed in the red lines (corresponding to a point close to the heater) has been reproduced properly. This is an effect of the coupling between the thermal and the hydraulic problems: an initial wetting is produced in the buffer close to the heater due to the vapour generation that moves outwards. After that, thermal effects prevail and drying develops again. Eventually, water from the rock saturates those points.

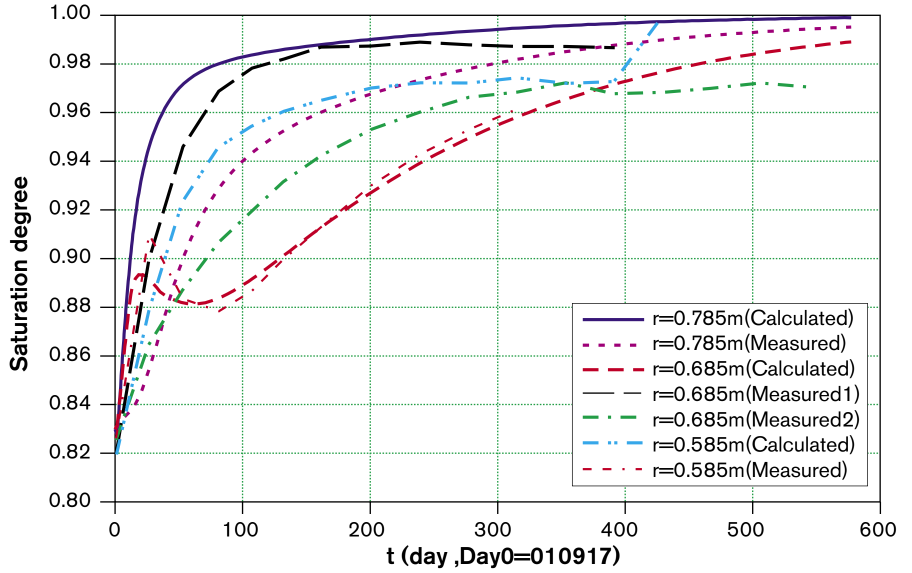


Figure 6-16. *Time evolution of saturation degree for some particular points of the buffer mid plane in Hole 1 (measured and computed values).*

Figure 6-17 presents the temperature evolution of some specific points of the bentonite for mid plane of Hole 1. Temperature is very sensitive to boundary conditions and the simplified geometry assumed in this analysis explains the small discrepancies between measurements and calculations. For the same hole and mid plane, Figure 6-18 shows the stress evolution of some points for which stress measurements are available. Note that the agreement is not so good although the order of magnitude of the stresses has been reproduced and this is indeed an important result considering the difficulties when simulating stress measurements. This is in fact a consequence of the consideration of the gaps in the analyses.

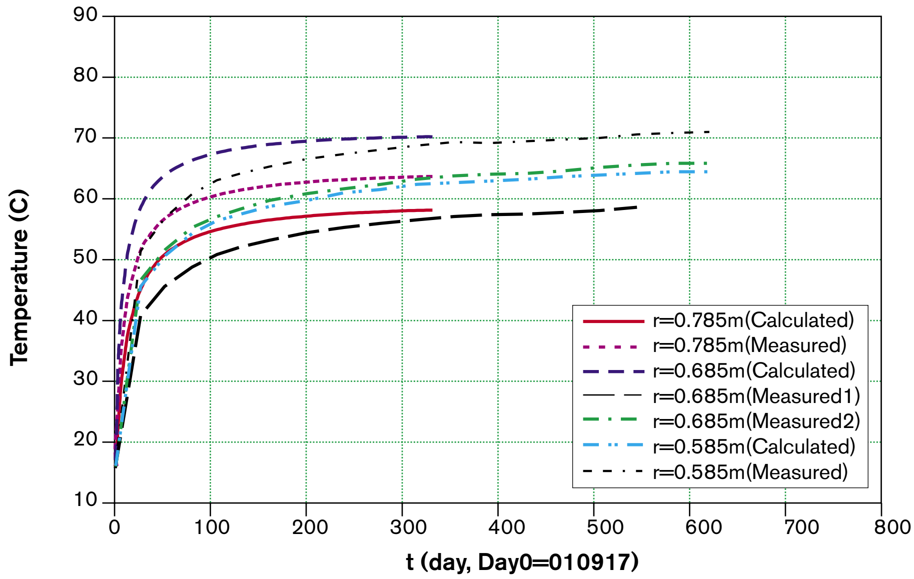


Figure 6-17. *Time evolution of temperature for some particular points of the buffer mid plane in Hole 1 (measured and computed values)*

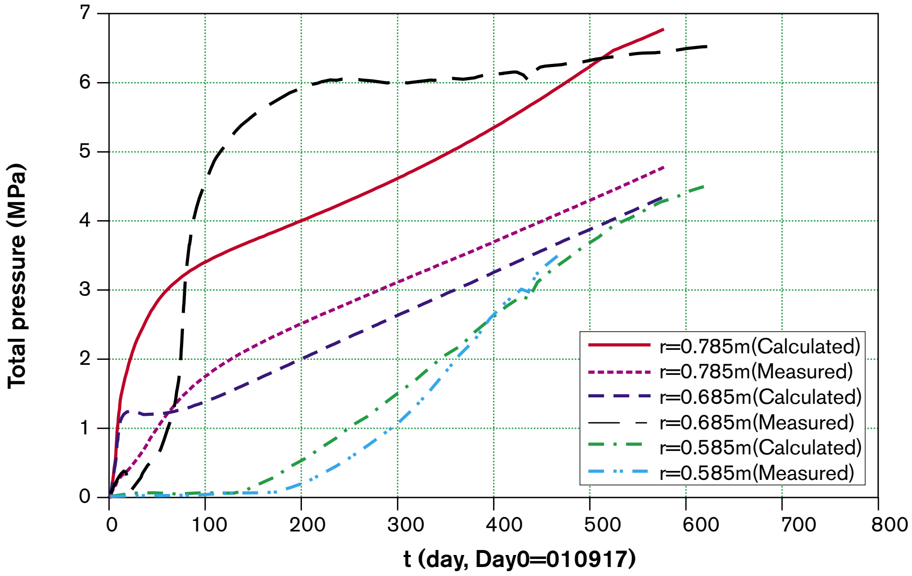


Figure 6-18. Time evolution of total pressure (total stress) for some particular points of the buffer mid plane in Hole 1 (measured and computed values).

Code Bright can not deal with gaps in a direct manner, but it is possible to consider elements with low stiffness including air and water. Those elements represent a gap. When buffer expands, the gap is reduced because its low stiffness, up to a point in which full contact between opposite sides is achieved. When that occurs, the gap element must be removed and a new grid is generated by hand. In the particular case of Prototype Repository experiment this operation has been performed easily due to the fact that buffer expansion has been quite homogeneous except for small portions of the gap in the upper and lower zones of the heater. Figure 6-19 presents the distribution of porosity in the buffer mid section for different times, a result that has been obtained using this strategy. Note that close to the heater, porosity increases at the beginning of the experiment due to buffer expansion, whereas when full contact is achieved and the gap is closed, the porosity decreases.

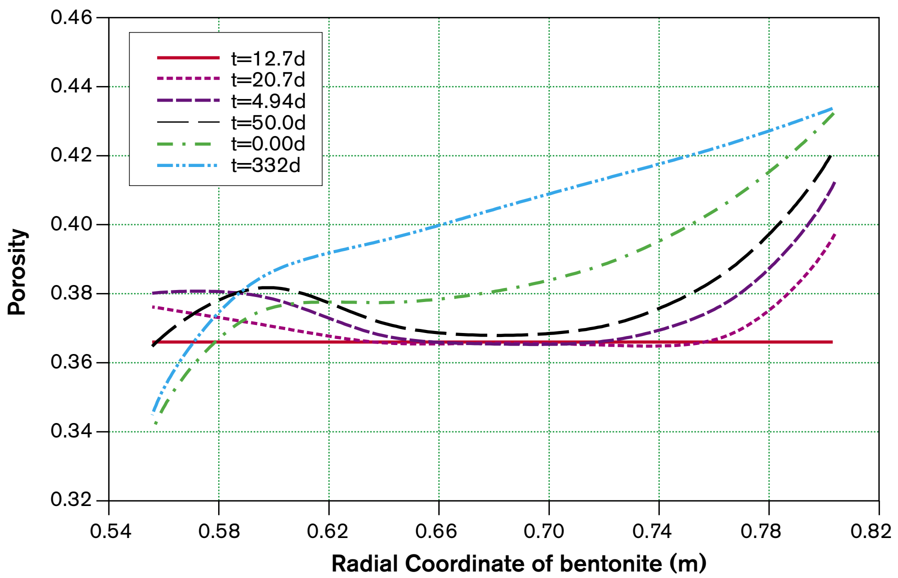


Figure 6-19. Distribution of porosity in the buffer for different times.

These analyses show how Code Bright can deal with THM analyses of large-scale experiments including some aspects that are not easy to handle using a continuum mechanics approach, i.e. gap closure. The measurements available have been used to calibrate the model and a full simulation of Holes 1 and 3 has been performed for operational conditions, achieving a reasonable agreement between computed and measured variables.

6.4.2 Backfill and Plug Test

Within the frame of this test it was scheduled for the year 2003 to performed monitoring and testing work, laboratory characterisation analyses, HM pulse tests analysis and modelling work.

Testing and monitoring work

As foreseen in the Äspö HRL Planning Report 2003, a first campaign of pulse tests was carried out during late March. The functionality of the sensors inside the piezometers was checked. For the first time a reading was obtained from one of the sensors (DPP13), considered damaged during the installation. The second campaign scheduled in the planning was carried out from the 11^{th} to 18^{th} of August.

Maintenance work and data reporting to Clay Technology was performed as foreseen.

Laboratory characterisation of backfill

Backfill material is difficult to characterise mainly because of the grain size distribution. On top of that, the salt content in the hydration water introduces a new variable that has to be taken into account.

Some laboratory tests have been performed for characterising the material and analysing the effect of salt on some of its HM properties. Particular attention was paid to the mechanical aspects, for complementing the laboratory work performed in Sweden. Figure 6-20 presents a summary of 3 oedometer tests carried out on backfill samples hydrated with different salt-water content. Special oedometer cells were designed in order to account for the maximum grain size (20 mm) of the material.

That figure shows the variation of void ratio (strain) against effective stress for samples with 16.6 kN/m^3 dry specific weight. It can be concluded that salinity (at least for salt contents up to 16 g/l) does not influence the mechanical response of the backfill. However, hydraulic conductivity computed from the oedometer experiments showed a clear dependence on salt content. The permeability of samples hydrated with 16 g/l of salt-water is one order of magnitude higher than that of those hydrated with fresh water. This result is important for the correct interpretation of the backfill behaviour.

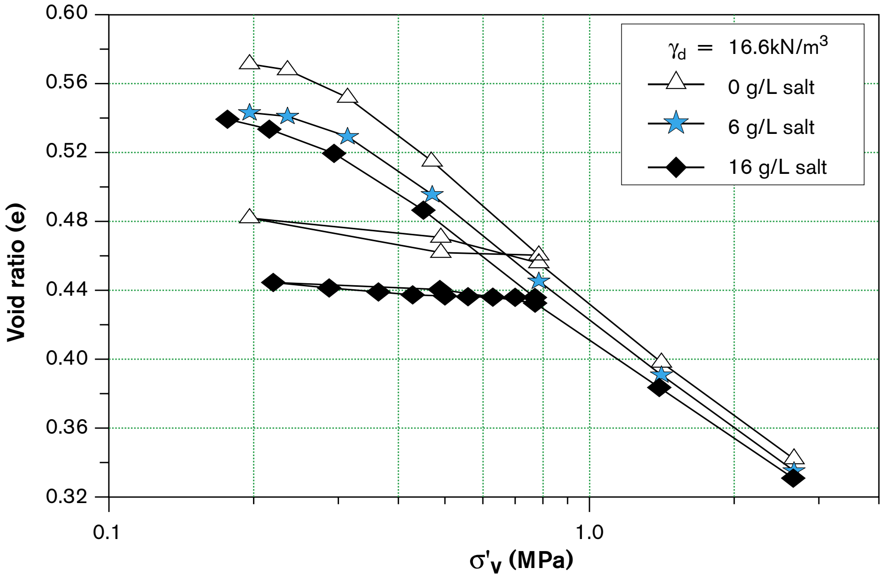


Figure 6-20. *Void ratio versus effective stress obtained in oedometer tests performed on samples hydrated with water containing 0, 6, and 16 g/l of salt.*

Modelling work and pulse test interpretation

During 2003, the backfill installed in the tunnel achieved full saturation from a practical point of view. In March 2003 it was decided to proceed with the flow and pulse tests under saturated conditions. The 7 sensors that are working properly, in particular sensors DPP3 and DPP7, provided valuable data for analysing the hydraulic behaviour of the backfill. Figure 6-21 and Figure 6-22 present the records of water pressure in those sensors.

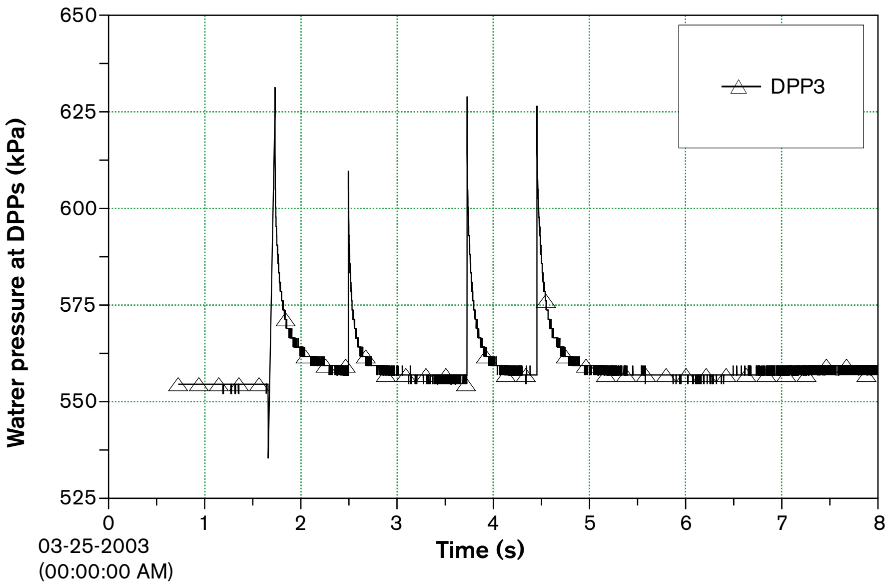


Figure 6-21. *Evolution of water pressure in sensor DPP3 when performing pulse tests.*

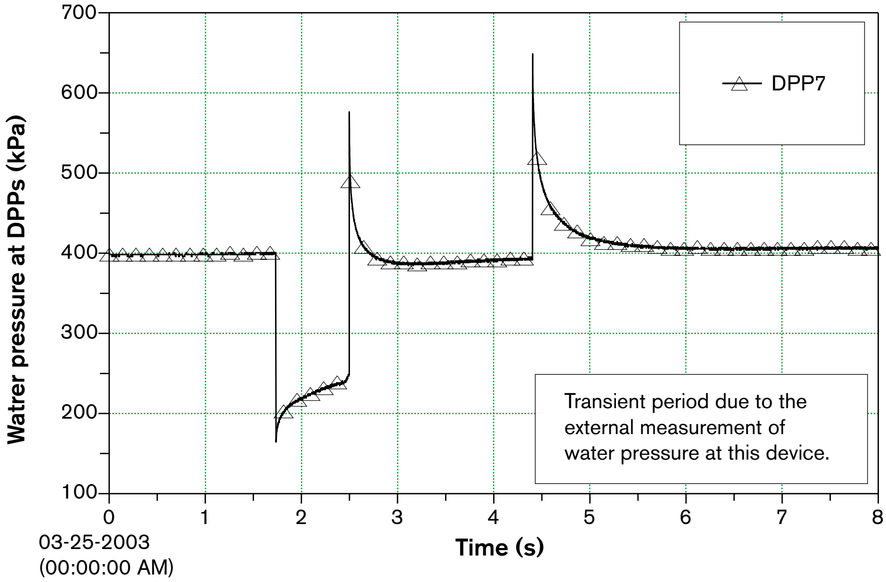


Figure 6-22. *Evolution of water pressure in sensor DPP7 when performing pulse tests.*

Sensor DPP3, located in layer 2 close to the rock, measured an initial water pressure of 552 kPa. A finite element simulation of the H-M problem around the sensor was performed in order to back-analyse the hydraulic conductivity of the backfill. Figure 6-23 presents a comparison between measured and computed data for a particular pulse in this sensor. The agreement seems reasonable, although it should be pointed out that the maximum discrepancy is located at the early times of the pulse (that is before 10 minutes). This effect has been associated to the axi-symmetric geometry considered in the analyses, because of the proximity of the sensor to the rock wall. The parameters required in the simulation were permeability 10^{-10} m/s and compressibility 0.150 MPa^{-1}.

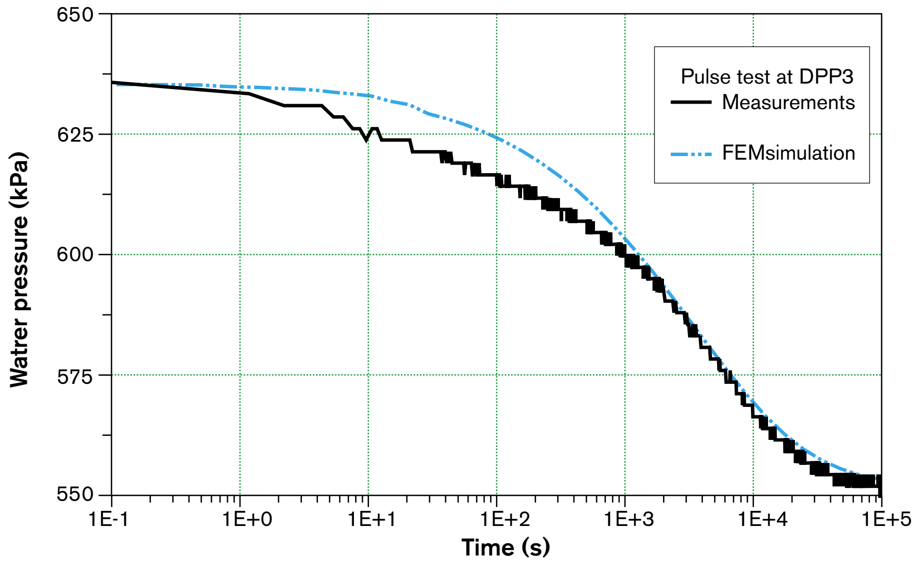


Figure 6-23. *Comparison between one measured pulse test performed in DPP3 and the corresponding finite element simulation.*

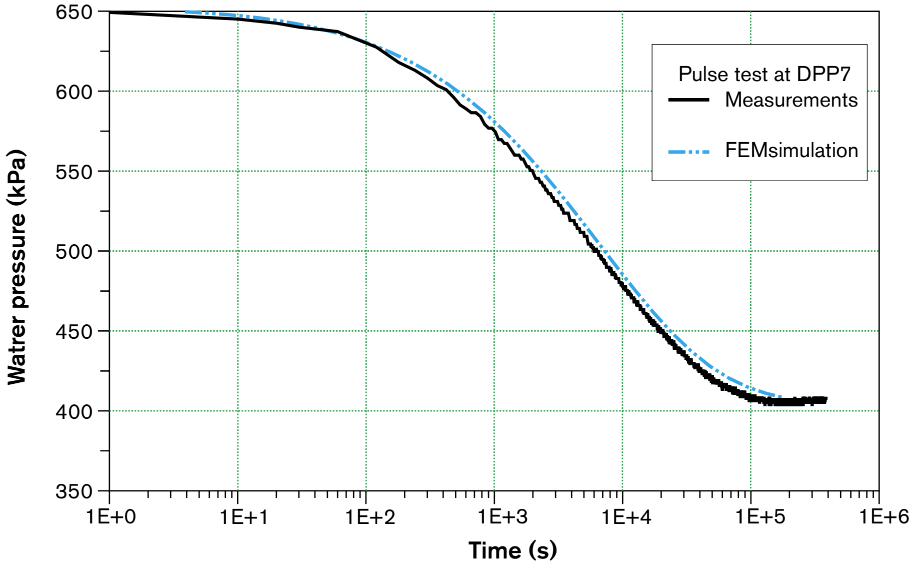


Figure 6-24. *Comparison between one measured pulse test performed in DPP7 and the corresponding finite element simulation.*

The pore water pressure measured before the tests at sensor DPP7, placed in layer 3 far away from the rock wall, was 405 kPa. Figure 6-24 shows a comparison between measurements and calculations for the evolution of water pressure in the transducer. Note that in this case the agreement is very good, probably because the theoretical assumptions regarding geometry are quite accurate. The main parameters involved in the analyses were permeability = $1.5 \cdot 10^{-11}$ m/s and compressibility = 0.052 MPa^{-1}. Note that the value of hydraulic conductivity is consistent with the information from laboratory flow experiments. This low value is related to the compaction conditions: i.e. compaction is easier far from the rock wall and, therefore, permeability and compressibility values are smaller in those areas.

6.4.3 Temperature Buffer Test

The participation of ENRESA in this experiment during 2003 was focussed on the THM pre-operational analysis of the experiment and the performance of some laboratory tests to determine those parameters needed by the models.

Supporting laboratory tests

Two main efforts were undertaken:

- Determination of retention curves at constant volume and temperatures as high as 120°C. For this analysis a new equipment had to be manufactured and tested. It is based on the use of capacitive sensors to measure the suction of compacted blocks with different water contents subjected to high temperatures.
- Infiltration tests, under thermal gradient, on compacted blocks of MX-80. Sensors will be used to follow the evolution of temperature and relative humidity in the clay. The heating surface will be at a temperature of 120°C.

THM analyses

A comparison between predictions and measurements has been performed including the work done by all the groups involved in the project. Code Bright was used in all analyses. In general the main trends of the test were predicted by the simulations, although the effect of the gas in the whole system is still uncertain. According to the computations, the high temperatures reached in the experiment will require considering gas pressure as an independent variable and that will require more attention in the future.

A brief summary of the results obtained could be summarised as follows. Figure 6-25 shows the distribution of temperatures in the buffer mid height of the upper heater, and Figure 6-26 presents the corresponding distributions for the lower heater. The different distributions predicted are due to the presence of a sand layer between the heater and the bentonite in the upper heater while in the lower the buffer only includes bentonite

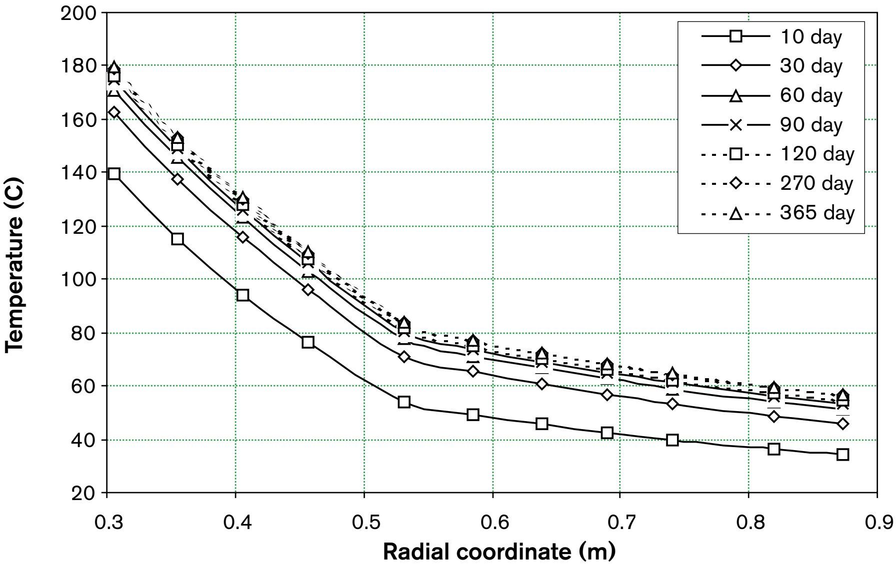


Figure 6-25. *Temperature distribution in the buffer (mid height of upper heater).*

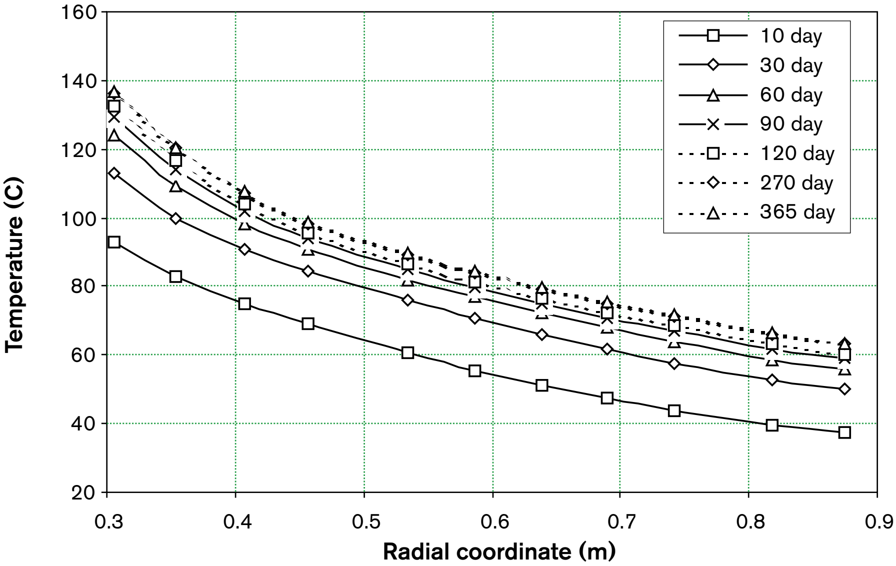


Figure 6-26. *Temperature distribution in the buffer (mid height of lower heater).*

Note that temperatures close to the heater are quite above 100ºC and that is the reason for considering a gas phase in all analyses. Vapour generation is faster than the saturation process due to water infiltration from the outer boundary. This effect could eventually become an issue if a fixed saturated front is generated. This possibility could be inferred from Figure 6-27 and Figure 6-28, they show the distribution of the degree of saturation in the buffer for the upper and lower heaters. It can be seen that the degree of saturation does not change substantially after 90 days, which is an evidence of a saturation front that moves slowly towards the heater.

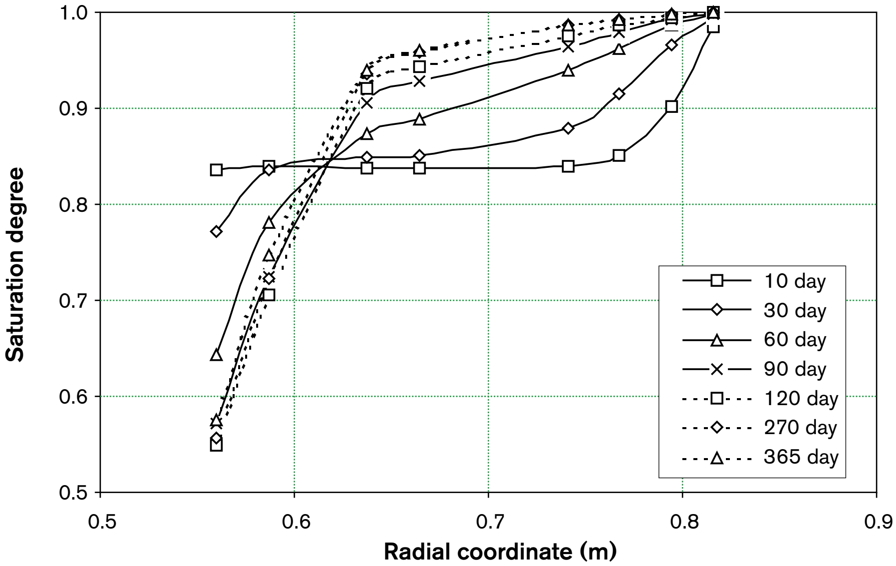


Figure 6-27. *Saturation degree distribution in the buffer (mid height of upper heater).*

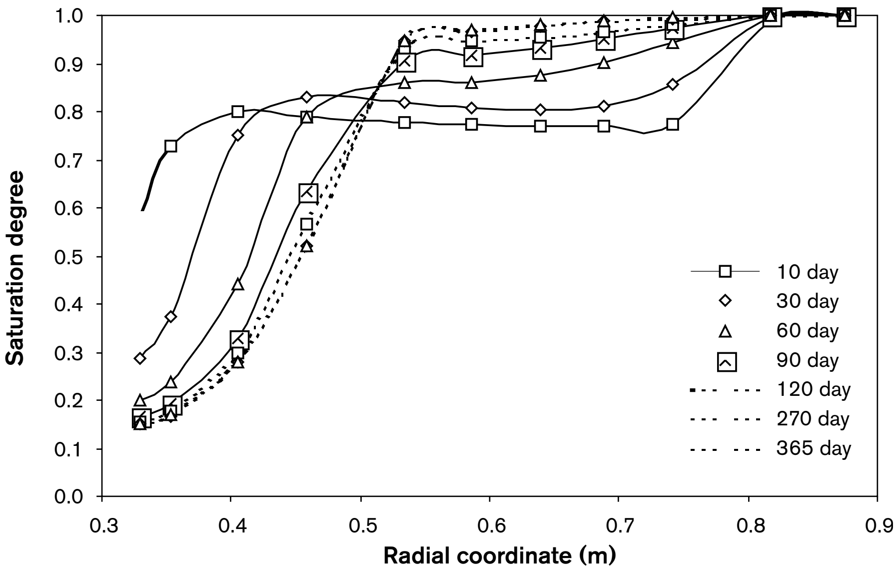


Figure 6-28. *Saturation degree distribution in the buffer (mid height of lower heater).*

It should be stressed, however, that parameter values play a fundamental role in these predictions and, therefore, further calibrations of the model are required in the future. Additionally, it is important to point out that these results are very sensitive to gas permeability and to gas boundary conditions, but information on these aspects of the test is still partial. Therefore, the results obtained during 2003 constitute only an estimation of the behaviour of the whole system.

6.5 JNC

JNC is actively conducting research to support both the implementation of disposal by the NUMO, the Japanese implementing body, and the regulation by the government. As part of its research programmes, JNC is currently constructing an underground research laboratory (URL) in crystalline rock at Mizunami, Gifu Prefecture, and an URL in sedimentary rock at Horonobe, Hokkaido. JNC continues to be active in repository research at Äspo HRL, which is directly applicable to the Japanese research programmes for high-level radioactive waste disposal.

The objectives of JNC research at Äspö during 2003 were to:

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

These objectives are designed to support high level waste repository siting, regulation, and safety assessment. Major efforts during 2003 focused on the True Block Scale Continuation and on Task 6 of the Äspö Modelling Task Force.

6.5.1 Prototype Repository

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

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

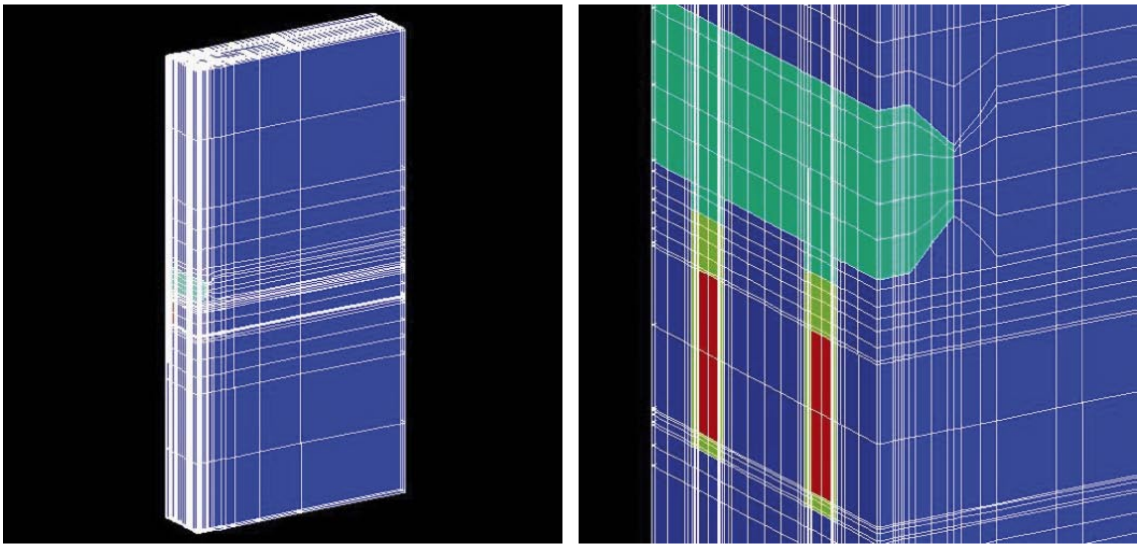
JNC has validated the coupled THM analysis numerical code Thames. Thames was originally developed by Professor Ohnishi, Kyoto University /Ohnishi et al. 1985/. JNC has validated Thames together with Hazama Corporation and Kyoto University. Thames was applied to the simulation of the coupled THM phenomena in and around the EBS /JNC, 2000/.

The main objective is to predict THM processes in and around the engineered barrier system (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 to estimate the performance of the bentonite buffer and the backfill.

Results

JNC has carried out the analysis of the Prototype Repository project (PRP) for the prediction analysis A (two dimensional analysis) /Sugita et al. 2002/ and the prediction analysis B (three dimensional analysis) /SKB, 2003/. This report describes the result of an additional analysis with a new grid which has been improved in accordance with the results of the prediction analysis B.

Figure 6-29 presents the improved grid which provides a correct geometry of a tunnel and deposition holes The input data for each material and other conditions is the same as those used in the prediction analysis B (three dimensional analysis) /SKB, 2003/. Figure 6-30 shows the time history of the calculated and measured temperatures. The calculated temperatures are higher than those measured. Figure 6-31 presents the calculated time history of relative humidity and measured values in Hole 3. In spite of a tendency for the measured relative humidity near the heaters PXPWBU313 and PXPWBU319 to decrease, the calculations show a tendency to increased relative humidity. This may be a result of the assumed larger permeability around the test pit. The discrepancy between the measurements and the calculations of the initial relative humidity is caused by the calculation of relative humidity from a water head suggested by the calculations. Figure 6-32 presents the relationship between measured and calculated stress in Hole 3, the calculations indicate a pressure of 5–7 MPa after 500 days. According to the results with a new grid, calibration of the input data will be carried out with reference to the laboratory tests.



(a) Full scale grid (b) Grid around the pits

Figure 6-29. *Improved grid for Prototype Repository.*

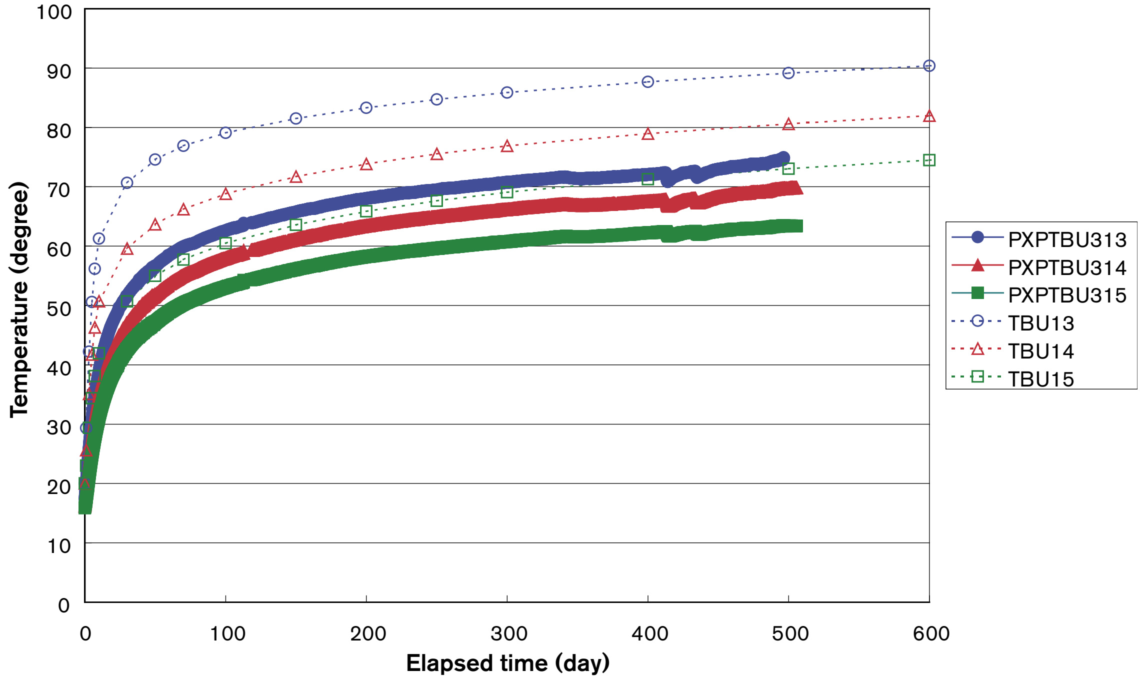


Figure 6-30. *Time history of calculated temperature (dotted lines) and measurement (full lines) in deposition Hole 3.*

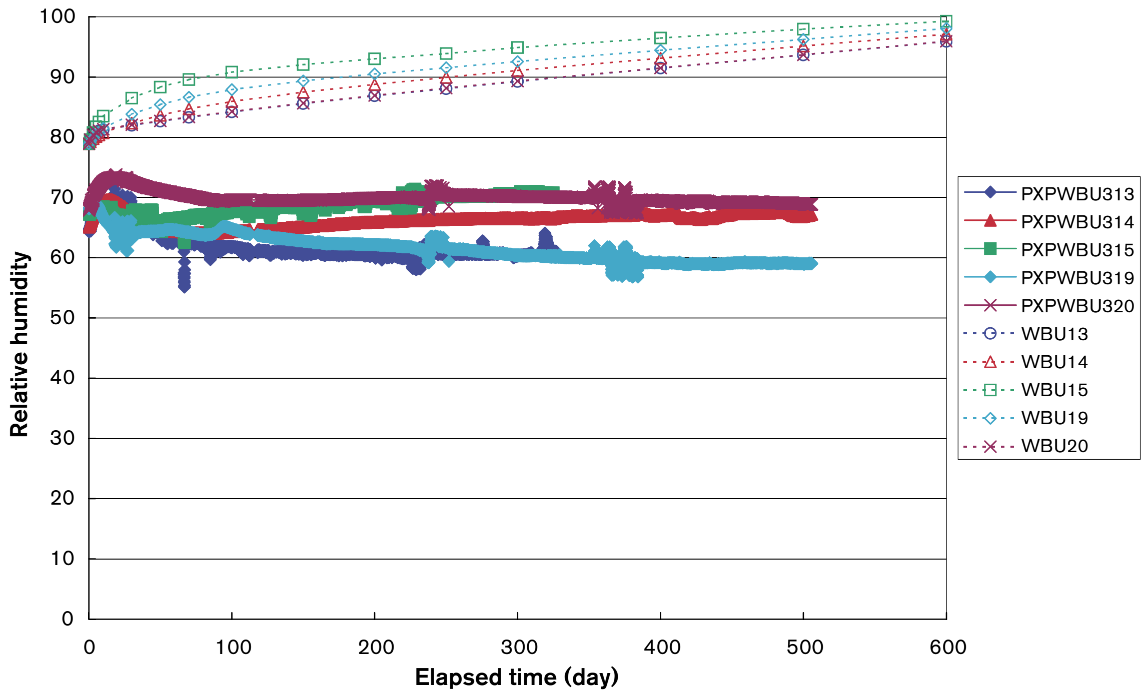


Figure 6-31. *Time history of calculated relative humidity (dotted lines) and measurement (full lines) in deposition Hole 3.*

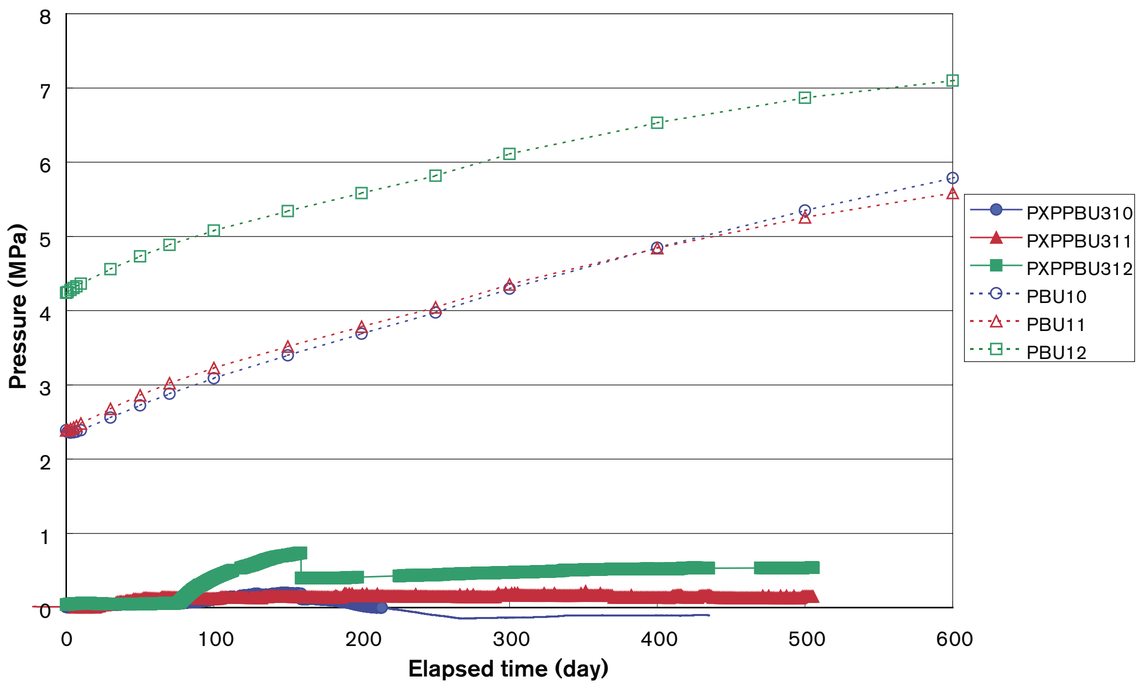


Figure 6-32. *Time history of calculated stress (dotted lines) and measurement (full lines) in deposition Hole 3.*

C-modelling of buffer, backfill and groundwater

Background

In the near-field of a high-level radioactive waste (HLW) repository, coupled thermo, hydro, mechanical, and chemical (THMC) processes will occur, involving the interaction of processes such as heat production by radioactive decay 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 of laboratory and *in situ* experiments are very short and information from natural analogue studies is very limited, numerical calculations are the only available approach to predicting the long-term evolution of the near-field.

In order 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 radionuclide migration and canister corrosion, should be predicted assuming an initial transient state, because the chemical processes are strongly dependent on temperature, water movement and pressure after the emplacement of engineered barriers. From a long-term viewpoint, the chemical processes can lead to changes in porosity, permeability and swelling pressure, and can affect the integrity of the near-field. In order to predict the long-term evolution of the near-field, JNC has initiated a research on the coupled THMC processes.

Objectives

The objectives are to predict near-field chemistry for canister corrosion and radionuclide migration as well as to predict near-field long-term integrity by chemical degradation.

Results

To develop the coupled THMC model, JNC defined the interactions between each process and other processes and built the conceptual model for the coupled THMC processes (Figure 6-33). Although many kinds of chemical process are assumed in the near-field of a HLW repository, the current focus is on the interaction between minerals and porewater in buffer material and surrounding rock. Based on this conceptual model, JNC has developed the coupled THMC model and prototype code /Ito et al. 2003; Neyama et al. 2003/.

The coupled THMC model is based on the coupled THM model (inside the broken line in Figure 6-33) /Ohnishi et al. 1985; Chijimatsu et al. 2000/ and reactive-mass transport model (inside the box named Chemical in Figure 6-33). The model is coupling heat flow, fluid flow, deformation, mass transport and geochemical reactions. The primary variables of this system are temperature, pressure head, displacement, total dissolved concentration of master species, and total dissolved and precipitated concentration of master species. In the model, master species are the independent basis for geochemical reactions, and speciation in solution and dissolution/precipitation of minerals are calculated by a series of governing equations for geochemical reactions. At present, JNC adopts equilibrium models for geochemical reactions, mainly because of the abundance of thermodynamic data for geochemical reactions.

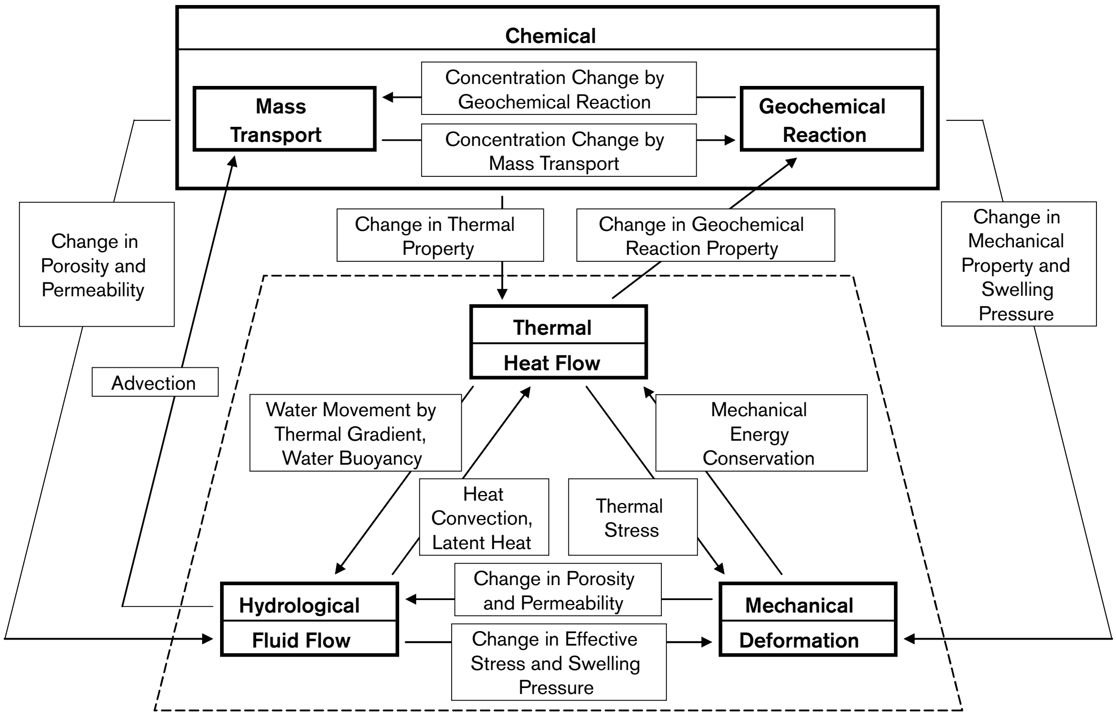


Figure 6-33. *Conceptual model for the coupled THMC processes.*

To ensure efficiency and quality of code development, JNC is developing a Prototype Code by combining existing codes. The Prototype Code is based on the coupled THM code Thames /Chijimatsu et al. 2000/, mass transport code Dtransu-EL /Nishigaki et al. 2001/ and geochemical code Phreeqe /Parkhurst et al. 1980/, all of which have been well verified and validated through benchmark tests and various experiments. Some of these codes are adopted in the second progress report on research and development for the geological disposal of HLW in Japan /JNC, 2000/. To realise the coupled THMC analysis by combination of existing codes, JNC has developed coupling system for the prototype code (Figure 6-34). This coupling system can control execution analyses by each individual code and can exchange data between codes. The coupled THMC analysis is then realised by defining the analysis sequence and common variables as the input to this system. Model parameters can also be related to each of the processes using the additional module for coupling, such as porosity change caused by dissolution/precipitation of minerals. This system is very useful for improving the efficiency and quality of code development, and provides us with the basis for numerical calculations on the coupled THMC processes.

In the near future, JNC will refine the model to take into account key processes of mass transport and geochemical reactions, e.g. gas transport, ionic exchange reactions, surface complexation and the kinetics of dissolution/precipitation reactions.

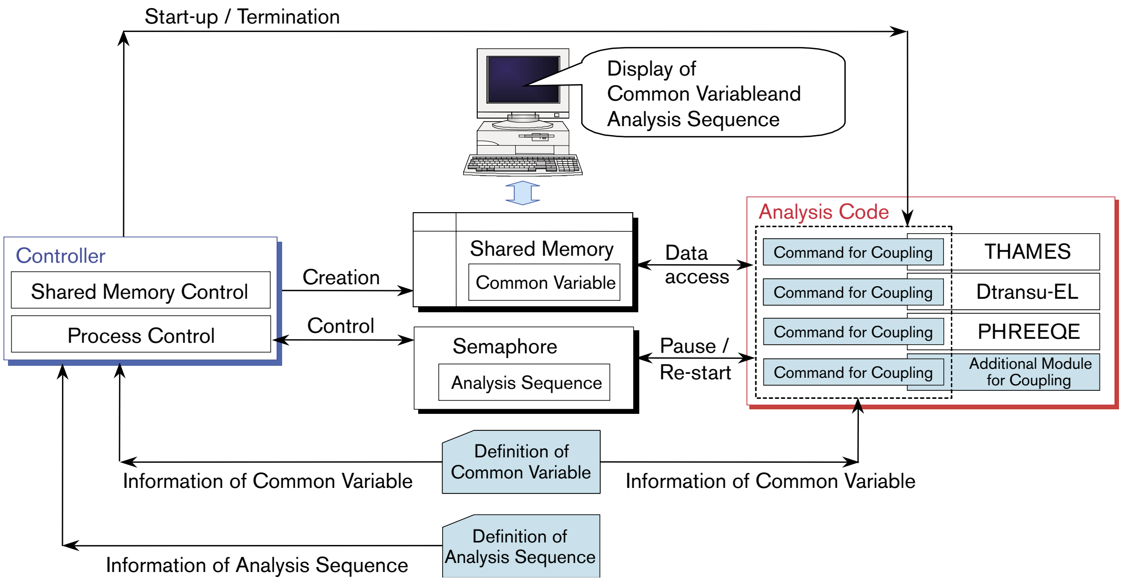


Figure 6-34. *Prototype Code for the coupled THMC processes.*

6.5.2 True Block Scale Continuation

During 2003, JNC provided significant support to the True Block Scale Continuation project. In addition to numerical modelling and analysis of experimental results, JNC played an important role in the development of the experimental plan including analysis of possible experimental configurations to achieve experimental objectives. JNC also participated in the development of the hypotheses to be tested during the project regarding radionuclide retention processes, fracture network connectivity/compartmentalisation, fracture microstructure, and transport pathway geometry.

Analysis of Experimental Alternatives

JNC carried out an extensive series of numerical model studies to simulate an alternative for tracer test designs for the True block scale continuation project. The modelling addressed the issues of remediation of the short circuit in KI0023B:P7 and the feasibility of long pathways using background fractures.

The JNC simulations were carried out using FracMan/PAWorks with Laplace Transform Galerkin (LTG) transport through a mapped pipe channel network. The DFN model used the True BS project reference hydrostructural model, see Figure 6-35, with Structures #8, #17, #18, and #19 removed. The background fracture population was generated using the parameters of /Winberg et al. 2002/. The fracture transport and immobile zone properties were based on correlations between fracture transmissivity and aperture, calibrated to the results of True Block Scale (True BS) tracer tests, Phase C /Dershowitz et al. 2002/.

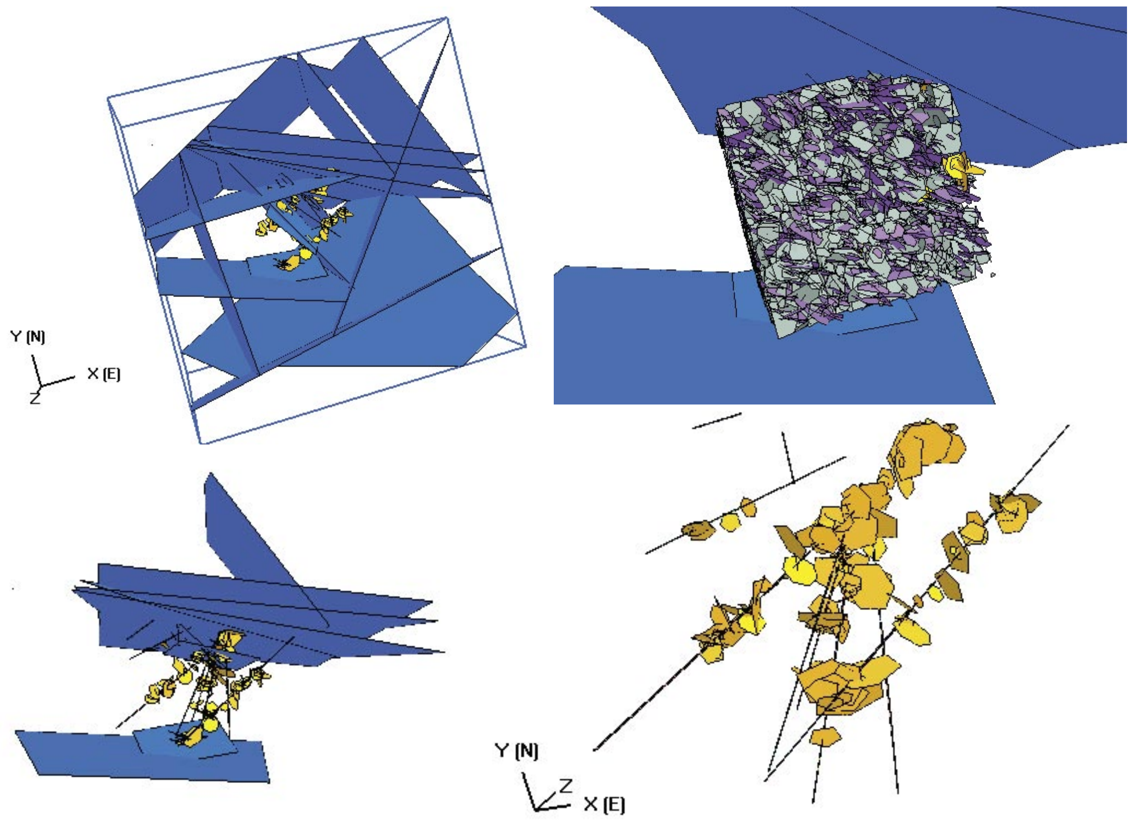


Figure 6-35. *True Block Scale Hydrostructural Model. Upper left – Model at 500 m to boundary conditions, Upper right – Detailed region of background fractures (zoom view), Lower left – Deterministic structures and Posiva flow low features (zoom view), Lower right – Boreholes with Posiva flow log features (zoom view).*

The modelling indicated that remediation of the short-circuit in KI0023B:P6 may not result in significant changes in tracer recoveries for either the long pathways or the background fracture pathways studied. The modelling also indicated that most of the longer pathways considered will have travel times longer than the duration of the True Block Scale Continuation project (True BSC).

Based on this modelling, the project developed a series of tracer tests to focusing on longer solute transport pathways, primarily within the identified Structure #19. These tests were designed to test the following hypotheses:

- Micro-structural information can provide significant support for predicting retention at experimental time scales.
- Transport at experimental time scales is significantly different for faults and joints, due to the microstructural differences between them.
- Longer distance pathways are dominated by fault fracture behaviour, while shorter pathways can be dominated by joint fracture behaviour.

The micro-structural information includes mineralogy, porosity distribution, and structural detail.

Flow and Transport Simulations

JNC carried out preliminary simulations for the CPT series of tracer experiments. These conservative tracer experiments provided the framework for evaluation of the hydrostructural model to be used for the True Block Scale project, and for evaluation of the transport pathways to be investigated with sorbing tracers. JNC's simulations indicated that the pathways envisioned for True BSC have travel times which are consistent with expectations. This makes further simulations feasible. The modelling demonstrated that the focused region in True BSC has transport and flow properties consistent with those observed in True BS Phase C.

Hydraulic Test Interpretation

JNC evaluated the hydraulic interference tests carried out during 2003 by the True BSC project using fractional dimension analysis approaches. These analyses determined the degree of connectivity and heterogeneity of the tested rock block, and the boundary conditions to be expected for longer term testing.

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

During 2003, JNC continued to participate actively in Task 6 of the Äspö Task Force on Groundwater Flow and Transport of Solutes. The purpose of JNC's participation in this project was to improve understanding of the relationship between site characterisation and safety assessment, particularly in the propagation of uncertainty between the different time and distance scales. JNC participated in Task 6AB, Task 6B2, Task 6D, and Task 6E during 2003.

For Task 6AB, JNC developed a new micro-structural model, and implemented it in GoldSim. This new micro-structural model provided a detailed 2D implementation of gouge, fracture coating, cataclasite, altered rock, and intact rock immobile zones. JNC carried out simulations using this model for the True-1 solute transport experiments, and carried out Monte Carlo simulations to quantify the ability of the short term experiments to constrain long term behaviour.

For Task 6B2, JNC simulated 2D transport in Feature A using the FracMan/PAWorks code. This model addressed the importance of alternative spatial patterns of the fracture surface for the development of transport pathways, and for constraining safety assessment simulations based on short term tracer testing.

For Task 6D, JNC carried out solute transport simulations using FracMan/PAWorks to determine the range of *in situ* conditions which are consistent with the single test result.

For Task 6E, JNC supported the project both by assisting in the development of task specifications, and by carrying out scoping simulations to determine whether the specifications could be expected to meet task force goals.

6.6 CRIEPI

The Central Research Institute of the Electric Power Industry (CRIEPI) has participated mainly in modelling activities. CRIEPI has been developing a numerical code for simulating coupled phenomena in the engineered barrier system and applied it to an *in situ* heater experiment. CRIEPI has participated also in the Task Force on Modelling Groundwater Flow and Transport of Solutes. CRIEPI has reported the results of its calculations on Task 6A, 6B and 6B2 in a draft International Progress Report and has performed modelling under Task 6D. In addition, CRIEPI made preparations for its voluntary project on the impact of microbes on radionuclide retention.

6.6.1 Prototype Repository

CRIEPI has been developing a code for evaluating coupled phenomena that will occur around the engineering barrier system. The code has been applied to an *in situ* heater experiment performed by JNC in Kamaishi mine. The experiment was based on the Japanese waste disposal concept. The schematic view of the experiment and the locations of monitoring points are shown in Figure 6-36. The heater had been kept at 100°C for 250 days. The initial water content and temperature were 13.5% and 12.3°C, respectively.

The surrounding boundaries are constrained at the same water content and temperature as the initial condition. The comparison between the calculated and measured results is shown in Figure 6-37 and Figure 6-38. In 2002, there was poor agreement between the measured and calculated change of water content in the middle of buffer material (W2, see Figure 6-36), where it was actually drying after being wetted once (see Figure 6-37). In 2003, we improved the numerical code which considers the evaporation rate as a function of the temperature and water content. As a result, the calculated change of water content agreed better with the measured one than the calculated one in the previous year. However, there are still some discrepancies. The change of water content in the middle of buffer material is almost governed by vapour transport. Therefore further experimental study of the evaporation rate is required to obtain better agreement between the calculated and measured change of water content. We will continue to improve the coupling code and apply it to the other experiments to enhance its reliability and applicability.

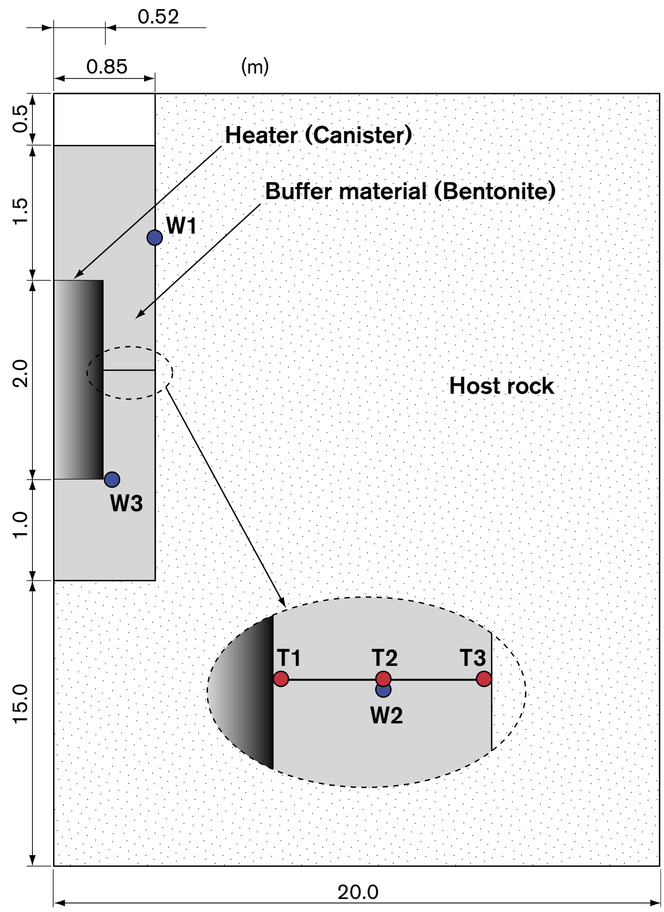


Figure 6-36. *Schematic view of heater experiment and locations of monitoring points.*

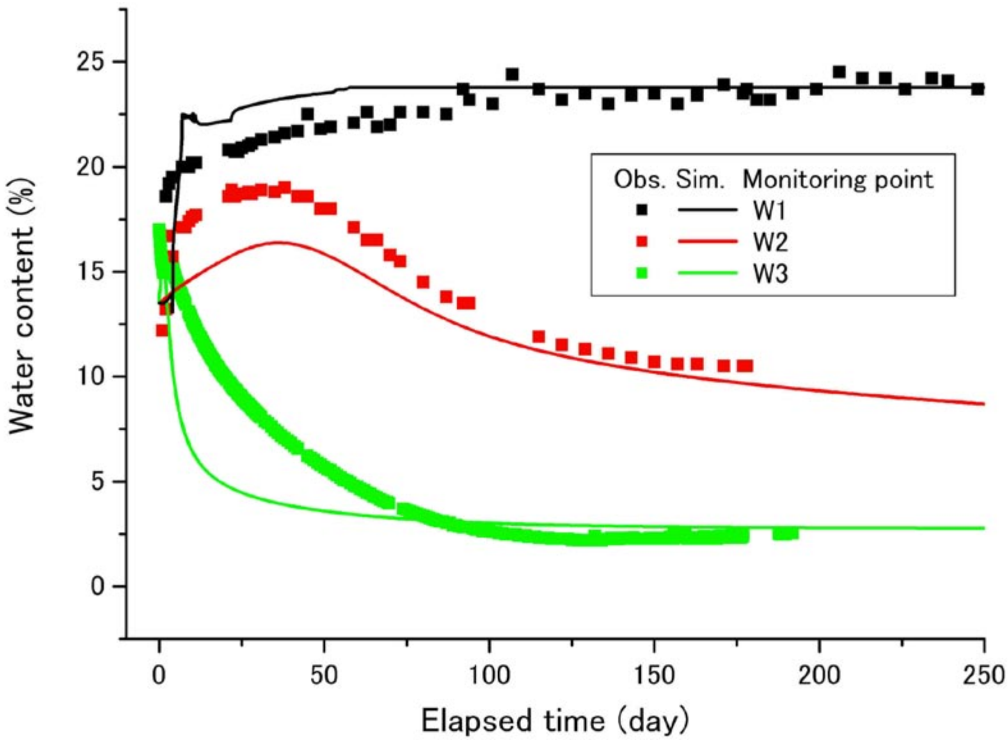


Figure 6-37. *Comparison between measured and simulated water content in the buffer material.*

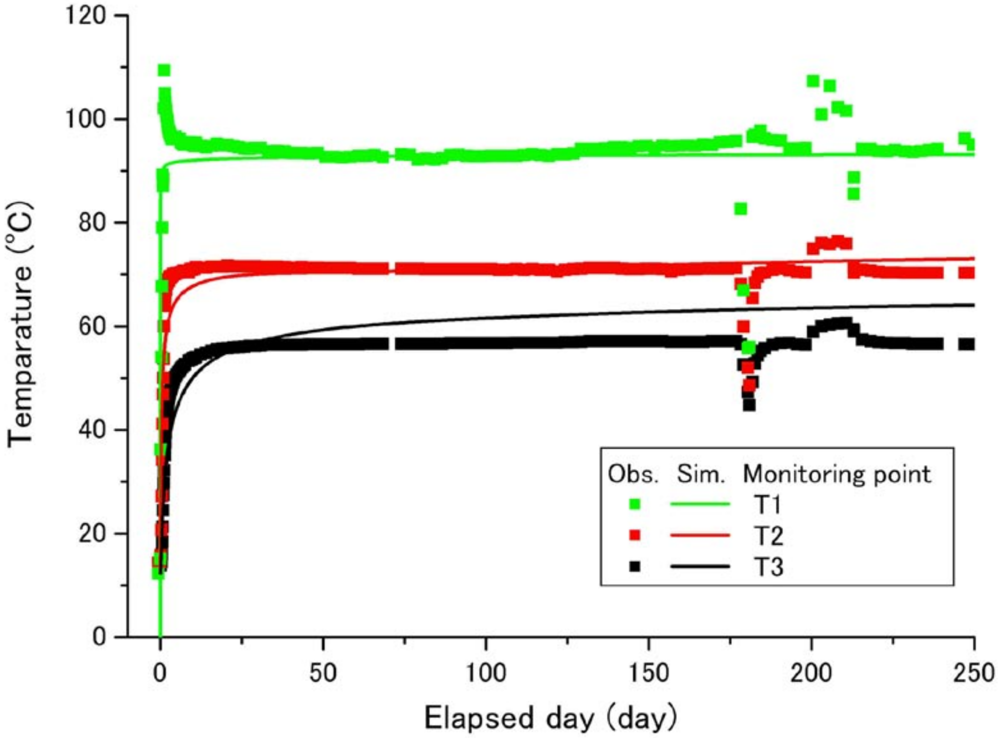


Figure 6-38. *Comparison between measured and simulated temperature in the buffer material.*

6.6.2 Task Force on Modelling Groundwater Flow and Transport of Solutes

CRIEPI has written a draft International Progress Report on the results of its calculations for Task 6A, 6B and 6B2. The report has been submitted to SKB.

In addition, CRIEPI performed numerical analyses for Task 6D. Numerical codes developed by CRIEPI for groundwater flow and solute transport in rock formations, FEGM and FERM, were used for the analysis.

In the groundwater flow analysis of Task 6D, 100 m scale structures were modelled explicitly (see Figure 6-39) and background fractures were expressed implicitly as equivalent porous media by using the smeared fracture model. While the measured head difference between the injection and pumping holes was 171 metres, the calculated difference was 267 metres. We recalculated the head difference using 1.65 times transmissivity values for deterministic 100 m structures. As a result, the calculated head difference agreed well with the measured one.

In the tracer migration analysis of Task 6D, only four structures and surrounding rock mass were taken into consideration. Each of these structures was trimmed and modelled as a single fracture (see Figure 6-40). The velocities in the fractures obtained from 200 metres block groundwater flow analysis were used for the tracer migration analysis. The calculated breakthrough curves were not in agreement with the measured ones. We recalculated the breakthrough curves using 0.25 times porosity values for surrounding rock mass and the calculated breakthrough curves of iodine and calcium agreed well with the measured ones (see Figure 6-41). However, the calculated breakthrough curve of Cs still differed remarkably from the measured one. Irreversible sorption process etc should probably be taken into consideration.

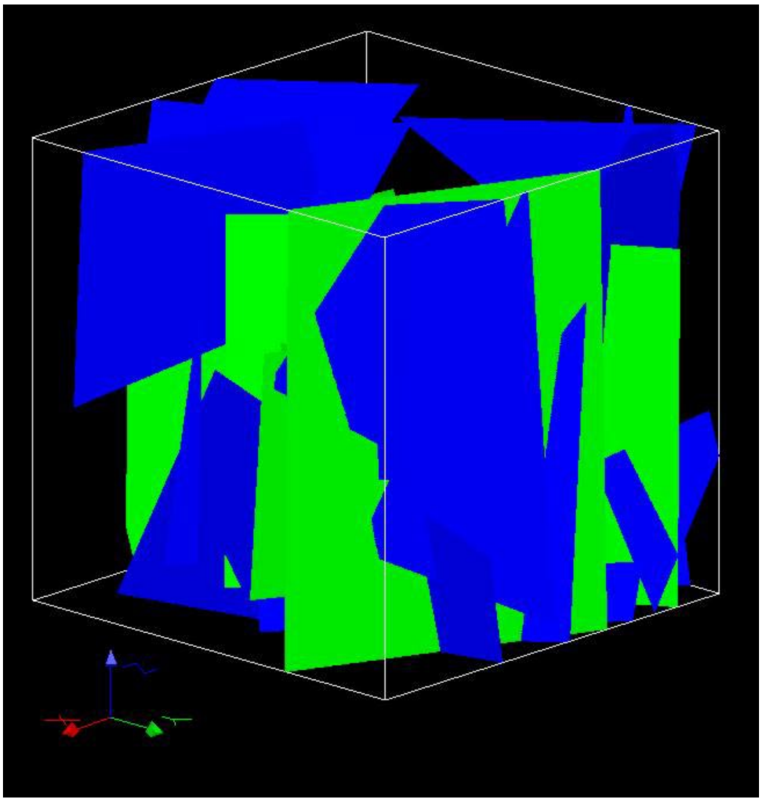


Figure 6-39. *100 m scale structures modelled explicitly for groundwater flow analysis of Task 6D.*

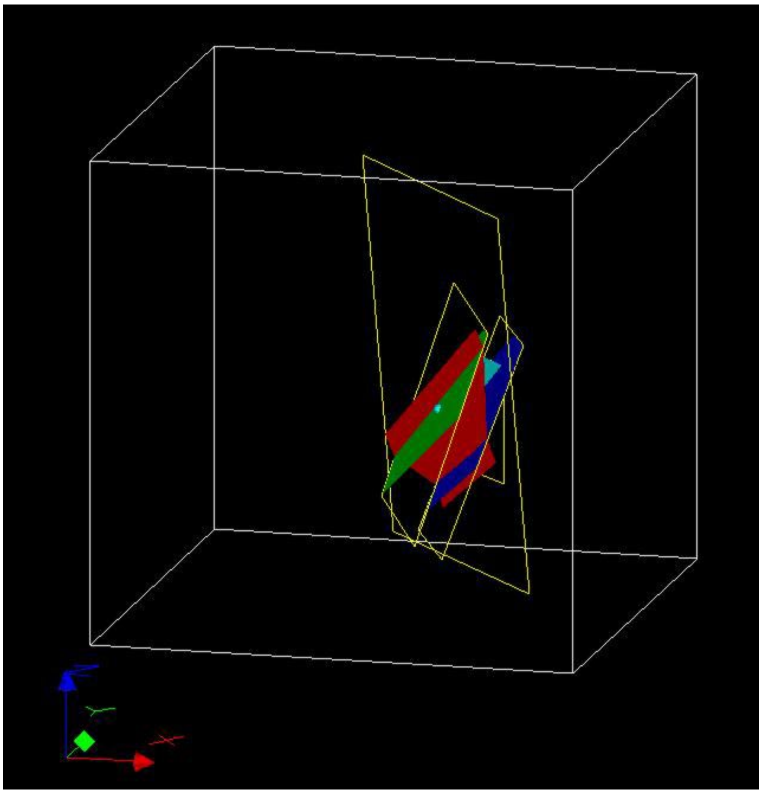


Figure 6-40. *4 structures modelled for tracer migration analysis of Task 6D. The yellow lines express the original extents of the fractures.*

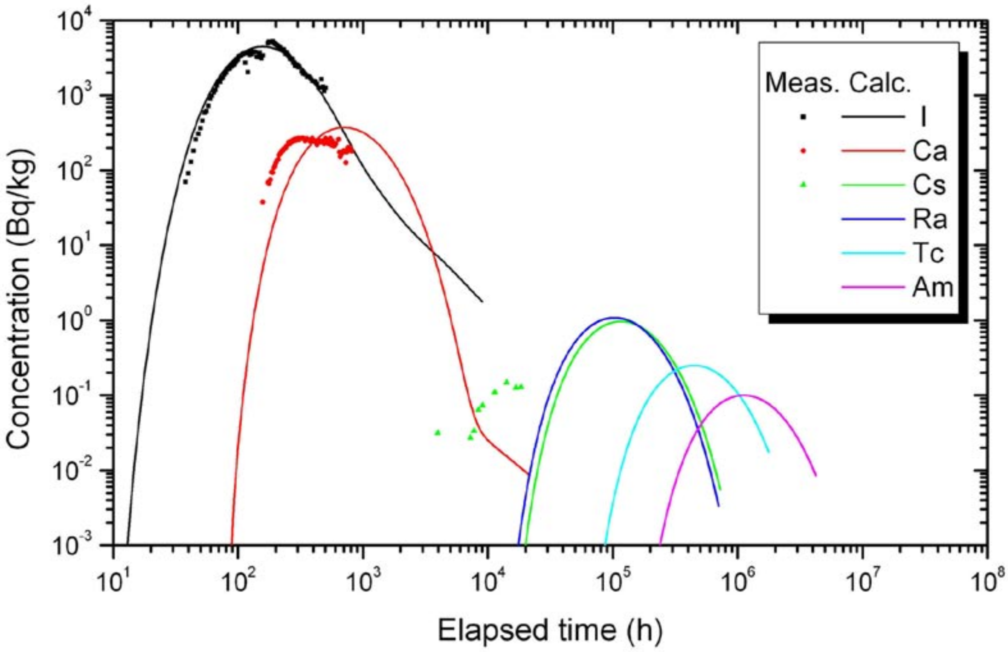


Figure 6-41. *Comparison between the calculated and measured breakthrough curves in Task 6D.*

6.6.3 Voluntary project on impact of microbes on radionuclide retention

CRIEPI has designed a facility for the evaluation of the microbial impact on geochemistry using the rock and groundwater of Äspö site. Techniques for minimising contamination, when collecting rock and groundwater for microbial characterisation have been developed. In 2004, the facility for indoor experiments will be developed and a laboratory experiment will start.

6.7 Nagra

In 2003, Nagra (National Cooperative for the Disposal of Radioactive Waste, Switzerland) participated in the Äspö projects shown below. The work carried out with the support of Nagra has been fully integrated in the projects and is described in detail in the respective project sections. An outline is provided herein for completeness. 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) expired this year. Discussions on its extension have been initiated.

6.7.1 Matrix Fluid Chemistry

The final report on the Matrix Fluid Chemistry experiment has been completed during 2003 /Smellie et al. 2003/.

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

Nagra continued its participation in the Task Force, during 2003. Nagra's main contributions were the finalisation of the Task 4 Overall Evaluation report /Marschall and Elert, 2003/ and review of on-going activities. Nagra also hosted the 17th Task Force meeting in Thun, Switzerland in March.

Two papers, on a combination of the Fracture Characterisation and Classification project and work on True-1 modelling were published in the Journal of Contaminant Hydrology /Mazurek et al. 2003; Jakob et al. 2003/.

6.7.3 Support to planning activities

Although not a participant to the corresponding Project, Nagra has had various discussions in 2003, with the support of SKB, on the transfer of experience from Nagra projects to upcoming activities in Äspö HRL, in particular the planning of KBS-3H (e.g. the contribution of experience from national and international collaborative projects) and EC projects (ESDRED, NFPRO).

6.8 Posiva

Posiva's participation in the work at Äspö HRL was mainly in the areas of research and development of disposal technology and site evaluation. The following text summarises the work done during 2003 as part of the joint projects with SKB and the multilateral projects at Äspö HRL. Posiva also participated to the EC project Prototype Repository.

6.8.1 Prototype Repository

The Posiva-VTT team concentrated on the geochemical modelling calculations of the engineered barrier system (EBS) of the Prototype Repository. The approach to the work has been to study the major element compositions of pore waters, and the changes in solid phases of the barrier materials. Calculations deal with time-dependent changes at the EBS boundaries. The modelling also considers processes that occur during the wetting of EBS. All the calculations are based on the assumption of the equilibrium thermodynamics, and are not tied to any strict time-span.

Results

Figure 6-42 shows an example of the modelling results. Subsequent parcels of average near-field water enter the rock-backfill in a boundary cell of the EBS. The subsequent evolution is modelled as a set of batch reaction cycles. The initially unsaturated boundary cell contains air in the pore volume. During the initial saturation of cell, all the oxygen from the air is consumed by pyrite dissolution and simultaneous goethite precipitation. The coupled first reaction cycles dissolve all the gypsum reserves from the boundary cell. The model predicts some calcite precipitation at the boundaries of the repository tunnel over time. Quartz is dissolved from the boundaries due to the temperature gradient effect. However, quartz will precipitate if temperature of pore water drops. A temperature-driven hydraulic convection cell may be generated around the repository and may redistribute e.g. quartz, calcite and gypsum. The pore water compositions evolve as a set of batch reaction cycles because of mineral reactions, and because of significant cation exchange processes present in the system.

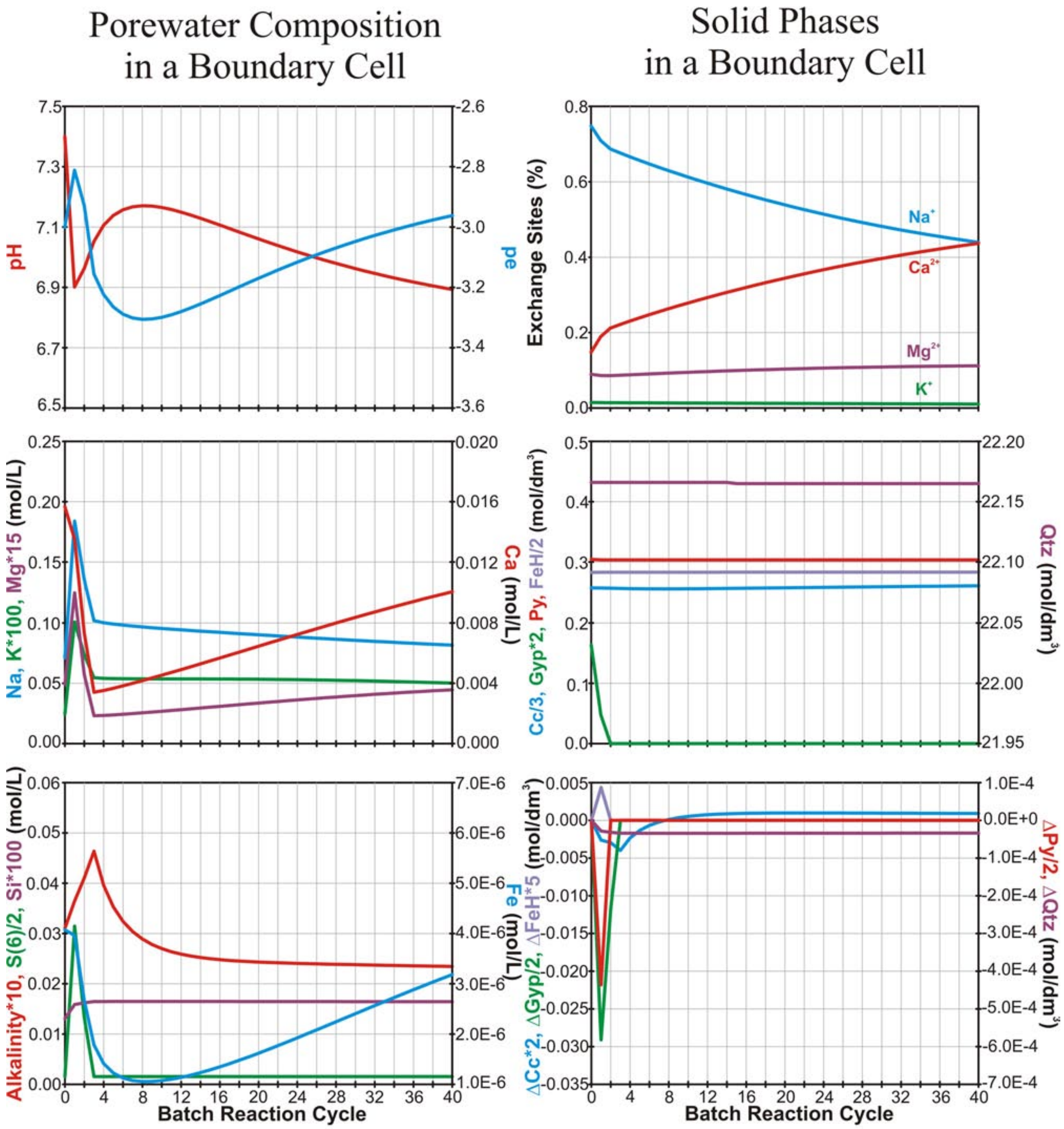


Figure 6-42. *Geochemical evolution and resulting porewater compositions in an EBS cell volume at the rock-backfill boundary. The cell volume is refilled 40 times with the near-field water. The equilibrium temperature assumption is 40°C. Cc = calcite, Gyp = gypsum, Py = pyrite, FeH = goethite.*

6.8.2 Long Term Test of Buffer Material

Posiva's task in the Long Term Test of Buffer Material project is to study the pore water chemistry in the bentonite. The task is carried out at VTT Processes. The aim of the work is to obtain data on the chemical conditions which develop in the bentonite considering the effect of the temperature, additives and rock fractures. The study gives information about the chemical processes occurring in the bentonite, but also supports the other planned studies of the chemical conditions.

Results

Analyses of the pore waters of the excavated one-year parcel (A0) were reported during the year 2003 /Muurinen, 2003/.

6.8.3 Injection grout for deep repositories

Posiva is responsible for sub-project 1 (low-pH cementitious injection grout for larger fratures) and sub-project 3 (Field testing in Finland) on the development of low-pH cement products. The aim is to find at least one low-pH grout that meets the given requirements and does not cause harm to the long-term safety of the deep repository. The following five systems (sets of materials) were selected for examination:

- OPC (Ordinary Portland Cement) + Silica (silica fume).
- Slag (granulated blast furnace slag).
- Supersulphate cement.
- Fly ash.
- LAC (a Japanese product).

The principle is to test all systems and select suitable ones for more elaborate development work and pH tests. The most promising material combinations will be studied in field tests during 2004.

Results

According to the results received during 2003 there are several grouts that fulfil all requirements (Table 6-2) with the exception of a pH peak in beginning. The best way to decrease pH is to add silica into the grout mixture. The workability of silica rich masses can be improved by Ettringite acceleration, but an increased W/C ratio is needed to ensure good penetrability. Optimisation of suitable grouts will continue during 2004.

Table 6-2. These requirements have been identified during the planning of subproject 1 and work as guidance for laboratory work.

Order of importance	Property	Measuring method	Requirement
1	pH	Leaching tests	≤ 11
2	Penetrability bmin (μm)	Penetrability metre	≤ 80
	Penetrability bcrit (μm)	At 60 min	≤ 120
	Viscosity (mPas)	Rheometry at 60 min	≤ 50
3	Bleed (%)	Measuring glass at 2 hours	≤ 10
4	Workability time (min)	Penetrability and viscosity	60
	Shear strength 6 h (Pa)	Fall cone	500
	Yield value (Pa)	Rheometry at 60 min	≤ 5

6.8.4 KBS-3 method with horizontal emplacement

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

Main tasks in 2003

The first milestone in 2003, during the Basic Design Phase of KBS-3, included an external expert review of the design from the point of view of post-emplacement behaviour and of the preliminary safety assessment, as well as an evaluation of some of the critical issues. A list of critical issues was defined in the sub-project plan for the long-term safety studies, the most critical issues being related to the post-emplacement, early phase behaviour and performance of the bentonite buffer in the distance blocks and in the perforated steel container.

Expert review

The main conclusions from the expert review by Enresa, Nagra and Numo were:

- Overall, the KBS-3H concept was considered as a feasible alternative to the reference disposal system with vertical displacement (KBS-3V).
- The review strengthened the earlier conclusions concerning the areas identified as most important for further studies and also stressed the need to focus on the early evolution of the system.
- It was foreseen that long-term safety can be achieved for the KBS-3H concept.

Some significant issues and demonstration work that should be addressed in the future were identified. Recommendations for further work on design issues are:

- The behaviour of the system prior to emplacement, e.g. the thermal behaviour before emplacement considering the time requirement for assembling and handling.
- More detailed analyses of the layout, especially by consideration of thermal effects (complementary thermal analyses have been done in 2003).

- Sealing capacity, piping and erosion in the bentonite constitute the most critical issues regarding the efficiency of the buffer and distance blocks. Clear arguments and evidence should be found (by demonstration complemented with modelling) that piping and erosion do not occur under the full range of possible inflow rates of groundwater into the deposition tunnel. The critical zone regarding piping and erosion is the distance block area. The filling with pellets of the gap between the distance block and rock as well between the perforated container and rock is recommended. The uncertainties related to assumptions regarding heat transfer across gaps could be reduced by this method.
- The need for low-pH cement for sealing and plugging of the deposition tunnel.

Recommendations for further work on Safety Case issues are due to:

- Mitigating measures to reduce the probability of piping and erosion in the immediate post-emplacement phase is a key issue also for the Safety Case.
- Gas build-up and migration due to the corrosion of the steel container introduces a complex set of gas issues into the safety assessment, such as gas bubble transport, transport of volatile radionuclides, accumulation of gas along the top of the tunnel and its effect on groundwater transport.
- Chemical and physical effects of the build-up of corrosion products, including interactions between the buffer and the container, the effect of Fe(II) uptake on the swelling pressure of bentonite, and the effects of corrosion products on transport conditions along the periphery of the tunnel.

Solving of critical issues

The specific tasks on critical issues which were performed in 2003 were the early evolution of the buffer (performed by Clay Technology within the sub-project Demonstration), a thermal analyses of the system, the chemical effects of the disposal container and its corrosion products and an evaluation of the effect of the distance between a water-conducting fracture and a canister defect on radionuclide transport.

Thermal effects

Thermal analyses were carried out by Posiva /Ikonen, 2003/. They investigated, especially, the effects of the emplacement gaps (canister – bentonite, bentonite – steel container, steel container – rock) on the thermal evolution of the KBS-3H type repository. VTT's calculations were verified against the analyses performed earlier by Clay Technology. In the verification case, the two analyses provided maximum temperatures very close to each other. However, after the peak temperature (which was reached already before 10 years), the decrease in the temperature at the canister surface was somewhat slower in VTT's analysis.

One area which requires further study is the internal temperature inside the canister and the thermal expansion of the cast iron insert and the copper canister. In this respect the horizontal emplacement concept is somewhat more favourable than the vertical concept for two reasons: In the horizontal concept the initial contact area of the insert and copper canister is larger, and the distance over which the heat must be conducted in iron, which has significantly lower heat conductivity than copper, to reach the copper canister is shorter.

Interaction between the disposal container and bentonite

The release of iron from the container and exchange of Na^+ by Fe^{2+} or Fe^{3+} may influence the swelling properties of the bentonite to an appreciable extent, especially in areas where the bentonite is of lower density. Transformation of montmorillonite to chlorite due to the uptake of iron in the hydroxyl layers has also been suggested to be a possible process.

Helsinki University of Technology performed a review of available information of iron interaction with bentonite and/or smectite in nature and in the laboratory /Marcos, 2003/. The review indicated that:

- Transformation of bentonite to chlorite or berthierine as a result of interaction with iron is a high temperature process and can be ruled out at temperatures below 85°C.
- Ion exchange of Na^+ by Fe^{2+} was reported but no data was found on the resulting effect on the properties of bentonite.
- The valence of iron in bentonite, either as Fe(II) or Fe(III) has profound implications for the swelling properties of bentonite, the swelling pressure being clearly lower for the Fe(II) form.

Solute transport (equivalent flow rates) in the saturated state

VTT Processes has carried out an analysis of solute transport (equivalent flow rates) from a defective canister into a rock fracture intersecting the deposition tunnel as a function of the transmissivity of the fracture and its distance from the defective part of the canister /Nordman and Vieno, 2004/. Equivalent flow rate, which has been used as a concept in the SR 97 and TILA-99 safety assessments, gives the steady state release rate of a stable specie from the canister interior into the geosphere when a constant concentration of one unit per litre is assumed to prevail in the canister interior. The results show that in the fully-saturated state of the buffer the release rates remain fairly low, even if the canister is assumed to have a large defect and even if a rock fracture with a rather high transmissivity is assumed to intersect the tunnel just opposite the defect in the canister.

6.8.5 Large Scale Gas Injection Test

The LASGIT project is conducted as a joint project between SKB and Posiva. Posiva's representative in the project management had the task of supporting the project manager. The task included, as part of the quality control process, reviews of technical documents.

6.8.6 Äspö Pillar Stability Experiment

In 2003, Posiva's contribution was to participate in supervising the investigations, plan the monitoring programme and perform the final three dimensional thermo-mechanical analyses and preliminary two dimensional particle-mechanical analyses. The work was carried out by Saanio and Riekkola Oy. The modelling of the experiment was performed using the three dimensional element code FLAC3D and the coupled FLAC/PFC2D code /Wanne and Johansson, 2003/. The latter code is a novel approach using coupled particle-mechanical – continuum code (FLAC/PFC). With the code, damage processes and crack propagation that may occur during the experiment can be better analysed and understood.

The final thermo-mechanical FLAC3D analyses with updated rock mechanics parameters identified regions of damage which reached two metres down the hole wall, see Figure 6-43. The final results did not differ remarkably from the preliminary results /Wanne and Johansson, 2003/. Particle mechanical analyses give additional information on the damage process. Most of the pillar area is in uniaxial compressive condition. To begin with, there is random scattered microcracking around the pillar but the cracks have not coalesced into an actual crack or fracture. As the heating proceeds and the resulting stresses increase, more microcracks starts to appear. The cracking concentrates at the hole wall as the induced stresses start to exceed the material strength, see Figure 6-44. The microcracks begin to concentrate and finally form a predominant fracture at the hole wall. Small parts of the pillar wall peel off into the hole void. Further, PFC analyses show that if the stresses rise high enough, or if the strength of the pillar is lower than expected, the damage that may occur has an extensive impact on pillar behaviour and the cracks can penetrate through the entire pillar.

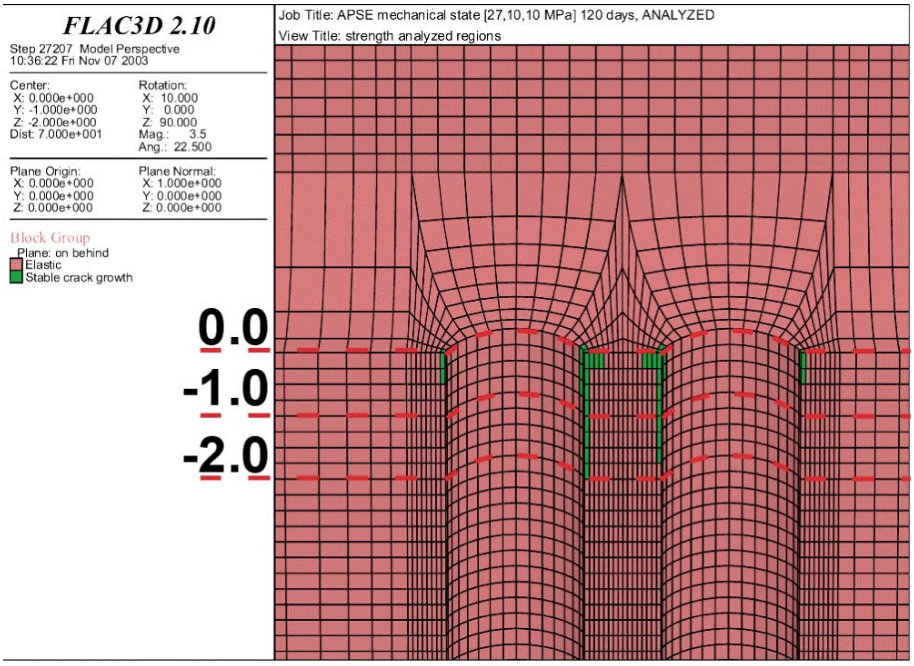


***Figure 6-43.** Damage regions identified after heating based on stress-strength analysis of FLAC3D. Stable crack growth areas (green blocks) reach down to 2 metres.*

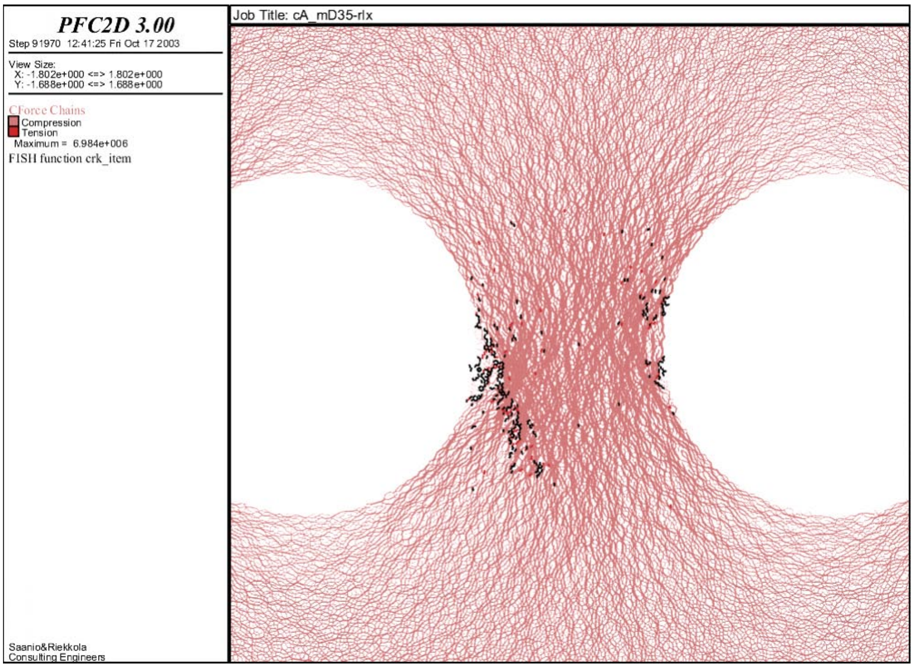


Figure 6-44. *Damages in the pillar during heating modeled by using coupled FLAC/PFC method.*

6.8.7 True Block Scale Continuation

During 2003, the first phase of the True Block Scale Continuation, BS2a, was finalised. Posiva's contribution to the BS2a modelling was reported in /Poteri, 2003/. This report shows that it is very difficult to discriminate different longitudinal or lateral types of heterogeneities along the flow paths because tracer retardation depends on integrated (or average) properties along the flow path. In principal, it is possible to gain more confidence on the dominating retention process by repeating the tests with different flow rates and applying tracers that have different pore diffusivities.

6.8.8 Colloid Project

During 2003, field tests were carried out in Olkiluoto VLJ-repository. Colloid reactors were installed into two groundwater stations PVA1 and PVA3. The chemical background of the water was analysed both from the sampling line and from the sampling line coming from the colloid reactor. Background colloids were measured from the sampling line and the role of the bentonite as source of the colloids were measured form the sampling line coming from colloid reactor. Different sampling methods were sued by VTT and Geosigma for taking samples for colloid analysis. The results of the colloid generation test will be reported at the beginning of 2004.

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

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

During 2003, the modelling of the Task 6D was initiated. Task 6D comprises modelling the transport in a fracture network using tracer test boundary conditions. In practice, Task 6D is a repetition of True Block Scale tracer test C2, but based on semi-synthetic fracture network and a micro-structural model of the immobile pore spaces. Preliminary plans and transport calculations for Task 6D were presented at the 17th Task Force meeting.

6.9 EC projects

SKB is through Repository Technology co-ordinating three EC contracts: Prototype Repository, Cluster Repository Project (Crop) and the project Net.Excel. SKB takes part in several EC projects of which the representation is channelled through Repository Technology. During 2003 the projects BENCHPAR and ECOCLAY II have been finalised.

6.9.1 Prototype Repository

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

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

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

6.9.2 Crop

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

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

The project has the objective of assessing the experience from the various large-scale underground laboratories for testing techniques and aims specifically at comparing methods and data obtained from the laboratories for evaluating present concepts and developing improved ones. Several of these underground projects, which deal with disposal in crystalline rock, salt, and clay formations have been supported by the EC. The Cluster Repository

Project (Crop) implies constitution of a forum − a cluster − for the intended evaluation and assessment, focusing on construction, instrumentation and correlation of theoretical models with field data, especially concerning engineered barrier systems.

6.9.3 Febex II

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

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

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

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

6.9.4 Benchpar

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

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

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

6.9.5 Ecoclay II

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

Start Date: 2000-10-01

End Date: 2003-09-30

Co-ordinator: National Radioactive Waste Management Agency of France

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

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

6.9.6 Safeti

Safeti – Seismic validation of 3D thermo-mechanical models for the prediction of the rock damage around radioactive spent fuel waste

Start Date: 2001-09-01

End Date: 2004-09-01

Co-ordinator: The University of Liverpool (Dep. of Earth Sciences), United Kingdom

Participating countries: France, Sweden and United Kingdom

The aim of this project is to develop an innovative numerical modelling methodology that is suitable for excavation scale simulation of geological repositories. The method, termed Adaptive Continuum/Discontinuum Code (AC/DC) will be developed from existing algorithms. Full validation of the codes will be carried out using laboratory and *in situ* acoustic emission and microseismic data collected in previous experiments. Further laboratory tests will be carried out during the proposed project for validation of the performance of both short- and long-term rock mass behaviour. The AC/DC represents a significant advance over current numerical modelling approaches and will have a wide range of application in waste repository engineering, including feasibility studies.

6.9.7 Padamot

Padamot – Palaeohydrogeological data analysis and model testing

Start Date: 2001-11-01

End Date: 2004-11-01

Co-ordinator: Nirex Ltd, United Kingdom

Participating countries: Czech Republic, Spain, Sweden and United Kingdom

During the Quaternary global climate has alternated between glacial conditions and climate states warmer than the today. In northerly latitudes the potential for cold region processes to affect groundwater pathways, fluxes, residence times and hydrochemistry is significant, whilst for southern European localities the alternation between pluvial and arid conditions is equally important. Padamot will investigate the evolution of minerals and groundwater through these climate changes. The project will use advanced analytical techniques and numerical modelling tools. This palaeohydrogeological approach investigates processes that are significant for repository safety studies on length and time scales that cannot be simulated by experiment. Interpretations will be used to constrain the range of scenarios for conceptual model development and time-variant modelling in performance assessments.

6.9.8 Net.Excel

Net.Excel – Network of excellence in nuclear waste management and disposal

Start Date: 2002-11-01	**End Date:** 2004-03-31
Co-ordinator: Swedish Nuclear Fuel and Waste Management Co, Sweden	**Participating countries:** Belgium, Finland, France, Germany, Spain, Sweden, Switzerland, and United Kingdom

The objectives are a future efficient use of European resources in research and development of safe methods for final disposal of high-level radioactive waste. This calls for close interaction between European end users in planning of national programmes as well as in development of international projects. The proposal concerns the forming of a network of end users for the intended analysis of present status and future requirements in RTD for the three different rock media: salt, clay sediments and crystalline rock. The expected results are common and systematic basis for priorities and co-ordination of future European RTD work for radioactive waste management, and suggested areas and priorities for joint RTD projects. The objective is to develop a common and systematic basis for priorities and co-ordination of future European RTD work for Radioactive Waste Management and suggest areas and priorities for joint RTD projects. This will be accomplished by forming a Network of Excellence with the main European organisations given the national responsibilities to develop systems for safe handling and disposal of long-lived radioactive waste and by jointly working out a document that can serve as an aid for the planning and execution of future co-ordinated RTD activities between European implementers.

7 Environmental research

7.1 General

Äspö Environmental Research Foundation was founded 1996 on initiative of local and regional interested parties. The aim was to make the underground laboratory at Äspö and its resources available for national and international environmental research. SKB's economic engagement in the foundation was ended in 2003, and the activities are now instead concentrated on the Äspö Research School, which was founded in 2002.

7.2 Äspö Research School

On the initiative of the Äspö Environmental Research Foundation, the University of Kalmar has set up the Äspö Research School. The research school is a commitment to provide conditions for today's and tomorrow's research concerning environmental issues. The research school has a special interest in the transport of pollutants and their distribution in rock, soil, water and biota. The research school is co-financed by the municipality of Oskarshamn, SKB, and the University of Kalmar. Currently the scientific team consists of a professor of Environmental geology, three assistant supervisors and six Ph.D students. The research is carried out both in the Äspö HRL and in nearby surface environments. As far as projects in the Äspö HRL are concerned, these have just started and no results are thus as yet available.

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12 Technical Documents were produced during 2003.

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1 International Technical Document was produced during 2003.

ISSN 1404-0344
CM Digitaltryck AB, Bromma, 2004