Technical Report

TR-10-10

Äspö Hard Rock Laboratory

Annual Report 2009

Svensk Kärnbränslehantering AB

December 2010

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

ISSN 1404-0344
SKB TR-10-10

Äspö Hard Rock Laboratory

Annual Report 2009

Svensk Kärnbränslehantering AB

December 2010

Abstract

The Äspö Hard Rock Laboratory (HRL) is an important part of SKB's work with the design and construction of a deep geological repository for the final disposal of spent nuclear fuel. Äspö HRL is located in the Simpevarp area in the municipality of Oskarshamn. One of the fundamental reasons behind SKB's decision to construct an underground laboratory was to create opportunities for research, development and demonstration in a realistic and undisturbed rock environment down to repository depth. The underground part of the laboratory consists of a tunnel from the Simpevarp peninsula to the southern part of Äspö where the tunnel continues in a spiral down to a depth of 460 m. Äspö HRL has been in operation since 1995 and considerable international interest has been shown in its research, as well as in the development and demonstration tasks. A summary of the work performed at Äspö HRL during 2009 is given below.

Geoscience

Geoscientific research is a basic activity at Äspö HRL. The aim of the current studies is to develop geoscientific models of the Äspö HRL and increase the understanding of the rock mass properties as well as knowledge of applicable methods of measurement. A main task within the geoscientific field is the development of the Äspö Site Descriptive Model (SDM) integrating information from the different fields. The main activities in the geoscientific fields have been: (1) Geology – evaluation of geological mapping techniques leading to the decision to develop a SKB mapping system and finalisation of the mapping of rock surfaces in the new tunnel, (2) Hydrogeology – monitoring and storage of data in the computerised Hydro Monitoring System, (3) Geochemistry – sampling of groundwater in the yearly campaign and for specific experiments and (4) Rock Mechanics – finalised the field tests on thermally-induced spalling in deposition holes and evaluated the effect of counterforce in the deposition holes.

Natural barriers

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

A programme has been defined for tracer tests at different experimental scales, the so-called *Tracer Retention Understanding Experiments* (TRUE). The overall objectives of the experiments are to gain a better understanding of the processes which govern the retention of radionuclides transported in crystalline rock and to increase the credibility of models used for radionuclide transport calculations. During 2009, work has been performed in the projects: TRUE Block Scale Continuation (writing of papers to scientific journals) and TRUE-1 Continuation (complementary laboratory sorption experiments, reporting of fault rock zones characterisation project) and TRUE-1 Completion (analyses of material, with focus on the target structure, from the over-coring of two boreholes at the TRUE-1 site performed in 2007).

The *Long Term Sorption Diffusion Experiment* complements the diffusion and sorption experiments performed in the laboratory, and is a natural extension of the TRUE-experiments. The in situ sorption diffusion experiment was ongoing for about six months and after injection of epoxy resin the over-coring was performed in May 2007. During 2009 the analyses on sample cores drilled from the fracture surface on the core stub and from the matrix rock surrounding the test section has continued. In addition, laboratory experiments have been performed on replica material.

The *Colloid Transport Project* was initiated in 2008 and is a continuation of earlier colloid projects. The overall goal for the project is to answer the questions when colloid transport has to be taken into account in safety assessments. The project comprises field tests at the Grimsel test site in

Switzerland and laboratory experiments to study colloid stability and mobility under different conditions. During 2009 a lot of results have been obtained, e.g. influence of water flow, groundwater conditions and bentonite type on colloid generation and transport.

Microorganisms interact with their surroundings and in some cases they greatly modify the characteristics of their environment. Several such interactions may have a significant influence on the function of a future repository for spent fuel, and are therefore studied in the *Microbe Projects*. In the microbe laboratory, located at the –450 m level in Äspö HRL, studies of microbial processes are ongoing within several projects. Bio-mobilisation and bio-immobilisation of radionuclides are studied in *Micomig* and microbial effects on the chemical stability of deep groundwater environments in *Micored.*

The project *Matrix Fluid Chemistry Continuation* focuses on the small-scale micro-fractures in the rock matrix which facilitate the migration of matrix waters. Understanding of the migration of groundwater, and its changing chemistry, is important for repository performance. Data from hydraulic testing of fracture-free and fracture-containing borehole sections in the matrix borehole are available. Evaluation and reporting of analyses of matrix pore water chemistry and the matrix borehole hydraulic studies has not been finalised as planned during 2009 due to other priorities.

Radionuclide Retention Experiments are carried out with the aim to confirm results of laboratory studies in situ. The experiments are to be carried out in special borehole laboratories. Preparations have been performed to define suitable conditions and tracer for the study of the *Transport Resistance at the Buffer Rock Interface* and the planning of the experiment *Spent Fuel Leaching* where the dissolution rate of uranium dioxide in natural groundwater will be studied is still ongoing.

The continuation of the project *Padamot* includes developments of analytical techniques for uranium series analyses applied on fracture mineral samples and focuses on the use of these analyses for determination of the redox conditions during glacial and postglacial time. The results from the analyses of drillcores from Äspö indicate that the present redox zone is situated in the uppermost 15 to 20 m. In addition, it is concluded that the handling and treatment of drillcores are crucial for obtaining correct results and the extraction scheme for sequential analyses of uranium can be simplified.

The basic idea behind the project *Fe-oxides in Fractures* is to examine Fe-oxide fracture linings, in order to explore suitable palaeo-indicators and their formation conditions. The experimental part of the continuation phase of the project entitled: ’To establish below ground surface’ was finalised during the last year, however, the final reporting has been delayed due to other priorities.

The *Single Well Injection Withdrawal (Swiw) Test with Synthetic Groundwater* constitutes a complement to the tests and studies performed on the processes governing retention of radionuclides in the rock. In the feasibility study the TRUE Block Scale Site was identified as a potential test site, however, during 2009 it was concluded that the site was so affected by the new tunnel so a new site was selected for initial field test. The present plan is to carry out the tests during 2010.

Important goals of the activities at Äspö HRL are the evaluation of the usefulness and reliability of different models and the development and testing of methods to determine parameter values required as input to the models. An important part of this work is performed in the *Task Force on Modelling of Groundwater Flow and Transport of Solutes*. The results from Task 6 (performance assessment modelling using site characterisation data) have been published in a number of papers in an issue of Hydrology Journal. During 2009, work has mainly been performed within Task 7 (Long-term pumping experiment at Olkiluoto, Finland) that is divided into several sub-tasks. Reports on sub-task 7A1–A5 have been finalised based on review comments. An updated task description for the sub-task 7B and 7C and more data have been sent out to the modellers. A workshop for Task 7 and 8 was held in January in Lund (Sweden) where modelling approaches and plans for the future modelling were presented and discussed. The 25th international Task Force meeting was held in Mizunami, Japan in October.

The overall objective of the project *Äspö Model for Radionuclide Sorption* is to formulate and test process quantifying models for geochemical retention of radionuclides, in granitic environments, using a combined laboratory and modelling approach. The ambition is to include experimental data for specific surface area and sorption capacity for each of the mineral phases that constitutes granitic rock into the model. During 2009, model interpretation of the specific surface area and radionuclide sorption properties of the mineral chlorite, has been initiated. The study of the specific BET area as function of particle size for pure minerals has started with labradorite and magnetite and tentative results are reported.

Engineered barriers

At Äspö HRL, an important goal is to demonstrate technology for and the function of important parts of the repository system. This implies translation of current scientific knowledge and state-of-the-art technology into engineering practice applicable in an operational repository. It is important that development, testing and demonstration of methods and procedures are conducted under realistic conditions and at an appropriate scale. A number of large-scale field experiments and supporting activities are therefore carried out at Äspö HRL. The experiments focus on different aspects of engineering technology and performance testing.

The *Prototype Repository* is a demonstration of the integrated function of the repository and provides a full-scale reference for tests of predictive models concerning individual components as well as the complete repository system. The layout involves altogether six deposition holes, four in an inner section and two in an outer. The relative humidity, pore pressure, total pressure and temperature in different parts of the test area are monitored. The measured data indicate that the backfill in both sections of tunnel is saturated and different degree of saturation in the buffer in the deposition holes.

The *Long Term Test of Buffer Material (Lot-experiment)* aims at validating models and hypotheses concerning physical properties in a bentonite buffer material and of related processes regarding microbiology, radionuclide transport and copper corrosion under conditions similar to those in a KBS-3 repository. No parcels were retrieved during 2009 so the activities have been limited to supplementary laboratory analyses and to finalise reports on earlier retrieved parcels.

The objective of the project *Alternative Buffer Materials* is to study clay materials that in laboratory tests have shown to be conceivable buffer materials. Three test parcels with different combinations of clay materials are installed in boreholes at Äspö HRL. The parcels are heated carefully to increase the temperature in the buffer materials to 130°C. The heaters in two parcels were activated initially and in the third parcel heaters were activated when the buffer was fully saturated. Test parcel 1 was retrieved in May 2009 and buffer samples have been sent to the participating organisations for analysis.

The *Backfill and Plug Test* is a test of the hydraulic and mechanical function of different backfill materials, emplacement methods and a full-scale plug. The inner part of the drift is backfilled with a mixture of bentonite and crushed rock and the outer part is filled with crushed rock. The wetting of the backfill started at the end of 1999 and the backfill was completely water saturated in 2003. Since then testing of flow to measure the hydraulic conductivity in different parts of the backfill and compressibility tests have been performed. During 2009 the test has been monitored and measured results from all sensors except for the relative humidity sensors have been logged. In addition, testing of the local hydraulic conductivity of the crushed rock has started.

The aim of the *Canister Retrieval Test* was to demonstrate readiness for recovering emplaced canisters even after the time when the surrounding bentonite buffer is fully saturated. The canister was successfully retrieved in 2006. The saturation phase had, at that time, been running for more than five years with continuous measurements of the wetting process, temperature, stresses and strains. During 2009, analyses of the retrieved buffer have continued. The laboratory work has produced data of the mechanical strength, the swelling pressure, hydraulic conductivity and the chemical/mineralogical constitution. The Canister Retrieval Test was selected to be one of the full scale assignments in the Task Force on Engineered Barrier Systems and during 2009 the modelling work has continued.

The *Temperature Buffer Test* aims at improving our current understanding of the thermo-hydromechanical behaviour of buffers with a temperature around and above 100°C during the water saturation transient. The experiment has generated data since the start in 2003 and the temperature in the buffer around the lower heater had, in the end of 2008, reached a value of 150°C. The dismantling of the experiment started during the last two months of 2009, when all the bentonite down to Cylinder 2 were sampled and removed and core drilling was used as the method for dismantling. In parallel to the dismantling operation, the core samples have been analysed for density and water content at the Bentonite Laboratory at Äspö and the results are under evaluation. The upper heater was retrieved after Cylinder 3 and 4 had been removed. This retrieval test was performed in two steps.

SKB and Posiva are co-operating on a programme for the *KBS-3 Method with Horizontal Emplacement* (KBS-3H). A continuation phase of the project is ongoing and the aim of the complementary studies is to develop KBS-3H to such a level that the decision of full scale testing can be made. During 2009 extensive work has been carried out with the compartment plug. The fastening ring was cast in the beginning of the year and the collar and the cap together with the instrumentation has been installed. Compartment plug tests have been performed and the casting was grouted with Silica sol gel. Also, the deposition equipment has been operated a couple of times each month throughout the year as a form of maintenance.

The aim of the *Large Scale Gas Injection Test* is to perform gas injection tests in a full-scale KBS-3 deposition hole. The installation phase, including the deposition of canister and buffer, was finalised in 2005. Water is artificially supplied and the evolution of the saturation of the buffer is continuously monitored. The preliminary hydraulic and gas injection tests were completed in 2008. The first quarter of 2009 began with a full calibration of Lasgit instrumentation in readiness for the second stage of preliminary gas testing. The hydraulic test was initiated after calibration. After the hydraulic test, the system was re-calibrated and configured ready for the gas testing that was still ongoing in the end of the year.

Although a repository will be located in rock mass of good quality with mostly relatively low fracturing, sealing by means of rock grouting will be necessary. The main goal of the project *Sealing of Tunnel at Great Depth* is to confirm that silica sol is a useful grout at the water pressures prevailing at repository level.

Although a repository will be located in rock mass of good quality with mostly relatively low fracturing, sealing by means of rock grouting will be necessary. The main goal of the project *Sealing of Tunnel at Great Depth* is to confirm that silica sol is a useful grout at the water pressures prevailing at repository level. To achieve this, the Tass-tunnel has been constructed at the –450 m level at Äspö HRL. The experimental work performed in 2009 indicates that the water inflow has stabilised at 1 litre per minute and 60 meter tunnel, which means that the inflow goal, taking into account the whole deposition tunnel, was reached.

The objective of the project *In situ Corrosion Testing of Miniature Canisters* is to obtain a better understanding of the corrosion processes inside a failed canister. In Äspö HRL in situ experiments are performed with miniature copper canisters with cast iron inserts. The canisters are exposed to both natural reducing groundwater and groundwater which has been conditioned by bentonite. In the beginning of 2007 all five canisters were installed in the boreholes and a report on the installation and results obtained up to May 2008 has been published. A decision has been taken to dismantle one of the experiments for examination during 2011 and plans are being made for this procedure to be carried out.

In the project *Cleaning and Sealing of Investigation Boreholes* the best available techniques are to be identified and demonstrated. In order to obtain data on the properties of the rock, boreholes are drilled during site investigations. These investigation boreholes must be cleaned and sealed, no later than at the closure of the repository. The major activity in 2009 has been to compare the sealing function of plugs of different quality in long and short boreholes in the vicinity of a KBS-3V repository. Two additional sub-projects of practical importance were introduced in 2009; Sub-project 3 dealing with permanent sealing of two 300 mm diameter boreholes used in the TRUE project, and Sub-project 4 concerning chemical interaction of plugs of CBI concrete and smectite-rich clay (MX-80).

The *Task Force on Engineered Barrier Systems* addresses, in the first phase, two tasks: (1) THM processes and (2) gas migration in buffer material. However, at the end of 2006 it was decided to start a parallel Task Force that deals with geochemical processes in engineered barriers. During 2009, two Task Force meetings have been held, in Stockholm (Sweden) and in Pori (Finland). In Benchmark 1 (laboratory tests) the modelling of THM processes and gas breakthrough is finalised. In Benchmark 2 (large scale field tests) the main work during 2009 has been within modelling of the Canister retrieval test at Äspö HRL and altogether 8 modelling teams have been involved. Most teams have finished their calculations in the year. The chemistry group has had two meetings. In the meeting in May, data for Benchmarks 2 and 3 was presented and in the meeting in November, calculations on Benchmark 1–3 as well as a correlation corrected Poisson-Boltzmann theory was presented. A final report which concludes the work performed in the chemistry part of the Task Force is under production.

Äspö facility

The Äspö facility comprises both the Äspö Hard Rock Laboratory and the Bentonite Laboratory. Important tasks of the Äspö facility are the administration, operation, and maintenance of instruments as well as development of investigation methods. The main goal of the operation of the facility is to provide a safe and environmentally sound facility for everybody working or visiting the Äspö HRL.

In May 2009 part of the Äspö operation underwent an organisational change as the units Äspö Hard Rock Laboratory and Repository Technology, both within the Technology department were united. The new and larger unit inherited the name Repository Technology and Äspö HRL is the residence of the unit which is organised in five operation groups and one administrative staff function.

The operation of the facility during 2009 has been stable, with a very high degree of availability. In the Bentonite Laboratory different methods and techniques for installation of pellets and blocks in deposition tunnels and tests on piping and erosion of buffer and backfill material are performed. During 2009 eight rock/pellet tests and four half-scale tests were performed.

The public relations and visitor services group is responsible for presenting information about SKB and its facilities. During the year 2009 the group has been engaged in activities related to the selection of the site for the Swedish final repository of spent fuel in Forsmark and the visits to the three SKB facilities in Oskarshamn by about 13,000 persons.

Environmental research

Äspö Environmental Research Foundation was founded in 1996 on the initiative of local and regional interested parties. In 2008, the remaining and new research activities were transferred within the frame of a new co-operation, Nova Research and Development (Nova FoU). Nova FoU is a joint research and development platform at Nova Centre for University Studies and R&D supported by SKB and the municipality of Oskarshamn. Nova FoU is the organisation which implements the policy to broaden the use within the society concerning research results, knowledge and data gathered within the SKB research program and facilitates external access for research and development projects to SKB facilities in Oskarshamn. Nova FoU provides access to the Hard rock laboratory and Bentonite laboratory at Äspö and the Canister laboratory in Oskarshamn. During 2009, seven projects were ongoing within the Nova FoU framework.

International co-operation

In addition to SKB, eight organisations from seven countries participated in the international co-operation at Äspö HRL during 2008. Six of them: Andra, BMWi, CRIEPI, JAEA, NWMO and Posiva together with SKB form the Äspö International Joint Committee which is responsible for the co-ordination of the experimental work arising from the international participation. The international organisations are participating in the experimental work at Äspö HRL as well as in the two Äspö Task Forces: (1) Task Force on Modelling of Groundwater Flow and Transport of Solutes and (2) Task Force on Engineered Barrier Systems.

Sammanfattning

Äspölaboratoriet i Simpevarp i Oskarshamns kommun är en viktig del i SKB:s arbete med utformning, byggande (och drift) av ett slutförvar för använt kärnbränsle. Ett av de grundläggande skälen till SKB:s beslut att anlägga ett underjordslaboratorium var att skapa förutsättningar för forskning, utveckling och demonstration i en realistisk och ostörd bergmiljö på förvarsdjup. Underjordslaboratoriet utgörs av en tunnel från Simpevarpshalvön till södra delen av Äspö där tunneln fortsätter i en spiral ner till 460 meters djup. Äspölaboratoriet har varit i drift sedan 1995 och verksamheten har väckt stort internationellt intresse. Här följer en sammanfattning av det arbete som bedrivits vid Äspölaboratoriet under 2009.

Geovetenskap

Forskning inom geovetenskap är en grundläggande del av arbetet vid Äspölaboratoriet. Det huvudsakliga målet med de pågående studierna är att utveckla geovetenskapliga modeller samt att öka förståelsen för bergmassans egenskaper och kunskapen om användbara mätmetoder. Den huvudsakliga uppgiften inom det geovetenskapliga området är utvecklingen av en platsbeskrivande modell för Äspö där information från olika ämnesområden integreras. De huvudsakliga aktiviteterna inom de olika områdena har varit; (1) Geologi – utvärdering av geologiska karteringsmetoder vilket lett till beslut att utveckla SKB:s egna karteringssystem och slutfört karteringen av bergytor i den nya tunneln, (2) Hydrogeologi – övervakning och lagring av data i det datoriserade hydromoniteringssystemet, (3) Geokemi – den årliga provtagningen av grundvatten samt provtagning för specifika experiment och (4) Bergmekanik – avslutat fältförsöken avseende termiskt inducerad spjälkning i deponeringshål och utvärderat effekten av mottryck i deponeringshål.

Naturliga barriärer

I Äspölaboratoriet genomförs experimenten vid förhållanden som liknar de som förväntas råda på förvarsdjup. Experimenten kopplar till berget, dess egenskaper och in situ förhållanden. Målet med de pågående experimenten är att ge information om hur de naturliga och tekniska barriärerna fungerar i ett långtidsperspektiv. Ett viktigt syfte med verksamheten vid Äspölaboratoriet är att vidareutveckla och testa beräkningsmodeller för grundvattenströmning, radionuklidtransport och kemiska processer på förvarsnivå. I programmet ingår att bestämma värden på de parametrar som krävs som indata till konceptuella och numeriska modeller.

Bergets förmåga att fördröja transport av spårämnen studeras i olika skalor i *TRUE-försöken*. Syftet är att öka förståelsen för de processer som styr fördröjningen av radionuklider i kristallint berg samt att öka tillförlitligheten hos de modeller som används för beräkning av radionuklidtransport. Under 2009 har arbete skett inom delprojekten: ”TRUE Block Scale Continuation” (framtagning av artiklar för publicering i vetenskapliga tidskrifter) och ”TRUE-1 Continuation” (kompletterande sorptionsförsök i laboratorium, rapportering av ”Fault rock zones characterisation”) och ”TRUE 1 Completion” (analys av material, fokus på målsprickan, från överborrningen av två borrhål vid TRUE-1 som genomfördes under 2007).

LTDE-försöket är ett komplement till de sorptions- och diffusionsförsök som genomförts i laboratorium och är också en utvidgning av de experiment som genomförts inom TRUE-programmet. Sorptions- och diffusionsförsöket pågick under cirka sex månader och efter injicering av epoxi slutfördes överborrningen i maj 2007. Under 2009 har arbetet med analyser av provkärnor som borrats från sprickytan på borrkärnan och från den omkringliggande bergmatrisen fortsatt. Dessutom har laboratorieexperiment genomförts på referensbergmaterial.

Kolloidtransportprojektet initierades under 2008 och är en fortsättning på tidigare genomförda kolloidprojekt. Målsättningen med projektet är att ge svar på frågor som rör hur kolloidtransport bör behandlas i kommande säkerhetsanalyser. I projektet ingår fältexperiment i Grimsellaboratoriet i Schweiz och laboratorieexperiment för att studera kolloiders stabilitet och rörlighet under olika förhållanden. En hel del resultat har erhållits under 2009 avseende påverkan av till exempel vattenflöde, vattenkemi och bentonittyp på generering och transport av kolloider.

Mikroorganismer samverkar med sin omgivning och kan i vissa fall ha en betydande inverkan på förhållandena där. Detta kan vara av betydelse för hur ett framtida förvar för använt bränsle fungerar och studeras därför inom *Mikrobprojekten.* I mikroblaboratoriet på 450 m djup i Äspö pågår studier av mikrobiella processer inom flera projekt. Mikrobers förmåga att mobilisera och binda radionuklider studeras i projektet *Micomig* och mikrobiella effekter på den kemiska stabiliteten i miljöer med djupt grundvatten studeras i *Micored.*

I fortsättningen av *Matrisförsöket* är fokus på hur de småskaliga mikrosprickorna i bergmatrisen underlättar matrisporvattnets rörelse. Förståelsen av grundvattnets rörelse och förändringar i vattenkemin är viktig för slutförvarets funktion. Data från de hydrauliska testerna av sprickfria och uppspruckna sektioner i matrisborrhålet finns tillgängliga. Utvärdering och rapportering av genomförda kemiska analyser på matrisporvatten och hydrauliska tester i matrisborrhålet har inte som planerats avslutats under 2009 på grund av andra prioriteringar.

Radionuklidfördröjningsexperimenten genomförs in situ för att befästa de resultat som erhållits i laboratoriestudier. I speciella borrhålslaboratorier ska försöken genomföras. Förberedande arbete har genomförts för att definiera lämpliga försöksbetingelser och spårämne för studier av transportmotståndet i gränssnittet mellan buffert och berg, och planeringen av bränslelakningsexperimenten där upplösningen av urandioxid i naturligt grundvatten ska studeras har fortsatt.

I fortsättningsprojektet av *Padamot* ingår utveckling av analytiska tekniker för uranserieanalyser på mineralprov i sprickor med fokus på användningen av dessa analyser för bestämningen av redoxförhållanden under glaciala och postglaciala förhållanden. Analyser av borrkärnor från Äspö indikerar att redoxfronten för närvarande ligger på ett djup av cirka 15–20 m. En slutsats är även att hantering och behandling av borrkärnor är av avgörande betydelse för analysresultatens relevans, dessutom har man funnit att extraktionsschemat för analys av uran kan förenklas.

I projektet *Järnoxider i sprickor* undersöks järnoxidtäckta sprickytor för att hitta lämpliga palaeoindikatorer och beskriva under vilka förhållande dessa bildas. Den experimentella delen av fortsättningsfasen med titeln: 'Fastställande av penetrationsdjupet för oxiderande vatten under markytan' avslutades under förra året men den slutliga rapporteringen har inte avslutats på grund av andra prioriteringar.

Swiw-tester med syntetiskt grundvatten utgör ett komplement till testerna och studierna som utförts rörande de processer som styr fördröjningen av radionuklider i berget. I förstudien valdes platsen för ”TRUE Block Scale” som lämplig kandidatplats, men det visade sig under 2009 att platsen var så påverkad av den nya tunneln att den inte var lämplig så istället valdes en ny plats för inledande tester. Planen är nu att utföra testerna under 2010.

Aktiviteterna vid Äspölaboratoriet omfattar projekt med syfte att utvärdera användbarhet och tillförlitlighet hos olika beräkningsmodeller. I arbetet ingår även att utveckla och prova metoder för att bestämma parametervärden 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*”. Resultaten från ”Task 6” (användandet av data från platsundersökning i modellering för säkerhetsanalys) har publicerats i en rad artiklar i Hydrology Journal. Under 2009 har det huvudsakliga arbetet bedrivits inom ”Task 7” som avslutats och modellering pågått inom ”Task 7” (pumptester under lång tid i Olkiluoto, Finland) som är uppdelat i flera ”sub-tasks”. Rapporter beskrivande ”sub-task” 7A1–A5 har färdigställts baserat på granskningskommentarer. En uppdatera projektbeskrivning för ”sub-task” 7B och 7C och mer data har skickats till modellörerna. En workshop genomfördes för ”Task 7” och ”Task 8” i januari i Lund då modelleringsansatser och planer för den framtida modelleringen presenterades och diskuterades. Det 25:e Task Force mötet hölls i Mizuanami i Japan i oktober.

Det övergripande målet med projektet *Äspömodell för radionuklidsorption* är att formulera och testa processkvantifierande modeller för geokemisk retention av radionuklider, i granitmiljöer, användandes av en kombinerad laborations- och modelleringsapproach. Ambitionen är att inkludera experimentella data för specifik ytarea och sorptionskapacitet för varje mineralfas som utgör granitiskt berg i modellen. Under 2009 har modelltolkning av specifik ytarea och radionuklidegenskaper för klorit initierats. Undersökningen av specifik ytarea som funktion av partikelstorlek för rena mineral har startats upp för labradorit och magnetit och preliminära resultat har rapporterats.

Tekniska barriärer

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

I Prototypförvaret pågår en demonstration av den integrerade funktionen hos förvarets barriärer. Prototypförvaret utgör dessutom en fullskalig referens för prediktiv modellering av slutförvaret och barriärernas utveckling. Prototypförvaret omfattar totalt sex deponeringshål, fyra i en inre tunnelsektion och två i en yttre. Mätningar av relativ fuktighet, portryck, totalt tryck och temperatur i olika delar av testområdet genomförs kontinuerligt. Genomförda mätningar indikerar att återfyllningen i båda sektionerna av tunneln är vattenmättade och att mättnadsgraden i bufferten varierar för de olika deponeringshålen.

I *Lot-försöket* genomförs långtidsförsök på buffertmaterial som syftar till att validera modeller och hypoteser som beskriver bentonitbuffertens fysikaliska egenskaper och processer relaterade till mikrobiologi, radionuklidtransport, kopparkorrosion och gastransport under förhållanden som liknar dem i ett KBS-3-förvar. Inget upptag av testpaket ägde rum under 2009 så året har ägnats åt kompletterande analyser och slutlig rapportering av tidigare upptagna testpaket.

Målet med projektet *Alternativa buffertmaterial* är att studera olika lermaterial som i laboratorietester har visat sig vara tänkbara buffertmaterial. Tre paket med olika kombinationer av lermaterial har installerats i borrhål i Äspölaboratoriet. Paketen ska värmas för att försiktigt höja temperaturen i bufferten till måltemperaturen 130°C. I två av paketen startades värmarna direkt och i det tredje paketet startades värmarna efter vattenmättad. I maj 2009 genomfördes upptag av paket 1 och buffert prover har skickats till de deltagande organisationerna för analys.

I *Återfyllningsförsöket* undersöker man den hydrauliska och mekaniska funktionen hos olika återfyllnadsmaterial. Försöket är också en demonstration av olika metoder för inplacering av återfyllnad och installation av tunnelförslutning. Sektionens innersta del är återfylld med en blandning av krossat berg och bentonit medan den yttre delen är återfylld med krossat berg. I slutet av 1999 startade bevätningen av återfyllningen och den blev fullständigt mättad under år 2003. Därefter har flödestester genomförts för att bestämma den hydrauliska konduktiviteten i olika delar av återfyllningen samt kompressibilitetstester. Under 2009 har kontinuerliga mätningar genomförts och resultat erhållits från alla sensorer förutom de som mäter relativ fuktighet. Dessutom har tester startat för att mäta den hydrauliska konduktiviteten lokalt i återfyllningen med krossat berg.

Återtagsförsöket syftade till att prova teknik för att återta kapslar efter det att den omgivande bentonitbufferten har vattenmättats. Under 2006 genomfördes ett lyckat återtag av kapseln. Vattenmättnadsfasen hade då pågått i mer än fem år med kontinuerliga mätningar av fukthalten, temperaturen och spänningar. Under 2009 har analyser på bentonitbufferten fortsatt. Resultat har erhållits avseende mekaniska egenskaper, svälltryck, hydraulisk konduktivitet och kemiska/mineralogiska förändringar i bentonitbufferten. Återtagsförsöket valdes som en fullskaleuppgift för ”Task Force on Engineered Barrier Systems” och modelleringsarbetet har fortsatt under 2009.

Syftet med *TBT-försöket* är att förbättra förståelsen av buffertens termiska och hydromekaniska utveckling under vattenuppmättnadsfasen vid temperaturer runt eller högre än 100°C. Experimentet har genererat data sedan starten 2003 och temperaturen runt den nedre värmaren hade i slutet av 2008 gått upp till 150°C. Försöket avbröts med början under de två sista månaderna av 2009 och all bentonit ner till cylinder 2 togs bort och provtogs genom kärnborrning. Kärnproverna har analyserats med avseende på densitet och vatteninnehåll i Bentonitlaboratoriet och resultaten utvärderas för närvarande. Den övre värmaren återtogs efter att cylinder 3 och 4 hade tagits borts. Återtagstestet genomfördes i två steg.

Ett forskningsprogram för ett *KBS-3-förvar med horisontell deponering* (KBS-3H) genomförs som ett samarbetsprojekt mellan SKB och Posiva. Nu pågår en fortsättningsfas av projektet med målsättningen att utveckla KBS-3H till en sådan nivå att beslut kan fattas om fullskaletest. Omfattande arbeten med förslutningen av deponeringsutrymmet ägde rum under 2009. Fästringen göts i början av året. Vidare installerades kragen och locket med den tillhörande instrumenteringen. Tester av förslutningen genomfördes och gjutningen kompletterades med en inektering av Silica sol gel. Dessutom kördes deponeringsutrustningen ett par gånger varje månad som en sorts underhållsprogram.

Syftet med ett *Gasinjekteringsförsök i stor skala* är att studera gastransport i ett fullstort deponeringshål (KBS-3). Installationsfasen med deponering av kapsel och buffert avslutades under 2005. Vatten tillförs bufferten på konstgjord väg och utvecklingen av vattenmättnadsgraden i bufferten mäts kontinuerligt. Under 2008 avslutades de preliminära hydrauliska testerna och gasinjekteringstesterna. Under det första kvartalet av 2009 genomfördes en fullständig kalibrering av instrumenteringen inför det andra steget av preliminära gastester. Det hydrauliska testet påbörjades efter kalibreringen. Systemet återkalibrerades och konfigurerades efter det hydrauliska testet inför genomförande av gastester som fortfarande var pågående i slutet av året.

Även om ett förvar kommer att lokaliseras till ett berg av god kvalitet med låg sprickförekomst kommer injektering av berget behövas. Målsättningen med projektet *Tätning av tunnel på stort djup* är att bekräfta att injekteringsmedlet silica sol är ett användbart injekteringsmedel som kan användas vid de höga vattentryck som råder på förvarsdjup. I Äspölaboratoriet på –450 m nivån har Tass-tunneln drivits för att visa detta. Genomfört arbete under 2009 visar att vatteninflödet har stabiliserats till 1 liter per minut och 60 m tunnel, vilket innebär att vattenflödet till deponeringstunnlar går att begränsas till de nivåer som efterfrågas.

Målet med projektet *In situ testning av korrosion av miniatyrkapslar* är att få en bättre förståelse av korrosionsprocesserna inuti en trasig kapsel. Vid Äspölaboratoriet genomförs in situ experiment med miniatyrkopparkapslar med gjutjärnsinsats där kopparkapslarna kommer att utsättas för både naturligt reducerande grundvatten och grundvatten som har jämviktats med bentonit under flera år. I början av 2007 var alla fem kapslar installerade i borrhålen och en rapport som beskriver själva installationen och resultat som erhållits, fram till maj 2008, har publicerats och en rapport håller på att tas fram med erhållna data fram till december 2009. Ett beslut har tagits att bryta ett av försöken under 2010 och planeringen av brytningen har skett under året.

I projektet *Rensning och förslutning av undersökningsborrhål* ska bästa möjliga tillgängliga teknik identifieras och demonstreras. I platsundersökningarna borras undersökningsborrhål och en noggrann karakterisering genomförs för att erhålla data på bergets egenskaper. Dessa borrhål måste rensas och pluggas senast när driften av slutförvaret avslutats. Det huvudsakliga arbetet under 2009 har inbegripit en jämförelse av förslutningsfunktionen hos pluggar med olika kvalitet i långa och korta borrhål i närheten av KBS-3V-förvaret. Två ytterligare underprojekt av praktisk karaktär startades upp under 2009; ”Sub-project 3” som behandlar permanent förslutning av två borrhål med en diameter på 300 mm som använts i TRUE-projektet och ”Sub-project 4” som behandlar kemiska interaktioner mellan pluggar av betong med smektitrik lera (MX-80).

Det internationella samarbetsprojektet *”Task Force on Engineered Barrier Systems”*, omfattar i den första fasen av projektet huvudsakligen två områden: (1) THM-processer och (2) gasmigration i buffertmaterial. Under 2006 beslutades det dock att starta upp en parallell ”Task Force” som behandlar geokemiska processer i ingenjörsbarriärer. Två ”Task Force” möten har hållits under 2009, i Stockholm och i Pori (Finland). I ”Benchmark 1” (laboratorietester) har -modelleringen av THM-processer och gasgenombrottet avslutats. I ”Benchmark 2” (storskaliga fälttest) har det huvudsakliga arbetet varit modellering av Återtagsförsöket i Äspölaboratoriet där totalt 8 modelleringsteam har varit involverade. De flesta teamen har slutfört sina beräkningar under det gångna året. Under mötet i maj presenterades data för ”Benchmark 2 och 3” och beräkningar för ”Benchmark 1–3” och en korrelationskorrigerad Poisson-Boltzmannteori presenterades under mötet i november. Arbete pågår med en slutrapport över det genomförda arbetet inom den geokemiska ”task forcen”.

Äspöanläggningen

I Äspöanläggningen ingår både det underjordiska berglaboratoriet och Bentonitlaboratoriet. 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.

I maj 2009 omorganiserades delar av Äspös verksamhet då enheterna Äspölaboratoriet och Slutförvarsteknik, båda inom avdelningen Teknik, slogs samman. Den nya större enheten ärvde namnet Slutförvarsteknik och har sitt säte på Äspö. Enheten består av fem operationella grupper och en administrativ personalfunktion.

Driften av anläggningen under 2009 har varit stabil och tillgängligheten har varit mycket hög. I bentonitlaboratoriet har olika metoder och tekniker för installation av pelletar och återfyllningsblock i deponeringstunnlar utförts, men även erosionstester på buffert och återfyllningsmaterial har genomförts. Under 2009 genomfördes åtta berg/pelletstest och fyra halvskaletest.

Information och besöksgruppen vid Äspölaboratoriet är ansvariga för att ta fram information om SKB och dess anläggningar. Gruppen har under 2009 varit engagerade i aktiviteter relaterade till valet av Forsmark som plats för det Svenska slutförvaret för använt kärnbränsle och besök av ungefär 13 000 personer till SKB:s tre anläggningar i Oskarshamn.

Miljöforskning

Äspö Miljöforskningsstiftelse grundades 1996 på initiativ av lokala och regionala intressenter. Under 2008 överfördes pågående och kommande forskningsaktiviteter, till den nya forsknings- och utvecklingsplattformen Nova FoU som är ett samarbetsprojekt mellan SKB och Oskarshamns kommun. Nova FoU är den organisation som implementerar policyn att bredda samhällets användning av de forskningsresultat, den kunskap och de data som kommer fram inom SKB:s forskningsprogram och underlättar tillträde till SKB:s anläggningar i Oskarshamn för externa FoU-projekt. Nova FoU tillhandahåller tillträde till Äspölaboratoriet och Bentonitlaboratoriet på Äspö samt Kapsellaboratoriet i Oskarshamn. Under 2009 pågick sju projekt inom Nova FoU:s ramverk.

Internationellt samarbete

Förutom SKB har åtta organisationer från sju länder deltagit i det internationella samarbetet vid Äspölaboratoriet under 2009. Sex av dem, Andra, BMWi, CRIEPI, JAEA, NWMO och Posiva utgör tillsammans med SKB “Äspö International Joint Committee” vilken ansvarar för att koordinera det experimentella arbetet som uppkommer från det internationella deltagandet. De utländska organisationerna deltar både i det experimentella arbetet i Äspölaboratoriet och i modelleringsarbetet inom de två Äspö ”Task Force”grupperna: (1) ”Task Force on Modelling of Groundwater Flow and Transport of Solutes” och (2) ”Task Force on Engineered Barrier Systems”.

Contents

1 General

1.1 Background

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

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

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.

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

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 detailed basis for the period 2008–2010 is described in SKB's RD&D-Programme 2007 /SKB 2007/.

1.2 Goals

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

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

The tasks in stage goals 1 and 2 were after completion at Äspö HRL transferred to the Site Investigations Department of SKB. The investigation methodology has here after been developed in the site investigations performed at Simpevarp/Laxemar in the municipality of Oskarshamn and at Forsmark in the municipality of Östhammar. In order to reach stage goals 3 and 4 the following important tasks are today performed at the Äspö HRL:

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

In 2007 the inauguration of the Bentonite Laboratory took place and at the laboratory studies on buffer and backfill materials are performed to complement the studies performed in the rock laboratory. In addition, Äspö HRL and its resources are available for national and international environmental research.

1.3 Organisation

The research, technical development and safety assessment work is organised into the Technology department, in order to facilitate co-ordination between the different activities. Within the Technology department a Technical-scientific council has been set up in order to prepare technical and scientific issues concerning the research and development of the KBS-3 method. The Council shall in different issues continuously judge the state of development and the need of further work as well as advice on ongoing and planned new projects aimed at development and scientific verifying of the different parts of the KBS-3 method.

In May 2009 part of the Äspö operation underwent an organisational change as the units *Äspö Hard Rock Laboratory* and *Repository Technology* within the Technology department were united. This change was done to focus the remaining development of the repository technology and performing of experiments and tests in a realistic repository environment at Äspö HRL. The new and larger unit inherited the name *Repository Technology.* Äspö HRL is the residence of the unit but the unit includes employees in both Äspö and Stockholm. The main responsibilities of the unit are to:

- Perform technical development commissioned by SKB’s programmes for nuclear fuel and for low- and intermediate level waste.
- Develop the KBS-3H concept.
- Perform experiments in the Äspö HRL.
- Secure a safe and cost effective operation of the Äspö HRL.
- Prosecute comprehensive visitor services and information activities in the Oskarshamn area.

The Repository Technology unit is organised in five operative groups and an administrative staff function:

- *Geotechnical barriers and rock engineering (TDG),* responsible for the development, testing and demonstration of techniques for installation of buffer, backfill and plugs in deposition tunnels, backfilling of the final repository and plugging of investigation boreholes.
- *Mechanical- and system engineering (TDM),* responsible for the development, testing and demonstration of equipment, machines and vehicles needed in the final repository.
- *Project and experimental service (TDP),* responsible for the co-ordination of projects undertaken at the Äspö HRL, providing services (administration, design, installations, measurements, monitoring systems etc) to the experiments.
- *Public relations and visitor services (TDI)*, responsible for presenting information about SKB and its facilities with main focus on the Äspö HRL.
- *Facility operation (TDD),* responsible for the operation and maintenance of the Äspö HRL offices, workshops and underground facilities and for development, operation and maintenance of supervision systems.
- *Administration, quality and planning (TDA*), responsible for planning, reporting, QA, budgeting, environmental co-ordination and administration. The staffing of the Äspö reception and the SKB switchboard are also included in the function.

Each major research and development task is organised as a project that is led by a project manager who reports to the client organisation. Each project manager is assisted by an on-site co-ordinator with responsibility for co-ordination and execution of project tasks at the Äspö facility. The staff at the site office provides technical and administrative service to the projects and maintains the database and expertise on results obtained.

1.4 International participation in Äspö HRL

The Äspö HRL has so far attracted considerable international interest. During 2009, eight organisations from seven countries in addition to SKB participated in the international co-operation at Äspö HRL. The participating organisations were:

- Agence Nationale pour la Gestion des Déchets Radioactifs (Andra), France.
- Bundesministerium für Wirtschaft und Technologie (BMWi), Germany.
- Central Research Institute of Electric Power Industry (CRIEPI), Japan.
- Japan Atomic Energy Agency (JAEA), Japan.
- Nuclear Waste Management Organization (NWMO), Canada.
- Posiva Oy, Finland.
- Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (Nagra), Switzerland.
- Radioactive Waste Repository Authority (RAWRA), Czech Republic.

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

Task Forces are another form of organising the international work. Several of the international organisations in the Äspö co-operation participate in the two Äspö Task Forces on (I) Modelling of Groundwater Flow and Transport of Solutes and (II) Engineered Barrier Systems. SKB also takes part in several international EC-projects and participates in work within the IAEA framework.

1.5 Allocation of experimental sites

The rock volume and the available underground excavations are divided between the experiments performed in Äspö HRL. It is essential that the experimental sites are located so that interference between different experiments is minimised. The allocation of the experimental sites in the underground laboratory is shown in Figure 1-2.

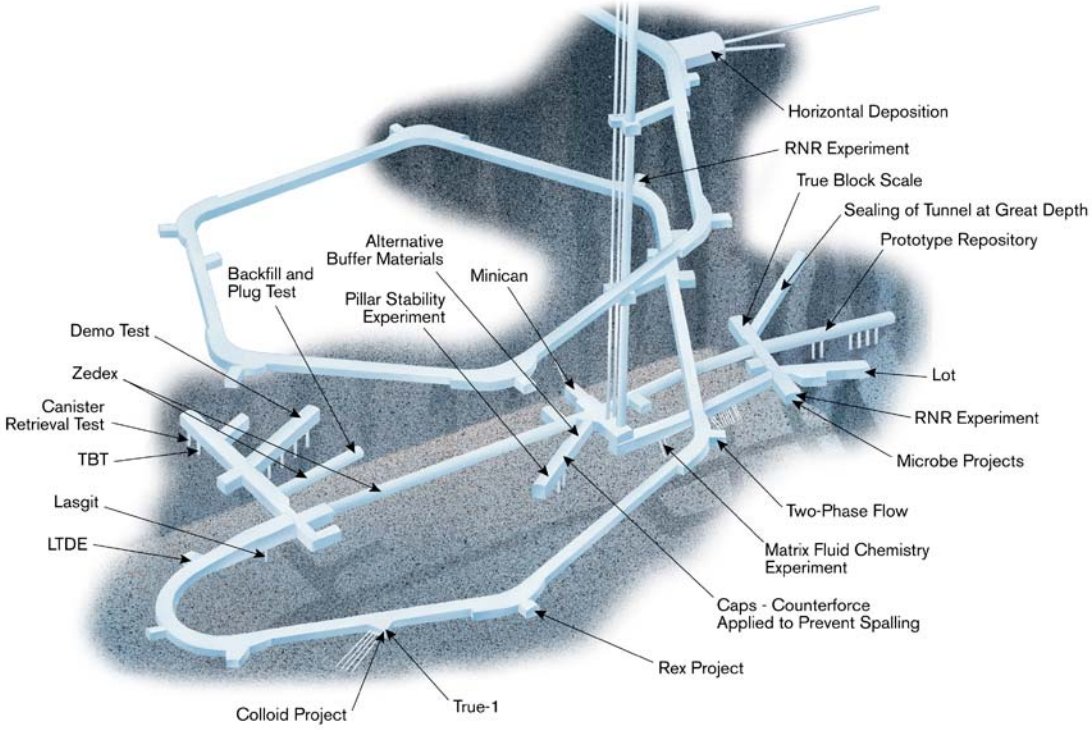


Figure 1-2. *Allocation of experimental sites from –220 m to –450 m level.*

1.6 Reporting

Äspö HRL is an important part of SKB's RD&D Programme. The plans for research and development of technique during the period 2008–2013 are presented in SKB's RD&D Programme 2007 /SKB 2007/. The information given in the RD&D Programme related to Äspö HRL is detailed in the Äspö HRL Planning Report /SKB 2009a/ and this plan is revised annually. Detailed account of achievements to date for the Äspö HRL can be found in the Äspö HRL Annual Reports that are published in SKB's Technical Report series. This report describes the achievements during 2009. In addition, the progress in the projects during the year has also been reported in three Status Reports /SKB 2009b, c and SKB 2010/.

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. Data collected from experiments and measurements at Äspö HRL are mainly stored in SKB's site characterisation database, Sicada.

1.7 Management system

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

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

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

1.8 Structure of this report

The achievements obtained at Äspö HRL during 2009 are in this report described in six chapters:

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

2 Geoscience

2.1 General

The responsibility of the geoscientists at Äspö today involves maintaining and developing the knowledge and methods of the geoscientific field, as well as providing geoscientific support to various projects conducted at Äspö HRL. Geoscientific research and activities are conducted in the fields of geology, hydrogeology, geochemistry and rock mechanics.

Geoscientific research is a part of the activities at Äspö HRL as a complement and an extension of the stage goals 3 and 4, see Section 1.2. The studies include laboratory and field experiments, as well as modelling work, e.g. obtaining tunnel geometries that can be used in modelling work by laser scanning combined with digital photography, see Figure 2-1. From 2006 the work follows a yearly scientific programme. The overall aims are to:

- Establish and develop geoscientific models of the Äspö HRL rock mass and its properties.
- Establish and develop the knowledge of applicable measurement methods.

The main task within the geoscientific field is the development of the Äspö Site Descriptive Model (SDM). The model will facilitate the understanding of the geological, hydrogeological and geochemical conditions at the site and the evolution of the conditions during operation of Äspö HRL. The activities further aim to provide basic geoscientific data to the experiments performed in Äspö HRL and to ensure high quality of experiments and measurements related to geosciences.

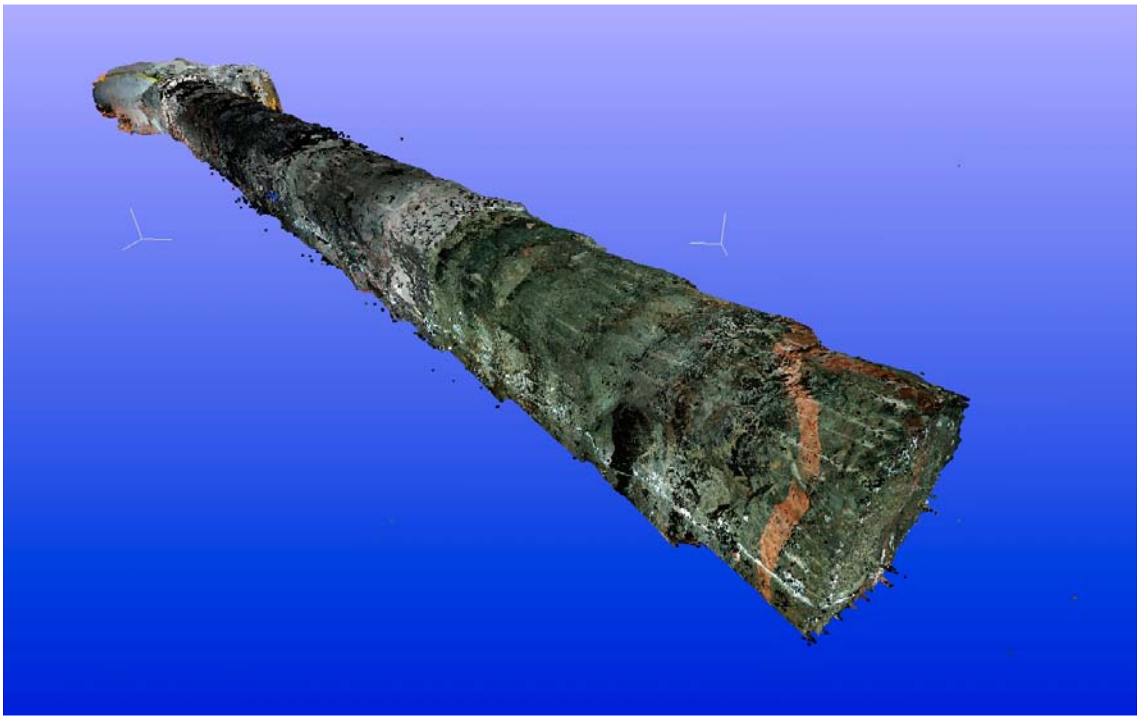


Figure 2-1. *The result of laser scanning combined with digital photography performed in the entire Tass-tunnel, with a length of approximately 80 m.*

2.2 Geology

The geological work at Äspö HRL covers several fields. Major tasks are mapping of tunnels, deposition holes and drill cores, as well as continuous updating of the geological 3D model of the Äspö rock volume and contribution with input knowledge in projects and experiments conducted at Äspö HRL. In addition, the development of new methods in the field of geology is a major responsibility. As a part of the latter, the project Rock Characterisation System (RoCS) is conducted, see Section 2.2.2.

2.2.1 Geological mapping and modelling

Background and objectives

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

Results

The Tass-tunnel used by the project "Sealing of Tunnel at Great Depth" ended at section 80.7 m in the end of 2008. The geological mapping of the tunnel as well as the digitising of the field maps and the entering of geological data into the TMS-system (Tunnel Mapping System) were completed in the beginning of 2009. All geological data, drawings and photos have been delivered to the SKB Sicada archive.

The entire Tass-tunnel has been scanned with digital laser combined with digital photography in order to get a 3D tunnel model in colour. The scanning of the last part of the tunnel was completed in February 2009. The scan data have been analysed and used in modelling work, see Figure 2-1. The report concerning the pre investigations of the Tass-tunnel has been published /Hardenby et al. 2008/. A report concerning the geological mapping of the Tass-tunnel is in preparation. Also, the report regarding possible differences in mapping procedure and achieved results from geological mapping of a drilled and blasted tunnel and a TBM bored tunnel has been published /Hultgren 2008/.

The modelling work that commenced in 2005 concerning water bearing fractures at the –450 m level is finished. Adjustments in the reviewed report are in progress.

Consensus has been reached about the rock type nomenclature used by the site investigation team of Oskarshamn /Carlsten et al. 2006/ and that used by the geologists at the Äspö HRL. This is essential for the ongoing work with the Äspö site descriptive model (SDM). The nomenclature will be used also by the TMS-system and the Boremap core logging system. New rock type codes have been implemented in the TMS-system. These codes are the same as those used by Boremap core logging system. This will, for example, simplify the ongoing transfer of geological data from the TMS to the database Sicada. The Boremap and Petrocore (the old core logging system) tables in the SKB database Sicada have been updated to "site investigation standard" which means that all used codes now are the same.

The great number of photos, taken during the mapping of the Tasa-tunnel at Äspö HRL since the beginning of 1990, has earlier been digitised. The sorting and labelling of these photos are now completed. The digitising work now continues with the minor tunnels and deposition holes.

2.2.2 RoCS – Method Development of a New Technique for Underground Surveying

Background and Objectives

The project Rock Characterisation System (RoCS) was initially conducted as an SKB-Posiva joint-project. The purpose is to investigate if a new system for rock characterisation could be adopted when constructing a final repository. The major reasons for the RoCS project are aspects on objectivity of the data collected, traceability of the mappings performed, saving of time required for mapping and data treatment including digitising and manual data handling, and precision in the final mapping results. These aspects all represent areas where the present mapping technique may not be adequate.

The feasibility study concerning modern geological mapping techniques has been completed. Based on the results SKB has commenced a new phase of the RoCS project. The project will concentrate on finding or constructing a new geological underground mapping system. Photogrammetry and/or laser scanning in combination with digital photography will be a part of that system. The resulting mapping system shall operate in a colour 3D environment where the xyz-coordinates are known.

Results

During the year a new project plan was approved. Documents concerning specification of requirements for various parts of the project have been completed; for example specification of requirements for the geological mapping and how to handle laser scan or photogrammetric data.

The final of four laser scanning events combined with digital photography in the Tass-tunnel has been completed, see section above. At the last event also scanning of the EDZ-slot took place. The data from all four events have been delivered. The scan data has been used to create 3D-models of the Tass-tunnel. There have been some problems, however, in fitting the data from the various scanning events together. The work concerning tests of software to handle the laser data continues.

Test of photogrammetric and laser scanning equipment, sometimes combined with rather "primitive" mapping software, proceeded during the year:

- The company 3G Software & Measurement has demonstrated their mapping system based on photogrammetry in the Tass-tunnel. The test gave promising results.
- A complementary demonstration of the SpheronCam digital camera was performed in the Tass-tunnel by the company Creative Tools AB.
- The company ATS AB demonstrated a new version of the Faro laser scanner combined with a digital camera in the Tass-tunnel.
- At a visit to Posiva's facility Onkalo at Olkiluoto, Finland, the Australian company Adam Technology demonstrated their mapping system based on photogrammetry (Figure 2-2).

The various tests, methods and equipment have been evaluated by the project group and after the evaluation SKB has decided to develop a geological mapping system of their own, based on the principles of the Boremap-core logging system, and at the time being, photogrammetry. SKB has chosen photogrammetry in favour of laser scanning.

The report concerning laser scanning combined with digital photography in the Tasq-tunnel is now published /Berlin and Hardenby 2008/.

Figure 2-2. *Adam Technology's field equipment; digital camera on a tripod (left) and portable illumination (right).*

2.3 Hydrogeology

The major aims of the hydrogeological activities are to:

- Establish and develop the understanding of the hydrogeological properties of the Äspö HRL rock mass.
- Maintain and develop the knowledge of applicable measurement methods.
- Support of experiments and measurements in the hydrogeological field so that they are performed with high quality.
- Provide hydrogeological support to active and planned experiments at Äspö HRL.

The understanding of the hydrogeology at Äspö has developed over time with a first descriptive model produced 1997 and a second one in 2002. The objective now is to upgrade the existing hydrogeology model by including data collected during 2002–2008. The main features are the inclusion of data collected from various experiments and the adoption of the modelling procedures developed during the Site Investigations at Oskarshamn and Östhammar. The intention is to develop the site descriptive model (SDM) into a dynamic working tool suitable for predictions in support of the experiments in the laboratory as well as to test hydrogeological hypotheses.

A number of quality issues with the basic datasets have been addressed and were resolved by the end of the year. Data compilation visualisation was initiated and some initial pre-modelling runs were performed with SKB’s numerical flow and transport code Darcy Tools.

2.3.1 Hydro Monitoring Programme

Background and objectives

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

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

The scientific grounds of maintaining the hydro monitoring programme are to:

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

Due to the large number of experiments and activities in the tunnel, it is a delicate task to plan new activities so they do not adversely affect the ongoing experiments. The HMS along with the site descriptive model, provide the basis for judgement in terms of likelihood on “what-if” scenarios. For example, this was provided for when assessing the impact of applying very high pressure in the KBS-3H tunnel on other ongoing experiments.

Results

The hydrogeological monitoring system has been performing well and the monitoring points in the tunnels have been maintained. Quality issues with the database HMS in respect to being incomplete and not harmonised with the activity database (Sicada) have been resolved.

A review of potential supporting and corrective measures for the surface boreholes has been performed followed by the refurbishing of boreholes KAS03 and KAS09. Figure 2-3 shows mobilisation for retrieval of monitoring equipment from KAS09. Extracted rods from KAS09, installed in April 1990, were partly quite corroded and very difficult to retrieve, while the rods in KAS03, installed in 1995, were in good condition and the complete equipment was extracted intact. New equipment was installed in KAS03 and is due to be operative early 2010. A borehole imaging measurement (BIPS) was performed in KAS09 to provide support for a risk assessment prior to flow logging with the PFL tool. As it turned out, the risk of jamming the PFL equipment was deemed too high and it was decided not to go ahead with the flow logging.

The hydrogeological monitoring is reported every four month period through quality control documents and on an annual basis, describing the measurement system and basic results. The annual report for monitoring year 2008 has been published /Wass and Nyberg 2009/ and the annual report for monitoring year 2009 is underway.

Figure 2-3. *Site mobilisation for retrieval of monitoring equipment from borehole KAS09.*

2.4 Geochemistry

Background and objectives

The major aims within geochemistry are to:

- Establish and develop the understanding of the hydrogeochemical properties of the Äspö HRL rock volume.
- Maintain and develop the knowledge of applicable measuring and analytical methods.
- Ensure that experimental sampling programmes are performed with high quality and meet overall goals within the field area.
- Provide hydrogeochemical support to active and planned experiments at Äspö HRL.

Results

The major achievement was the compilation of the hydrogeochemical data for the Äspö Site Descriptive Model (SDM) which was completed and evaluated by use of "explorative analyses". This was made on data from all depths in order to produce mixing models by use of the M3 code. In this exercise end-members will be chosen and reaction modelling will be done using PhreeqC. These models will be used to establish a conceptual model of the Äspö site in detail.

During the year a microbe project was initiated and the work on identification and quantification of the ligands will soon be completed. The final documentation on the result from previous years' analyses in the Tass-tunnel was completed and is now available for review. The finalising of the main report is expected during the first four-month period in 2010.

The method development on examination of the contents in the rock after blasting was evaluated and the work will be compiled in a PM and presented in a final report. The results from the sampling of gases and isotopes which were completed in 2008 will be compiled and evaluated. The groundwater sampling and analyses within the experiment in the project Sealing of Tunnel at Great Depth was successfully implemented and completed. Colloids which were sampled in connection to the project will be analysed and the results from residual traces of nitrogen gas will be compiled.

The geochemical part of a basic programme for the geoscientific investigations has been developed and included together with a speciation of the budget.

2.4.1 Monitoring of Groundwater Chemistry

Background and objectives

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

The monitoring programme is designed to provide information to determine where in the rock mass, the hydrogeochemical changes are taking place and at what time stationary conditions are established. In addition, all ongoing experiments have the possibility to request additional sampling of interest for their projects.

The sampling programme followed the same sampling as in 2008. Discussions were initiated on how to modify the current monitoring to better fit the ongoing experiments in the tunnel.

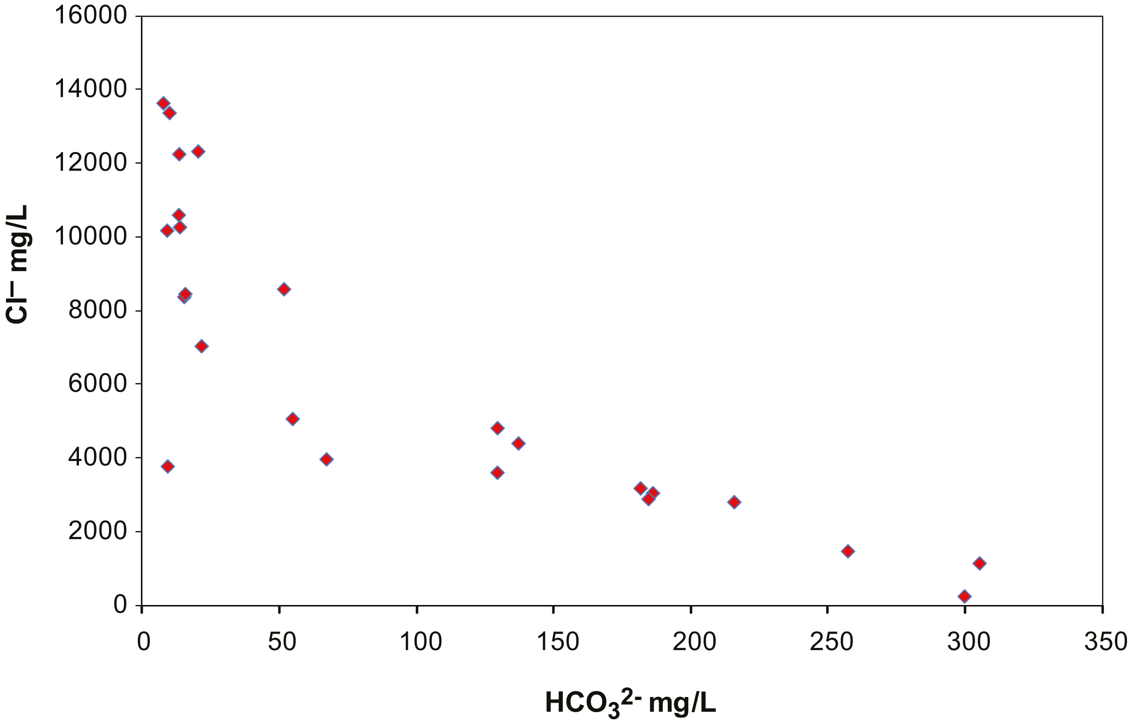


Figure 2-4. *The concentration of HCO_3^{2-} plotted versus Cl^- in groundwater from all boreholes sampled during the monitoring campaign in the Äspö tunnel.*

Results

The autumn monitoring campaign during September/October has been completed and data is now being quality assured for the database Sicada. All analytical results are expected to be reported during the first four-month period in 2010.A total of 48 groundwater samples were collected in the regular monitoring from the selected boreholes and other stations in the tunnel. In addition, several other groundwater samples have been collected in specific areas connected to the ongoing experiments. Preliminary result reveal that there are overall minor changes in the groundwater chemistry compared to previous year sampling. Interestingly there is still, after several years of monitoring, an increase in HCO_3^{2-} concentrations with a decrease in Cl^- as can be seen in Figure 2-4.

2.5 Rock Mechanics

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

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

In addition, a project called Counterforce Applied to Prevent Spalling (Caps) comprising field tests in Äspö HRL and numerical modelling is performed, see Section 2.5.1.

2.5.1 Counterforce Applied to Prevent Spalling

Background and objectives

The field experiment within Counterforce Applied to Prevent Spalling (Caps) was initiated to determine if the application of dry bentonite pellets is sufficient to suppress thermally-induced spalling in KBS-3 deposition holes. The experience gained from Äspö Pillar Stability Experiment, conducted between 2002 and 2006, indicated that spalling could be controlled by the application of a small confining pressure in the deposition holes /Andersson 2007/.

Experimental concept

The field experiment included a total of eight boreholes that were heated up in a series of demonstration experiments in the Tasq-tunnel. Each test consisted of two heating holes with a diameter of approximately 0.5 m and a depth of 4 m, separated by a 0.7 m thick pillar, which were surrounded by a number of boreholes equipped with temperature gauges. A photograph of the test site is presented in Figure 2-5.

The first and the second heating tests were performed in open holes without any confining pressure on the borehole wall. The third and the fourth heating tests were carried out in holes with loosely placed Leca pellets (expanded clay), in a 50 mm gap created between an inner tube and the borehole wall, to observe any difference in the occurrence of spalling compared to the previous tests. The first heating test was initiated at the end of August 2008 and the final test was finished by the end of May 2009.

After the final heating test, post characterisation of the spalled damaged zone in the heating holes was carried out. The post characterisation included examination of the hydraulic transmissivity of the spalled zone in one heating hole in the final test, and documentation of the geometry of the spalled zone in the other heating holes. The post characterisation of the spalled zone was completed by mid-September 2009.

Figure 2-5. *The test site of Caps in the Tasq-tunnel at Äspö HRL. The photograph was taken before all of the instrumentation holes had been drilled. The test sequence of the field experiment as well as labels of the heating holes, are indicated in the figure (Photo C-R Lindqvist).*

Results

The results from the third heating test, being the first test with confinement provided by the Leca pellets, indicated that dry pellets cannot prevent the borehole wall from cracking, whereas they will keep slabs in place with larger dimensions than the pellet fraction. The results generated a focus on the hydraulic transmissivity of the spalled damaged zone in the final field test and this parameter was examined by water injection tests in boreholes penetrating the damaged zone in heating hole KQ0046G03. Before the drilling of the water injection holes, the pellet-filled slot was sealed by a grout of ordinary Portland cement.

The results from the water injection tests are presented in Figure 2-6. The stationary transmissivity evaluated for the borehole sections indicated in the figure are marked on the water injection holes. In all measurements presented in the figure the water was injected below the double packer.

Except for one borehole, KQ0045G02, the evaluated hydraulic transmissivity corresponds to the measurement limit of the equipment used (2 mL/min). The lower transmissivity for the test sections in borehole KQ0044G02 and KQ0047G03 is determined from measurements with a doubled injection pressure.

The results from the water injection tests with confinement provided by LECA filling demonstrate that the transmissivity of the damaged zone was typically below $5 \cdot 10^{-9}$ m^2/s. The corresponding hydraulic conductivity for an assumed thickness of the damage zone between 10–50 mm was estimated to be less than $5 \cdot 10^{-7}$ m/s. The measured conductivity is much lower than the expected hydraulic conductivity of a damage zone with incomplete confinement, which is estimated to be approximately $1 \cdot 10^{-4}$ m/s /Neretnieks and Andersson 2009/.

No interference was detected between the water injection holes penetrating heating hole KQ0046G03. This indicates that the thermal spalling has not produced a continuous hydraulic zone along the heating borehole with confinement provided by LECA filling, which is a promising observation.

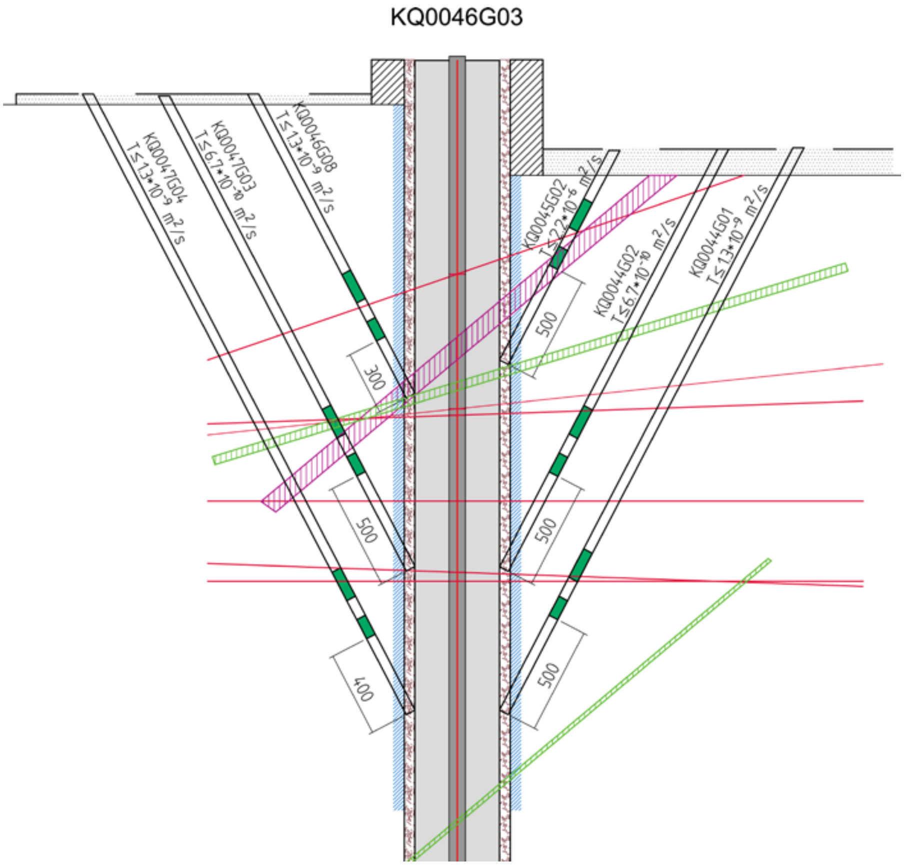


Figure 2-6. *Stationary transmissivity evaluated for the borehole sections indicated on the drawing. The higher transmissivity ($2 \cdot 10^{-6}$ m^2/s), that was measured in the shortest most shallow drill hole, was judged to be a result of faulty sealing in the contact between the rock and the pellet filling.*

3 Natural barriers

3.1 General

To meet Stage goal 3 (see Section 1.2), experiments at Äspö HRL are performed at conditions that are expected to prevail at repository depth to further develop and test methods and models for description of groundwater flow, radionuclide migration and chemical conditions.

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

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

During 2009, the ongoing experiments and projects within Natural barriers were:

- Tracer Retention Understanding Experiments.
- Long Term Sorption Diffusion Experiment.
- Colloid Transport Project.
- Microbe Projects.
- Matrix Fluid Chemistry Continuation.
- Padamot.
- Fe-oxides in fractures.
- Swiw-tests with Synthetic Groundwater.
- Task Force on Modelling of Groundwater Flow and Transport of Solutes.
- Äspö Model for Radionuclide Sorption.

3.2 Tracer Retention Understanding Experiments

A programme has been defined for tracer tests at different experimental scales, the so-called Tracer Retention Understanding Experiments (TRUE). The overall objective of the defined experiments is to increase the understanding of the processes which govern retention of radionuclides transported in crystalline rock, and to increase the credibility in models used for analyses of radionuclide transport in safety assessments.

The TRUE experiments should achieve the following general objectives:

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

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

Experimental concept

The basic idea is to perform a series of in situ tracer tests with progressively increasing complexity. In principle, each tracer experiment will consist of a cycle of activities beginning with geological characterisation of the selected site, followed by hydraulic and tracer tests. An option is to characterise the tested pore space and analyse tracer fixation using epoxy resin injection. Subsequently, the tested rock volume will be excavated and analysed with regards to flow-path geometry and tracer concentration.

Together with supporting laboratory studies of diffusion and sorption characteristics made on core samples, the results of the in situ tests will provide a basis for integrating data on different scales, and testing of modelling capabilities for radionuclide transport up to a 100 m scale, see Figure 3-1. The integration and modelling of data from different length scales and assessments of effects of longer time perspectives, partly based on TRUE experimental results, was made as part of Task 6 in the Task Force on Modelling of Groundwater Flow and Transport of Solutes /Gustafson et al. 2009/.

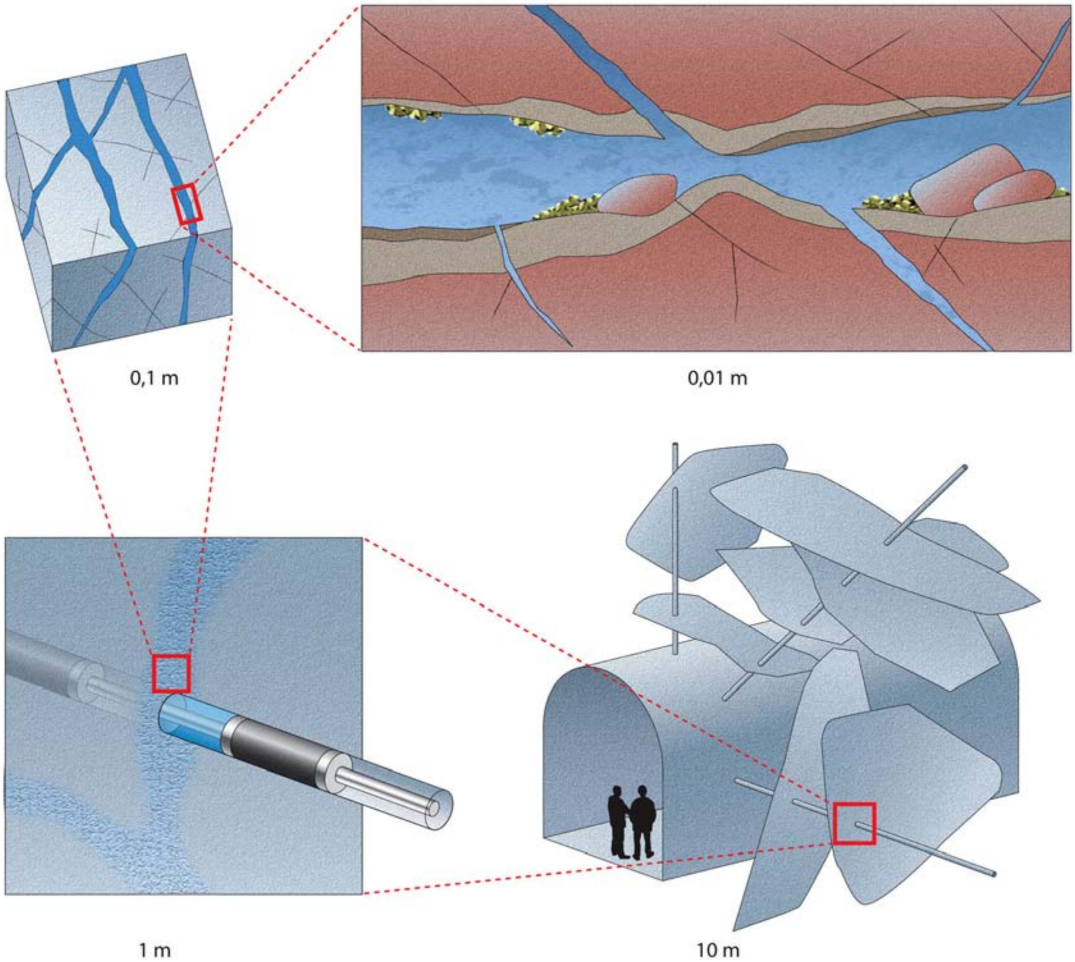


***Figure 3-1.** Schematic representation of transport scales addressed in the TRUE programme.*

3.2.1 TRUE Block Scale Continuation

The TRUE Block Scale Continuation (BS2) project had its main focus on the existing TRUE Block Scale site. Work performed included in situ tracer tests with sorbing tracers and subsequent assessment of the relative retention in flow paths made up of fault rock zones and background fractures. Results verified lower retention material properties in the background fractures flow path but also showed a higher overall retention in this flow path owing to the much lower flow rate therein /Andersson et al. 2007/. In the aftermath to the BS2 project, a second step of the continuation of the TRUE Block Scale (BS3) was set up. This step has no specific experimental components and emphasises consolidation, integrated evaluation and presentation of all relevant TRUE data and findings collected so far, and reporting in the scientific literature.

Objectives

This work aims to account for the TRUE Block Scale and TRUE Block Scale experimental and modelling in a series of peer-reviewed scientific papers. A further aim is to produce a few peer-reviewed papers to be published in high-ranked scientific journals.

Results

During 2009 the two papers evaluating and exploring macro-scale flow-field related constraints for the evaluation of tracer tests performed in the TRUE Block Scale rock volume, using fracture network simulations, have been completed /Cvetkovic et al. 2010, Cvetkovic and Frampton 2010/. A third paper, providing an assessment of the role of enhanced porosity in the rock wall immediately adjacent to the fracture applicable both to detailed and block scales, has also been completed /Cvetkovic 2010a/. The principal endeavour during 2009 is the development of a draft of a TRUE synthesis paper directed to a high-ranked scientific journal. This draft paper is seconded by a supporting paper elucidating the ability of the TRUE experiments to provide firm evidence of in situ diffusion-controlled retention at multiple scales, see below.

Evidences for diffusion-controlled retention

Analyses of the equilibrium sorption and diffusion-controlled retention models relative to the array of TRUE tracer results is presented in a paper submitted to Geophysical Research Letters /Cvetkovic 2010b/. The analyses is made by employing two portable and robust measures of retention; the normalised peak arrival time (t_p/τ) and the dimensionless fractional arrival time measures θ_I, θ_{II} and θ_{III}, see Figure 3-2. The comparison in the figure of model and data, taking advantage of the large span in Kd* (=Kd·ρ) in the TRUE test data, shows that for $\theta > 10$ (corresponding to higher Kd*) the diffusion-controlled model correlates reasonably well with the data, whereas the correlation of the equilibrium model to data is significantly weaker.

Extrapolating TRUE findings to application time scales

An additional step includes an attempt to hypothetically extrapolate the TRUE experimental spatial scales and experimental conditions to the transport and retention of actinides, with an almost two orders of magnitude higher Kd* compared to the TRUE tracer inventory. Assessment of barrier efficiency shows that use of the equilibrium model would entail a significant underestimation of the barrier function of the rock formation.

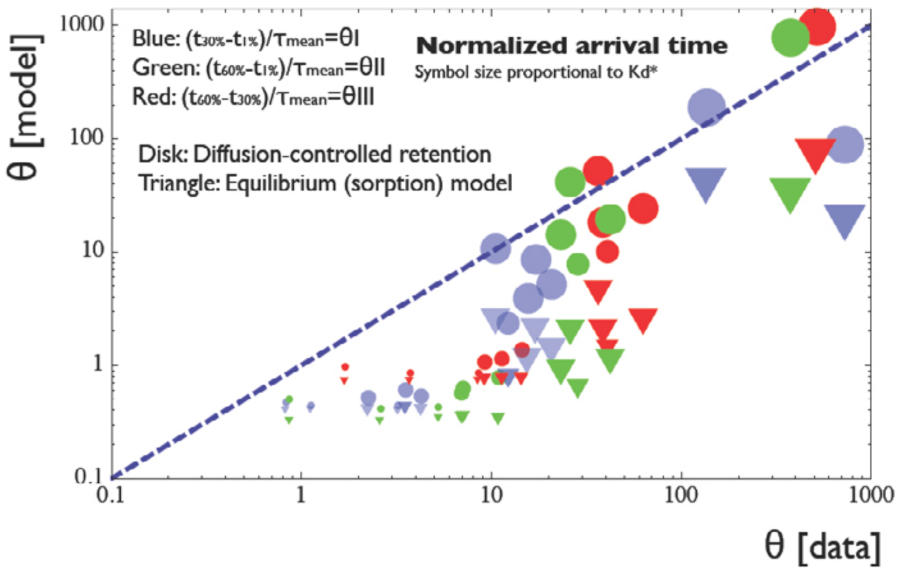


Figure 3-2. Correlation between model and experimental data, for the relative fractional measures θ [θI, θII, θIII], the values assigned largest blue symbols (for θ_I of Cs) are most affected by the hydrodynamic transport, compared to θ_{II} and in particular θ_{III} . For θ, the estimated mean water residence time is used for normalisation. Modified after /Cvetkovic 2010b/.

3.2.2 TRUE-1 Continuation

The TRUE-1 Continuation project is an extension of the TRUE-1 experiments, and the experimental focus is primarily on experimental activities related to the TRUE-1 site and Feature A in particular. The continuation work includes injection of epoxy resin in Feature A at the TRUE-1 site and subsequent overcoring and analysis (TRUE-1 Completion, see Section 3.2.3). Additional activities include: (a) test of the developed epoxy resin technology to fault rock zones distributed in the access tunnel of the Äspö HRL (Fault Rock Zones Characterisation project), (b) laboratory sorption experiments for the purpose of establishing Kd-values for altered wall rock (rim zone) and fault gouge, (c) writing of scientific papers relating to the TRUE-1 project.

Objectives

The objectives of TRUE-1 Continuation are to:

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

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

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

Results

The principal achievement is the progress made within the TRUE-1 Completion project, see below. Furthermore, within the Fault Rock Zones Characterisation project, the report presenting the results of the image analysis of the epoxy resin injection in fault rock zones /Hakami and Wang 2005/ has been published, to be followed by finalisation of the associated final report early 2010. Similarly, experimental work related to the laboratory sorption work on rim zone and fault gouge has been finalised and worked in to the report being prepared. However, inclusion of results of additional experimental work linking the results more firmly to those established during the site investigations will delay the reporting until March 2010. The above mentioned scientific papers on TRUE-1 were published in 2007.

3.2.3 TRUE-1 Completion

TRUE-1 Completion is a sub-project of the TRUE-1 Continuation project and is a complement to already performed and ongoing projects. The main activity within TRUE 1 Completion was the injection of epoxy with subsequent overcoring of the fracture and following analyses of pore structure and, if possible, identification of sorption sites. Furthermore, several complementary in situ experiments were performed prior to the epoxy injection. These tests were aimed to secure important information from Feature A, and the TRUE-1 site before the destruction of the site.

Objectives

The general objectives of TRUE-1 Completion are to:

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

Experimental concept

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

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

Results

In January 2009 a reference group meeting was held with the purpose of discussing the analysis plan of the cores from KXTT3 and KXTT4 in relation to the project budget. In order to agree with the project means it was decided that the analyses should focus on the target structure Feature A in KXTT4 and that the amount of analyses for Feature A' in KXTT4 and Feature A in KXTT3 should be reduced.

The analyses of the cores from KXTT3 and KXTT4 were in general carried out according to the activity plan updated after the reference group meeting. The analyses and reporting will be finalised during 2010. The most important preliminary results from 2009 are:

- Epoxy from the previous injection was found in the fractures that had been classified as open in previous characterisations of the 56 mm boreholes but also in some other fractures. This may indicate a more complex system of open fractures within the borehole intervals than previous interpretations.
- Radioactive cesium is heterogeneously distributed in Feature A in KXTT4 with higher concentrations close to the injection borehole but also in the expected flow direction towards KXTT3.
- Radioactive cesium in Feature A' in KXTT4 is found close to the injection borehole.
- Some parts of Feature A in KXTT4 includes only low levels of radioactivity. This may open up for additional mineral analyses compared to the original plan.
- The character of the main fracture of Feature A in KXTT3 and KXTT4 is rather similar according to image analysis.
- There is a rather substantial difference between the character of Feature A and A' according to image analysis.

3.3 Long Term Sorption Diffusion Experiment

Background

The Long Term Sorption Diffusion Experiment (LTDE-SD) 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 at Äspö. The difference is the longer duration (approximately 6 months), the absence of advective flow and the well controlled geometry of the experiment. Matrix diffusion and sorption studies are usually performed in laboratory 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 sorption and rock matrix diffusion at 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 and sorption in non-disturbed rock is therefore preferably investigated in situ.

Objectives

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

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

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 is circulated in the test section for a period of 6 ½ months after which the core stub is over-cored and analysed for tracer content and tracer fixation.

The experiment is focussed on a typical conductive fracture identified in a pilot borehole (KA3065A02). A telescoped large diameter borehole (300/197 mm) (KA3065A03) is drilled sub-parallel to the pilot borehole in such a way that it intercepts the identified fracture some 10 m from the tunnel wall and with an approximate separation of 0.3 m between the mantel surfaces of the two boreholes.

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, see Figure 3-3. The remainder of the borehole is 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 in matrix rock that is exposed for the tracers. The system of packers and the pressure regulating system is used to eliminate hydraulic gradient along the borehole.

During circulation of the tracer labelled groundwater the decreasing tracer concentration, resulting from sorption and diffusion, is followed by analysing water samples collected at various times over the duration of the experiment. On-line measurements by HPGe is also used for a continuously follow up of the γ-emitting tracers. The temperature, pH and Eh are monitored continuously with a flow through electrochemical cell. After completion of tracer circulation, the rock surrounding the core stub and the test section in the matrix rock is retrieved by large diameter (300 mm) over-coring. Sample cores (24 mm diameter) are extracted from the fracture surface on the core stub and from the matrix rock surrounding the test section in the small diameter extension borehole. The sample cores are sectioned into thin slices and analysed for radionuclide tracer content.

The project also involves laboratory experiments using the core material from the pilot borehole and the experimental borehole KA3065A03 (Ø 277, 177 and 22 mm) and the fracture "replica" material. Both batch sorption and through diffusion experiments are included.

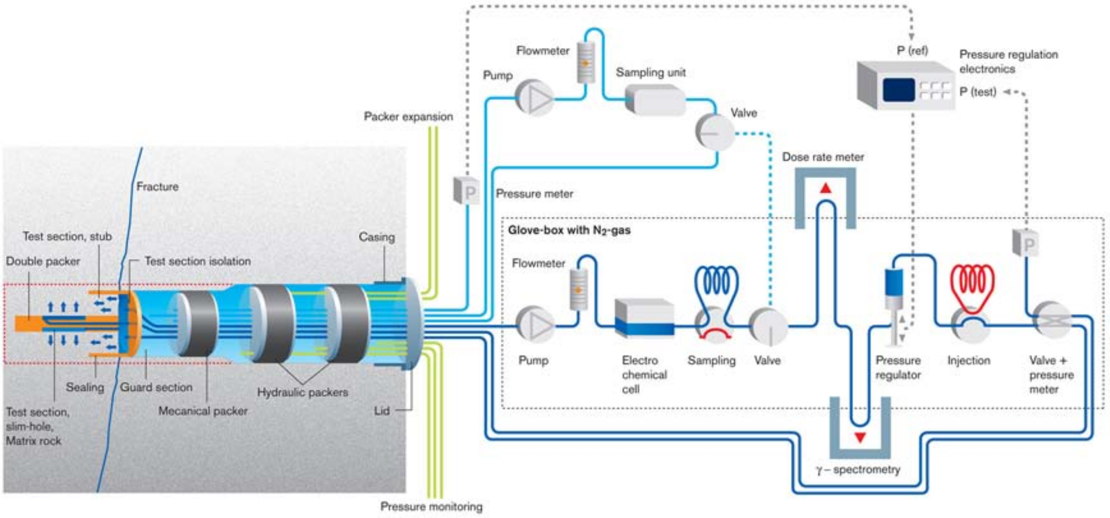


Figure 3-3. *LTDE-SD experimental set-up in the experimental borehole KA3065A03 including the hydraulic pressure control system and the water circulation system for the test-section in front of natural fracture and in matrix rock.*

Results

The crushed and intact rock slices selected for analysis have been measured by HPGe for γ-emitting tracers. The tracers mainly sorbed by surface complexation, e.g. ^{57}Co, ^{109}Cd, ^{100m}Ag, and ^{153}Gd are sorbed within the depth of the first millimetre slice, both on the fracture surface and on the pure matrix rock.

A method for nickel separation in dissolved rock core samples has been developed and the method has been adopted on crushed and dissolved rock slices extracted from fracture surface on the core stub and on samples extracted from the matrix rock. Preliminary results from the subsequent analysis of ^{63}Ni, using liquid scintillation (LSC) indicates a strong surface sorption and penetration depth within a few millimetres.

Crushed and intact rock slices have been leached, followed by separations on the leachate and subsequent analysis of ^{36}Cl, using LSC. Penetration depths of about 6 centimetres have been observed.

The laboratory experiments with specimen from the core of the small diameter extension borehole, the replica core stub and the pilot borehole core were, after prolongation, finalised in late April. The experiments included batch sorption tests on crushed material (three particle size fractions) and sorption/diffusion tests on intact drill core samples. The same tracer cocktail as for the in situ experiment, with HTO added, was used. Some completing sampling and tracer analysis have been done and is ongoing, as well as evaluation of the resulting data. The relative sorption strength obtained from the laboratory tests on intact drill core samples seems to be the same as in the in situ experiment for the tracers used.

3.4 Colloid Transport Project

Background

The overall goal for the Colloid Transport Project is to identify when in the life time of the repository colloid transport can play a role, and what type of colloids are involved. The aim is also to quantify the impact of colloids on radionuclide transport. In the beginning of the lifetime of a deep repository, in bedrock with groundwater of high ionic strength, montmorillonite and natural colloids are not stable wherefore colloid transport can be neglected. If dilute groundwater from a melting ice reaches the repository depth with high flows, montmorillonite colloids may be generated from the bentonite buffer. If large amounts of montmorillonite colloids are transported away from the buffer, the functionality of the buffer will be endangered. In addition, colloids can possibly facilitate the transport of sorbed radionuclide towards the biosphere. If montmorillonite colloids are generated from the buffer, and are stable, the transport will be the limiting factor.

The Colloid Transport Project was initiated 2008 and will be finalised in 2010. The project is in the Colloid Formation and Migration (CFM) collaboration and in situ experiments are performed at the Grimsel Test Site in Switzerland. A large in situ experiment to study montmorillonite generation from the bentonite barrier is under planning with the partners in the collaboration. An extensive amount of experimental work is undertaken, at laboratories of all the collaborators, to optimise the in situ experiment. In Sweden colloid stability and colloid sorption tests under varying conditions are performed, as well as colloidal characterisations in the laboratory. Transport experiments in fracture filling material are performed to try to quantify the retardation mechanisms of colloids during transport. Modelling efforts are ongoing, now with the aim to separate the retention into the physical and chemical process such as filtration, sorption and sedimentation.

Objectives

The objectives in the project are to:

- Determine under which conditions montmorillonite colloids are generated from the bentonite buffer, in what concentrations, and to understand the mechanisms behind the generation.
- Determine the structure of montmorillonite colloids equilibrated in different waters.
- Determine at what groundwater conditions montmorillonite colloids as well as natural colloids are stable.
- Study colloid transport in different types of fractures and in different types of waters to understand the impact of fracture characteristics (e.g. aperture distribution, mineral surfaces and filling minerals) and colloid properties (e.g. size distribution, surface charge density and structure).
- Study the impact of the presence of montmorillonite and humic colloids on actinide transport in water bearing fractures.
- Develop models for colloid transport in water bearing fractures to be able to predict colloid transport in any fracture with different aperture distributions, fracture surface roughness and mineral composition, with montmorillonite as well as natural colloids with varying structures, surface potentials and size distributions.

Experimental concept

Generation experiments are performed in synthetic Plexiglas fractures (horizontal or inclined) at AECL in Canada. The compacted bentonite plugs are exposed for flowing water with varying chemistry and the colloid concentration is measured downstream the bentonite plugs.

The geometry and structure of montmorillonite colloids are measured at the Swiss Light Source with X-Ray Microspectroscopy.

Stability experiments with montmorillonite colloids are performed in sedimentation and generation experiments where the colloid concentration above the sedimented colloid bed is monitored with a Single Particle Counter or with Photon Correlation Spectroscopy. Stability experiments are now performed to determine the effect of irradiation on the colloids ability to stay in solution.

Colloid transport experiments are performed in clean fractures as well as in fractures filled with minerals to find retardation mechanisms such as sorption and filtration.

Actinide transport experiments are performed in well defined bore cores from Äspö to quantify the effect of the presence of inorganic material and colloids on the actinide transport at oxidising and reducing conditions.

Results

The geometry of Ca-montmorillonite colloids equilibrated for a year was analysed with X-ray microspectroscopy. The images show that the colloids are spherical or ellipsoidical and have regions of lower and higher density in the structure. The interpretation is that the particles are aggregates of flexible montmorillonite flakes which are surrounded by gel. This result justifies that it is reasonable to assume spherical and not planar geometry in modelling /Degueldre et al. 2009/.

Sedimentation and generation experiments give the same pseudo-equilibrium concentrations above the colloid bed whereas both type of experiments can be used to achieve values for the montmorillonite colloid concentration outside the bentonite buffer under different conditions. In a dilute groundwater (0.001 M ionic strength and pH 9), the concentration of colloids outside the bed will be in the range of 10 mg/L /García-García et al. 2009a/.

The impact of temperature and γ-irradiation on montmorillonite colloid stability has been studied. Unexpectedly, montmorillonite colloid stability is enhanced in higher temperatures, in dilute water (0.001M) and at pH around 9. Further, the stability is enhanced after exposure of γ-irradiation, however the reason for this is not yet explained and the work is still ongoing /García-García et al. 2009b, Holmboe et al. 2009/.

Transport experiments of montmorillonite and latex colloids in a fracture in granite block in a variety of conditions showed for example that the transport of montmorillonite and latex colloids is very similar as long as the flow rate is not extremely low. Divergences start to appear when the interaction time of the colloids in the system is longer. Differences in for example structure can then start to show up /Vilks and Miller 2009/. All the experimental data have been used for modelling, and the retention in the transport can be attributed to an irreversible and reversible attachment during the time for the experiments /Cheng and Cvetkovic 2009/.

Sorption and transport experiments with latex and montmorillonite colloids show that colloid sorption to mineral surfaces is significant even in unfavourable conditions. In transport in fractures filled with minerals, smaller colloids take a longer time to breakthrough than larger colloids.

The bentonite swelling and gel propagation tests in the synthetic Plexiglas fracture have given a lot of data concerning the differences in different bentonite types in contact with different waters and the impact of flow rate and inclination of the fracture. The most important results are:

- Even a small amount of salt in the water (0.001 M) holds back the gel propagation and further the colloid release.
- Gravity plays an important role and colloid release will be increased in an inclined fracture. However, released colloids seem to clog the system preventing colloids to be transported in this direction.

3.5 Microbe Projects

Microbial processes

Microorganisms interact with their surroundings and in some cases they greatly modify the characteristics of their environment. Several such interactions may have a significant influence on the function of a future deep repository for spent fuel /Pedersen 2002/. The study of microbial processes in the laboratory gives valuable contributions to our knowledge about microbial processes in repository environments. However, the concepts suggested by laboratory studies must be tested in a repository like environment. The reasons are several. Firstly, at repository depth, the hydrostatic pressure reaches close to 50 bars, a setting that is very difficult to reproduce in the microbiology laboratory. The high pressure will influence chemical equilibriums and the content of dissolved gases. Secondly, the geochemical environment of deep groundwater, on which microbial life depends and influence, 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 /Hallbeck and Pedersen 2008a, Pedersen et al. 2008/.

The university laboratory is best suited for pure cultures and therefore the effect from consortia of many participating species in natural ecosystems cannot easily be investigated there. The limitations of university laboratory investigations arrayed above have resulted in the construction and set-up of an underground laboratory in the Äspö HRL tunnel. The site is denoted the Microbe laboratory /Pedersen 2000/. During 2009–2010 research on microbial effects on the chemical stability of deep groundwater environments is ongoing in the Microbe laboratory.

The Microbe laboratory

The Microbe laboratory is situated at the –450 m level in the F-tunnel. A laboratory container has been installed with laboratory benches and a climate control system. Three core drilled boreholes, KJ0050F01, KJ0052F01 and KJ0052F03, intersect water conducting fractures at 12.7, 43.5 and 9.3 m, respectively. They are connected to the Microbe Laboratory via 1/8" PEEK tubing. The boreholes are equipped with metal free packer systems that allow controlled circulation of groundwater via respective fracture. Each borehole has been equipped with two circulation systems offering a total of 2,112 cm^2 of test surface in each circulation flow cell set up (four flow cells) for biofilm formation at in situ pressure, temperature and chemistry conditions. One system is metal free and one system is made of stainless steel (Figure 3-4). The systems operate at pressures around 25 bars. The flow

Figure 3-4. Three of the circulation systems in the Microbe laboratory.

through the flow cells is adjusted to 25–30 ml per minute, which corresponds to a flow rate over the surfaces of about 1 mm per second. Temperature is controlled and kept close to the in situ temperature at around 15–16°C. Remote alarms and a survey system have been installed for high/low pressure, flow rate and temperature. A detailed description of the Microbe laboratory can be found in /Pedersen 2005a/ and as original work published in scientific papers /Nielsen et al. 2006, Hallbeck and Pedersen 2008a/.

3.5.1 Micored

Background and objectives

Microorganisms can have an important influence on the chemical situation in groundwater. Especially, they may execute reactions that stabilise the redox potential in groundwater at a low and, therefore, beneficial level for the repository /Haveman and Pedersen 2002/. It is hypothesised that hydrogen from deep geological processes contributes to the redox stability of deep groundwater via microbial turnover of this gas. Hydrogen, and possibly also carbon mono-oxide and methane energy metabolisms will generate secondary metabolites such as ferrous iron, sulphide, acetate and complex organic carbon compounds. These species buffer towards a low redox potential and will help to reduce possibly introduced oxygen /Banwart et al. 1996/. The circulations in the Microbe laboratory have microbial populations that are reproducible in numbers and species distribution over time under stable hydrological conditions /Pedersen 2005b/. All groups execute influence on the redox situation. Anaerobic microbial ecosystems generally force the redox potential towards the range of redox in which they are active. Iron and manganese reducing bacteria are active at higher redox potentials (approximately –100 to –200 mV) than the methanogens and acetogens (approximately –300 to –400 mV). Sulphate reducing bacteria are most active between the optimal redox potentials for those groups (approximately –200 to –300 mV). The stable populations of sulphate reducing bacteria and methanogens and acetogens at the Microbe laboratory makes it very well suited for research on the influence of microorganisms on the evolution and stability of redox potential in groundwater.

The major objectives for the Micored project are to:

- Clarify the contribution from microorganisms to stable and low redox potentials in near-and far-field groundwater.
- Demonstrate and quantify the ability of microorganisms to consume oxygen in the near-and far-field areas.
- Explore the relation between content and distribution of gas and microorganisms in deep groundwater.

Results

The influence of microorganisms on redox potential has been studied. Investigations of the effect from drainage of a borehole on microbes and dissolved sulphide and ferrous iron were performed. It was found that the number of sulphate reducing bacteria was positively correlated with the concentration of sulphide and negatively with redox potential. During the site investigations for a nuclear waste repository in Forsmark and Laxemar, significant correlations have been found between the measured redox with the so called Chemmac redox electrodes and the number of sulphate reducing bacteria and the concentration of manganese /Hallbeck and Pedersen 2008b, c/. The results demonstrate that the measurement of the concentration of single variables such as sulphide or manganese will not allow indication of the redox state of a natural system. Rather than focus on a single parameter, it will be more meaningful to analyse reactants such as the sulphide, sulphate, organic carbon and hydrogen and their biological turnover rates. Such work is now being performed in the Microbe Laboratory under controlled conditions.

3.5.2 Micomig

Background and objectives

It is well known that microbes can mobilise trace elements /Pedersen 2002/. Firstly, unattached microbes may act as large colloids, transporting radionuclides on their cell surfaces with the groundwater flow /Pedersen and Albinsson 1991, 1992/. Secondly, microbes are known to produce ligands that can mobilise soluble trace elements and that can inhibit trace element sorption to solid phases /Johnsson et al. 2006, Essén et al. 2007, Moll et al. 2008a, b/. A large group of microbes catalyse the formation of iron oxides from dissolved ferrous iron in groundwater that reaches an oxidising environment /Ferris et al. 1999, 2000/. Such biological iron oxide systems (Bios) will have a retardation effect on many radionuclides. Typically, microbes form stalks and sheaths that increase the volume of the iron oxides from densely packed inorganic oxides to a fluffy, rust-like material with water contents of up to 99%. The microbes contribute to the exposure of a large oxide area to trace elements flowing by with the groundwater and the organic biological material adds a strong retention capacity in addition to iron oxides /Anderson and Pedersen 2003, Anderson et al. 2006c/.

Biofilms in aquifers will influence the retention processes of radionuclides in groundwater. Work by Anderson et al. /2006a, b/ indicates that these surfaces adsorb up to 50% of the radionuclides in natural conditions with Ka (m) approaching 10^5 and 10^6 for Co and Pm respectively. The formation of colloids accounted for a further 20% to 40% of aqueous Co and Pm complexation. The anaerobic biofilms and rock surfaces share similar adsorption capacities for Pm but not for Co. The biofilms seemed to isolate the rock surface from the groundwater as diffusion to the rock surface must first proceed through the biofilms. The possible suppression of adsorption by biofilms needs further research.

The major objectives for the Micomig project are to:

- Evaluate the influence from microbial complexing agents on radionuclide migration.
- Explore the influence of microbial biofilms on radionuclide sorption and matrix diffusion.

Results

Viruses that attack bacteria, so called phages, were earlier found to be ten-fold more abundant than prokaryotes in deep granitic groundwater at Äspö HRL /Kyle et al. 2008/. This result suggested that phages may play an important role in the control of microbial abundance and activity and the influence of phages on sulphate reducing bacteria was investigated in detail. Using a most probable number method, 8–30,000 cells of sulphate-reducing bacteria per mL were found in groundwater from seven boreholes at the Äspö HRL. The content of lytic phages infecting the indigenous bacterium *Desulfovibrio aespoeensis* in Äspö groundwater was analysed using a most probable number technique for phages. In four of ten boreholes, 0.280 phages per mL were found at depths of 342–450 m. Isolates of lytic phages were made from five cultures. Using transmission electron microscopy, these were characterised and found to be in the *Podoviridae* morphology group. The isolated phages were further analysed regarding host range, and were found not to infect five other species of *Desulfovibrio* or ten *Desulfovibrio* isolates with up to 99.9% 16S rRNA gene sequence identity to *D. aespoeensis*. To further analyse phage–host interactions, using a direct count method, growth of the phages and their host was followed in batch cultures, and the viral burst size was calculated to be approximately 170 phages per lytic event, after a latent period of approximately 70 h. When surviving cells from infected *D. aespoeensis* batch cultures were inoculated into new cultures and reinfected, immunity to the phages was found. The parasite–prey system found implies that viruses are important for microbial ecosystem diversity and activity and for microbial numbers in deep subsurface groundwater. It is possible that phages mitigate sulphate reduction to sulphide, thereby reducing the rate of copper corrosion by sulphide from groundwater, see Figure 3-5.

In a recent study, six drill cores were retrieved from the Äspö HRL tunnel from a depth of 186 m below ground. Fracture surface materials (FSM) were sampled from the intersected, water conducting fractures from the 186 m site and nucleic acids were collected by DNA extraction. PCR primers for amplification of a conserved stretch of the 16S rRNA gene were used to analyse diversity of fracture surface biofilm DNA with cloning and sequencing. Primers for real time, quantitative PCR were designed and optimised for biomass quantification using 16S rRNA genes for domain *Bacteria*

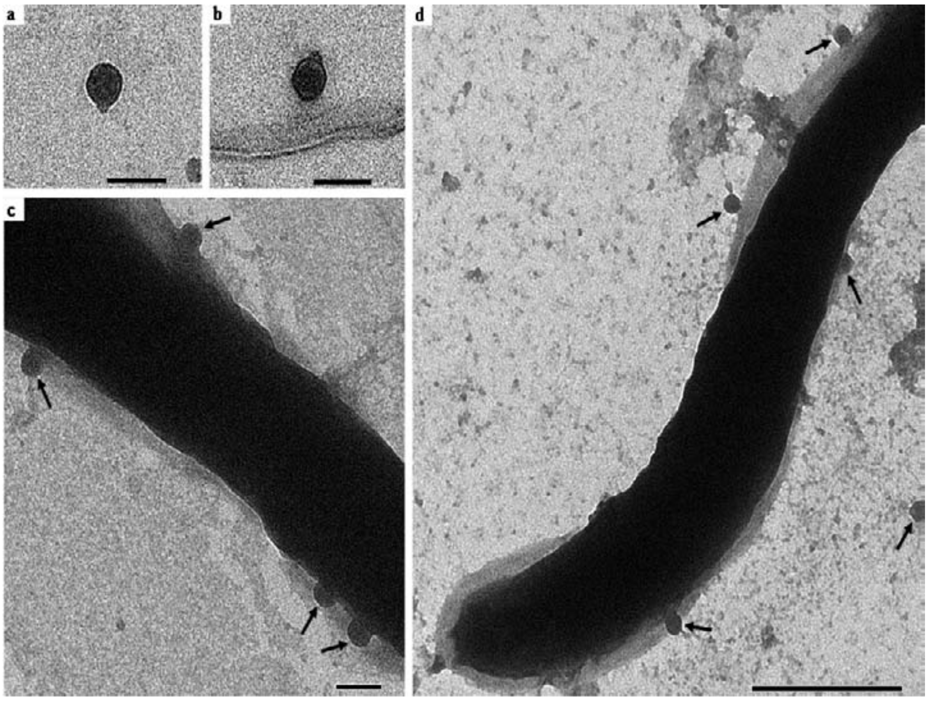


Figure 3-5. *The morphologies of phages isolated from deep groundwater lytic to Desulfovibrio aespoeensis growing in a medium for sulphate-reducing bacteria are shown in transmission electron micrographs a and b. Images c and d show phages (arrows) at the surface of a bacterium. Images were taken using 70,000 × magnification in a–c and 45,000 × magnification in d. Images a and b are from phage isolate HEy5, c from isolate HEy4, and d from isolate HEy2. The scale bar is 100 nm in a–c and 500 nm in d.*

and for quantification of sulphate reducing bacteria (SRB) using adenosine-phosphosulphate reductase genes (*apsA*). The results from analysis of intrinsic biofilms on rock aquifer surfaces were compared to results from similar analyses of biofilms on glass surfaces in laminar flow reactors (LFR) installed with circulating groundwater from 450 m depth in the Microbe Laboratory. The experimental objectives with these reactors were to investigate the influence of hydrogen and acetate additions on redox potential, biofilm diversity and activity. Sequences belonging to the deltaproteobacteria *Desulfovibrio, Desulphorphalus, Desulfomicrobium* and *Desulfobulbus* dominated the clones from the Microbe Laboratory (43.4%) and alphaproteobacteria (31.6%) were also common among the biofilm forming bacteria found at the Microbe site. However, in the natural FSM, 50% of the clones could be assigned to sequences closest related to gammaproteobacteria, mostly *Stenotrophomonas maltophilia*, 18.3% were closest related to the epsilonproteobacteria and 12.5% to the genus *Desulfobulbus*. The diversity shifted from mostly epsilonproteobacterial sequences at shallow positions inside the natural fracture towards more deltaproteobacterial sequences deeper inside the fracture, relative to the tunnel face. Some strains were found in several systems from the two different sites LFR and FSM but none of these strains were found in both systems. These results imply a broad diversity between biofilms detected in the LFR respectively FSM clones and between different positions in the natural fracture supporting the idea of LFR as a first rough estimation about the diversity of biofilms in natural fractures in the deep biosphere. Biofilms appear to be present on surfaces in natural water conducting aquifers which can have implications for radionuclide mobility, and precipitation and dissolution processes.

3.6 Matrix Fluid Chemistry Continuation

Background and Objectives

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

The continuation phase (2004–2006) focussed on the remaining areas of uncertainty:

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

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

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

Experimental concept

The first phase of the Matrix Fluid Chemistry Experiment was designed to sample matrix porewater 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 ongoing experiments at Äspö HRL.

Special downhole equipment (Figure 3-6) was constructed ensuring: (a) an anaerobic environment, (b) minimal contamination from the installation, (c) minimal dead space in the sample section, (d) the possibility to control the hydraulic head differential between the sampling section and the surrounding bedrock, (e) in-line monitoring of electrical conductivity and drilling water content, (f) the collection of porewaters (and gases) under pressure and (g) convenient sample holder to facilitate rapid transport to the laboratory for analysis.

This experimental equipment, with some modifications, was used in the continuation phase from 2005-11-28 through to 2006-08-11 to sample groundwater from the microfractures and to measure the hydraulic parameters of the microfractures and the rock matrix.

Results

Due to other priorities, the final reporting and integration of the Matrix Fluid Chemistry Continuation phase of the Matrix Fluid Chemistry experiment was not completed during 2009. This will instead be realised in 2011.

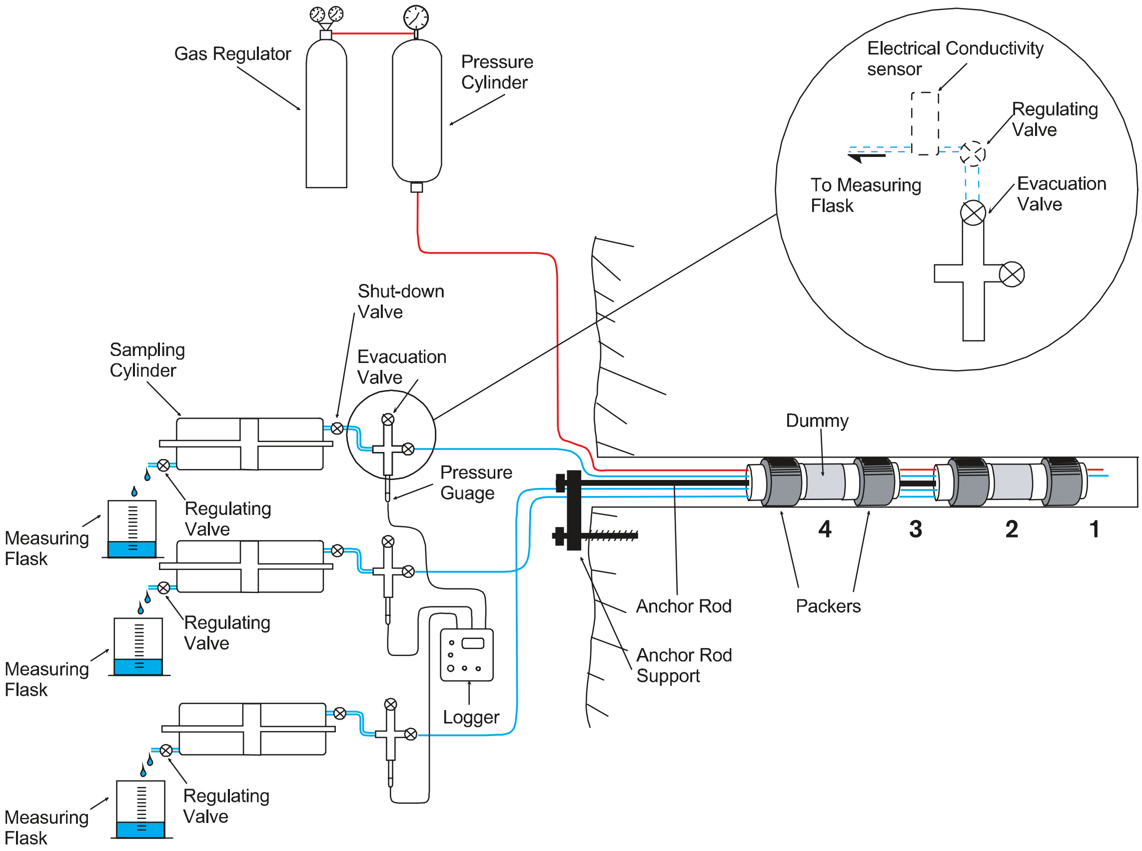


Figure 3-6. *Matrix Fluid Chemistry experimental set-up. Borehole sections 2 and 4 were selected to collect matrix fluid and sections 1–4 were continuously monitored for pressure.*

3.7 Radionuclide Retention Experiments

Radionuclide Retention Experiments are carried out with the aim to confirm results of laboratory studies in situ, where natural conditions prevail concerning e.g. redox conditions, contents of colloids, organic matter and bacteria in the groundwater. The experiments are carried out in special borehole laboratories, Chemlab 1 and Chemlab 2, designed for different kinds of in situ experiments. The laboratories are installed in boreholes and experiments can be carried out on for instance bentonite samples and on tiny rock fractures in drill cores.

3.7.1 Spent Fuel Leaching

Background and Objectives

The dissolution rate for spent nuclear fuel (i.e. mostly uranium dioxide) determines the release rate of radionuclides from a deep geological storage of spent nuclear fuel, since all fission products and actinides are incorporated in the uranium dioxide matrix. The dissolution rate has been investigated in a number of studies under oxic as well as anoxic conditions. The probably most interesting observation made is that the dissolution rates of spent fuel in flow-through tests with $H_2(g)$ saturated solutions decreased by up to four orders of magnitude as compared to oxidising conditions dissolution rates.

The aim of the Spent Fuel Leaching project is to determine the dissolution rate of uranium dioxide when using natural groundwater.

Experimental concept

The experiments are planned to be performed in three different set-ups. One will be in the Chemlab 2 probe where only groundwater will be used. Another will be performed in a glove box in the gallery close to the Chemlab 2 borehole, using natural groundwater from the borehole. In the glove box set-up H_2 will be added to the water used. To simplify the radiologic handling, α-doped uranium dioxide will be used in the CHEMLAB-2 experiment. α-doped uranium dioxide will give the same α-dose as that of 80,000 years old spent nuclear fuel, while most γ-radiation is avoided.

Results

The planning of the project is still ongoing.

3.7.2 Transport Resistance at the Buffer Rock Interface

Background and Objectives

The transport resistance is concentrated to the interface between bentonite and fracture. /Neretnieks 1982/ has estimated that only 6% of the mass transfer resistance is due to diffusional resistance in the backfill and 94% is due to the diffusive resistance in the small cross section area of the fissures in the bedrock. Q-equivalent is a concept often used in safety assessment scoping calculations. The concept assumes that at some steady-state condition a certain flow will carry a certain amount of species. Not many experiments have been performed to validate the Q-equivalent concept.

The aims of the Transport Resistance at Buffer-Rock Interface project are to: (1) experimentally verify that the concept of Q-equivalents is relevant and (2) perform studies to estimate the magnitude of the transport resistance at the buffer-rock interface.

Experimental concept

The experiments will mainly be performed in the same artificial fracture that was used in the Bentonite Erosion project /Jansson 2009/.

Results

Tests to find a suitable tracer have been performed. The tracer shall have low solubility so that the concentration at the tracer container is constant without disturbing the tracer. In addition, the solubility shall be sufficient to allow detection, preferably by the bare eye.

The tracer that has been selected is fluorescein, which has low solubility (80 mg/100 ml). The tracer has a yellow colour, which turns green under UV-light and is fluorescent with a very high extinction coefficient (68,000 M^{-1} cm^{-1}), which enables detection of very low concentrations using fluorescence spectroscopy. Solubility studies have been performed and calibration curves have been produced, both for UV-VIS spectroscopy as well as fluorescence spectroscopy.

Flow rates for the experiments have been performed and different designs of how and in what form the tracer shall have in the tracer container has been discussed and tested.

3.8 Padamot

Background

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

A continuation of the Swedish part of the project at Äspö has thereafter been agreed by SKB. This has been called Padamot Continuation and is focused on the use of uranium series analyses in order to give time and space constraints on redox processes in the bedrock aquifer. One of the most important criteria to ensure the long-term stability of a deep geological radioactive waste disposal system is maintenance of reducing hydrochemical conditions over the lifespan of the repository and the behaviour of redox sensitive elements (e.g. Fe, U, Ce) under present and past bedrock conditions is therefore of great interest in this context. Of particular relevance is the potential for deep penetration of oxidising, sub-glacial water during periods of glaciation. Uranium, being a redox-sensitive element which occurs naturally in the bedrock and groundwaters can therefore be used, in conjunction with its decay series descendants, to indicate groundwater redox conditions. Not only can contemporary conditions be characterised, but evidence of past changes (e.g. during the last glaciation) can be preserved in minerals which coat the fracture walls along groundwater pathways.

Objectives

The aims of the continuation of the Padamot project are to:

- Test different analytical techniques for uranium series analyses applied on fracture mineral samples and to recommend a methodology to be used in further studies.
- Use these analyses for determination of the redox conditions during glacial and postglacial time.
- Summarise the experiences of palaeohydrogeological studies carried out at Äspö.

Experimental concept

The basic idea has been to sample open fractures from the surface and down to a depth of approximately 150 m in order to get samples typical of various redox conditions. Drillcore KAS 17, transecting the large Mederhult zone, provided excellent material for this study. Six samples from various depth ranging from 19 to 200 m core length were sampled and sieved into different grain sizes and where the most fine grained (usually <0.125 micrometers) fraction was split into three (and if possible four) parts (Figure 3-7). Two for USD analyses at the different laboratories and one for ICP analyses (chemical characterisation). The fourth part was used for XRD diffractometry showing that the sampled material consisted of quartz, K-feldspar, albite, chlorite, calcite and clay minerals of mixed layer clay type. Uranium contents in the samples varied from 6 to 27 ppm.

All six samples were analysed for uranium and thorium content by ICP at ALS Scandinavia AB in Luleå. Bulk uranium series analyses (USD) were applied on all six samples by the Helsinki University, with duplicate analyses carried out on three. In addition, two samples were analysed by SUERC in Scotland. Sequential extraction was applied to four samples by the Helsinki University (2 to 4 steps depending on amount of available sample). SUERC applied sequential extraction on two samples using a similar approach (applying 4 leaching steps). Samples from 19.6 m and 20.38 m (the uppermost samples showing distinct disequilibria) were analysed by both laboratories using both bulk analyses and sequential extraction. In addition, uranium and thorium contents were analysed on these samples by a third laboratory.

Results

The uppermost samples from 19.6, 20.3 and 20.38 m core lengths represent a transition zone with changing redox conditions and thereby a shift from uranium mobilisation to uranium deposition. Only the uppermost sample (19.6 m) indicates uranium mobilisation caused by oxidative leaching. However, this sample also has the highest uranium content (around 25 ppm) suggesting older uranium precipitation (before the last 1 million years). Recent deposition was obvious in sample from 20.38 m whereas sample from 20.3m showed much less influence of recent redistribution, once again underlining the heterogeneity in the bedrock fracture system. The deepest samples, from 156 and 196 m, show activity ratios approaching equilibrium, whereas sample from 102 m shows uranium deposition, considered older than the last deglaciation.

Figure 3-7. Photo of samples from a fracture zone at a depth of 196.55–196.75 m in KAS 17.

It can thus be concluded that the present redox zone is situated in the upper 15 to 20 m (if the core lengths are recalculated to vertical depth), see Figure 3-8. Uranium mobilisation shifts to uranium deposition within a very short distance, depending on changes in groundwater flow and chemistry (maybe annual variations).

The major conclusions from the discussions concerning sampling and the methodology approaches are:

- Drillcore samples are required to study the redistribution of trace elements (in this case uranium) along conductive fractures in the bedrock. Drillcores from triple tube drilling provides the best possible material in that the fracture surface, often comprising friable fracture material, will be, in the best case, undisturbed, or at least to large extent preserved. The subsequent handling of the drillcores is also an important link. During core mapping the drillcores are often wetted with water (repeatedly) to reveal grains and structures and, in the worst case, HCl is applied directly on the fracture surface to test for calcite. To be able to take samples as soon as possible following drilling, and thereafter protect the samples from water, acid and long exposure to the atmosphere, is therefore optimal. A sampling methodology to achieve these requirements is presently ongoing on drill core material from one of the SFR drill cores at Forsmark. These samples have been put in PVC bags which are then flushed with nitrogen and then vacuum sealed directly following drilling. These samples will subsequently be analysed and the sampling method evaluated.
- It was concluded, after comparing the results from the bulk analyses samples with the sequential extraction analyses, that a combination of these methods are optimal for the understanding and evaluation of the redistribution of the uranium. Sequential extraction gives more specific information on the mobile phase, while the bulk analyses provide solid background information. However, it is concluded that the original 4 steps extraction scheme, (1) ammonium acetate, (2) Tamm´s oxalate, (3) 6 M HCl and (4) dissolution of the residual with aqua regia, used can be simplified and replaced by a two steps procedure, (I) extraction with 1M ammonium acetate and 0.05 M EDTA solution (buffered to pH 4.8 with acetic acid) and (II) complete dissolution of the residue by using aqua regia and HF. In practice, this gives the amount and the activity ratio of the mobile versus the immobile part of the uranium.

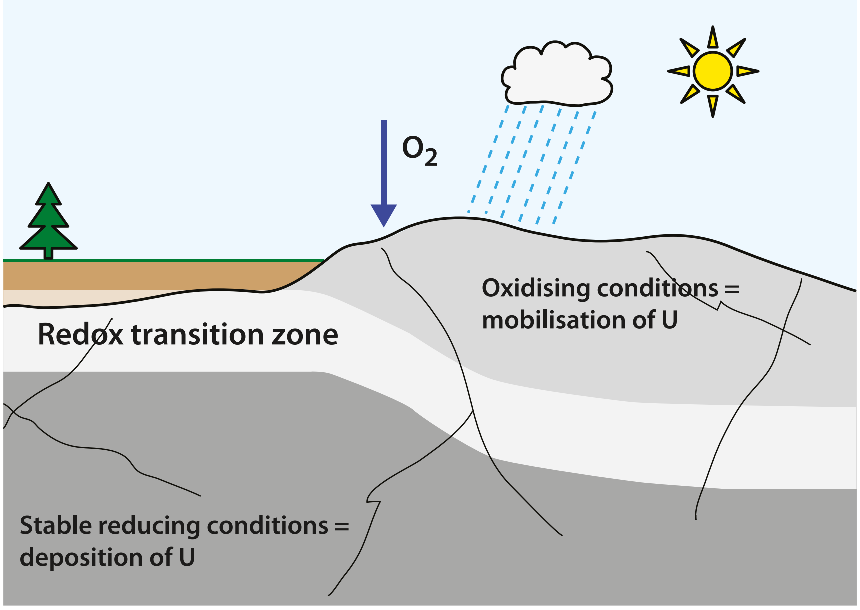


Figure 3-8. *Oxygen entering the bedrock via recharge water will be consumed by organic and inorganic processes along the bedrock fractures. This transition can be detected by studies of uranium and uranium isotopes.*

3.9 Fe-oxides in Fractures

Background

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

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

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

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

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

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

Objectives

The basic idea of the project is to examine Fe-oxide fracture linings in order to explore suitable palaeo-indicators and their formation conditions. For example, potential low temperature oxidation under a deglaciation is expected to result in the removal of Fe(II)-bearing phases with precipitation of Fe(III)-oxides. At the same time, knowledge about the behaviour of trace component uptake can be obtained from natural material as well as studies in the laboratory under controlled conditions.

Following the original project, a continuation phase of the project was started. The aim with this phase is to establish the penetration depth of oxidising water below ground level. Oxidising waters may represent present-day recharge, or reflect penetration of glacial melt waters during the last glaciation.

Experimental concept

A glove-box set-up, where Atomic Force Microscopy is possible in situ, was used to investigate green rust under a stable atmosphere at reducing conditions. More possibilities for extracting chemical information from the secondary Fe-oxides were tested and the merits of stable Fe- and O-isotope fractionation as well as Mössbauer (MS) and energy dispersive X-ray (EDS) spectroscopy were examined. Scanning electron micrographs of the secondary Fe-oxide phases were obtained on a JEOL 6320F scanning electron microscope using secondary electrons.

Results

Due to other priorities, the final reporting of the continuation phase of the project was not completed during 2009. This will instead be realised in 2011.

3.10 Swiw-tests with Synthetic Groundwater

Background

Single Well Injection Withdrawal (Swiw) tests were used frequently within the site investigations in Forsmark and Oskarshamn with the purpose of demonstration and investigation of tracer transport in fractures. In a normal Swiw test, one or more tracers are added to natural water injected in the fracture to be tested. After a period of injection, pumping (withdrawal) starts and the tracer breakthrough is analysed and evaluated. Swiw tests with synthetic groundwater constitute a complement to performed tests and studies on the processes governing retention, e.g. the TRUE-1 and the TRUE Block Scale experiments as well as the Swiw tests performed within the SKB site investigation programme.

Objectives

The general objective of the project is to increase the understanding of the dominating retention processes by means of Swiw tests with synthetic groundwater. More specifically, the objective is to establish if fast or slow diffusion processes, i.e. diffusion from stagnant zones or matrix, dominates in the studied scale. The project is also expected to provide supporting information for the interpretation of the Swiw tests performed within the site investigation programme.

Experimental concept

The basic idea is to perform Swiw tests with a water composition similar to the natural water at the site but with some ions excluded, e.g. chloride, potassium and strontium. Besides, in order to compare to a normal Swiw test, tracers normally used within the site investigations will also be added. This synthetic groundwater is injected in the fracture. In the withdrawal phase of the test the content of the "natural" tracers (e.g. chloride, potassium and strontium) as well as the added tracers in the pumping water is monitored. The combination of tracers, both added and natural, may then provide desired information of diffusion, for example if the diffusion is dominated by the rock matrix or stagnant zones.

Results

In June 2009 the project decision and project plan for Swiw-test with Synthetic Groundwater were approved. During the second half of 2009 site selection, scoping calculation of radon and preparation of an activity plan for the field experiments were initiated and finalised.

TRUE Block Scale was identified in the feasibility study as a potential test site. However, after completion of the new Tass-tunnel, it was clear that the hydraulic pressure and gradients were affected to a large degree. It was therefore not recommended to perform Swiw tests at the TRUE Block Scale site. Instead, other parts of Äspö HRL were considered for selection of test site. In this process, the borehole KA2858A was identified as a promising site for Swiw tests with synthetic groundwater and recommended for the initial field tests.

The scoping calculations regarding usage of radon showed that it may provide some additional information but not any new way to estimate the fracture aperture in the Swiw tests. Due to high expected cost and relative limited benefits, it was decided that radon should not be used for evaluation of tracer breakthrough during the Swiw test. Instead, only a few samples of radon will be taken and analysed during the test.

The activity plan for the field tests was based on the project plan and site selection of KA2858A and is scheduled to be carried out from January to November 2010 at Äspö HRL followed by evaluation and reporting.

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

Background

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

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

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

Task 2: Scooping 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 (completed).

Task 7: Reduction of Performance Assessment uncertainty through modelling of hydraulic tests at Olkiluoto, Finland (ongoing).

Task 8: The interface between the natural and the engineered barriers (initiated in terms of planning and scoping calculations).

Objectives

The Äspö Task Force is a forum for the organisations supporting the Äspö HRL project to interact in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock. In particular, the Task Force shall propose, review, evaluate, and contribute to such work in the project. The Task Force shall interact with the principal investigators responsible for carrying out experimental and modelling work for Äspö HRL of particular interest for the members of the Task Force. Much emphasis is put on building of confidence in the approaches and methods in use for modelling of groundwater flow and migration in order to demonstrate their use for performance and safety assessments.

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

Task 7 was presented at the 19th International Task Force meeting in Finland, 2004. Hydraulic responses during construction of a final repository are of great interest because they may provide information for characterisation of hydraulic properties of the bedrock and for estimation of possible hydraulic disturbances caused by the construction. Task 7 will focus on the underground facility Onkalo at the Olkiluoto site in Finland, and is aimed at simulating the hydraulic responses detected during a long-term pumping test carried out in borehole KR24. In addition, Task 7 is addressing the usage of Posiva Flow Log (PFL) data and issues related to open boreholes. During the project, one more objective has been added, and that is to address the reduction of uncertainty by using PFL data. In fact, the title of the task has been altered to "Reduction of Performance Assessment uncertainty through modelling of hydraulic tests at Olkiluoto, Finland".

Results

Task 6 is completed, and a number of papers were published in the same issue of the Hydrogeology Journal. An essay /Gustafson et al. 2009/, describing the framework of Task 6, initiates the series of papers. A summary of the outcome of Task 6 was written by /Hodgkinson et al. 2009/. In addition, papers from four modelling groups /Grenier et al. 2009, Moreno and Crawford 2009, Poteri 2009, Uchida et al. 2009/ are published in conjunction with the summary paper.

During 2009, work has mainly been performed within Task 7 that is divided into several sub-tasks. Reports on sub-task 7A1–A5 have been finalised based on review comments. An updated task description for the sub-task 7B and 7C and more data have been sent out to the modellers.

A workshop for Task 7 and 8 was held in January where modelling approaches and plans for the future modelling were presented and discussed. The venue took place in Lund, Sweden.

The 25th international Task Force meeting was held in Mizunami, Japan in October. The presentations were mainly addressing modelling results on sub-tasks 7B and 7C. In addition, scoping calculations for Task 8 were presented. The discussions on the continuation of Task 7 and also the start up of Task 8 were constructive. Task 8 will be a joint effort with the Task Force on Engineered Barriers, and will be addressing the processes at the interface between the rock and the bentonite in deposition holes. The minutes of this venue have been distributed to the Task Force. Planning for the Task 7 and 8 Workshop in Vuojoki, Finland January 2010, has been ongoing and the first notice of this meeting was distributed to the modellers in December.

The description and the status of the specific modelling tasks within Task 7 are given in Table 3-1. For more detailed information about performed work within the different tasks by the international organisations, see Sections 7.4 to 7.7.

Table 3-1. Descriptions of the specific modelling sub-tasks in Task 7 and status (within brackets).

7	**Reduction of Performance Assessment uncertainty through modelling of hydraulic tests at Olkiluoto, Finland.**
7A	Long-term pumping experiment. (Final results are reported as ITDs).
	7A1 Hydrostructural model implementation.
	7A2 Pathway simulation within fracture zones.
	7A3 Conceptual modelling of PA relevant parameters from open hole pumping.
	7A4 Quantification of compartmentalisation from open hole pumping tests and flow logging.
	7A5 Quantification of transport resistance distributions along pathways.
7B	Sub-task 7B is addressing the same as sub-task 7A but in a smaller scale, i.e. rock block scale. Sub-task 7B is using sub-task 7A as boundary condition. (Updated results presented at the 25th Task Force meeting).
7C	Here focus is on deposition hole scale issues, resolving geomechanics, buffers and hydraulic views of fractures. (Preliminary results presented at the 25th Task Force meeting).
7D	Sub-task 7D concerns integration on all scales (Tentative).

3.12 Äspö Model for Radionuclide Sorption

Background

Today, geochemical retention of radionuclides in the granitic environment is commonly assessed using Kd-modelling. However, this approach relies on fully empirical observations and thus to a limited degree contribute to the evaluation of the conceptual understanding of reactive transport in complex rock environments.

In the literature, the process based Component Additivity (CA) approach, which relies on a linear combination of sorption properties of different minerals in a geological material, has been suggested for estimation of sorption properties. For adoption of this approach to granitic material, the particle size/surface area dependence of radionuclide sorption and effects of grain boundaries need to be resolved. Furthermore, it is desirable to verify possible localisation of sorption of radionuclides to specific minerals within the rock.

Objectives

The overall objective of this project is to formulate and test process quantifying models for geochemical retention of radionuclides, in granitic environments, using a combined laboratory and modelling approach. The operational objectives are to:

- Experimentally quantify how the sorption of some selected radionuclides depends on particle size and BET surface area for some important minerals that occur in Äspö rock and for some authentic Äspö rock material.
- Experimentally identify the minerals in the Äspö rock material that mainly contribute to the sorption of some selected radionuclides and clarify which information about localisation of sorption to grain interfaces and structures at the particle surface that can be obtained from autoradiography.
- Formulate and parameterise predictive models for radionuclide sorption on Äspö rock material and to test the models against small-scale laboratory experiments with support from the experimental results linked to the objectives above as well as literature data.

Experimental concept

The project is divided into four research activities:

- Preparatory studies.
- Surface area dependency of sorption.
- Localisation of sorption.
- Predictive modelling.

The project works with pure mineral samples (“museum specimen”) and also a drill core, similar to the rock material used in the LTDE experiment. The concept follows the CA approach, where the behaviours of the individual pure minerals are studied and the knowledge synthesised into a prediction of the behaviour of the full rock sample. During 2009, the work has focused on: (1) acquiring pure mineral samples, (2) establishing their characteristics in terms of purity and chemical composition and (3) preparing mineral powders of various particle sizes (Figure 3-9, left). Experimentally, the specific surface area, as given by the BET-method (Figure 3-9, right), has been determined for particle size in the range 0.075–8 mm and for monoliths of some minerals.

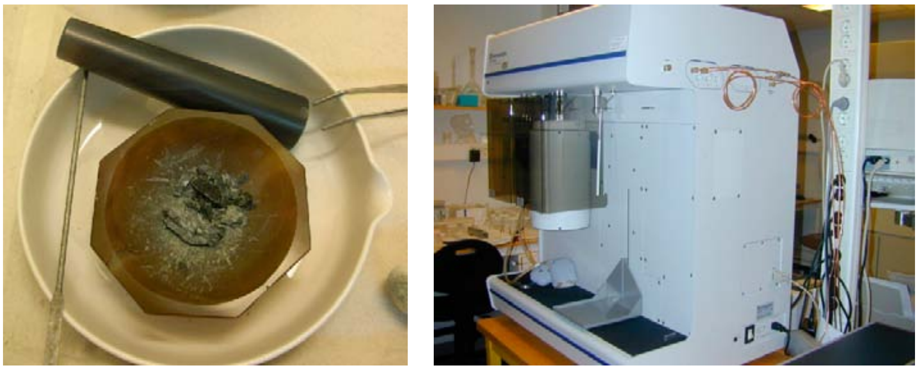


Figure 3-9. *Powder preparation from a chlorite specimen in an agate mortar (left). Instrument for making surface area determinations (right).*

Results

Modelling of Nickel sorption onto chlorite

A co-operation between researchers at Nuclear Chemistry and Inorganic Chemistry at Royal Institute of Technology in Stockholm, on the model interpretation of the specific surface area and radionuclide sorption properties of the mineral chlorite, has been initiated. As part of this co-operation, a surface complexation model for Ni^{2+} sorption onto chlorite as function of pH in small scale laboratory experiments was tested for two different chlorite samples. The samples had been characterised as Mg-rich (Taberg) and Fe-rich (Karlsborg). The Taberg chlorite had been reported to have about one order of magnitude larger surface area than the Karlsborg specimen /Zazzi 2009/.

A surface complexation model for Ni^{2+} onto the Karlsborg chlorite was adopted from the literature /Zazzi 2009/ and combined with a model for precipitation of $Ni(OH)_2$ using the Phreeqc code /Parkhurst and Appelo 1999/. Despite the order of magnitude difference in the specific surface area between the two chlorites, the sorption could be modelled with the same model, due to similar sorption strengths of the two samples (Figure 3-10). Furthermore, it was found that while the model predictions agreed fairly well with the experimental observations at pH 6.0, it over predicted the sorption at both pH 7.4 and 8.3.

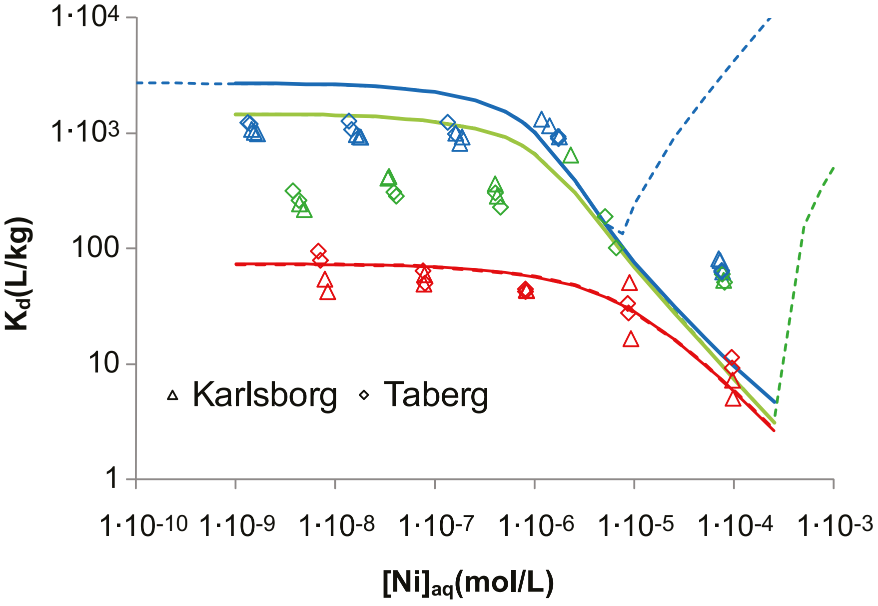


Figure 3-10. *Kd as function of aqueous Ni concentration at different pH (red 6.0, green 7.4 and blue 8.3) for the two different chlorites. Markers show experimental data and lines show model results, with (dotted lines) and without (full lines) precipitation. Triangles – Karlsborg Chlorite. Diamonds – Taberg Chlorite.*

It was proposed that this similarity in sorption reactivity is due to similar reactive surface areas between the samples, despite difference in the total specific surface area, as determined by N_2 sorption through the BET-method /Zazzi 2009/. This can be explained, for example, if the edge surface of the particles is much more sorption reactive than the basal plane, as has been suggested in literature, and the amount of edge surface is similar between the two samples. From theory it was shown that this situation may occur, e.g. if the basal plane of the chlorite is rough or the particle partly disintegrated, as had been observed by SEM (Scanning Electron Microscopy) for one of the chlorite samples used, see Figure 3-11.

BET area dependency of grain size

Laboratory quantification of sorption reactions usually employs crushed geological material. As a first approximation, the specific surface area is often used to scale surface reaction capacities to the field situation. In addition, based on geometric considerations, it is often assumed that there is an inverse proportionality between the surface area and the particle size. However, /Byegård et al. 1998/ and /André et al. 2009/ have observed a deviation from this inverse proportionality when relatively large particle size fractions or large pieces of granite were considered. /André et al. 2009/ proposed that this was due to artificial new surfaces associated with newly developed micro cracks within a mechanically disturbed zone in the outer layer of the particle.

/André et al. 2009/ proposed that the specific surface area of a fine powder of spherical particles, for which the disturbed zone (δ) extends throughout the whole particle, can be expressed as:

$$SSA_{tot} = \frac{3\lambda}{\rho R} + \frac{a_r}{\rho} + \frac{a_{dist}}{\rho} \quad \text{for } R \leq \delta \qquad \text{(Eq. 3-1a)}$$

However, for larger particles (R>δ) only the outer part of the particle is affected by the mechanical treatment and the specific surface area is given as:

$$SSA_{tot} = \frac{3\lambda}{\rho R} + \frac{a_r}{\rho} + \frac{a_{dist}(3R^2\delta - 3R\delta^2 + \delta^3)}{\rho R^3} \quad \text{for } R > \delta \qquad \text{(Eq. 3-1b)}$$

In Eq. 3-1 the first term is associated with the outer, geometric surface area. Deviation from perfectly smooth particles is given by a surface roughness factor λ defined as $\lambda = \frac{SSA_{real}}{SSA_{ideal}}$. The second term accounts for the intrinsic internal specific surface area and the third term quantifies additional internal specific surface area, occurring as a consequence of developed micro cracks within the mechanically disturbed zone. In Eq. 3-1, R is the particle radius, ρ is the density of the mineral, and α is the specific internal surface area.

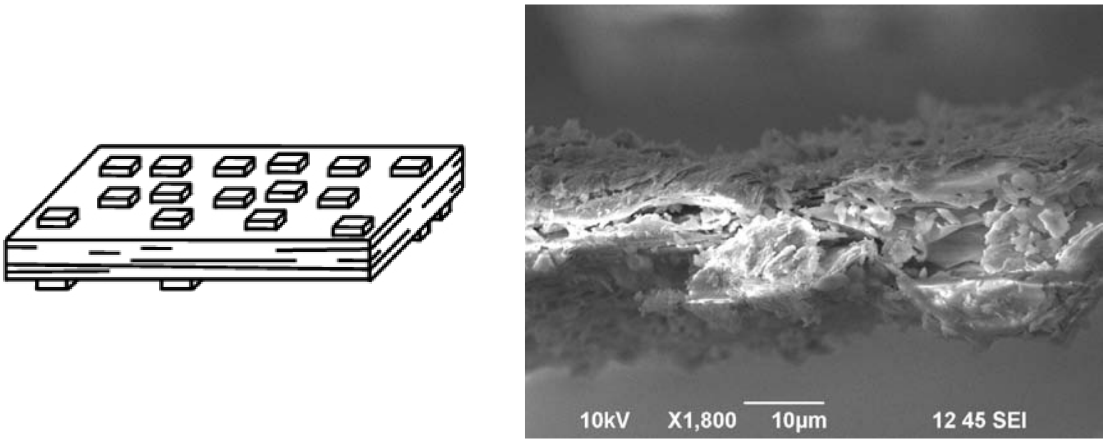


Figure 3-11. *A sketch of a rough and partly disintegrated chlorite particle (left) and a SEM image of a chlorite particle (right) /Zazzi 2009/.*

The study of the specific BET area as function of particle size for pure minerals, started with labradorite and magnetite. Labradorite belongs to the plagioclase (feldspar) group of minerals and is one of the major minerals in the host rock at Äspö. Magnetite, on the other hand, is an iron oxide that generally occurs only in small amounts in the Äspö rock, but is one of the minerals that in the literature is known to be a strong radionuclide sorbent and also to have a comparatively large specific surface area. The alternative use of N_2 or Krypton as the sorbing gas in the BET-analysis gave no considerable difference in the surface area determined for the two minerals. However, the precision in the determinations using Krypton was better than when using N_2.

For labradorite a linear relationship between the specific surface area and the inverse of the particle size was observed for particle size 1-2 mm and smaller, as predicted from Eq. 3-1a (Figure 3-12). In a linear regression of Eq. 3-1a to experimental data, the preliminary fitting parameters were the roughness factor $\lambda=8$ and the entity $(\alpha_r + \alpha_{dist}) = 36\times10^3\ m^{-1}$. For larger particles, there is a negative deviation from this linear trend, just as proposed by Eq. 3-1b, indicating that the disturbed zone to a lesser degree contributes to the measured specific surface area of these samples. Magnetite, on the other hand, showed a somewhat more complex behaviour, which is currently under further investigation (Figure 3-12).

The vertical error bars represent one standard deviation in replicate BET area determinations. The horizontal error bars represent the upper and lower cut-off of the particle size. Broken lines show linear regression of Eq. 3-1a to data from /Dubois et al. 2009/.

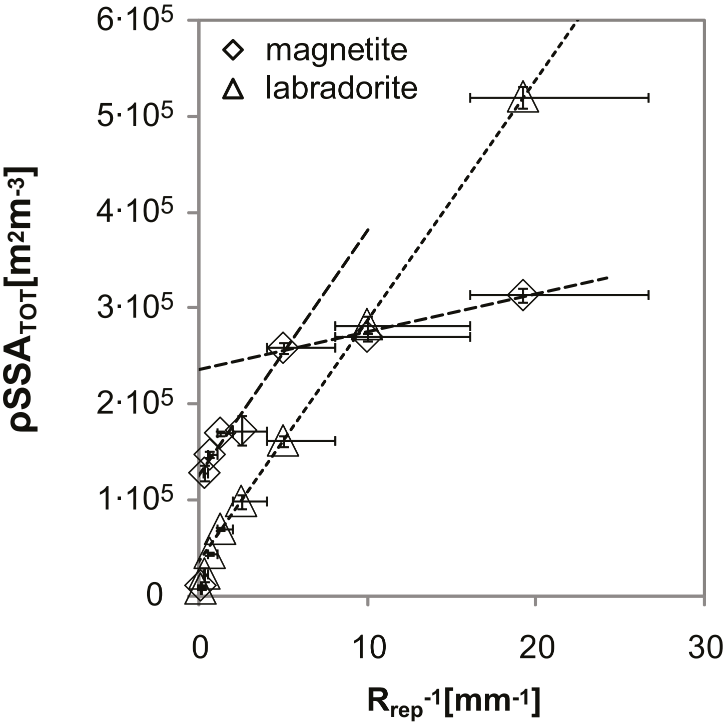


Figure 3-12. *Specific BET surface area (ρSSAtot [m^{-1}]) as function of the inverse of the particle size [mm^{-1}] for magnetite (◊) and labradorite (Δ).*

For both minerals, a much lower specific surface area was measured on large mineral parallelepipeds (3×3 cm basis and about 5 cm long) than what would be expected from a linear extrapolation of experimental results of the smaller particles (Table 3-2). With relevance for the determination of radionuclide sorption properties of rocks and minerals, this indicates that the radionuclide sorption for intact material may be greatly overestimated if it is based only on extrapolation of laboratory experiments with crushed material.

A tentative result of this study is also that the specific surface area of the large mineral pieces are just 2–4% of that of the particle size fraction 0.075–0.125 mm, a size fraction which is representative of particles employed in many radionuclide sorption experiments using crushed rock or mineral samples. This implies that the majority of the surface area in such experiments is associated with fresh mineral surfaces, not originally present, and possibly with different sorption properties from the intrinsic sample.

Table 3-2. Specific surface area [$m^2 g^{-1}$] experimentally determined for 3×3 cm pieces, extrapolated from crushed material and calculated ratio [–] (preliminary data from /Dubois et al. 2009/).

Specific surface area	Labradorite	Magnetite
Experimental – 3×3 cm piece [$m^2\ g^{-1}$]	0.0027	0.0022
Extrapolated – from particles 0.075–0.5 mm [$m^2\ g^{-1}$]	0.013	0.049
Extrapolated – particle particles 0.25–8 mm [$m^2\ g^{-1}$]	0.013	0.025
Ratio [–]	5	11–22

4 Engineered barriers

4.1 General

To meet stage goal 4, to demonstrate technology for and function of important parts of the repository barrier system, work is performed at Äspö HRL. This implies translation of current scientific knowledge and state-of-the-art technology into engineering practice applicable in a future repository.

It is important that development, testing and demonstration of methods and procedures, as well as testing and demonstration of repository system performance, are conducted under realistic conditions and at 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 the important overall objectives of this programme are to:

- Furnish methods, equipment and procedures required for excavation of tunnels and deposition holes, near-field characterisation, canister handling and deposition, backfilling, sealing and plugging tunnels, monitoring and also canister retrieval.
- Integrate these methods and procedures into a disposal sequence that can be demonstrated to meet requirements of quality in relation to relevant standards, as well as practicality. With respect to repository function, the objectives are to test and demonstrate the function of the engineered barriers as well as the function of the integrated repository system.

During 2009, the ongoing experiments and projects within Engineered barriers were:

- Prototype Repository.
- Long Term Test of Buffer Material.
- Alternative Buffer Materials.
- Backfill and Plug Test.
- Canister Retrieval Test.
- Temperature Buffer Test.
- KBS-3 Method with Horizontal Emplacement.
- Large Scale Gas Injection Test.
- Sealing of Tunnel at Great Depth
- In situ Corrosion Testing of Miniature Canisters.
- Cleaning and Sealing of Investigation Boreholes.
- Task Force on Engineered Barrier Systems.

4.2 Prototype Repository

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. In addition, it is needed to demonstrate that it is possible to understand the processes that take place in the engineered barriers and the surrounding host rock.

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

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

Objectives

The main objectives for the Prototype Repository are to:

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

The evolution of the Prototype Repository should be followed for a long time, possibly up to 20 years. This is 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.

Experimental concept

The test is located in the innermost section of the TBM-tunnel at the –450 m level. The layout involves altogether six deposition holes, four in an inner section and two in an outer, see Figure 4-1. Canisters with dimension and weight according to the current plans for the final repository, with heaters to simulate the thermal energy output from the spent nuclear fuel, have been positioned in the holes and surrounded by bentonite buffer. The deposition holes are placed with a centre distance of 6 m. This distance was evaluated considering the thermal diffusivity of the rock mass and the maximum acceptable surface temperature of the canister. The deposition tunnel is backfilled with a mixture of bentonite and crushed rock (30/70). A massive concrete plug, designed to withstand full water and swelling pressures, separates the test area from the open tunnel system, and a second plug separates the two sections. This layout provides two more or less independent test sections.

The decision when to stop and decommission the test will be influenced by several factors including performance of monitoring instrumentation and results successively gained. It is envisaged that the outer test section will be decommissioned after approximately five years to obtain interim data on buffer and backfill performance. Instrumentation is used to monitor processes and evolution of properties in canister, buffer, backfill and near-field rock. Examples of processes that are studied include:

- Water uptake in buffer and backfill.
- Temperature distribution (canisters, buffer, backfill and rock).
- Displacement of canister.
- Swelling pressure and displacement in buffer and backfill.
- Stress and displacement in the near-field rock.
- Water pressure build up and pressure distribution in rock.
- Gas pressure in buffer and backfill.
- Chemical processes in rock, buffer and backfill.
- Bacterial growth and migration in buffer and backfill.

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

Results

The installation of Section I was done during summer and autumn 2001. The heating of the canister in deposition hole 1 started at 17th September. This date is also marked as start date. The backfilling was finished in the end of November and the plug was cast at in the middle of December. The installation of Section II was done during spring and summer 2003. The heating of the canister in hole 5 started at 8th of May. This date is also marked as start date for Section II. The backfilling was finished in the end of June and the plug was cast at in September. The interface between the rock and the outer plug was grouted at the beginning of October 2004.

At the beginning of November 2004 the drainage of the inner part of Section I and the drainage through the outer plug were closed. This affected the pressure (both total and pore pressure) in the backfill and the buffer in the two sections dramatically. Example of data from the measurements in the backfill of the total pressure is shown in Figure 4-2. The maximum pressures were recorded around 1st January 2004. At that date the heating in canister 2 failed. It was then decided to turn off the power to all of the six canisters. Four days later, also damages on canister 6 were observed. The drainage of the tunnel was then opened again. During the next week further investigations on the canisters were done. The measurements showed that the heaters in canister 2 were so damaged that no power could be applied to this canister. The power to the rest of the canisters was applied 15th of November 2004 again. The drainage of the tunnel was kept open. At the beginning of August 2005 another failure of canister 6 was observed. The power to this canister was switched off until beginning of October 2005 when the power was switched on again. During 2008 new problems were observed with the heaters in canister 6, resulting in that the power was reduced to 1,160W. A data report covering the period 17th September 2001 up to 1st June 2009 is available /Goudarzi and Johannesson 2009/.

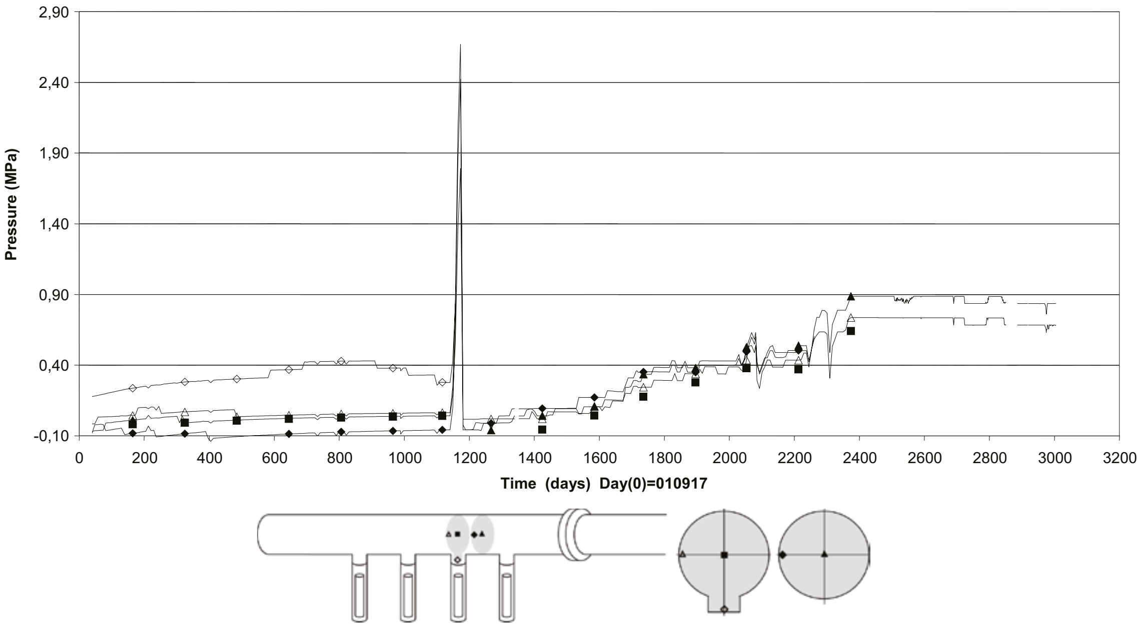


Figure 4-2. *Examples of measured total pressure in the backfill around deposition hole 3 (17th September 2001 to 1st December 2009).*

Measurements in rock, backfill and buffer

Altogether more than 1,000 transducers were installed in the rock, buffer and backfill /Collin and Börgesson 2001, Börgesson and Sandén 2003, Rhén et al. 2003/. The transducers measure the temperature, the pore pressure and the total pressure in different part of the test area. The water saturation process is recorded by measuring the relative humidity in the pore system of the backfill and the buffer, which can be converted to total suction.

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

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

A large programme for measuring the water pressure in the rock close to the tunnel is also ongoing /Rhén et al. 2003/. The measurements are made in boreholes which are divided into sections with packers. In connection with this work a new packer was developed that is not dependent of an external pressure to seal off a borehole section. The sealing is made by highly compacted bentonite with rubber coverage. Tests for measuring the hydraulic conductivity of the rock are also made with the use of the drilled holes. The latest tests (test campaign 10) were made at the end of 2009 and the results from the tests have not yet been published.

An ultrasonic monitoring system has been installed around deposition hole 6. The system consists of twenty-four ultrasonic transducers installed into four instrumentation boreholes. The ultrasonic monitoring has been conducted since 1999 and the latest measurements were published in three reports during 2009 /Zolezzi et al. 2008, Duckworth et al. 2008, Duckworth et al. 2009/. Two techniques are utilised here to investigate the processes occurring within the rock mass around the deposition hole: ultrasonic survey and acoustic emission (AE). Ultrasonic surveys are used to “actively” examine the rock. Amplitude and velocity changes on the ray paths can then be interpreted in terms of changes in the material properties of the rock. AE monitoring is a “passive” technique similar to earthquake monitoring but on a much smaller distance scale (source dimensions of millimetres). AE’s occur on fractures in the rock when they are created or when they move. Results from AE monitoring during the heating phase of the Prototype Repository are shown in Figure 4-3.

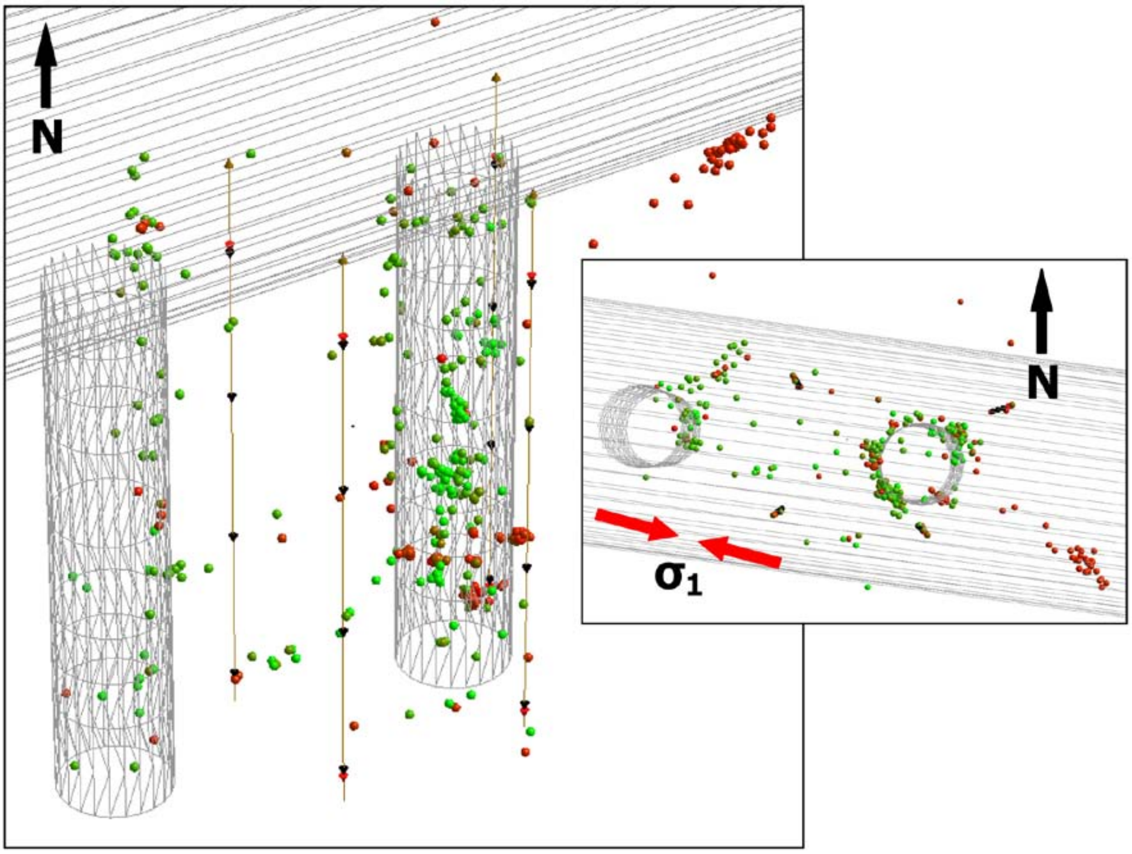


Figure 4-3. Projections of all acoustic emissions during the heating phase (20th March 2003 to 30st September 2008). In total there have been 848 events over the last six years of monitoring (events are scaled by time) /Duckworth et al. 2009/.

Equipment for taking gas and water samples both in buffer and backfill are installed /Puigdomenech and Sandén 2001/. A report where analyses of microorganisms, gases and chemistry in buffer and backfill during 2004–2007 are described is available /Eriksson 2007/. New gas and water samples have been taken during 2009. The results from these tests have not been reported yet.

The saturation of the buffer in the six deposition holes

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

Many of the sensors for measuring total pressure, relative humidity and pore pressure in deposition hole 1 are indicating that the buffer around the canister is close to saturation while the buffer above and under the canister is not saturated. Corresponding measurements in the buffer in deposition hole 3 are indicating that the buffer is not saturated.

The saturation of the buffer in deposition hole 5 indicated by RH-sensors and total pressure sensors is complex. Some total pressure sensors are measuring rather high pressures (higher than 2.5 MPa) while others measure very low pressures. The sensors giving high pressures are placed both in block C1 and rings R5 and R10 (the uppermost ring). There are also some RH-sensors which are measuring relative humidity of ~100%, indicating a high saturation of the buffer. In other parts of the buffer most of the sensors (both RH-sensors and total pressure sensors) indicate a slow wetting of the buffer with time.

At present in deposition hole 6, several total pressure sensors and pore pressure sensors placed in the buffer below the canister lid are measuring high pressures, indicating a high degree of saturation while the sensors placed above the canister are measuring lower pressures, indicating a lower degree of saturation.

The saturation of the backfill

Sensors for measuring total pressure, pore pressure and relative humidity have been installed in the backfill. Data from these measurements together with resistivity measurements made by Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) are indicating that the backfill in both sections of the tunnel is saturated, see Section 7.3.2.

4.3 Long Term Test of Buffer Material

Background

Comprehensive research and development work has been carried out during the last thirty years in order to determine the basic behaviour of unaltered bentonite material. The results have been technical reports, scientific articles, and computer codes concerning both unsaturated and saturated buffer conditions. The models are believed to well describe the function of an unaltered MX-80 bentonite buffer after water saturation with respect to physical properties, e.g. swelling pressure, hydraulic conductivity and rheological behaviour.

The decaying spent fuel in the HLW canisters will increase temperature of the bentonite buffer. Initially there will also be a thermal gradient over the buffer by which original water will be redistributed parallel to an uptake of water from the surrounding rock. No significant alteration of the buffer is expected to take place at these physicochemical conditions in a KBS3 repository neither during, nor after water saturation.

Objectives

The general objectives in the Lot test series may be summarized 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, hydraulic conductivity and rheological properties.
- Check of existing models concerning buffer degrading processes, e.g. mineral redistribution and montmorillonite alteration.
- Check of existing models concerning cation diffusion in bentonite.
- Collect information concerning survival, activity and migration of bacteria in bentonite under repository-like conditions.
- Check of calculated data concerning copper corrosion, and collect information regarding the character of possible corrosion products.
- Collect information, which may facilitate the realization of the full-scale test series (e.g. the Prototype project) with respect to preparation, instrumentation, retrieval, subsequent analyses, evaluation and data handling.

Experimental concept

The Lot test series includes seven test parcels, which all contain a heater, central tube, clay buffer, instruments and parameter controlling equipment. The test parcels have been placed in boreholes with a diameter of 300 mm and a depth of around 4 m. The test concerns realistic repository conditions except for the scale and the controlled adverse conditions in four parcels. 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 mineralogical analyses and physical tests of the buffer material are made, see Table 4-1.

Table 4-1. Buffer material test series.

Type	No.	max T (°C)	Controlled parameter	Time (years)	Remark
A	1	130	T, [K$^+$], pH, am	1	Reported
A	0	120–150	T, [K$^+$], pH, am	1	At review
A	2	120–150	T, [K$^+$], pH, am	6	Reported
A	3	120–150	T	>10	Ongoing
S	1	90	T	1	Reported
S	2	90	T	9	Ongoing
S	3	90	T	>10	Ongoing

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

Results

A decision was taken by SKB not to retrieve any Lot test parcel during 2009, but instead one of the parcels in the test Alternative Buffer Materials, see Section 4.4. The activity within the Lot project was therefore limited to supplementary laboratory analyses, and to finalise the reports on the A0 parcel and the A2 parcel /Karnland et al. 2009/ which now are at hand.

4.4 Alternative Buffer Materials

Background

Bentonite clay has been proposed as buffer material in several concepts for HLW repositories. In the Swedish KBS-3 concept the main demands on the bentonite buffer are to minimise the water flow over the deposition hole, reduce the effects on the canister of a possible rock displacement and prevent sinking of the canister. The MX-80 bentonite from American Colloid Co (Wyoming) has so far been used by SKB as a reference material.

In the Alternative Buffer Material test, ABM, eleven different buffer candidate materials with different amount of swelling clay minerals, smectite counter ions and various accessory minerals are tested. The test series is performed in the rock at repository conditions except for the scale and the adverse conditions (the target temperature is set to 130°C). Parallel to the field tests, laboratory analyses of the reference materials are going on.

ABM is an SKB project with several international partners collaborating in the part of laboratory experiments and analyses.

Objectives

The project is carried out using materials that are possible as future buffer candidate materials. The main objectives are to:

- Compare different buffer materials concerning mineral stability and physical properties, both in laboratory tests of the reference materials but also after exposure in field tests performed at realistic repository conditions.
- Discover possible problems with manufacturing and storage of bentonite blocks.
- Study the interaction between metallic iron and bentonite. This is possible since the central heaters are placed in tubes made of straight carbon steel. The tubes are in direct contact with the buffer.

Experimental concept

The experiment is carried out in similar way and scale as the Lot experiment at Äspö HRL, see Section 4.3. Three test parcels containing heater, central tube, pre-compacted clay buffer blocks, instruments and parameter controlling equipment have been emplaced in vertical boreholes with a diameter of 300 mm and a depth of 3 m, see Figure 4-4. The target temperature in all three parcels is 130°C. Parcel 1 will be retrieved after 1–2 years operation, parcel 2 after 2–4 years and parcel 3 after at least five years operation.

Parcel 1 and 2 are artificially wetted whereas parcel 3, which will be in operation for the longest time, only will be wetted if it at some point is found necessary.

Parcel 1 and 3 are heated from the very beginning, whereas the heaters in parcel 2 were activated when the buffer was saturated.

The slots between buffer blocks and rock are filled with sand which is different compared to the Lot tests. The sand serves as a filter and will facilitate the saturation of the bentonite blocks.

In addition to the bentonite blocks deposited in the three test parcels, identical bentonite blocks are stored, covered in plastic, in order to monitor the effects of storage.

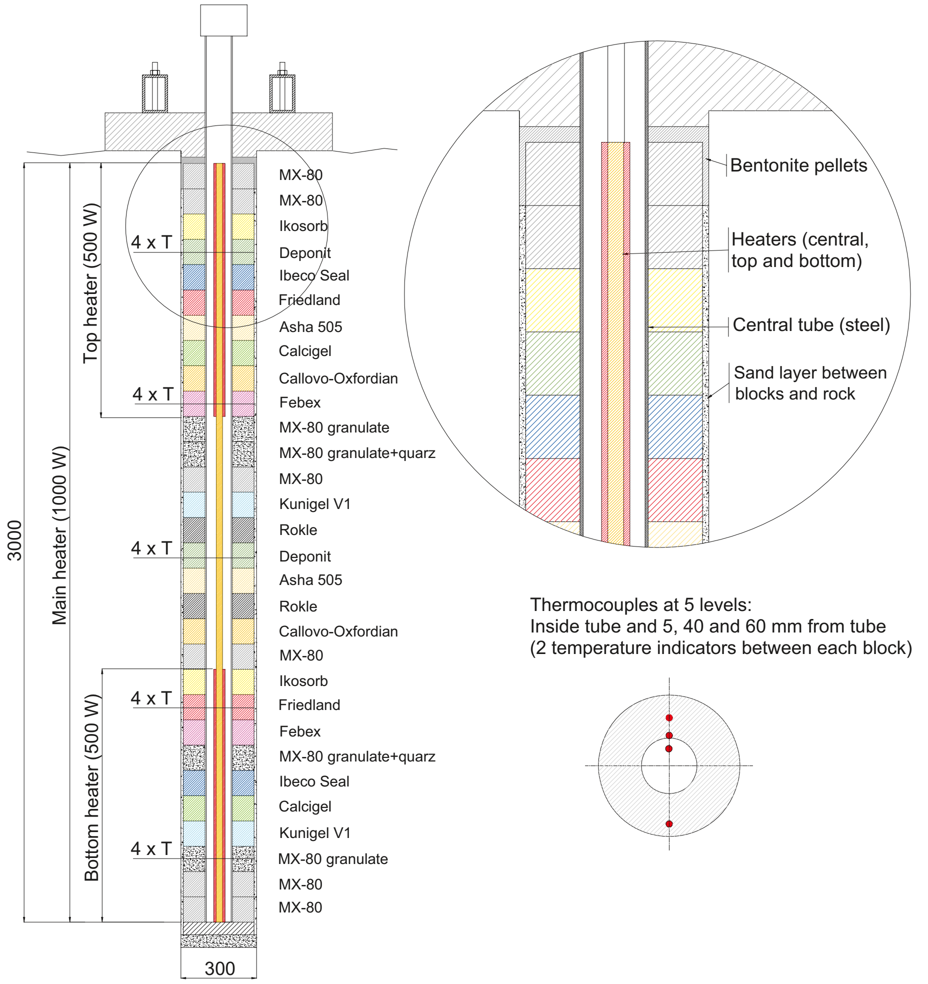


Figure 4-4. *Cross section showing the experimental set-up in the ABM test. The picture also shows the block configuration in test parcel 1.*

Results

Test parcel 1 was retrieved in May 2009, thirty months after installation and after about eighteen months heating at the intended test temperature (130°C). The technique used for retrieval was to drill bore holes to a depth of 3.2 meter (length of test parcel was 3.0 m) in the rock surrounding the parcel. The rock covering the clay had a thickness of about 10 cm. This seam drilling was then completed with two core drilled holes, with diameters of 300mm, which were used for installation of wire sawing equipment. With this equipment it was possible to saw off the rock column at the bottom. The rock column including the bentonite blocks could then be lifted up on the ground. The work with division of the rock column and uncovering the bentonite blocks started immediately after retrieval. Samples from the different bentonite materials were sent out to all participating organisations (Nagra, Andra, BGR, JAEA, Posiva, RAWRA and AECL) that are going to contribute with analyses of the test materials.

The analyses financed by SKB are focusing on three materials: MX-80, Deponit CAN and Asha 505. The work is performed by Daniel Svensson, SKB (mineralogy), Clay Technology AB (physical properties) and MICANS (microbiology). Some preliminary result from the laboratory analyses of parcel 1 are:

- The degree of saturation was high in all positions of the test parcel (water content and density has been determined in all blocks).
- Swelling pressure and hydraulic conductivity have been determined in some positions for the three materials of main interest. A slightly decrease in swelling pressure could be determined, especially for the Asha 505 material.
- X-ray Absorption Near Edge Structure (XANES) spectroscopy was performed at MAX-Lab, Lund. The clay blocks were sampled radially and preliminary results indicate higher FeII/FeIII ratio in the vicinity of the iron heater compared to the reference clays. Time resolved experiments were also performed in contact with oxygen to determine the stability of the FeII-phase(s). These indicate that the FeII/FeIII ratio to some extent decrease with time.

4.5 Backfill and Plug Test

Background and objectives

The Backfill and Plug Test includes tests of backfill materials, emplacement methods and 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 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 their function.

Experimental concept

The test region for the Backfill and Plug Test is located in the old part of the Zedex tunnel. In Figure 4-5 a 3D visualisation of the experimental set-up is shown. The test region, which is about 30 m long, is divided in three test parts:

- The inner part (six sections).
- The outer part (four sections).
- The concrete plug.

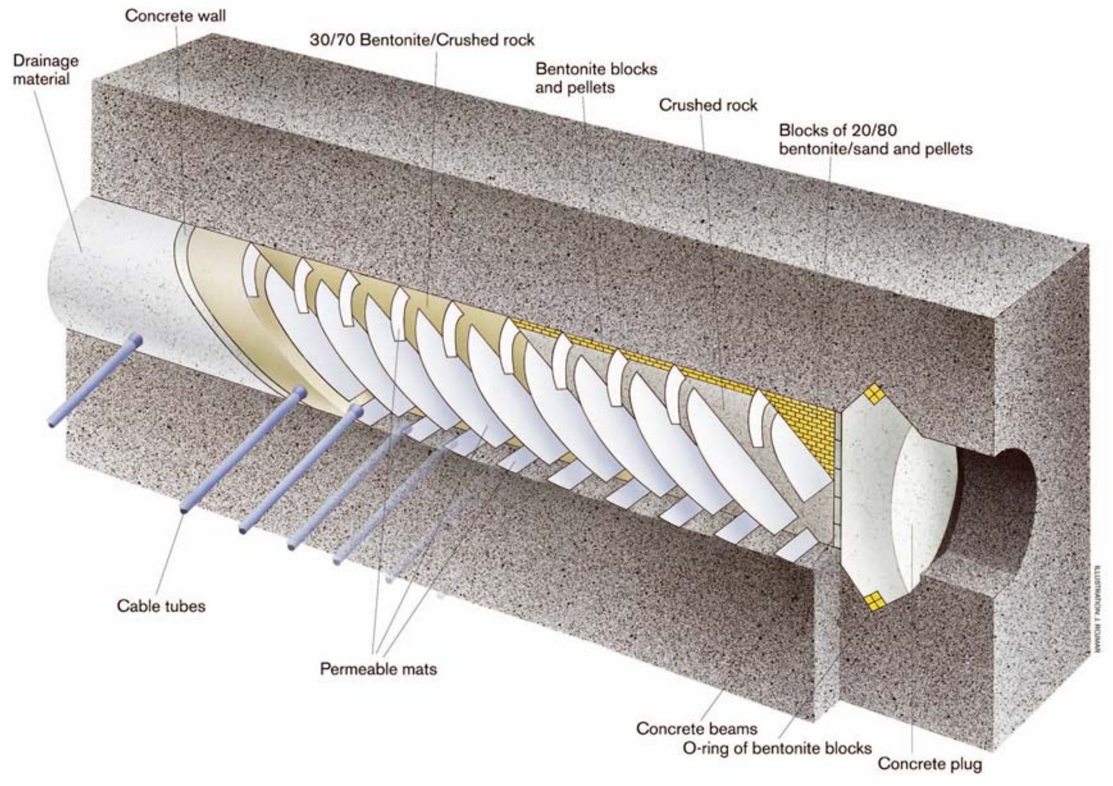


***Figure 4-5.** Illustration of the experimental set-up of the Backfill and Plug Test.*

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

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 ceiling and that the inclination should be about 35 degrees.

Both the inner and outer test parts are divided by drainage layers of permeable mats in order to apply hydraulic gradients between the layers and to study the flow of water in the backfill and near-field rock. The mats are also used for the water saturation of the backfill. The mats were installed in both test parts with the individual distance of 2.2 m. Each mat section was divided in three units in order to be able to separate the flow close to the ceiling 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, thermo-couples, moisture gauges, and gauges for measuring the local hydraulic conductivity. The axial conductivities of the backfill and the near-field rock were after water saturation tested by applying a water pressure gradient along the tunnel between the mats and measuring the water flow. All cables from the instruments are enclosed in Tecalan tubes 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 acquisition room.

Results

The installation was completed and the wetting of the backfill from the permeable mats started at the end of 1999. The water pressure in the mats was increased to 500 kPa in steps of 100 kPa between October 2001 and January 2002 and kept at 500 kPa until the backfill was judged to be water saturated in the beginning of 2003. During 2003 the equipment was rebuilt for flow testing and the flow testing started at the end of that year. The year 2004 and most of 2005 were used for flow testing of the six test sections of the 30/70 bentonite/crushed rock mixture in the inner part of the tunnel.

In 2006 measurements of (a) hydraulic conductivity in single points by pressurising filter equipped tubes and (b) the water flow into the backfill were performed in the inner part. These tests largely confirmed the previous results although a somewhat lower hydraulic conductivity was measured. During 2007 the compressibility of the backfill was measured by a stepwise pressurisation of the four pressure cylinders (diameter 0.5 m).

During 2009 it was planned to do hydraulic testing of the local hydraulic conductivity of the crushed rock with the so called “CT-tubes” but due to priority changes these measurements have been delayed. They have started but not been finished yet

The test has been monitored and measured results from all sensors except for the relative humidity sensors have been logged.

4.6 Canister Retrieval Test

Background

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

The Canister Retrieval Test (CRT) 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.

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:

- Two vertically bored test holes in full repository scale, which fulfil the quality requirements deemed necessary for the real repository.
- Careful and documented characterisation of the properties of these holes including the boring disturbed zone.
- Emplacement of bentonite blocks, bentonite pellets and canisters with heaters, and artificial addition of water. However, only one of these deposition holes has been used for implementation of the Canister Retrieval Test.
- Saturation and swelling of the buffer are monitored under controlled conditions.
- Preparations for and demonstration 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 test the retrieval technique, the data from monitoring the processes in the buffer and data from laboratory tests on excavated parts of the buffer will be used to increase the understanding of the THM processes in the buffer material.

Experimental concept

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

- Installation Phase – Boring of deposition holes and installation of instrumented bentonite blocks and canister with heaters in one hole. This hole is covered in the top with a lid of concrete and steel.
- Saturation Phase – Saturation of the bentonite and evolution of the thermal regime with measurement of thermal, hydraulic and mechanical processes.
- Retrieval Phase – 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 nine cables anchored to the rock. The tunnel was left open for access and inspections of the plug support. The experimental set-up is shown in Figure 4-6.

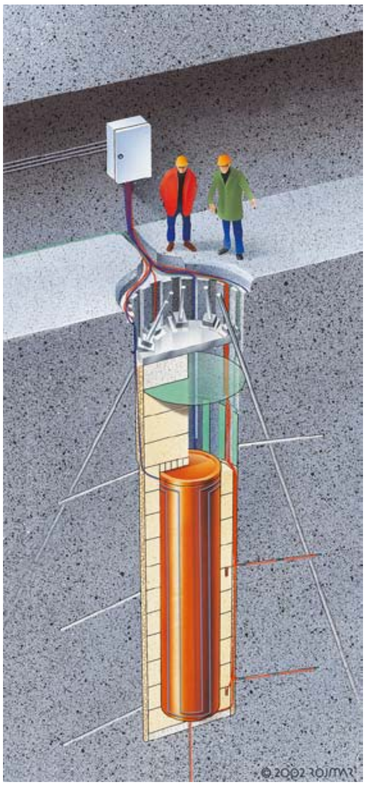


Figure 4-6. *Illustration of the experimental set-up of the Canister Retrieval Test.*

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

The predicted saturation time for the test was 2–3 years in the 350 mm thick buffer along the canister and 5–10 years in the buffer below and above the canister. The instrumentation in the buffer was similar to the instrumentation in the Prototype Repository and yield comparable information during the saturation phase.

Results

Besides verifying the retrieval technique, the test also provides possibilities to study the characteristics of the buffer at a fully water saturated state. When excavating the experiment, the upper half of the buffer was therefore sampled. Analyses of these samples have been continued during the past year.

The recorded sensor data during the experiment and the analyses after the excavation provide possibilities to test how well numerical models capture the processes in the buffer during saturation. The data may also be used for calibrating numerical models. In the Task Force on Engineered Barrier Systems (EBS Task Force) the Canister Retrieval Test was selected to be one of the full scale assignments, see Section 4.13.

Buffer analyses

The penetration of the lubricant, used when manufacturing the bentonite blocks, has been analysed. The results are shown in Figure 4-7, where 0 mm is situated at the interface between the canister and the bentonite block.

When studying the profiles of the total fraction of carbon and sulphur, an approximate penetration of 5 mm from the interface can be seen. Thus, the mineralogical/chemical analyses performed on material closer then 5 mm from the interface are influenced by the presence of the lubricant and are consequently of limited value.

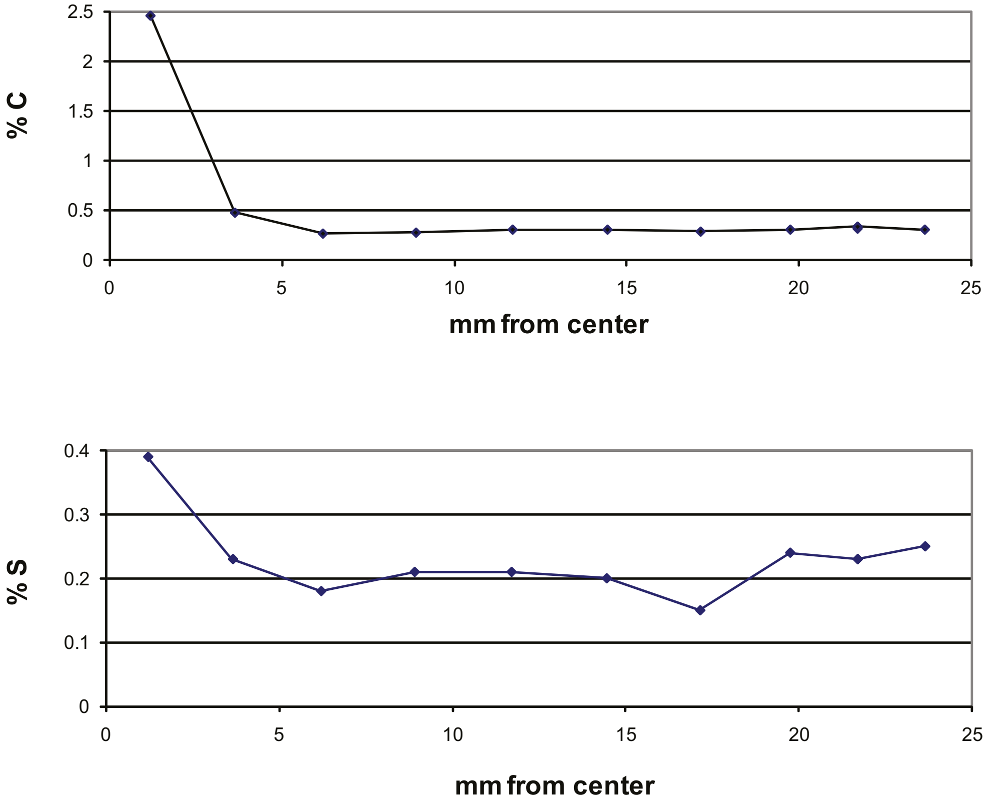


Figure 4-7. *Profiles of the total fraction of carbon (upper) and sulphur (lower).*

Modelling

During 2009, the EBS Task Force teams have continued their modelling of the CRT experiment and presented their new results at the meetings held in Stockholm and Pori. Several teams have presented results, both for smaller models where a disc of the buffer are studied in detail and for larger models of the entire experiment.

As an example, results from a simulation of the entire experiment are shown below. Iso-maps of dry density, obtained after running the experiment the number of days indicated at the top of each iso-map, are shown in Figure 4-8. In the simulation also the total force on the plug was calculated. In Figure 4-9 the total force on the plug obtained by the model is given in the left graph and the lower three curves in the right graph show the force measured in three of the total nine rock anchors. To obtain an estimate of the total force on the plug in the experiment, the sum of the three forces is multiplied by three. At the end of the simulation/experiment the values 8 kN and 9 kN are obtained, respectively.

Simulations of the Thermal, Hydraulic and Mechanical processes in CRT are also a part of the safety assessment analysis (SR-Site). In that context, the topic of buffer homogenisation has been studied with CRT data used for comparison. In Figure 4-10 a compilation of responses of an analytical model of a disc of buffer (containing a ring-shaped bentonite block and an outer pellet-filled slot) are shown. The pellet slot – buffer block void ratio combinations given by the analytical model, where different wetting processes (parallel or serial) and pellet slot – buffer block pressure ratios have been assumed, are shown in the left graph, where the CRT average void ratio combination is indicated with the red circle. To the right simplified void ratio profiles, corresponding to the points A–D in the left graph, are shown.

The void ratio profile obtained from a finite element model (developed for the Code Bright solver) of a disc of the buffer at canister mid-height is shown together with filtered experimental data in Figure 4-11. As can be seen, the match is very satisfying.

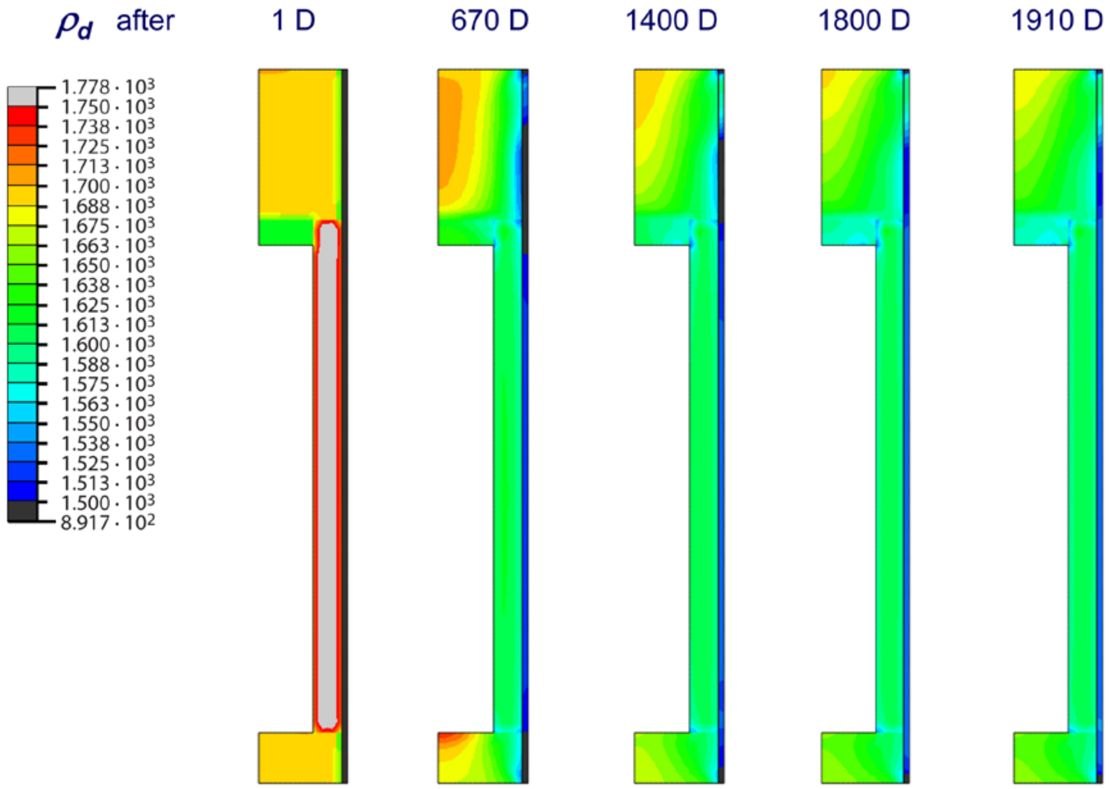


***Figure 4-8.** Simulated iso-maps of dry density after running the experiment the number of days indicated at the top of the iso-map.*

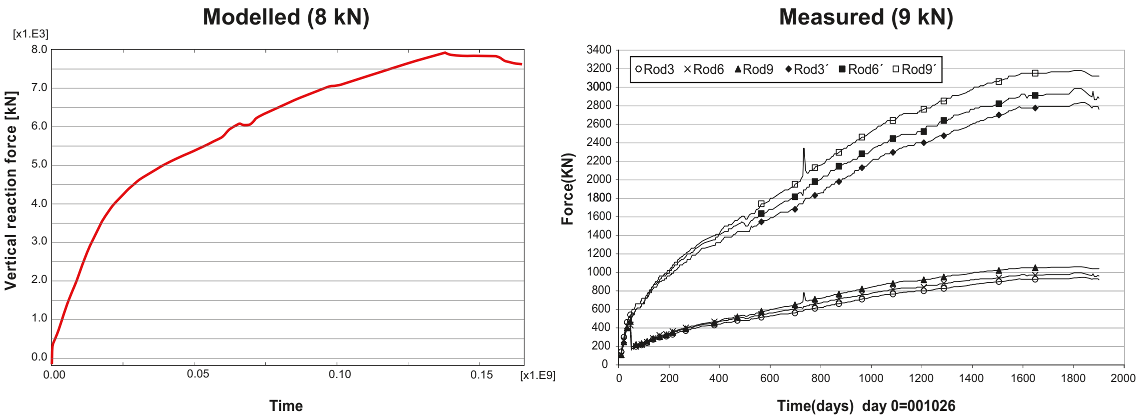


Figure 4-9. *Total force on the plug obtained from the model (left). Lower three measured curves, the force in three of the nine rock anchors (right). Note that to obtain the measured total force on the plug the sum of the three lower experimental measurements should be multiplied by three.*

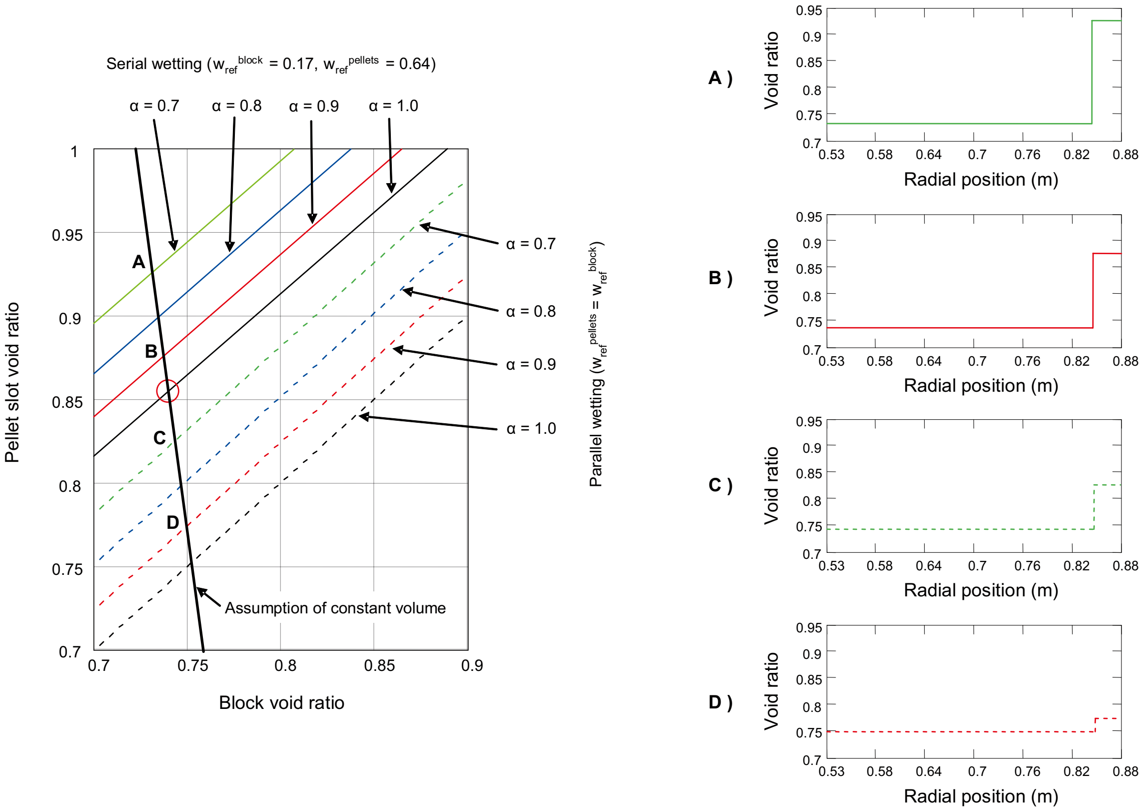


Figure 4-10. *Compilation of the analytical model results for serial (solid lines) and parallel wetting (hatched lines) assuming different pressure ratios. The obtained average void ratio profiles are shown for four different choices in wetting process and pressure ratio along the constant volume assumption with the CRT state (indicated by the red circle) as a reference.*

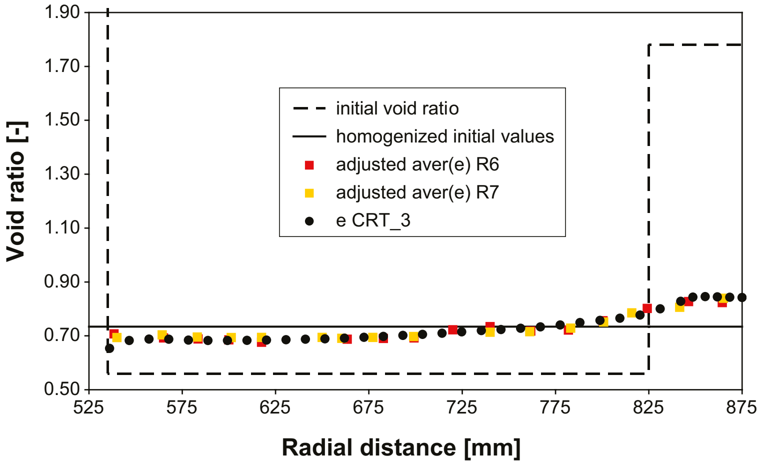


Figure 4-11. *Code Bright void ratio profile shown together with filtered experimental data from CRT.*

4.7 Temperature Buffer Test

Background

The Temperature Buffer Test (TBT) is carried out by Andra at Äspö HRL in co-operation with SKB. TBT aims at verifying and possibly improving current THM models of buffer materials at high temperatures, well over 100°C. Moreover, the experimental setup has been characterised by stationary, well defined, boundary conditions. This implies that the experimental activities at the test site up until 2006 have been run mostly at a routine basis, while the focus has been on different modelling tasks and general successive evaluation of obtained results.

Objectives

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

Experimental concept

TBT is located in the same test area as the Canister Retrieval Test (CRT) at the –420 m level. Two identical heaters, each 3 m long and 0.6 m in diameter, are stacked in a vertical 1.8 m diameter deposition hole. The principle design of the test and the experimental set-up are shown in Figure 4-12.

Two buffer arrangements are being investigated:

- One heater is surrounded by bentonite in the usual way, allowing the temperature of the bentonite to exceed 100°C locally.
- The other heater has a ring of sand between the heater 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.

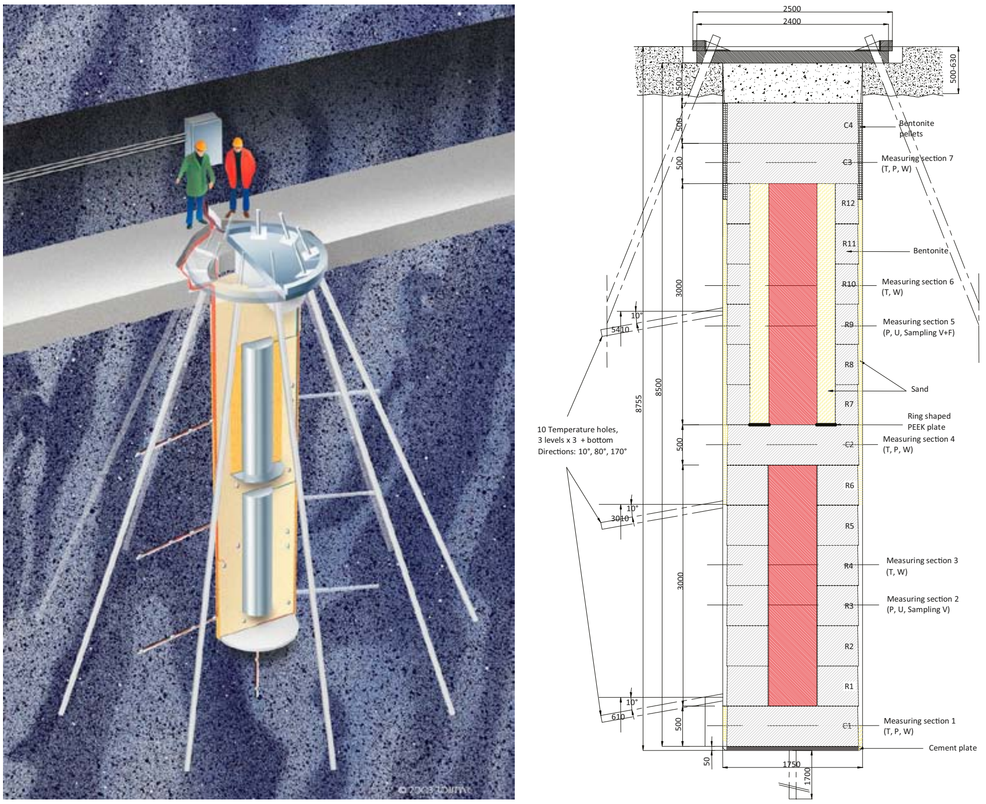


Figure 4-12. *Principle design and experimental set-up of the Temperature Buffer Test.*

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

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

Results

The evaluation of THM processes has been made through analysis of sensors data (for the latest report, see /Goudarzi et al. 2008/), through numerical modelling /Åkesson 2006a, Hökmark et al. 2007, Ledesma and Jacinto 2007/ and through evaluation and numerical modelling of parallel lab-scale mock-up tests /Åkesson 2006b, Åkesson 2008, Åkesson et al. 2009, Ledesma et al. 2006/. The final evaluation of the field test will be made when data from the dismantling will be available.

A number of experimental activities were earlier planned for the period 2007–2009. Three steps have been identified for the activity planning of the upper package: (i) evaluation of the THM processes (ii) a gas injection test and (iii) a retrieval test. The gas test will however not be carried out since it was shown that the buffer around the sand shield was not tight.

For the lower package the evaluation of the THMC processes, with operation at high temperatures, is the main point of interest. In order to promote mineralogical alteration processes in the lower package, the thermal output from the heaters was changed during the last two months of 2007. The power from the lower heater was increased from 1,600 to 2,000 W, while the output from the upper heater was decreased from 1,600 W to 1,000 W. The temperature distribution at the beginning of 2009 is shown in Figure 4-13. At this time the temperature on the mid-section of the lower heater was 155°C. The corresponding value for the upper heater was 86°C.

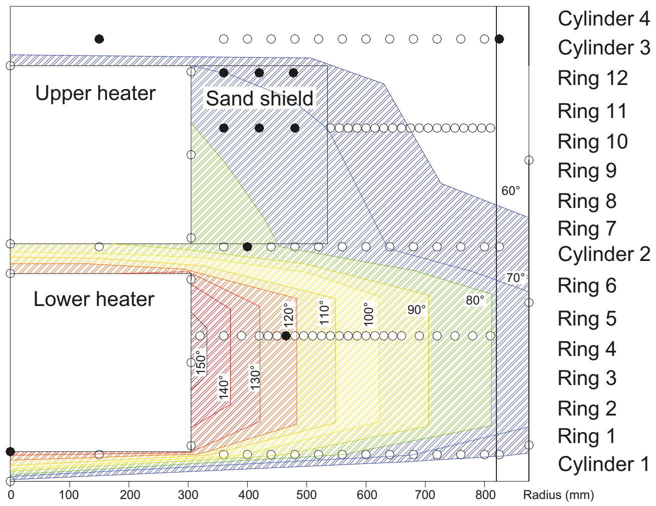


Figure 4-13. *Temperature distribution at January 1 2009. Rings indicate sensor positions. Filled rings indicate sensors out of order.*

Dismantling operation

The first dismantling planning meeting was held in December 2008. At this meeting it was decided that the time schedule for the dismantling would be moved to a date one year earlier than has previously been considered and therefore stated in the planning report for 2009. A second planning meeting was held in June 2009 at which a decision was taken to terminate the heating and the hydration and the end of August 2009; and also that the actual dismantling would begin at the end of October 2009. After this meeting, the detailed planning commenced. The operation has since been organised in thirteen different activities, out of which eight were started during 2009.

During the last two months of 2009 all the bentonite down to Cylinder 2 were sampled and removed. Core drilling (with 50 mm diameter cores) was used as the method for dismantling. The plan was to take core samples at 50 mm distance in four perpendicular directions in each block (Figure 4-14). In addition to this, two pieces (big sectors) representing the entire radial distance were to be taken from each block. In parallel to the dismantling operation, the core samples have been analysed for density and water content at the bentonite lab at Äspö. The evaluation of the results from these analyses is ongoing.

Figure 4-14. *Core sampling in Cylinder 4.*

The upper heater was retrieved after Cylinder 3 and 4 had been removed. This retrieval test was performed in two steps. The sand in the shield was first removed with an industrial vacuum cleaner after loosening the material through mechanical means (with hammer drill and core machine). After cutting the power cables to the heater, this was finally lifted from deposition hole (Figure 4-15). A front loader was used for applying a sufficient lifting force to release the heater from the bentonite underneath.

Significant fallout of material from the bentonite rings in the upper package (especially Rings 10–7) took place soon after the retrieval test. This appears to be a consequence of the removal of the sand shield which implied a radial unloading of the blocks. Traces of another mechanical event were found on the top surface of Ring 12 and at the bottom surface of Cylinder 3 (see Figure 4-16). Together with results from gauging, these traces suggest that the Ring 12 was pressed against and sheared the outer parts of the Cylinder 3. Finally it can be noted that it was fairly easy to separate large pieces of bentonite from the block surface underneath. This demonstrates that the interfaces between the bentonite blocks had not been fully healed.

Figure 4-15. *Lifting of Heater 2.*

Figure 4-16. *Traces of shear deformation in Ring 12.*

4.8 KBS-3 Method with Horizontal Emplacement

Background

The KBS-3 method, which is based on the multi-barrier principle, has been accepted by the Swedish authorities and the government as a basis for planning of the final disposal of spent nuclear fuel. The possibility to modify the reference design and make a serial deposition of canisters in long horizontal drifts (KBS-3H), see Figure 4-17, instead of vertical emplacement of single canisters in separate deposition hole (KBS-3V) which is SKB's reference design, has been considered since early nineties. The deposition process for KBS-3H requires the assembly of each copper canister and its buffer material in a prefabricated, so-called Supercontainer.

Most of the positive effects of horizontal emplacement compared with vertical emplacement are related to the smaller volume of excavated rock. Examples of positive effects are:

- Less environmental impact during construction.
- Reduced disturbance on the rock mass during construction and operation.
- Reduced cost for construction and backfilling of the repository compared to KBS-3V. However, great efforts are required developing the KBS-3H design.

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

Feasibility study and basic design, 2001–2003

The work on evaluating the feasibility of the method during 2001–2003 showed that KBS-3H is a promising alternative to KBS-3V, and therefore SKB and Posiva jointly decided to develop and demonstrate technology and to further investigate safety, environment and cost issues. A new feature of the KBS-3H design was the use of a Supercontainer, i.e. that the canister and buffer, surrounded by a shell would be deposited as a package in the horizontal deposition drift.

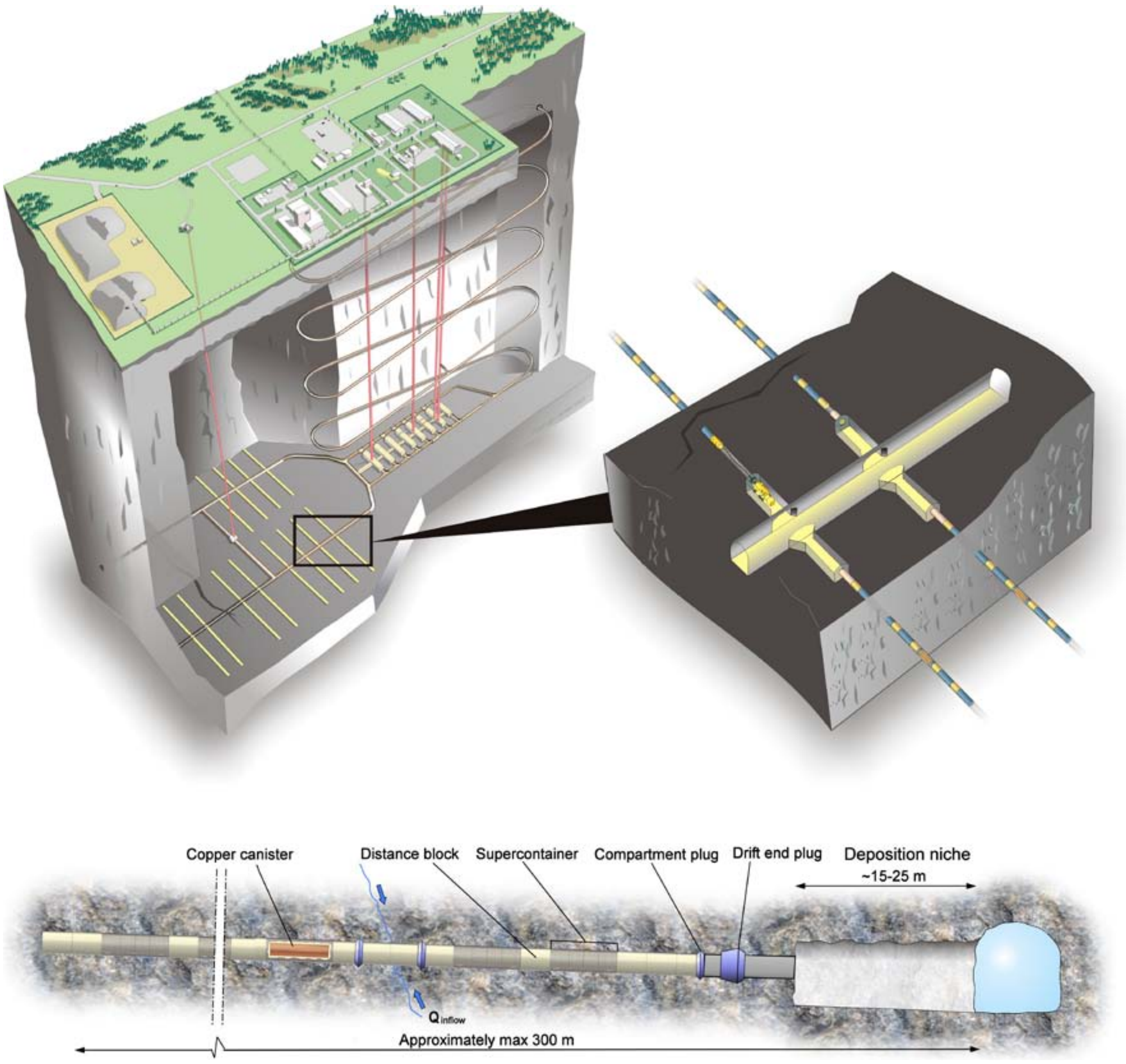


Figure 4-17. Schematic illustrations of KBS-3 with horizontal emplacement.

Demonstration, 2004–2007

The key issues that were highlighted for further study in the 2004–2007 phase of the programme were long-term safety, the overall KBS-3H design and specific buffer issues, the excavation of the deposition drift, assemblage and emplacement of the Supercontainer as well as retrievability, cost and environmental impacts.

The KBS-3H project made substantial achievements during 2004–2007: Two full-scale horizontal drifts were bored at Äspö HRL for the demonstration of the deposition of a mock-up Supercontainer and several other full-scale tests. The prototype equipment for the deposition was manufactured and tested in Äspö in realistic environment. The trial deposition of the 46 tonnes mock-up container was successful. Alternative designs for the KBS-3H have been prepared, as well as, an adaptation of an exploratory layout of a KBS-3H repository at the Olkiluoto site. Buffer tests were carried out at different scales. A safety assessment for a deep repository at Olkiluoto site, which is based on KBS-3H, has been carried out. The conclusion of the assessment is that the KBS-3H design alternative has the potential to demonstrate the safety of a repository at Olkiluoto site and that it fulfils the same long-term safety requirements as KBS-3V.

Some major uncertainties were detected during the project of which several are common with KBS- 3V. For example the behaviour of the buffer during the operational period and subsequent period of buffer saturation, where the risk for piping and erosion of bentonite may occur even for very low amount of water inflows (the present estimated limit is 0.1 L/min). KBS-3H specific issues were identified based on the safety assessment. Many of these are related to the impact of the steel shell in the Supercontainer and other steel structural materials present in the drift.

The work from the project phase during 2004–2007 is compiled in three main reports:

- Horizontal deposition of canisters for spent nuclear fuel – Summary of the KBS-3H project 2004–2007 /SKB 2008/.
- KBS-3H Design Description 2007 /Autio et al. 2008/.
- Safety assessment for a KBS-3H spent nuclear fuel repository at Olkiluoto – Summary report /Smith et al. 2008/.

Objectives

The results of the technical investigations, practical trials and assessments of the long-term safety and the benefits of the alternative show that there is justification for continuing with a fourth stage of the research programme – Complementary studies. Therefore SKB and Posiva jointly decide to continue the RD&D programme for KBS-3H for the period 2008 to 2010. The main goal of this project phase is to develop the KBS-3H method to such a state that the decision on full-scale testing and demonstration can be made. This requires additional evidence on:

- The behaviour of the buffer and other components (container and plugs) after emplacement.
- The long-term performance of the buffer including interaction with other materials.
- Construction, manufacturing and installation of the system.

The project is divided in four sub-projects: (a) Drift design, (b) Safety case, (c) Production and operation and (d) Demonstration and planning of full-scale test.

Demonstration site

Several suitable tests of the KBS-3H design were identified during the feasibility study. Investigations into a suitable location and preparation of a demonstration site at Äspö HRL were decided upon. The demonstration site is located at the –220 m level in a niche with the dimensions 15 by 25 meters. The niche is designed to accommodate the vehicles, machinery and auxiliary equipment used for drilling the holes. Two horizontal holes with a diameter of 1.85 m have been excavated, one being 15 m long and the other being 95 m. The short hole is used for construction and testing, e.g. of a low-pH shotcrete plug and a steel compartment plug, for design of drift components. The long hole is primarily used for demonstration of the deposition equipment and also for some full-scale tests.

Results

The main work carried out at Äspö HRL during 2009 and results is presented below. Work in the current project phase not performed at Äspö is not presented in this report.

Compartment plug tests

Extensive work has been carried out with the compartment plug, the rock notch was excavated without problems and the fastening ring was installed during the last weeks of 2008. The fastening ring was cast in the beginning of 2009, the collar and then the cap was installed together with the instrumentation, Figure 4-18.

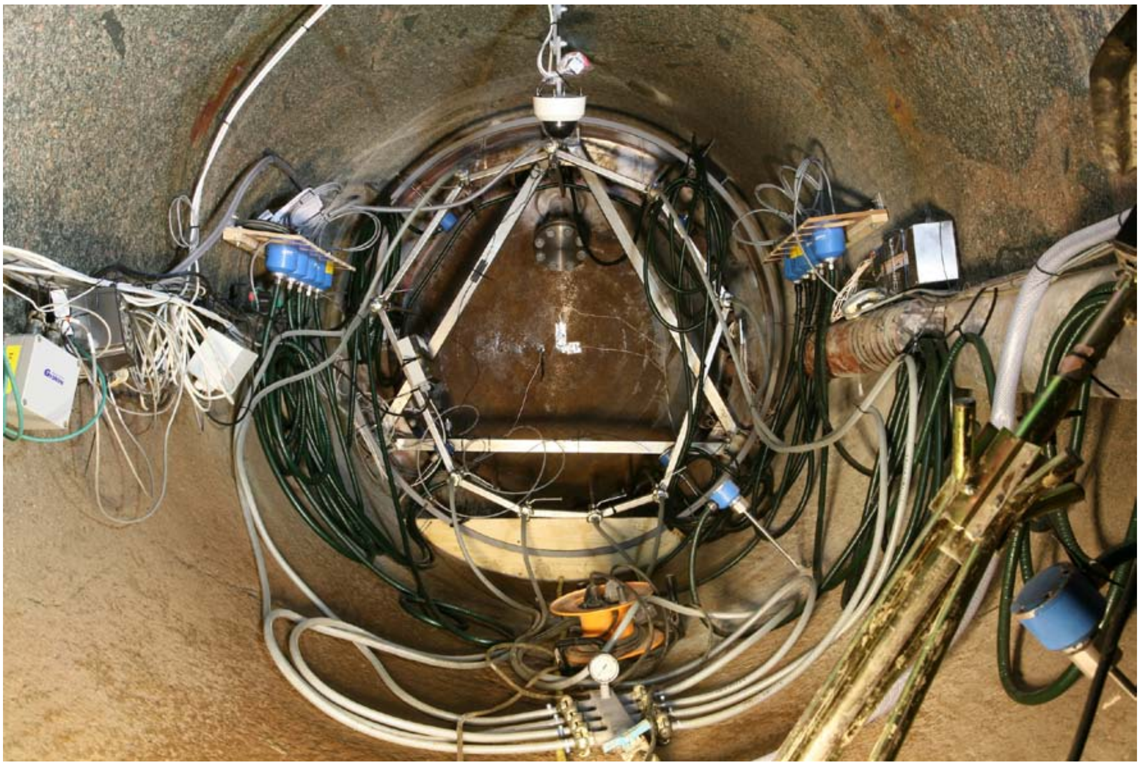


Figure 4-18. Fully instrumented compartment plug in DA1622A01.

In the first test the closed off section behind the plug was filled with water. A very low groundwater pressure was measured prior to the pressurisation of the plug. The test was then started and the water pressurised. The test design stipulates a target pressure of 5 MPa. Due to high initial leakages, above the allowed 0.1 L/min, the target pressure could not be reached, despite the use of an additional pump. The leakages appeared around the outer edge of the plug with the most significant leakage from a grouting tube running through the casting.

The casting was grouted with Silica sol gel in the preinstalled FUKO-tubes running through the casting. Grouting design was based on a water loss measurement carried out with a pressure of about 5 bars (3 bars over pressure) during 5 minutes, the flow was approximately 2.5 L/min. During the water loss measurement a small water leakage was noted at the threading between the grouting- and FUKO- tube but the main leakages were from the rock and concrete around the compartment plug.

Figure 4-19 shows the silica sol grouting process, a total amount of 30 L of silica sol was injected during 60 minutes at a pressure of approximately 5 bars (3 bars overpressure). The initial surface leakages were similar to the water leakages noted during the water loss measurement. The leakages decreased continuously during the grouting and were very low at the end.

The second test phase was initiated after grouting. The groundwater pressure measured in the section behind the plug was considerably increased after the grouting and there were no significant leakages. The section was subsequently pressurised to 5 MPa. During the 30 day test period the leakage was reduced from an already low starting level to virtually no leakage at all, Figure 4-20. An extra test also verified that the leakages were low from the beginning when a new pressurisation was carried out some days later.

KBS-3H deposition machine

The deposition equipment has been operated a couple of times each month throughout 2009 as a form of maintenance. The deposition method has worked well but the function of the equipment is no longer fully satisfactory and a larger fault localisation will be carried out during 2010.

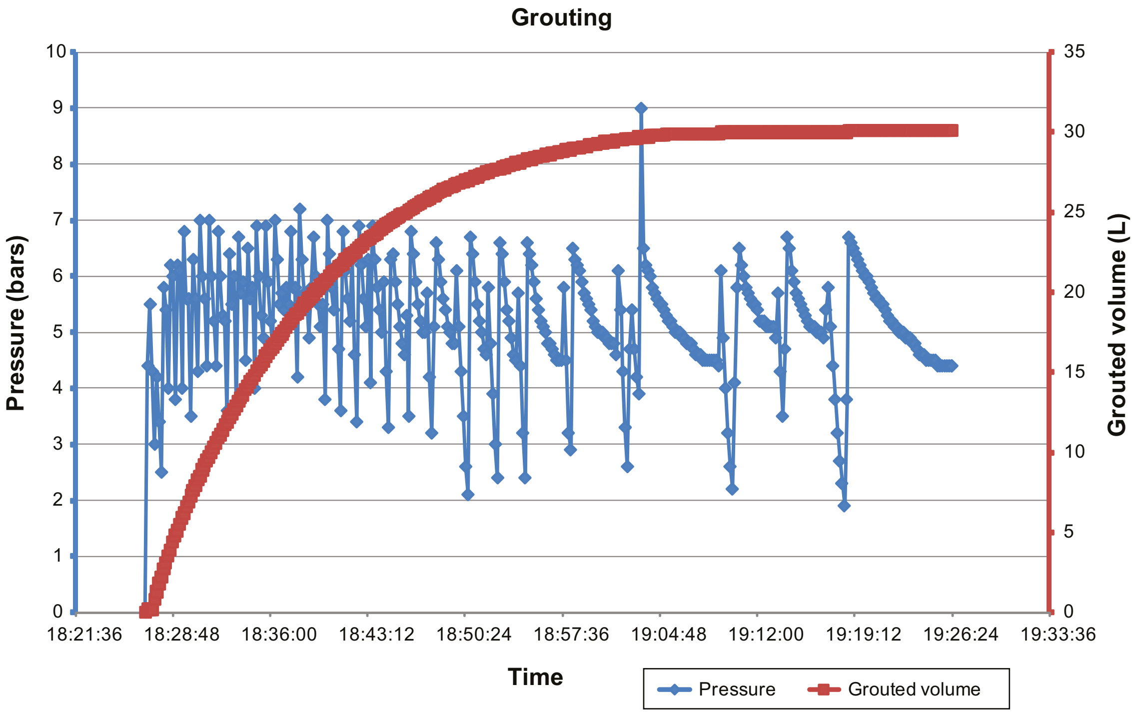


Figure 4-19. Grouting process with silica sol in the FUKO-tube around the steel plug.

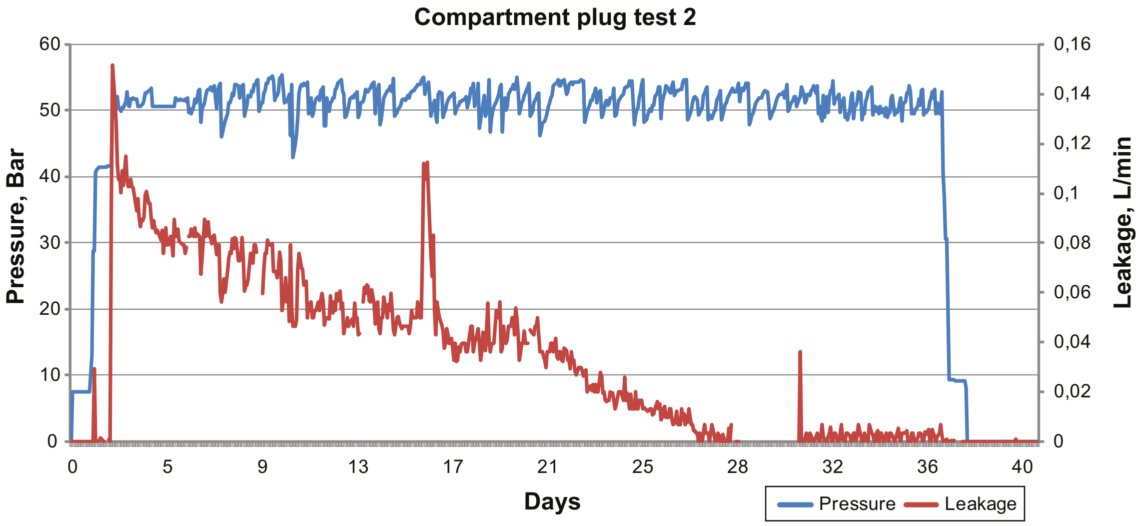


Figure 4-20. Pressurisation of the compartment plug after grouting.

4.9 Large Scale Gas Injection Test

Background

The large-scale gas injection test (Lasgit) is a full-scale in situ test designed to answer specific questions regarding the movement of gas through bentonite in a mock deposition hole located at the –420 m level in Äspö HRL.

The multiple barrier concept is the cornerstone of all proposed schemes for the underground disposal of radioactive wastes. Based on the principle that uncertainties in performance can be minimised by conservatism in design, the concept invokes a series of barriers, both engineered and natural, between the waste and the surface environment. Each successive barrier represents an additional impediment to the movement of radionuclides. In the KBS-3 concept, the bentonite buffer serves as a diffusion barrier between the canister and the groundwater in the rock. An important performance requirement of the buffer material is that it should not cause any harm to the other barrier components. Gas build-up from, e.g. 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 gas can not escape through the buffer, the increase in pressure could lead to mechanical damage of other barrier components.
- The gas could de-hydrate the buffer.

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

The experiment has been in continuous operation since February 2005. The first two years (Stage 1, up to day 843) focused on the artificial hydration of the bentonite buffer. This was followed by a year-long programme of hydraulic and gas injection testing (Stage 2, day 843 to 1110). A further year of artificial hydration occurred (Stage 3, day 1110 to 1385), followed by a more complex programme of gas injection testing, which is currently on going (Stage 4, after day 1385).

Objectives

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

- Perform and interpret a series of 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 processes governing gas migration.
- Provide high-quality test data to test/validate modelling approaches.

Experimental concept

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

In the field laboratory (Figure 4-21) instruments continually monitor variations in the relative humidity of the clay, the total stress and porewater pressure at the borehole wall, the temperature, any upward displacement of the lid and the restraining forces on the rock anchors. The experiment is a "mock-up test" which does not use any radioactive materials.

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

The *hydration phase* began on the 1st February 2005 with the closure of the deposition hole. The aim of this phase of the experiment is to fully saturate and equilibrate the buffer with natural groundwater and injected water. The saturation and equilibration of the bentonite is 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 provides an additional set of data for (T)HM modelling of water uptake in a bentonite buffer.

When the buffer is considered to be fully saturated, the main *gas injection phase* will start. A series of detailed gas injection tests will be performed and the processes and mechanisms governing gas flow in the bentonite will be examined. However, this will be augmented by a series of preliminary gas and hydraulic measurements performed at regular intervals as the buffer hydrates. This will provide detailed data on hydraulic and gas transport parameters for a bentonite buffer during the hydration process.

Results

The first quarter of 2009 began with a full calibration of Lasgit instrumentation in readiness for the second stage of preliminary gas testing. At this time, the interface vessel used during gas testing was reconnected and pressurised with helium in order to leak test the system. This was left at pressure for the remainder of the first quarter of 2009, which verified that the vessel was indeed gas tight.

Soon after calibration was complete (day 1472; February 11th) the hydraulic test was initiated. In the first set of gas tests performed during 2008 all artificial hydration filters were allowed to decay, including FL903 – the filter subsequently selected for gas testing. However, in order to save time the hydraulic pressure in FL903 was raised to the target value (4,250 kPa) and held constant for the duration of the test stage. Flux into the buffer was monitored, allowing permeability and storage to be calculated. Once the test stage was complete, the hydraulic pressure in FL903 was reduced to 1,000 kPa on day 1507. This value was estimated from the pressures of the neighbouring filters in the lower filter array. Analysis of the flow data indicated that the permeability of the clay around FL903 had reduced since the previous hydraulic tests undertaken in 2007.

Figure 4-21. *Panorama of the laboratory area for the large-scale gas injection test at the –420 m level at Äspö HRL.*

Following completion of the hydraulic tests, the system was re-calibrated and configured ready for gas testing (day 1577; May 28th). Contrary to the initial tests performed in 2007, neon was selected at the test permeant for this phase of testing (since neon is absent from the natural porewaters of Äspö, porewater samples could then be taken at regular intervals from surrounding boreholes in an attempt to track the movement of the gas). At the onset of testing, a known volume of neon was introduced into the interface vessel (and connecting tubework) and the pressure within filter FL903 set at 1,300 kPa. This pressure was maintained constant for approximately 4 weeks to allow the system to equilibrate while neon moved into solution saturating the fluid contained within the interface vessel.

Gas testing began on day 1606. Pressure within the test system was gradually raised over a 9 day period to the target value of 2,550 kPa, at which point the gas pressure was held constant and flux into the clay monitored with time. However, as gas pressure increased, gas flow into the clay began almost immediately, indicating that the pressure within FL903 was above the gas entry pressure. Once the pressure was maintained constant at 2,550 kPa gas flow into the clay dramatically reduced, resulting in a small background flux. This observation (which was seen in all successive constant pressure steps) was also observed during the initial gas tests performed in 2007.

Gas pressure was held constant at 2,550 kPa for approximately 12 days, at which point the second stage of gas testing was begun. As before, the gas pressure was gradually raised to the next target value of 3,800 kPa over a 9 day period, at which point the pressure was once again held constant.

On day 1659 (18th August) the interface vessel was recharged with neon in order to provide sufficient gas to complete testing. For the remainder of August pressure was kept constant in order to allow the system to equilibrate.

A third pressure ramp was initiated on day 1674, which gradually raised gas pressure to 5,050 kPa over a 16 day period. As with the previous steps, pressure was then held constant and flow into the clay continually monitored. Pressure was held constant for a total of 52 days (from day 1690 to 1742) for two reasons, (i) to see if gas flow into clay evolved with time and (ii) to maintain stable conditions near the Lasgit deposition hole in order to minimise its impact on a neighbouring test underway within the Äspö HRL.

The final gas injection stage was initiated on day 1742 (12th November) with a relatively slow injection rate of 500 micro litres per hour. Similar to previous pressure steps, gas flow into the clay rapidly increased following the start of gas injection. Pressure continued to rise until it reached a maximum of 5,870 kPa after 25 days of injection. This was followed by a spontaneous negative pressure transient very similar in form to those observed in small-scale laboratory tests /Harrington and Horseman 2003/.

Figure 4-22 shows gas flow into the bentonite buffer and the evolution of the injection pressure during this constant flow rate stage. As can be seen, prior to day 1766 gas flow into the clay was relatively small and constant, showing no sign of any significant pressure dependency. However, at day 1766 gas flow spontaneously increased. At day 1767 the pressure in FL903 began to drop as the gas permeability of the buffer increased. As observed in the laboratory experiments by Harrington and Horseman, the pressure in FL903 reduced and then increased as the system "under-shot" its ultimate level. By the end of the 2009 flow into the clay and the pressure in FL903 had appeared to asymptote. However this will be confirmed by continued injection in 2010.

Analysis of the total stress and porewater pressure sensors located within the Lasgit deposition hole indicate that gas flow is both localised and a highly complex dynamic process with pathways opening and closing probably in response to localised changes in gas pressure. Significant changes have been observed in a number of porewater pressure and total stress sensors, giving insight into the direction and propagation of the gas, as well as the complex hydromechanical response of the buffer clay. As observed in the previous gas test in 2007, propagation has been predominantly in a downwards direction. However, the extended period of gas injection post-break through has shown that gas pathways within the system are both highly dynamic, tortuous and continuously evolving, propagating to new locations within the deposition hole.

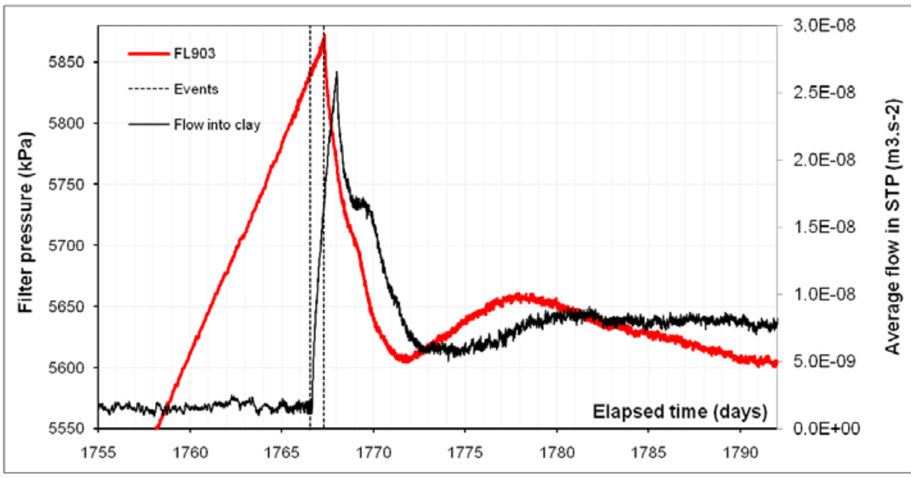


Figure 4-22. *The evolution of the injection gas pressure and the flow into the clay. The two black event lines represent the start of major gas flow into the clay at 5,833 kPa and the maximum gas pressure experienced (5,872 kPa).*

The test has now been in successful operation for in excess of 1790 days. In summary, the complete test programme has comprised of (i) initial hydration for approximately 2 years, (ii) hydraulic and gas test stages lasting for about one year, (iii) continued artificial hydration for a further year, and (iv) a second series of hydraulic and gas test stages (which are ongoing). The Lasgit experiment continues to yield high quality data amenable to the development and validation of process models aimed at repository performance assessment.

4.10 Sealing of Tunnel at Great Depth

Background

Although the repository facility will be located in rock mass of good quality with mostly relatively low fracturing, control of the groundwater will be necessary. The measures to control groundwater will include the sealing of fractures that are conducting groundwater, and may also include local draining or waterproofing as well as infiltration of water. Sealing will be achieved by means of grouting, which means filling the water-conducting fractures with grout so that the permeability of the rock mass close to the tunnel or rock cavern is reduced.

Experience from the grouting of road- and railroad tunnels shows that ordinary grouts based on cement cannot penetrate very fine fractures. Further, from a long-term safety view-point, a sealing agent that produces a leachate with a pH below 11 is preferred. Silica sol, which consists of nanosized particles of silica in water, has shown to be a promising grout. When a salt is added to the sol, a gel is formed. The concentration of the salt determines the gelling time and thus the grouting can be controlled. However, the use of silica sol under high water pressures has to be tested and equipment and grouting designs evaluated.

Another issue for the planned repository is the contour and status of the remaining rock after blasting. The rock is a natural barrier in the KBS-3-system and further KBS-3 includes a backfill with a defined density in the repository rock openings. In order not to unnecessarily disturb the natural barrier (the rock mass) and to provide good conditions for the engineered barrier (the backfill), the resulting rock wall has to be smooth and the fracturing induced by blasting in the so called excavation damaged zone (EDZ) has to be limited.

Objectives

The main goals of the project is to confirm that silica sol is a useful grout at the water pressures prevailing at repository level, and to confirm that it is possible at this water pressure to seal to the preliminary tightness requirement for a deposition tunnel. The project also has to show that it is possible to fulfil the demands related to blasting of the tunnel.

Experimental concept

To achieve the above mentioned objectives, SKB constructs the Tass-tunnel at the –450 m level in Äspö HRL. Execution is step-wise and includes grouting with ordinary grouting fans outside the contour, grouting with grout holes inside the contour and post-grouting. Low-pH cementitious grout is also tested. The project implements and evaluates grouting characterisation methods and grout spread models as developed by Chalmers.

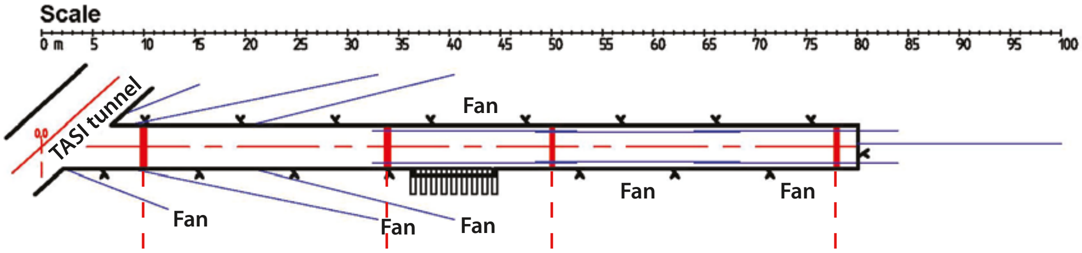
The requirements related to blasting are to minimise the EDZ, and that the resulting contour after blasting should follow the theoretical with very small deviations, to allow for efficient and controlled backfilling. Special attention is therefore given to drilling and blasting. The results are followed and evaluated closely and subsequent adjustments made.

To be able to evaluate the EDZ through direct observation of the fractures induced by blasting, the project also includes the excavation of rock blocks from the tunnel wall. The blocks are divided in 0.1 m thick slices in order to examine the character of the EDZ.

Results

Following the results, the execution of works with implementation of different fan geometries has been altered compared to the original set-up. The tunnel has a length 80 of meters. It includes two full grouting fans outside the contour (fans 2 and 3) and three fans inside the contour (fans 4, 5 and 6) and post grouting (fan 4), see Figure 4-23.

The inflow as encountered in core drilled holes in the pre-investigations, had peaks around 40, 25 and 50 L/minute at sections 20 m, 55 m and 75 m respectively. The requirement is to achieve an inflow that is limited to 1 L/60 meter and minute, or less. The inflow limit is distributed corresponding to the length of the section, so that e.g. the acceptable inflow for the 24 meter long section along fans 2 and 3 is 0.4 L/minute. In the tunnel, weirs are built at sections 10 m, 34 m, 50 m and 78 m and inflow measurements are carried out. The measurements show that the requirement on tightness is fulfilled along fans 2 and 3 (0.3 litres, section 10–34 m), as well as along fans 5 and 6 (0.4 litres, section 50–78 m), whereas the inflow is too large along fan 4 (1.2 litres, section 34–50 m).



Requirement	0.4	0.3	0.5	L/min
Inflow	0.3	0.8	0.4	L/min
Inflow	OK		OK	

Figure 4-23. *The Tass-tunnel fans, measuring weirs and inflows. Post grouting is planned for the middle section.*

Both silica sol and low-pH grout based on cement have been used in the sealing operations. Thus, the major project goal has been achieved, to show that it is possible to limit the inflow to less than 1 L/60 meter and minute in a tunnel at deposition depth, using grouts that are suitable for the final repository. This has been possible with ordinary grouting fans with grouting holes outside the tunnel contour. During grouting the reduction in inflow between the successive grouting rounds has been followed by inflow measurements in the control holes. A reduction of the transmissivity of the rock mass with a factor of up to 1,000 has been indicated.

The work with planning, preparation, follow-up and feedback during the rounds has contributed a lot to the improvement and the result of the rock excavations. The scanning result for the contour shows that the overbreak is about 15% which fulfil the requirement < 30% from the backfilling. The test with different look out angles of the blasting holes shows that 25 cm is manageable, less is possible but increases the risk for underbreak and it also slows down the process.

4.11 In Situ Corrosion Testing of Miniature Canisters

Background

The evolution of the environment inside a copper canister with a cast iron insert after failure is of great importance for assessing the release of radionuclides from the canister. After failure of the outer copper shell, the course of the subsequent corrosion in the gap between the copper shell and the cast iron insert will determine the possible scenarios for radionuclide release from the canister. This has been studied experimentally in the laboratory and been modelled. In this project miniature copper canisters containing a cast iron insert are being exposed for several years in boreholes in the Äspö HRL. Defects have been deliberately introduced into the outer copper canister so that evolution of corrosion inside the canisters can be investigated. The corrosion will take place under reducing, oxygen-free conditions in the presence of microbial activity present in the groundwater; such conditions are very difficult to create and maintain for longer periods of time in the laboratory. Consequently the in situ experiments at Äspö HRL will be invaluable for understanding the development of the environment inside the canister after initial penetration of the outer copper shell.

Objectives

The main objective of the work is to provide information about how the environment inside a copper canister containing a cast iron insert would evolve if failure of the outer copper shell were to occur. This is important because the development of corrosion products in the gap between the copper shell and the cast iron insert could affect the rate of radionuclide release from the canister. The results of the experiment will be used to support process descriptions and safety analyses. The following specific issues are being addressed:

- Does water penetrate through a small defect into the annulus between the cast iron insert and the outer copper canister?
- How does corrosion product spread around the annulus in relation to the leak point?
- Does the formation of anaerobic corrosion products in a constricted annulus cause any expansive damage to the copper canister?
- Is there any detectable corrosion at the copper welds?
- Are there any deleterious galvanic interactions between copper and cast iron?
- Does corrosion lead to failure of the lid on the iron insert?
- Are there any effects of microbial corrosion on the canister?
- What are the corrosion rates of cast iron and copper in the repository environment?
- What is the risk of stress corrosion cracking of the copper?

Experimental concept

Miniature canisters with a diameter of 14.5 cm and length of 31.5 cm have been set up in five boreholes, each with a diameter of 30 cm and a length of 5 m. The model canister design simulates the main features of the SKB canister design. The cast iron insert contains four holes simulating the fuel pin channels, together with a bolted cast iron lid sealed with a Viton O-ring. The copper lid and base are electron beam welded to the cylindrical body. The annulus between the cast iron insert and the outer copper body is <30 µm wide. All the canisters have one or more 1 mm diameter defect(s) in the outer copper shell, in a range of different orientations. The canisters are mounted in electrically insulated support cages, which contain bentonite clay of two different densities (Figure 4-24). There is no direct electrical contact between the copper canister and the stainless steel support cages. One experiment does not contain any bentonite, to investigate the direct effect of raw groundwater on the corrosion behaviour. Cast iron and copper corrosion coupons are mounted inside the support cages of each experiment and corrosion behaviour is monitored electrochemically (Figure 4-25). Cast iron and copper weight loss specimens are also present. Each support cage contains a 'sandwich type' copper-cast iron specimen to investigate oxide jacking effects and galvanic corrosion. U-bend and wedge open loading stress corrosion specimens are mounted in one of the boreholes in direct contact with the groundwater, to assess the possible risk of stress corrosion cracking of copper. In addition, two of the canisters are monitored using strain gauges to monitor any expansion effects. The redox potential, E_h, is being monitored using a combination of metal oxide, platinum and gold electrodes. The experiments are located where there are many fractures around the boreholes, leading to a plentiful supply of natural reducing groundwater to the experiments.

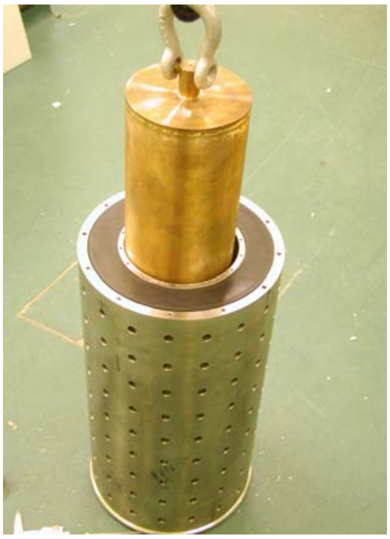


Figure 4-24. *Model canister being lowered into support cage containing bentonite pellets in annulus.*

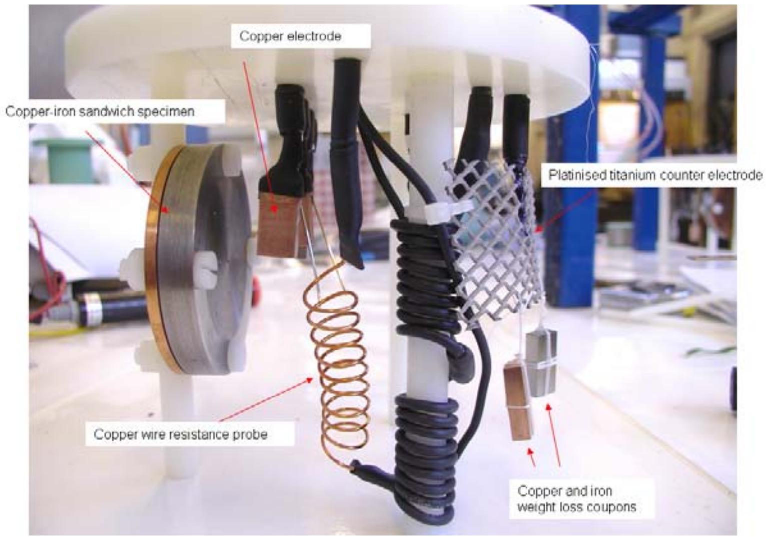


Figure 4-25. *Test electrodes inside support cage around model canister experiments.*

Results

During 2009, monitoring of the miniature canister experiments has continued. Data are being collected for corrosion rate of copper and iron electrodes, and electrochemical potentials for a range of electrodes, including E_h, iron and copper. In addition, strain gauge data are being collected for two of the canisters. Water analysis, including analysis of gases and microbial content of the water, was carried out up to autumn of 2007. A further campaign of water analysis was performed in the autumn of 2008. The results up to May 2008 have been compiled in to a report which has now been published /Smart and Rance 2009/. A decision has been taken to dismantle one of the experiments for examination (Experiment 3) and plans are being made for this procedure during 2011. Detailed analysis will be carried out to characterise the extent and form of any corrosion and the condition of the surrounding bentonite. The highlights of the results obtained to date are as follows:

- Water analyses have shown an increased concentration of iron (Figure 4-26) and a decrease in pH inside the support cages, which may be associated with microbial activity (particularly by sulphate reducing bacteria) affecting the corrosion rate of iron-based materials in the experiment (i.e. cast iron and/or stainless steel). Microbial activity has been characterised by Microbial Analytics.
- The measured E_h values are compatible with published literature and show a fall in Eh with time as any residual oxygen is consumed (Figure 4-27). This is confirmed by dissolved gas analysis. There have been some reliability problems with internal reference electrodes but these have been overcome by using alternative reference electrodes mounted in the boreholes outside the support cages.
- The electrochemically measured corrosion potentials and corrosion rates for both copper and iron coupons were initially comparable to published literature, but since then they have increased. It is not clear what is causing this increase in the measurement and whether or not it is a genuine result. The copper corrosion rates measured using an electrical resistance probe in two experiments remained low during 2009. The corrosion extent will be confirmed by weight loss measurements when the experiments are dismantled.

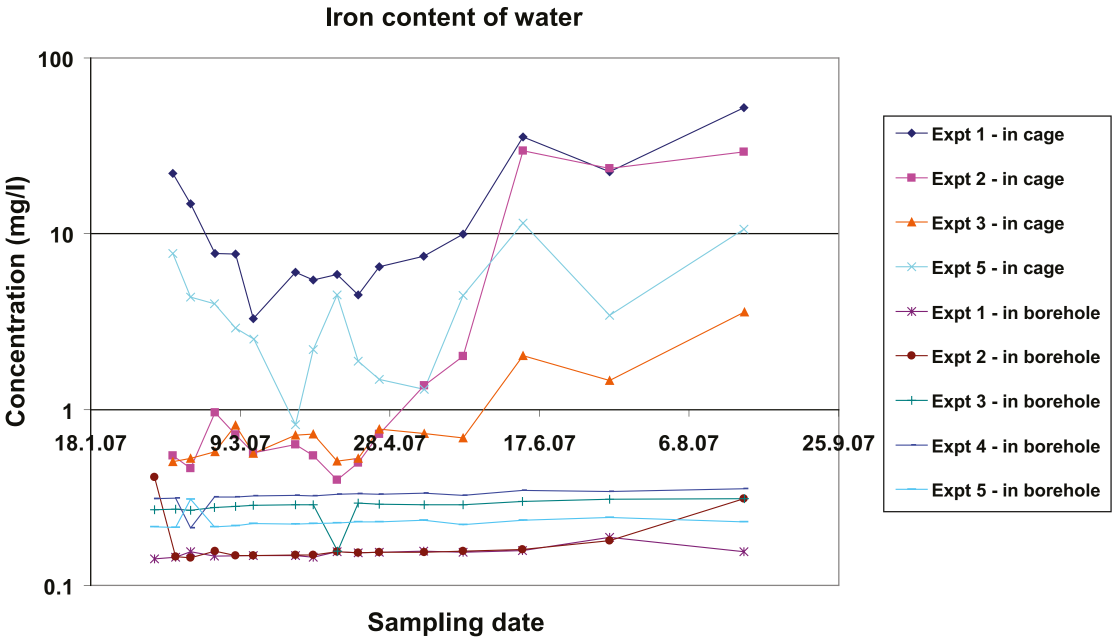


Figure 4-26. *Iron concentration inside and outside support cage around model canister experiments.*

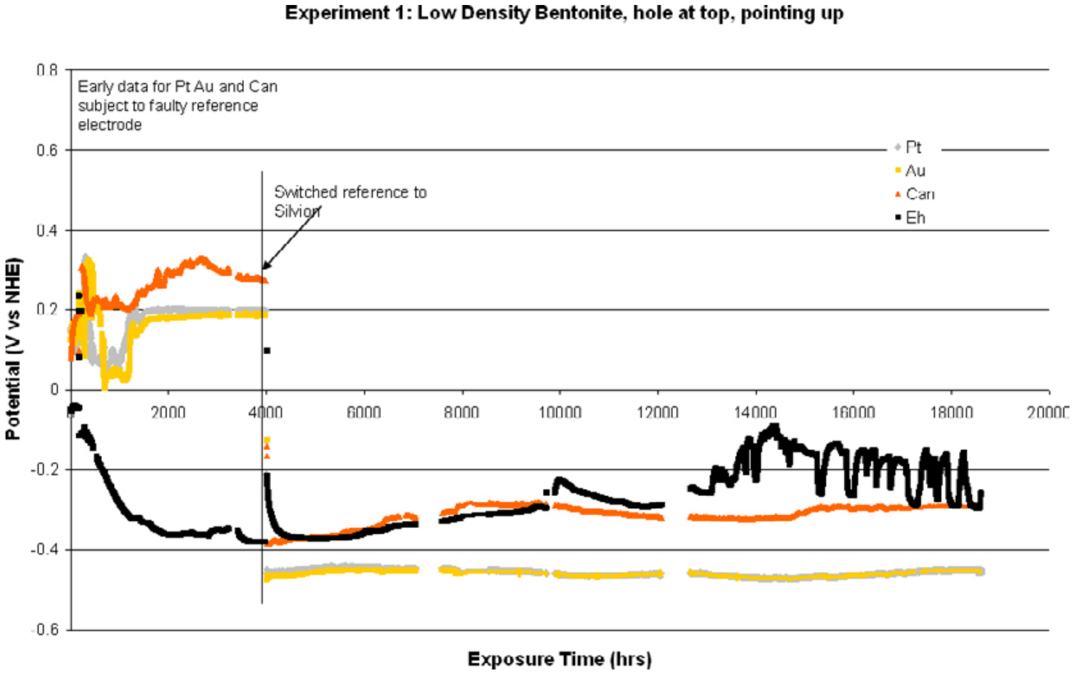


Figure 4-27. *Example results of electrochemical potential measurements for model canister experiments.*

4.12 Cleaning and Sealing of Investigation Boreholes

Background and objectives

The ultimate goal of the project is to find out how investigation boreholes can be sealed so they do not constitute flow-paths from repository depth to the biosphere. This requires development and selection of suitable sealing methods and to develop strategies for application to holes of different length and orientation. This has been investigated in earlier phases which led to practically useful materials and techniques. The two sub-projects 1 and 2 of the present Phase 4 have included characterization of a number of investigation boreholes with respect to the frequency and nature of water-bearing and weak fracture-rich zones including use of the DFN model for identifying suitable location of clay and concrete plugs. This has been made for reference boreholes at Forsmark, Laxemar and Äspö and formed the basis of the technical/economical assessment that was initiated in year 2009.

Results

The major activity in year 2009 has been to compare the sealing function of plugs of different quality in long and short boreholes in the vicinity of a KBS-3V repository. This activity included assessment of the importance of time-related degradation from initially being tighter than the surrounding rock to being absent by dissolution and erosion. It forms the basis of an ongoing technical/economical assessment of plugging efforts. The results from the conceptual modelling work will be presented in the final report by early 2010.

Two additional sub-projects of practical importance were introduced in 2009; Sub-project 3 dealing with permanent sealing of two 300 mm diameter boreholes used in the TRUE project, and Sub-project 4 concerning chemical interaction of plugs of low pH concrete (developed by the Swedish Cement and Concrete Research Institute, CBI) and smectite-rich clay (MX-80). The first mentioned involved development of a plan for locating concrete and clay plugs following the principle of casting concrete where strongly water-bearing fracture zones are intersected and actual performance of the plugging. The other comprised retrieval of an 80 mm borehole with CBI concrete cast upon a clay plug consisting of pure MX-80 bentonite covering a plug of "Basic" type, i.e. a tube of perforated copper tube containing very strongly compacted clay elements. The outcome of the Project 4 is summarised as follows:

Sub-projects 1 and 2

Following the proposed principle of selecting and characterising reference boreholes the work included:

- Assessment of the importance of the holes before and after sealing with respect to the hydraulic function, the major parameter being the frequency of intersected zones.
- Assessment of the importance of expected difficulties in performing stabilization and plugging, (water inflow, unstable rock).
- Consideration of the representativeness of the boreholes ("typical" i.e. few fracture zones, and "extreme" i.e. frequent fracture zones).
- Estimation of the importance of hydraulic short-circuiting of fracture zones.
- Preparation of development of alternative techniques for placing clay plugs ("Container Plug") by investigating the evolution of compacted clay elements placed directly in the boreholes containing clay and concrete.

The work included assessment of the impact of curvature and diameter variation of boreholes with respect to the placeability of borehole plugs. The main conclusions are summarised below.

Measurement of the borehole shape has given the basis of evaluation of the curvature of the holes. For a clay plug length of 12 m the critical deviation from an assumed straight axis would be about 4 mm over this length, corresponding to a radius of curvature of about 4,000 m. This is fulfilled by several but not all of the examined holes, but any local sharper bend would imply that the tube is in contact with the borehole walls at its ends. The sensitivity of the curvature is hence such that very careful characterisation of the shape of the borehole is required.

Calliper measurements have shown that the diameter varies between 76 and 78 mm over the larger part with widening to 78–80 mm over about ¼ of the total length and locally to 80–82 mm of the intended 76 mm holes. One concludes from available data that there may be considerable deviations from the intended diameter and smoothness of the boreholes and that one has to further investigate the actual variations in diameter and topography of the borehole walls for drawing safe conclusions of how they can affect the density and tightness of clay plugs.

Sub-project 3 – sealing of 300 mm boreholes

The principal design of the borehole sealing is shown in Figure 4-28.

The construction steps were as follows:

- Gravel filled in the lower 2–5 m part of the hole.
- Water pumped out.
- Packer removed for placement of a clay plug.
- Sets of blocks of compacted clay placed around a central copper rod.
- Mechanical packer placed for securing the stack of blocks for 3 days.
- Concrete cast to seal the uppermost part of the holes and secured by a steel beam bolt-anchored to the rock.

The concrete was prepared according to the CBI recipe. For preparation of clay blocks, a soda-activated bentonite with 80% montmorillonite and 16% water content was used (CEBOGEL).

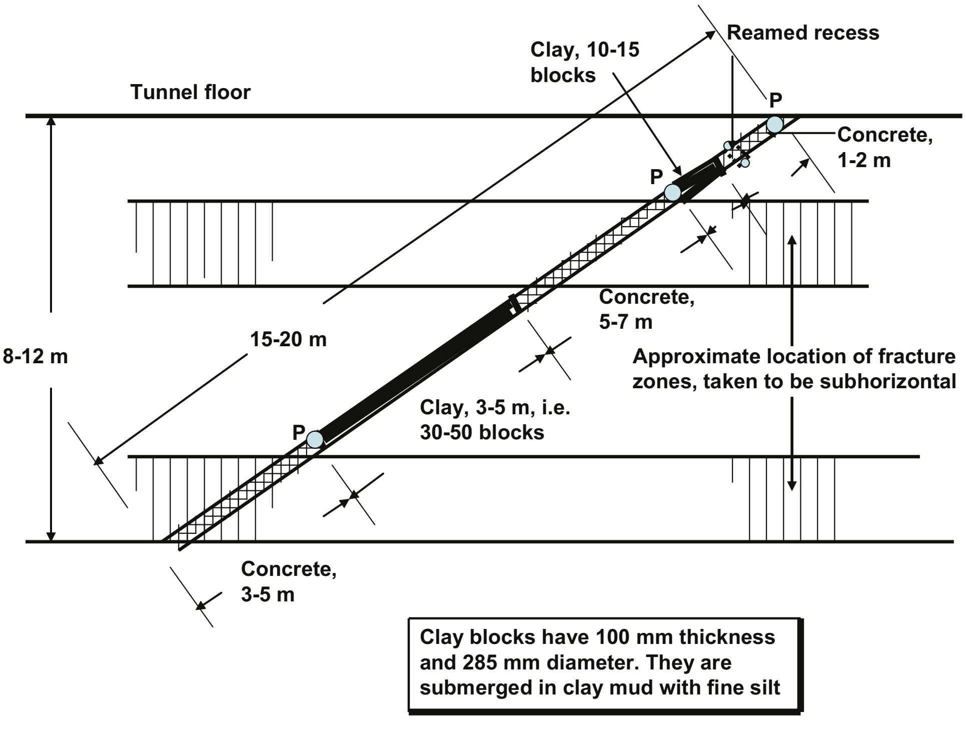


Figure 4-28. *The finally proposed borehole sealing method for the 300 mm holes.*

The matured clay plugs will have a density of around 2,000 kg/m^3 (dry density about 1,550 kg/m^3) and a hydraulic conductivity of less than 10^{-12} m/s, which is at least one order of magnitude lower than the bulk conductivity of the surrounding rock mass. This provides excellent sealing of the holes deeper than about 1–2 m below the tunnel floor. Groundwater flowing around the clay plugs can cause some minor erosion of the clay where it is in contact with expected water-bearing fractures but this effect is deemed negligible.

Sub-project 4

The proposed concept of sealing deep boreholes in repository rock implies that the parts of a borehole that passes through fracture zones in the rock shall be filled with a mixture of suitably graded quartz material stabilized by a small amount of low pH cement (Q/C plug). Between these fillings the hole shall be sealed by a tightly fitting plug of dense smectite-rich clay. While the larger parts of clay plugs are believed to stay chemically intact for hundreds of thousands of years, the parts adjacent to Q/C plugs may undergo changes and so can the Q/C plugs. Degradation of the clay plugs can generate zeolites or amorphous silica/aluminium complexes with high hydraulic conductivity and no swelling pressure. Two boreholes with 80 mm diameter were plugged with clay and concrete plugs in 2006 and one of them was retrieved in December 2009 for detailed analysis of the contact region. This work is ongoing and will be reported in early 2010.

General conclusions

The performed modelling and practical work have been successful. However, it still remains to be demonstrated that stabilisation of intersected fracture zones can actually be made in deep holes. Also, it must be certified that the intended borehole diameters are really obtained since they strongly determine the net density of the clay plugs and thereby their hydraulic conductivity.

4.13 Task Force on Engineered Barrier Systems

Background

The Task Force on Engineered Barrier Systems is divided in two parts, one related to THM/gas processes and one related to chemical processes.

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

- THM modelling of processes during water transfer in buffer, backfill and near-field rock. Only crystalline rock is considered in this phase.
- Gas transport in saturated buffer.

Since these tasks do not include chemical interactions, a decision was taken by IJC to also start a parallel Task Force that deals with chemical processes in engineered barriers. This Task Force was initiated at the end of 2006.

The two Task Forces have common secretariat (Clay Technology) but separate chairmen (THM/Gas: A. Gens, UPC and Chemistry: Urs Mäder, University of Bern).

Objectives

THM/Gas

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

Chemistry

The objectives of the chemical part of the EBS Task Force can be summarized as:

- Development of models and concepts for reactive transport. This is particularly important for bentonite, for which many of the available general numerical geochemical tools are not suitable. In this context code developers have been invited for discussions and presentations. A related issue is to make clear the validity range for different conceptual models.
- Link the atomic scale to the macroscopic scale in bentonite.
This link is crucial for fundamental understanding of coupling between mechanics (swelling) and chemistry. This area is explored by e.g. Molecular dynamics modelling of the interlayer space and Poisson-Boltzmann theory.
- Test numerical tools on provided experimental data (benchmark testing). This objective naturally couples back to the two previous.

Concept

THM/Gas

All defined tasks are given in Table 4-2. Participating organisations besides SKB are at present: Andra (France), BMWi (Germany), CRIEPI (Japan), Nagra (Switzerland), Posiva (Finland), NWMO (Canada) and RAWRA (Czech Republic). All together 12–14 modelling teams are participating in the work.

Chemistry

SKB (Clay Technology), Nagra (University of Bern), Posiva (VTT, B+Tech), and Andra has participated in the chemistry part of the Task Force. Several experimental data sets have been made available for modelling (Benchmarks 1–4), listed in Table 4-3. Each participating modelling team are free to approach this data with the concepts and models they find suitable.

The chemistry part of the Task Force also allows for presentations of model developments and calculations made outside the scope of the proposed benchmarks (e.g. Molecular Dynamics).

Table 4-2. Modelled tests in the Task Force on Engineered Barrier System.

Benchmark 1 – Laboratory tests

Task 1 – THM tests
- 1.1.1 Two constant volume tests on MX-80 (CEA)
- 1.1.2 Two constant volume tests on Febex bentonite – one with thermal gradient and one isothermal (Ciemat)
- 1.1.3 Constant external total pressure test with temperature gradient on Febex bentonite (UPC)

Task 2 – Gas migration tests
- 1.2.1 Constant external total pressure (BGS)
- 1.2.2 Constant volume (BGS)

Benchmark 2 – Large scale field tests

Task 1 – URL tests (AECL)
- 2.1 Buffer/Container Experiment and Isothermal Test

Task 2 – Äspö HRL test (SKB)
- 2.2 Canister Retrieval Test

Table 4-3. Experiments for which data has been provided for tests in the chemistry part of the Task Force on Engineered Barrier System.

Benchmark 1 – Diffusion of NaCl in Na-montmorillonite and $CaCl_2$ in Ca-montmorillonite (ClayTechnology)
Benchmark 2 – Gypsum dissolution and diffusion in Na- and Ca-montmorillonite (ClayTechnology)
Benchmark 3 – Ca/Na-exchange in montmorillonite (ClayTechnology)
Benchmark 4 – Core infiltration test on material form parcel A2 in the Lot-experiment (UniBern)

Results

Two Task Force meetings have been held during 2009; one in Stockholm (Sweden) in May and one in Pori (Finland) in November. For information about performed work within the different tasks by the international organisations, see Chapter 7.

The first phase of the Task Force has been concluded and a second phase will start in 2010.

THM/Gas

Benchmark 1 – Laboratory tests

The modelling of Benchmark 1 (Tasks 1 and 2) was finished and reported in 2007. A summary report of Task 1 will be published.

Benchmark 2 – Large scale field tests

Task 1 (modelling of the Buffer/Container Experiment and the Isothermal Test) has been finished during 2008 and 2009 and results have been presented at the meetings. Many modelling teams could get good results by changing parameter values, especially the retention curve of the buffer and the properties of the rock, but not for both the laboratory tests and the field tests with the same parameters (unless using different approaches like a "cluster model"). Final reports have been delivered.

Task 2 that concerns modelling of the Canister Retrieval Test at Äspö HRL has been the main modelling object during 2009 and altogether 8 modelling teams have been involved. The task is divided into two parts where the first part is to model the thermo-hydro-mechanical behaviour of a central section of the test hole with given boundary conditions. The second part is to model the whole test. Most teams have finished their calculations in 2009. Five of the teams have modelled the entire test, while the other three have only modelled the central section. Reports of these results are requested before the end of March.

Four suggestions of modelling tasks in the next phase were presented at the meeting. They will be prepared during spring 2010.

Sensitivity analyses

This task that implies sensitivity analyses with simple models. The purpose is to provide better understanding of the relationship between simulation variables and performance results regarding:

- Understanding of coupled processes active in the field.
- Identification of relevant key coupled processes.
- Identification of key parameters.
- Effects of parameter uncertainty on results.

Task 8: hydraulic interaction rock/bentonite

This task focuses on the hydraulic interaction between the rock and the bentonite and is a joint task with the hydrogeology group. The main project goals are:

- Scientific understanding of the exchange of water across the bentonite-rock interface.
- Better predictions of the wetting of the bentonite buffer.
- Better characterisation methods of the canister boreholes.

The task is related to and concerns modelling of a planned Äspö test in a project called Brie (Buffer-rock interaction experiment). Preparations for this task have been ongoing in 2009.

Homogenisation

This is a task related to erosion and subsequent homogenisation but can also refer to homogenisation in general. The general understanding of bentonite is that it has excellent swelling properties but the homogenisation is not complete due to friction, hysteresis effects and anisotropic stress distributions. The task is proposed to involve two phases. In the first phase a number of simple laboratory tests that have been made will be modelled and used for checking/calibrating the mechanical model. In the next phase one or two laboratory tests that simulate bentonite lost in a deposition hole will be performed and preceded by predictive modelling.

Prototype Repository

This task is to model one of the two outer deposition holes in the Prototype Repository in Äspö HRL. The motivations for this task are:

- Identical geometry with CRT but natural hydraulic interaction with the rock.
- Extensive instrumentation.
- Interaction buffer/backfill.
- The test will be excavated just in time to be included in the next phase.
- It is partly a true prediction.
- It can be a joint task with the TF groundwater modelling.

Chemistry

At the May meeting data for Benchmarks 2 and 3 was presented by Clay Technology (SKB).

The creator of the reactive transport code Crunchflow, Carl Steefel (contracted by Nagra), presented new features implemented in the code, specifically the ability to define a diffuse double layer. Further, discussions were held regarding the possibilities to treat equilibrium with interlayers /Birgersson and Karnland 2009/ in the code.

Further, Clay Technology (SKB) presented theoretical calculations of the Ca/Na selectivity coefficient using Poisson-Boltzmann theory (couples to Benchmark 3), B+Tech (Posiva) presented modelling of cement-bentonite interaction in a buffer using the numerical tool Thoughreact, PSI (Nagra) gave a status report on their ongoing diffusion experiments of charged species in bentonite, and UPC presented a chemo-elastoplastic model for bentonite.

At the Meeting in November, calculations on Benchmark 1 – 3 as well as a correlation corrected Poisson-Boltzmann theory was presented by Clay Technology (SKB). The latter provides a numerically efficient way to calculate swelling pressure in systems containing di-valent ions.

Further, VTT (Posiva) presented a microstructural interpretation of XRD, SAXS and chloride porosity measurements in bentonite and Martinel (Posiva) discussed a thermodynamic approach to bentonite as a mixture.

A final report which concludes the work performed in the chemistry part of the Task Force is under production.

Issues to be addressed in the new phase of the geochemical part of the Task Force is a further focus on coupling between chemistry and mechanics, interactions with bentonite and other phases (e.g. cement, metal or gases), and to model larger scale experiments, in particular the Lot-test. Also, calculation on the atomic level, molecular dynamics in particular, will be further developed.

5 Äspö facility

5.1 General

The Äspö facility comprises both the Äspö Hard Rock Laboratory and the Bentonite Laboratory. Important tasks of the Äspö facility are the administration, operation, and maintenance of instruments bas well as development of investigation methods. The Public Relations and Visitor Services group is responsible for presenting information about SKB and its facilities. They arrange visits to the facilities all year around as well as special events

In May 2009 part of the Äspö operation underwent an organisational change as the units *Äspö Hard Rock Laboratory* and *Repository Technology*, both within the Technology department were united. This change was done to focus the remaining development of the repository technology and performing of experiments and tests in a realistic repository environment at Äspö HRL. The new and larger unit inherited the name *Repository Technology.* Äspö HRL is the residence of the unit but the unit includes employees in both Äspö and Stockholm. The main responsibilities of the unit are to:

- Perform technical development commissioned by SKB's programmes for nuclear fuel and for low- and intermediate level waste.
- Develop the KBS-3H concept.
- Perform experiments in the Äspö HRL.
- Secure a safe and cost effective operation of the Äspö HRL.
- Prosecute comprehensive visitor services and information activities in the Oskarshamn area.

The Repository Technology unit is organised in five operative groups and an administrative staff function:

- *Geotechnical barriers and rock engineering (TDG),* responsible for the development, testing and demonstration of techniques for installation of buffer, backfill and plugs in deposition tunnels, backfilling of the final repository and plugging of investigation boreholes.
- *Mechanical- and system engineering (TDM),* responsible for the development, testing and demonstration of equipment, machines and vehicles needed in the final repository.
- *Project and experimental service (TDP),* responsible for the co-ordination of projects undertaken at the Äspö HRL, providing services (administration, design, installations, measurements, monitoring systems etc) to the experiments.
- *Public relations and visitor services (TDI)*, responsible for presenting information about SKB and its facilities with main focus on the Äspö HRL.
- *Facility operation (TDD),* responsible for the operation and maintenance of the Äspö HRL offices, workshops and underground facilities and for development, operation and maintenance of supervision systems.
- *Administration, quality and planning (TDA*), responsible for planning, reporting, QA, budgeting, environmental co-ordination and administration. The staffing of the Äspö reception and the SKB switchboard are also included in the function.

5.2 Bentonite Laboratory

Background and objectives

Before building a final repository, further studies of the behaviour of the buffer and backfill under different installation conditions are required. SKB has built a Bentonite Laboratory at Äspö, designed for studies of buffer and backfill materials. The laboratory has been in operation since spring 2007. The bentonite Laboratory enables full-scale experiment under controlled conditions and makes it possible to vary the experiment conditions in a manner witch is not possible in the Äspö HRL.

The laboratory, a hall with dimensions 15×30 m, includes two stations where the emplacement of buffer material at full scale can be tested under different conditions. The hall is used for testing of different types of backfill material and the further development of techniques for the backfilling of deposition tunnels.

Experimental concept

The project is termed Impact of water inflow in backfilled deposition tunnels. The objective of the project is to investigate the impact of inflow from the rock on the constitution and properties of the pellet backfill in deposition tunnels. It is preceded by tests on different scales with similar intentions but without the present objective of identifying the detailed, actual process of water uptake of the pellet fill, and of determining realistic multi-point inflows corresponding to real rock structure.

Rock/pellet tests

Focusing on the mechanisms that control migration and distribution of water entering pellet fills from inflow spots in the rock. The tests made on blasted rock slabs for identifying how water is taken up from “dry” and “wet” rock by pellet fills and flows along the rock/pellet contact.

- The mechanisms that control the migration and distribution of water entering pellet fills from water-bearing rock fractures.
- Rock in the form of blasted slabs with a volume of 0.1 to 0.5 m^3.
- The impacts of the tunnel wall surface on the maturation of contacting pellet fill.
- The flow of water along rock/pellet contacts.

Results from these eight tests will be a complement in the interpretation of the half-scale tests.

Half-scale tests

In the “1/2-scale” tests, water entering from inflow spots into the pellet fill in steel tunnels simulates water bearing fractures. A series of tests are made with inflow from sets of inflow spots that are connected and injected with Äspö water at realistic flow rates, preliminarily 0.1 to 0.2 L/min. The selection of the location of the spots is based on actual fracture mappings of water-bearing fractures in blasted Äspö tunnels. One test series is made so that wetted pellet fill is placed in contact with “dry pellets” for simulating the case of quick water saturation of parts of the tunnel backfill separated by less wet pellet fill into which water flows at a late stage.

Test series will describe:

- The distribution of water migration from fractures providing water at different rates before breakthrough takes place. The purpose is to find out what the critical inflow rate is in order to estimate what the backfilling rate is in meters per day without meeting significant problems with softening of placed backfill.
- Creation of piping in partly water-saturated pellet fills. The phenomenon may appear in deposition tunnels that have been backfilled to a distance of several tens of meters from the filling front. In such tunnels the progressing saturation of the backfill has led to an increased water pressure in the backfill causing piping if the pressure gradient is critically high. Outflowing water may cause softening of the just-placed backfill and require removal of it and of buffer and canister at the front.

In parallel to the dismantling operation in TBT, the core samples have been analysed for density and water content at the bentonite lab at Äspö. The evaluation of the results from these analyses is ongoing.

Results

The eight rock/pellet tests and four half-scale tests performed during 2009 will be reported in first quarter 2010 when all the tests are finished, see Figure 5-1 and Figure 5-2.

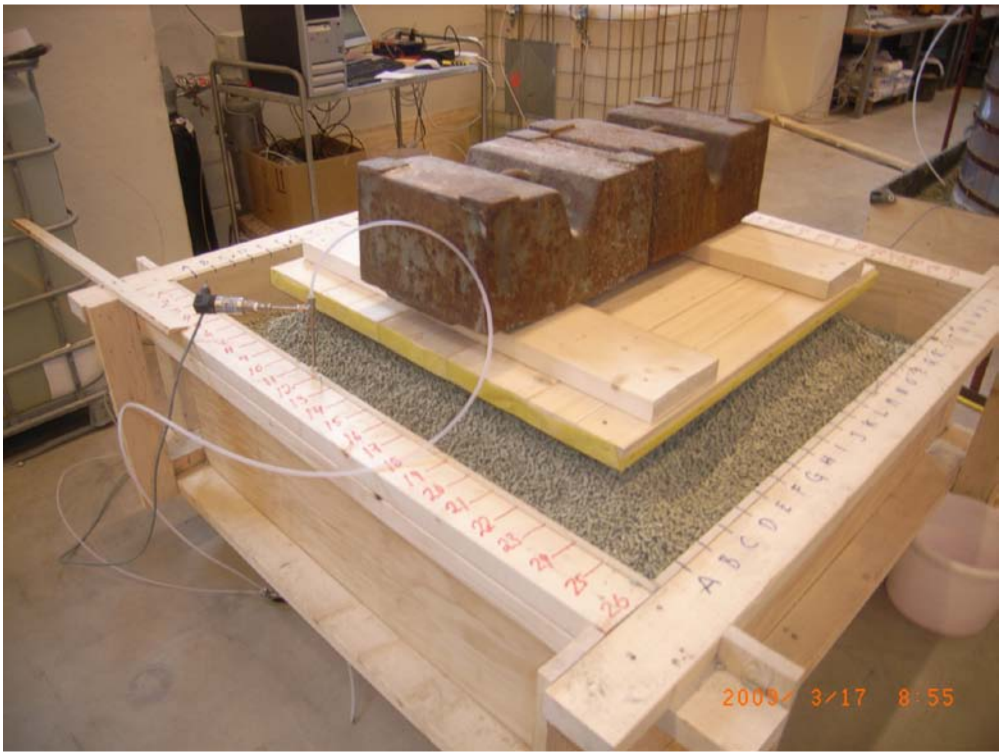


Figure 5-1. *Rock/pellet test.*

Figure 5-2. *Half-scale test.*

5.3 Facility Operation

Background and objectives

The main goal for the operation of the rock laboratory 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.

Results

The operation of the facility during 2009 has been stable, with a very high degree of availability. At the beginning of the year, the newly built archive was opened and transferred to department V. The construction of the catering dining-room where employees and visitors can have lunch was completed in March.

A new store room and a new environment-station have been built by the entrance to the tunnel. A warehouse has been hired in Oskarshamn for the storage of large amounts of bentonite under frost-free conditions.

During the spring, routines for entry to the facility were updated, and the object-surveillance system which has been developed by SKB for the registration of people and vehicles underground was introduced. Upgrading of the shell-protection (the break-in alarm) has been carried out in order to cover all the new buildings at the facility.

The planned replacement of electrical installations in the elevator shaft was carried out during the summer holiday period. As usual, the elevator cable was inspected during the summer and was approved without any remarks. A short pre-study has been carried out regarding an upgrade of the elevator's steering system. The planned work will be divided into two stages in 2010.

In order to improve traffic safety, the road to Äspö laboratories has been widened in some places and crash barriers have been put in.

The facility has installed a larger diesel tank for the special fuel which is used underground. The fuel is also available for purchase to contractors.

A reserve-power feed-system has been installed underground to ensure the function of the network in case of power-cuts. The network collects and sends information to the facility's operational surveillance system and must work in emergencies for a period of at least four hours.

The last days of the year were very cold and the ventilation and heating system was operating at its limits. A heat-pump for the offices broke-down and an extra electric boiler was installed to cope with the demand for heating. Other heating systems needed adjusting to cope with the cold weather.

Restoration work is being carried out where the project Sealing of Tunnel at Great Depth was earlier and will be completed during 2010.

Four of the facility operation group's personnel have moved to the new machine group. Responsibilities within the group are therefore being reallocated.

Work with the planned laying of a sewage pipe to OKGs treatment plant has still not been able to be performed because no agreement had been made with the owners of the fishing rights. An agreement was reached at the end of 2009 and pipe-laying is planned for 2010. An agreement was also reached between OKG and SKB regarding SKB's building of a water reservoir at the Äspö HRL for its own use and also to supply neighbouring external properties.

5.4 Public Relations and Visitor Services

Background and objectives

The main goal for the Public Relations and Visitor Services Group is to create public acceptance for SKB, which is done in co-operation with other departments at SKB. The team is responsible for visitor services at Äspö HRL, the Central interim storage facility for spent nuclear fuel (Clab) and the Canister Laboratory. The information group has a special booking team at Äspö HRL which books and administrates all visits. The booking team is also at OKG's service according to agreement. The team also has the responsibility for the production of SKB's exhibitions.

During 2009, the three facilities in Oskarshamn were visited by 13,129 persons. The visitors represented the general public, municipalities where SKB has performed site investigations, teachers, students, politicians and journalists. The number of visitors representing the media has tripled this year, much due to the selection of site for the building of the final repository. In addition, the information group takes care of and organises visits for a great amount of foreign guests every year and we see an increase in these as well. The visits from other countries mostly have the nature of technical visits and the total number of foreign visitors 2009 was 1,726. The total number of visitors to all SKB facilities and site investigation activities in Oskarshamn and Forsmark was 21,157, see Figure 5-3.

Site selection

In June 2009 SKB decided to select Forsmark as the site for the final repository for Sweden's spent nuclear fuel. The information officers have been engaged in different PR activities related to the site selection and M/S Sigyn on tour June-July.

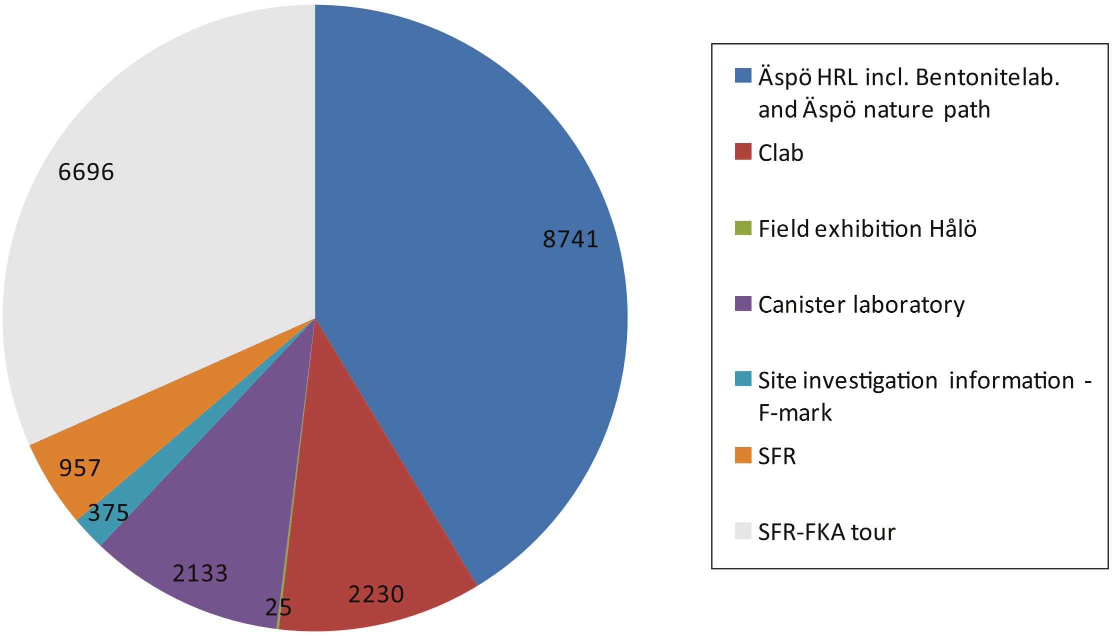


Figure 5-3. *Number of visitors to the SKB facilities.*

Special events and activities

In 2009 following events and activities took place:

- SKB has special exhibitions open for the public at Forsmark and Oskarshamn. The exhibitions in combination with visits to the facilities give the visitors a good picture of what SKB does and wants to do. A new design for exhibitions has been developed during spring 2009, and in May there was a grand opening of a quite new exhibition in Forsmark at the nuclear power plant.
- There have been a number of VIP-visits during the year, e.g. the European Atomic attachés meeting, which took place 13–15th of July. All the facilities in Oskarshamn were visited. The meeting was an arrangement within the Swedish Presidency of the European Union.
- The special summer arrangement "Urberg 500" at Äspö and "Urberg 50" at SFR went on for six weeks. Just as last year Äspö HRL was closed for maintenance work during two weeks in July. Around 2,200 persons participated at Äspö and around 2,300 at SFR.
- During the summer time SKB has, with good result, run radio ads to invite local people to the different facilities.
- Like every year, SKB visited the harbour of Visby with the transportation ship M/S Sigyn during the traditional political week "Almedalsveckan" (June 28– July 3). Every party with a seat in the Swedish parliament is present. SKB had the opportunity to meet many of the politicians and organisations. This summer Sigyn also was on tour to Stockholm, Öregrund (Östhammar) and Oskarshamn. Members of the group have been engaged in the whole tour.
- On account of an inquiry from SKB's technical staff and the Swedish Ministry of the Environment, an exhibition took place at IAEA General Conference in Vienna in September. Personnel from the Public Relations and Visitor Services group and the technical staff prepared the exhibition and also represented SKB in Vienna. The exhibition contained information about SKB's facilities, site investigations, history and planned future facilities.
- The national event "The Geology Day" takes place every year all over Sweden to give people the opportunity to learn more about geology. One of the participating organisations is SKB and in September people were invited to geological and cultural excursions at Stensjö village. Focus was on the issue why the bedrock is important to a final repository. About 90 people participated.
- The 25th of September a contribution to "EU's Researchers' Night" was held at Äspö, with research on groundwater in focus. The event attracted about 60 persons. Another 171 persons listened to the lectures online.
- On the 28th of November the Äspö Running Competition was held in the Äspö-tunnel. 70 participants, men and women, ran all the way up to the surface from –450 metres depth. This event has been a tradition for eleven years now and is much noticed by media.
- An event called "The Environmental Day" was held at Äspö on the 1st of December. The theme of the day was the eutrophication of the Baltic Sea. The event was held in co-operation with Äspö Environmental Research Foundation and about 60 persons participated.
- On the 5th of December an event was held at Äspö as a contribution to "Oskarshamn in Light". The event consisted of a light and music show down in the laboratory. 65 people took the chance to visit Äspö and at the same time see the show.
- SKB IC and SKB's technical staffs have predicted an increase of visits from international visitors. Preparations for dealing with this have been intensified during the period and are an important part of SKB's strategy for visits, that the group chief is about to complete. Parallel to the work with a visit strategy, also an exhibition strategy is prepared.
- An organisational review of the department of EIA and public information has been initiated. The group has been interviewed and workshops have been taking place.

6 Environmental research

6.1 Nova Research and Development (Nova FoU)

Background and objectives

SKB and Äspö HRL have a general policy to broaden the use within the society concerning research results, knowledge and data gathered within the SKB research program. Nova FoU (www.novafou.se) is the organisation which implements this policy and facilitates external access for research and development projects to SKB facilities in Oskarshamn (Figure 6-1). Nova FoU is a joint research and development platform at Nova Centre for University Studies and R&D supported by SKB and the municipality of Oskarshamn. Nova FoU provides access to the Hard rock laboratory and Bentonite laboratory at Äspö and the Canister laboratory in Oskarshamn.

Nova FoU can co-finance the projects by providing access to the SKB facilities, knowledge and data. The costs for these accesses will be calculated by Nova FoU, and will correspond to the amount co-funded by Nova FoU. The aim with the research and development projects through Nova FoU is to create long term spin-offs and business effects beneficial to the region.

Nova FoU supports new and innovative research, for example environmental studies, where the extensive SKB data set from geological, hydrogeological, hydrogeochemical and ecological investigations and modelling can be used (Figure 6-2).

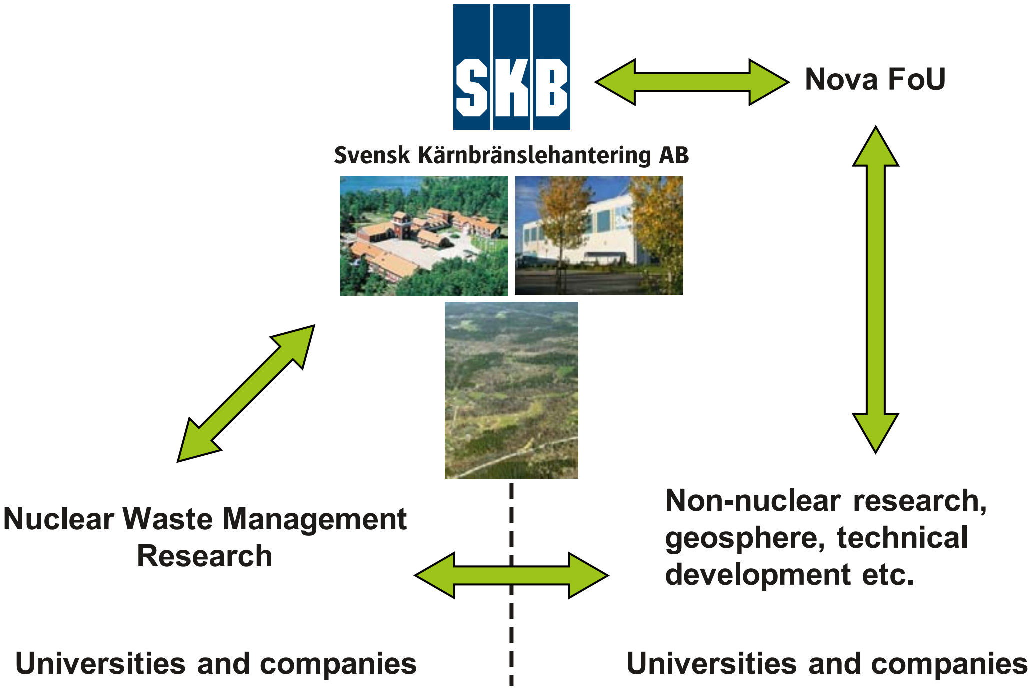


Figure 6-1. *Nova FoU provides access to the SKB facilities and data for universities and companies for non-nuclear research and technical development. Nuclear waste management research is handled by SKB.*

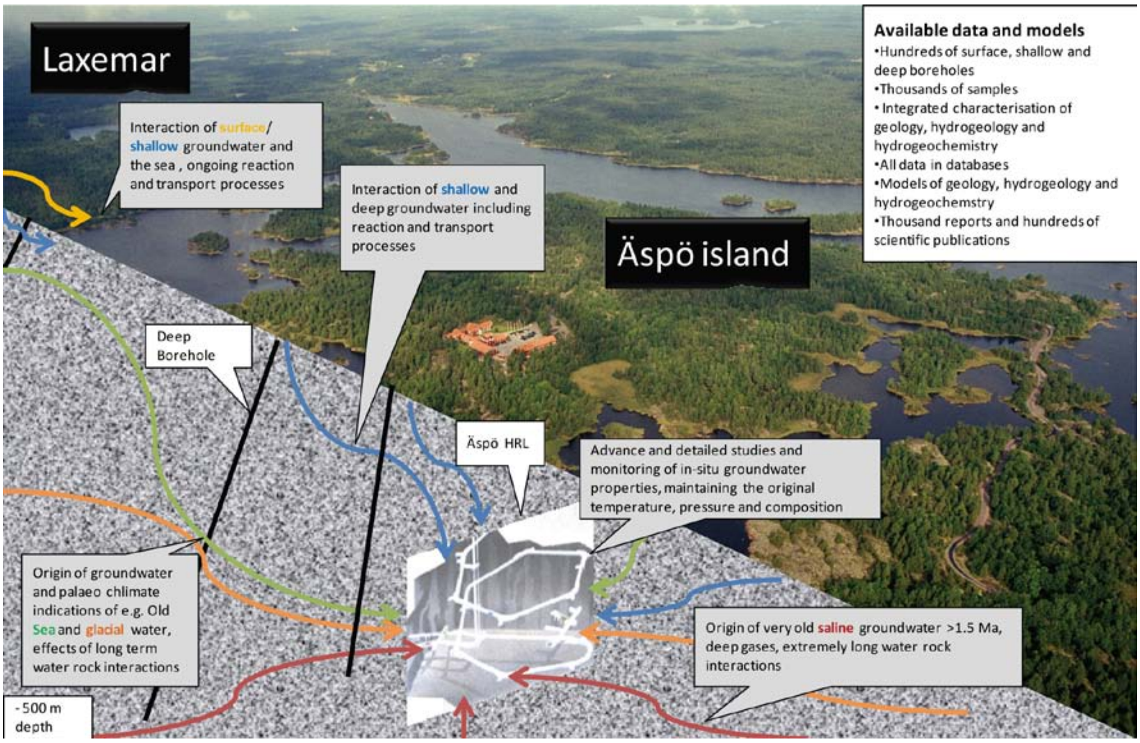


***Figure 6‑2.** The Äspö and Laxemar areas have been studied in terms of geology, hydrogeology, hydrogeochemistry and ecology. This information can be used for a number of purposes, for example to describe the water cycle and hydrogeochemical processes in 3D.*

The data can be used e.g. for assessing the consequences of natural resource management and pollution risks. The data and models can be used to estimate exposure both at individual and population levels. Development of monitoring and analytical systems can be performed relating to the management of various renewable natural resources in, for instance, agriculture, fisheries, forests and groundwater. Studies which give a better knowledge concerning pollution problems coupled to toxicological and epidemiological issues are possible. Technology, innovations and spin-off effects at pre-market stages are of special interest. Other possible studies are:

- Groundwater origin, mixing and evolution.
- Interaction between surface/shallow groundwater with deep groundwater and sea.
- Model and technology development.
- Tunnel and borehole experiments.

Results

Ongoing research and development projects, new project activities and marketing activities at Nova FoU:

Ongoing projects

- Linneaus geochemistry group at Äspö HRL (LnU)
- Research on microorganisms in groundwater (GU)
- Research on microorganisms in groundwater (University of Göttingen)
- Modelling of hydrological pathways (KTH)
- System development, RFID software Alfagate (NeoSys)
- System development, Fireprotection (NeoSys)
- Energy Efficiency (EoS)

Proposed projects/activities

- Formation of an expert group associated with the harbour remediation project in Oskarshamn
- Master education for final disposal
- Water management
- EU-project
- Added value discussion
- Input to the monitoring program for Laxemar and Äspö / Äspö HRL
- Commercialisation of existing SKB-technique

Communication activities

- Meetings with EU, Vinnova, Formas, Mistra, VR and other corresponding organisations
- Communication activities together with SKB to invite universities
- Identification of research teams

Short description of the ongoing Nova FoU projects:

- **Research and education**: The Linné Geochemistry Group (for details see the chapter below) at Äspö HRL consists of a professor, an associated professor, a post doc and three Ph.D. students. Focus is on research of chemical elements in soil, water, bedrock fractures and biota, and includes detailed studies of how elements are distributed in streams and groundwater at various depths. The research includes field monitoring, laboratory work and modelling. The research projects are funded by Linnaeus University, SKB and KK-Stiftelsen.
- **Microbes**: Research concerning geogas driven biosphere at Äspö HRL (University of Gothenburg). For details see chapter 3.5.
- **Coastal modelling**: Hydrogeological pathways and coastal dynamics with integrated transport and altering processes in water from land to sea (Royal Institute of Technology, KTH).
- **3D localisation system of persons, the Alfagate project**: Development and application of RFID-technology in tunnel environment. Creates an open software structure which is not dependent of hardware and which will be integrated with other Äspö HRL systems (NeoSys AB).
- **Integrated fire protection, the SAFESITE project**: Fire alarm and safety system associated with the final repository development and application of the RFID-technique (NeoSys AB).
- **Microbes II**: Biomineralisation, biogeochemistry and biodiversity of chemolithotrophic microorganisms in the Äspö tunnel (University of Göttingen).
- **Utilisation of low graded heat, the EoS project**: Research and technological development to utilise excess heat from industry (Municipality of Oskarshamn).

The research and education programme is the most matured activity within Nova FoU and is therefore described in more detail in the section below.

6.1.1 Linné Geochemistry Group

Background and objectives

The Linné Geochemistry Group (previously called "Geochemistry Research Group") is part of the Nova FoU platform. It is financed mainly by SKB and the University of Kalmar.

A major progress was that two new persons were hired to participate in the research group. Dr Henrik Drake was employed as a post doc and Tobias Berger as Ph.D. student. Drakes´ research will focus on characterisation of young fracture filling minerals, including pyrite and calcite, in bedrock cores drilled in Laxemar and Äspö. Ph.D. student Berger will also work in Laxemar and Äspö and focus on hydrogeochemical studies of groundwaters and surface waters. He will initially work with characterisation of sources and pathways of fluoride, which occurs in exceptionally high concentrations e.g. in Kärrsviksån. After that he will continue to work on lanthanides in the same area. Both Drake and Berger have been working with detailed planning and performed successful sampling campaigns. Details on the research activities are found on: www.skb.se/asporesearch.

Results

During 2009, five articles were published (see section 8.2). A seminar for PhD students was arranged twice. In the first seminar five PhD students gave a presentation and in the second one seven PhD students. The theme of this seminar series is "geochemistry" (in the broad sense). The total number of participants in each seminar was about 20, and each presentation (20–25 min) was followed by an equally long time of questions and discussions. The PhD students were representing Royal Institute of Technology, Kalmar University, Lund University and Umeå University. The PhD students are partly or entirely connected to Äspö HRL and SKB and/or Nova FoU.

The work included new findings on trace metal distribution in solid materials (mainly fracture minerals) and the aqueous phase (stream waters, groundwaters, sea water). Particular focus was on uranium and typical trace metals such as nickel, zink, cadmium, cobalt and copper. A special emphasis was also on black shale, which is a bedrock type carrying high amounts of sulfide and trace metals and thus constitutes a source of environmental contamination. Details of the scientific investigations are provided in the scientific papers listed in section 8.2. Below follows some selected and important results.

Figure 6-3 shows SEM-picture of pyrite in borehole KLX10 at –357 m depth. The pyrite crystals are supposed to be young, and will be analysed for isotopic composition in order to more precisely define the prevailing conditions during precipitation.

In Figure 6-4 SEM-pictures of calcite in borehole KLX10 at –698 m is shown. The calcite has been analysed for its content of several major and trace elements. These data show that for example the lanthanoid group of metals occur in highly variable concentrations and also with different fractionation patterns in the calcite crystal. This will provide information on the conditions prevailing when the calcite was precipitated on the fracture walls.

A laboratory experiment showed that several toxic metals, including uranium and nickel, are abundantly mobilised when black shale material is exposed to oxidising conditions (Figure 6-5). The rate of release will depend to a considerable extent of the grain-size distribution of the rock and soil material.

In Figure 6-6 uranium versus Cl concentrations for terrestrial and Baltic Sea surface waters is shown. The origin of the data is listed below:

– Atlantic water /Chen et al. 1986/.

– Atlantic water / Kalix river mixing line based on data in /Andersson et al. 1995/.

– Baltic Sea surface water includes 30 water samples (0–5 m) from various sampling stations /Löfvendahl 1987/.

– Finnish rivers to Gulf of Bothnia consists of median of time series of 21 rivers including the Munsala stream /Roos and Åström 2005/.

– Finnish and Swedish rivers to Baltic Sea consist of 13 rivers measured once /Edén and Björklund 1993/.

Cl concentrations, when not available, were calculated from salinity and/or the Na-concentration, and for the first three references the data is given in µg/kg and for the others in µg/L. Notable is that for the coastal waters in Forsmark there are an opposite trend relative to the general one. This is evidence of substantial input of uranium from the terrestrial environment to the near-coastal waters in the Forsmark area.

It was also shown that overburden (near-surface) groundwaters in Simpevarp in general contain considerably higher concentrations of trace elements than corresponding waters in Forsmark. It was also shown that some chemical elements are concentrated in the water in discharge zones (Figure 6-7) whereas other elements are enriched in the water in recharge zones.

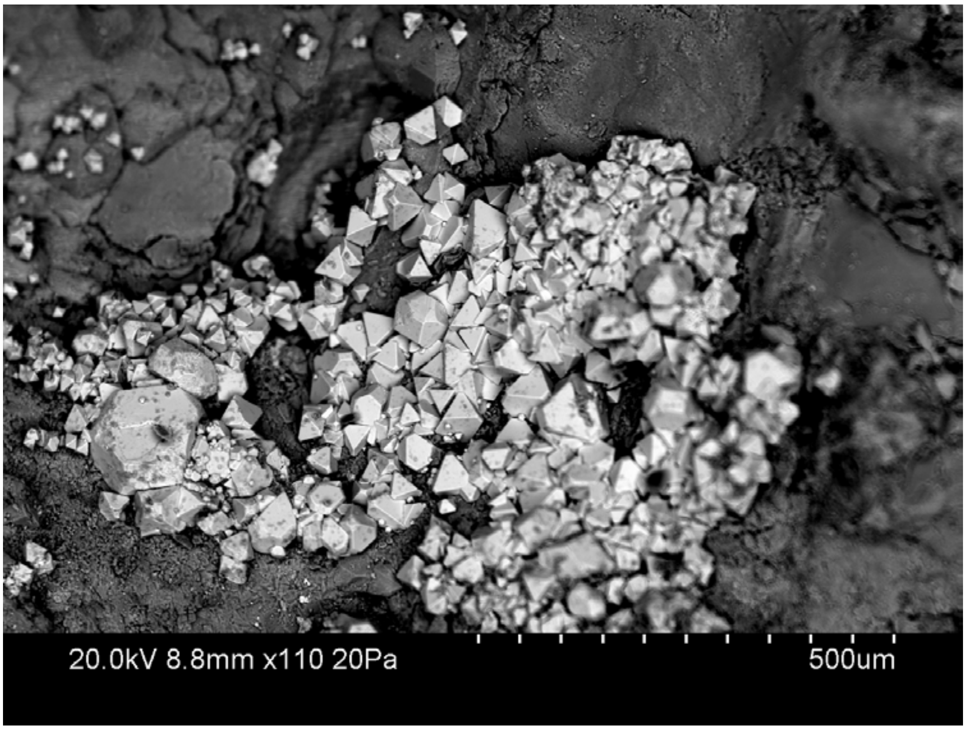


Figure 6-3. *SEM-picture of pyrite in borehole KLX10 at –357 m.*

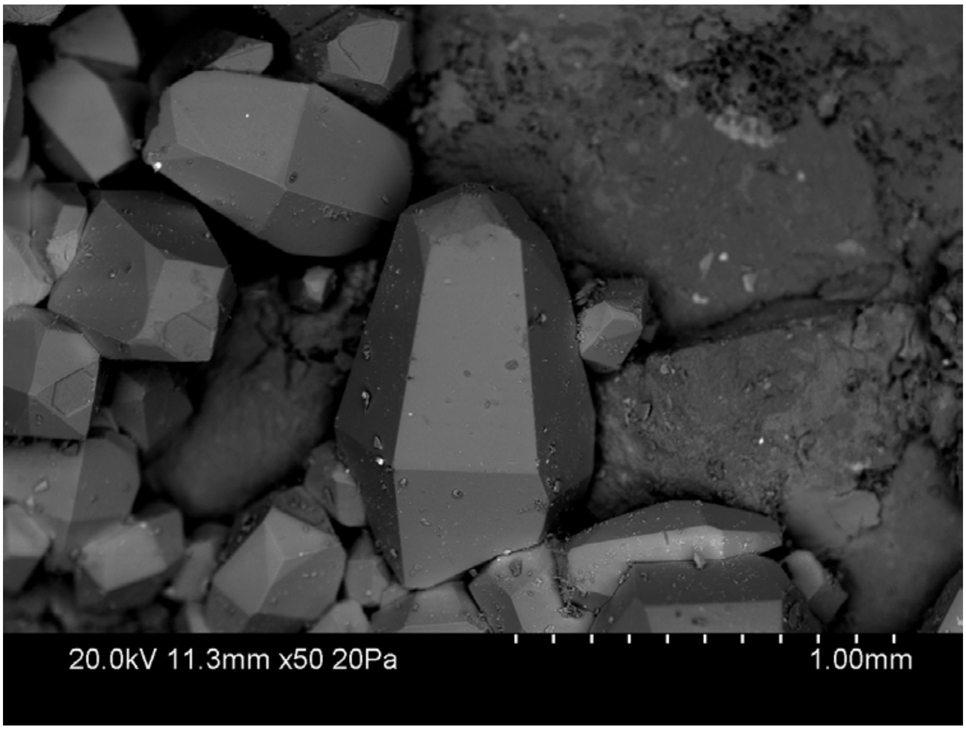


Figure 6-4. *SEM-pictures of calcite in borehole KLX10 at –698 m.*

***Figure 6-5.** A laboratory experiment showed that several toxic metals, including uranium and nickel, are abundantly mobilised when black shale material is exposed to oxidising conditions.*

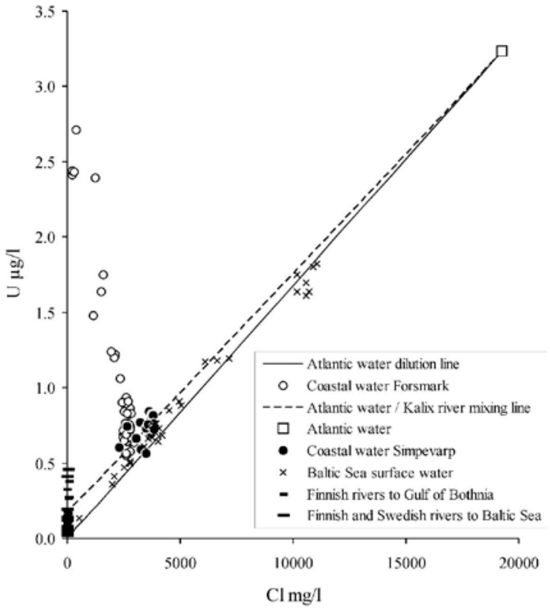


***Figure 6-6.** Uranium versus Cl concentrations for terrestrial and Baltic Sea surface waters.*

Figure 6-7. *Discharge zones in which some chemical elements are concentrated in the water.*

7 International co-operation

7.1 General

Eight organisations from seven countries have in addition to SKB participated in the co-operation at Äspö HRL during 2009, see Table 7-1. Six of them together with SKB form the Äspö International Joint Committee (IJC), which is responsible for the co-ordination of the experimental work arising from the international participation. The committee meets once every year. In conjunction with each IJC meeting a Technical Evaluation Forum (TEF) is held. TEF consists of scientific experts appointed by each participating organisation. For each experiment the Äspö HRL management establishes a peer review panel consisting of three to four Swedish or international experts in fields relevant to the experiment.

Most of the organisations participating in the Äspö HRL co-operation are interested in groundwater flow, radionuclide transport, rock characterisation and THMC modelling. Several of the organisations are participating in the two Äspö Task Forces on (a) Modelling of Groundwater Flow and Transport of Solutes, which is a forum for co-operation in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock and (b) THMC modelling of Engineered Barrier Systems, which is a forum for code development on THMC processes taking place in a bentonite buffer and gas migration through a buffer. These specific technical groups, so called Task Forces, are another form of organising the international work. The international co-operation is based on separate agreements between SKB and the organisations in question. The participation by JAEA and CRIEPI is regulated by one agreement. The participation of each organisation is given in Table 7-2. SKB also takes part in several international EC-projects and participates in work within the IAEA framework. Äspö HRL is part of the IAEA Network Centres of Excellence for training and demonstration of waste disposal technologies in underground research facilities.

Table 7-1. List of participating organisations and members of IJC.

Agence nationale pour la gestion des déchets radioactifs, Andra, France (IJC)
Bundesministerium für Wirtschaft und Technologie, BMWi, Germany (IJC)
Central Research Institute of the Electronic Power Industry, CRIEPI, Japan (IJC)
Japan Atomic Energy Agency, JAEA, Japan (IJC)
Nuclear Waste Management Organisation, NWMO, Canada (IJC)
Posiva Oy, Finland (IJC)
Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle, Nagra, Switzerland
Radioactive Waste Repository Authority, RAWRA, Czech Republic

Table 7-2. International participation in the Äspö HRL projects during 2009.

Projects	Andra	BMWi	CRIEPI	JAEA	NWMO	Posiva	Nagra	RAWRA
Natural barriers								
Colloid Transport Project (Part of Colloid Formation and Migration CFM)					X			
Microbe Project		X						
Radionuclide Retention Project								
Task Force on Modelling of Groundwater Flow and Transport of Solutes			X	X	X	X		
Engineered barriers								
Prototype Repository		X						
Alternative Buffer Materials	X	X		X		X	X	X
Long Term Test of Buffer Materials		X				X		
Temperature Buffer Test	X	X						
KBS-3 Method with Horizontal Emplacement						X		
Large Scale Gas Injection Test	X	X			X	X		
Sealing of Tunnel at Great Depth						X		
Task Force on Engineered Barrier Systems	X	X	X		X	X	X	X

7.2 Andra

The Agence nationale pour la gestion des déchets radioactifs, Andra, takes part in various Äspö projects all devoted to the understanding of the THMC behaviour of the engineered barrier systems. Andra is most interested in the Temperature Buffer Test (TBT) dismantling which began late 2009. Information on the bentonite blocks mechanical behaviour has already been collected. New data on bentonite evolution are expected in 2010 following dismantling termination and samples analysis.

7.3 BMWi

In 1995 SKB and the BMBF (Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie) signed the co-operation agreement being the framework and basis for participating in the activities in the Äspö HRL. After the first prolongation in 2003, in 2008 the agreement was extended a further five years. On behalf of and/or funded by the BMWi (Bundesministerium für Wirtschaft und Technologie) five research institutions are currently participating in experiments and activities connected with the Äspö HRL programme: Federal Institute for Geosciences and Natural Resources (BGR), Hannover, DBE TECHNOLOGY GmbH, Peine, Forschungszentrum Dresden-Rossendorf (FZD), Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig, and Ruhr-Universität Bochum, Bochum.

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

- Studying and investigating buffer material behaviour and all the related basic processes occurring in a repository system by laboratory and in situ experiments.
- Modelling coupled processes, and improvement, refinement and test of codes.
- Investigation of the microbial activity with regard to the interaction with radionuclides.
- Investigations of the migration behaviour of radionuclides, especially actinides, under near field and far field conditions. Geochemical modelling of individual processes controlling migration.

The work carried out in 2009 is described below.

7.3.1 Microbe Project

The contributions of the Forschungszentrum Dresden-Rossendorf (FZD)/Institute of Radiochemistry (IRC) to the microbe project are related to the characterisation of interaction processes of selected actinides (U, Pu, Cm) with biofilms generated by Äspö relevant bacteria. The work is focused on studying (i) the generation and characterisation of biofilms produced by Äspö bacteria under aerobic conditions, (ii) the interaction of U, Pu, and Cm with these biofilms, and (iii) the spectroscopic characterisation of the formed actinide species.

A summary of the main results of BMWi's last project is published in /Moll et al. 2009/. The focus was on: (i) isolation and characterisation of microbial ligands produced from a subsurface strain of *Pseudomonas fluorescens* isolated at Äspö, (ii) interaction of U(VI), Np(V), and Cm(III) with the microbial ligands including compounds simulating the functionality of the microbial ligands and the surface of the bacteria and (iii) spectroscopic characterisation of the formed actinide complexes/compounds. Together with the Swedish partners (Prof. K. Pedersen, Göteborg University) a review article is planned about the radionuclide geomicrobiology in the deep subsurface in 2010. The results of this project and the outcome of our former study on actinide interactions with the Äspö bacterium *Desulfovibrio aespoeensis* will be included (to be published in Geomicrobiology Journal).

Interaction of selected actinides U(VI), Cm(III), and Np(V) with pyoverdines secreted by the Äspö bacterium Pseudomonas fluorescens and related model compound

The aim was to study the interaction reactions of bioligands secreted by the groundwater bacterium *Pseudomonas fluorescens* (CCUG 32456) with the actinides uranium, curium, and neptunium. This includes also complexation studies with model systems simulating the main functionalities of both the identified bioligands and the surface of bacteria.

The groundwater bacterium *Pseudomonas fluorescens* (CCUG 32456) identified at a depth of 70 m in the Äspö HRL, secretes pyoverdine type siderophores. The isolation of the different bioligand fractions was performed at the Department of Cell and Molecular Biology, Microbiology, Göteborg. Mass spectrometry indicated that the cells produce a pyoverdine mixture with four main components: pyoverdine with a succinamide side chain, pyoverdine with a succinic acid side chain, ferribactin with a succinamide side chain, and ferribactin with a glutamic acid side chain (Figure 7-1). However, the results of an absorption spectroscopy study of the aqueous bioligand mixture demonstrated the dominant influence of the pyoverdines. Three pK values could be determined from the pH-dependent changes in the absorption spectra of the pyoverdine mixture: log $\beta_{012} = 22.67$ ($pK_1 = 4.40$), log $\beta_{013} = 29.15$ ($pK_2 = 6.48$), and log $\beta_{014} = 33.55$ ($pK_3 = 10.47$). The fluorescence properties of the pyoverdine mixture were pH dependent. The emission maximum changed from 448 nm at pH = 2.1 to 466 nm in the pH-range 3.8 – 8.9. A drastic change in the intrinsic fluorescence properties, e.g., static fluorescence quenching, occurred due to the complex formation with UO_2^{2+}.

The functional groups of the pyoverdines that participate in the metal binding are the catechol group of the chromophore and one or two ligand sites in the peptide chain, i.e. the hydroxamate groups and the α-hydroxy acid moieties (Figure 7-1). Model ligands were chosen to simulate these functionalities. For the simulation of the hydroxamate functionality the monohydroxamates salicylhydroxamic acid (SHA) and benzohydroxamic acid (BHA) and the natural trihydroxamate desferrioxamine B (DFO) and for the simulation of the catechol groups 6-hydroxyquinoline (6-HQ) and 2,3-dihydroxynaphthalene (NAP) were used (Figure 7-1). The surface of bacteria was simulated by two isolated bacterial cell wall components. Lipopolysaccharide (LPS) is an important compartment of the cell envelope of Gram-negative bacteria and contains a high amount of phosphoryl groups. The other biomacromolecule simulating the bacterial cell wall was the peptidoglycan (PG). This molecule is the main part of Gram-positive bacteria. The functionalities for metal binding of PG are carboxyl and amino groups from the peptide chains and hydroxyl groups from the polysaccharide chains.

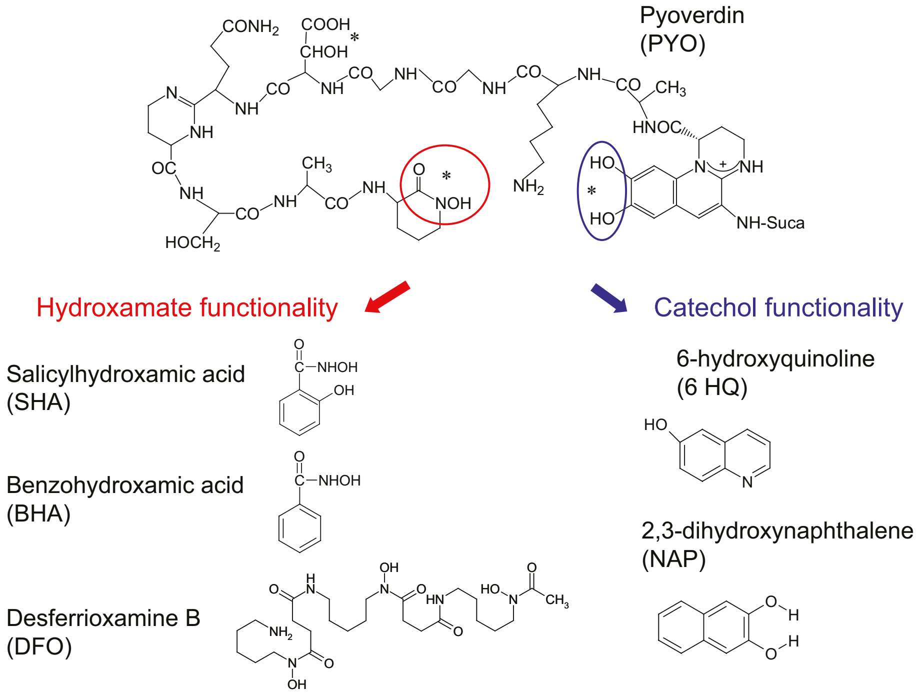


Figure 7-1. *Structure of both the pyoverdin from P. fluorescens (CCUG 32456) with a succinamide (Suca) side chain and the used model systems.*

The comparison of the stability constants of actinide species (U(VI), Cm(III), Np(V)) with model ligands simulating the functional groups of the pyoverdines results in the following order of complex strength: DFO > NAP > 6-HQ > SHA, BHA.

Both monohydroxamates, SHA and BHA, form 1:1 and 1:2 complexes with similar stability. The natural occurring siderophore DFO has the highest stability constants with the three actinides. The model ligands for the chromophore functionality NAP and 6-HQ form stronger complexes than SHA and BHA, but weaker complexes than DFO. From this it can be reasoned that the chromophore functionality probably plays an important role for the coordination of the actinides to the pyoverdines. Strong complexes are formed between the actinides and the selected bioligands providing hydroxamate and catechol functionalities. The comparison of the stability constants of the complexes with the three studied actinides U(VI), Cm(III) and Np(V) with each other shows that the strength of the complex formation decreases from U(VI) via Cm(III) to Np(V).

The dissociation constants and corresponding site densities of functional groups provided by the biopolymers LPS and PG were determined with potentiometry. The best fit of the titration data of LPS was obtained with a four-site model. The pK_a of 5.56 can be assigned to carboxyl groups, the pK_a of 6.96 to the second dissociation step of phosphoryl groups, and the pK_a of 8.90 to amino or hydroxyl groups. With some test solutions titrated up to pH 11 an additional pK_a over 10 could be detected, due to the dissociation of amino or hydroxyl groups. The best fit for all titration curves of PG was obtained with a three site model. The pK_a values of 4.55 and 6.31 can be dedicated both to carboxyl groups. The PG molecule offers two different free carboxyl groups, from the glutamic acid and the diaminopimelic acid. The third pK_a of 9.56 can be dedicated to both, amino and hydroxyl groups.

This project showed that different functionalities of LPS and PG are involved in actinide coordination depending on the pH of the test solutions. In general strong species are formed with all three actinides. With one exception, no Np(V) species could be detected with PG using NIR spectroscopy. Probably due to the low affinity of Np(V) to interact with carboxyl sites of biopolymers as shown for LPS. At an excess of LPS, the uranyl(VI) ion is mainly complexed through monodentate coordinated phosphoryl groups ($\log \beta$ 7.5–13.8). At equimolar ratios of uranyl(VI) and functional groups of LPS additional carboxyl coordination ($\log \beta$ 5.9) in a bidentate manner becomes important. In the LPS system three Cm(III) complexes were identified for with high stability constants. Speciation calculations using the formation constants showed predominant Cm(III) coordination to phosphoryl groups within pH 1 and 4 ($\log \beta$ 26.9; 1:2 stoichiometry), carboxyl groups within pH 4 and 9 ($\log \beta$ 9.3; 1:1 stoichiometry), and hydroxyl groups at pH values above 9 ($\log \beta$ 26.7; 1:4 stoichiometry). Two relatively strong NpO_2^+ complexes were formed with coordination to the phosphoryl ($\log \beta$ 6.3; 1:1 stoichiometry) and deprotonated hydroxyl ($\log \beta$ 11.6; 1:2 stoichiometry) groups of LPS. Both monohydroxamates, SHA and BHA, form 1:1 and 1:2 complexes with similar stability. The natural occurring siderophore DFO has the highest stability constants with the three actinides. The model ligands for the chromophore functionality NAP and 6-HQ form stronger complexes than SHA and BHA, but weaker complexes than DFO. From this it can be reasoned that the chromophore functionality probably plays an important role for the coordination of the actinides to the pyoverdines. Strong complexes are formed between the actinides and the selected bioligands providing hydroxamate.

In the PG system four U(VI) complex species were identified, three with the carboxyl group as functionality ($\log \beta$ 4.0 and 7.0; 1:1 stoichiometry and $\log \beta$ 12.1; 1:2 stoichiometry) and one with an additional involvement of an amino or hydroxyl group ($\log \beta$ 14.9). One Cm(III) complex species was detected with the carboxyl site as the binding group ($\log \beta$ 10.4; 1:2 stoichiometry). Possible Np(V) interactions with the dominant carboxyl groups of the PG molecule were too weak for a detection using the NIR spectroscopy.

The interaction of *P. fluorescens* (CCUG 32456) pyoverdines with U(VI), Cm(III), and Np(V) was studied using absorption spectroscopy (UV-vis-NIR) and time-resolved laser-fluorescence spectroscopy (TRLFS, fs-TRLFS). Two 1:1 UO_2^{2+} species with formation constants of $\log \beta_{121} = 30.50$ (UO_2H_2PYO) and $\log \beta_{111} = 26.60$ (UO_2HPYO^-) were identified. Strong Cm^{3+}-pyoverdine species with 1:1 stoichiometry are formed. The three Cm^{3+} complexes, CmH_2PYO^+, $CmHPYO$, and $CmPYO^-$, could be identified by their individual emission spectra. The stability constants of the three complexes were calculated to be $\log \beta_{121} = 32.50$, $\log \beta_{111} = 27.40$, and $\log \beta_{101} = 19.30$. Also three NpO_2^+-pyoverdine complex species, $NpO_2H_2PYO^-$, NpO_2HPYO^{2-}, and NpO_2PYO^{3-}, are formed with stability constants of $\log \beta_{121} = 26.90$, $\log \beta_{111} = 20.90$, and $\log \beta_{101} = 13.40$, respectively. The different Np(V)-pyoverdine species could be identified by their individual absorption spectra.

It is not surprising that pyoverdines have their largest formation constants with Fe^{3+} /Albrecht-Gary et al. 1994/, because pyoverdines are chelating agents synthesised by fluorescent Pseudomonas spp. to provide the cells with the essential Fe^{3+}. However, this project shows that pyoverdins are also able to complex elements other than Fe(III) at a considerably high efficiency. The comparison of the stability constants of the complexes with the three studied actinides U(VI), Cm(III) and Np(V) shows that the strength of the complex formation decreases from Cm(III) via U(VI) to Np(V). It is known that ethylenediaminetetraacetic acid (EDTA) may form the strongest actinide complexes among the various organic components of for instance nuclear waste. The stability constants of 1:1 species formed between Cm^{3+} and UO_2^{2+} and *P. fluorescens* (CCUG 32456) pyoverdines are by a factor of 1.05 and 1.3, respectively, larger compared to the corresponding EDTA stability constants. Remarkable is that the Np(V)-PYO stability constant is by a factor of 1.83 greater than the EDTA stability constant. The identified NpO_2^+-PYO species belong to the strongest NpO_2^+ species with organic material reported so far. The results of this project contribute to an improved understanding of the coordination chemistry of uranium(VI), curium(III), and neptunium(V) towards bioligands containing hydroxamate and catecholate functionalities in aqueous solution. The determined stability constants can be used directly in safety calculations to quantify the actinide-mobilising effect of pyoverdines type bioligands released, for example, in the vicinity of a nuclear waste disposal site.

With the simplification that metal binding properties of bacteria are mainly determined by the functional groups of the cell wall (LPS: Gram-negative bacteria and PG: Gram-positive bacteria), raw estimates are possible, on the basis of the determined stability constants, if actinides prefer to interact with the cell wall compartments of the bacteria (LPS, PG) or with the secreted pyoverdine bioligands (PYO). The calculations were performed using nearly equimolar conditions of actinides and functional groups of the biosystems (LPS, PG, and PYO). All identified species influence the uranyl(VI) speciation within the biologically relevant pH range. For U(VI) strong interactions were measured in all three biosystems. By taking pH 5 as an example, uranyl(VI)-pyoverdin interactions (~90% bound) are slightly stronger than those observed with LPS (~70% bound) and PG (~65% bound). For Cm(III) we found a much stronger affinity to aqueous pyoverdin species (~100% bound at pH 5) than to functional groups of the cell wall compartments (~35% bound at pH 5 to LPS). A similar behaviour was observed for Np(V). More than 85% of all Np(V) is bound to pyoverdine species at pH 8 compared to ~37% bound to LPS and less than 1% bound to PG. This shows the importance of indirect interaction processes between actinides and bioligands secreted by resident bacteria.

7.3.2 Prototype Repository

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

The measuring programme, agreed on by SKB and GRS, includes the monitoring of two electrode arrays in the backfilled drift above the deposition boreholes 3 and 6, an electrode array in the buffer at the top of deposition hole 5, and three electrode chains in the rock between deposition holes 5 and 6, see Figure 7-2.

Special water-tight cables and connectors had been selected for connections between the electrodes and the geoelectric monitoring system which was installed in the data acquisition room in the parallel G-tunnel. The first measurements were started in Section I in October 2001; from June 2003 all arrays were active.

In 2009, the measurements have been continued as planned. In section I of the backfill the resistivity decreased until the end of 2007 when it was below 2 Ωm in the whole measuring cross section. This corresponds to water content above 25%, compared to water content at backfill emplacement of 13 to 14%. From the geoelectric point of view the backfill in section I could be regarded as fully saturated.

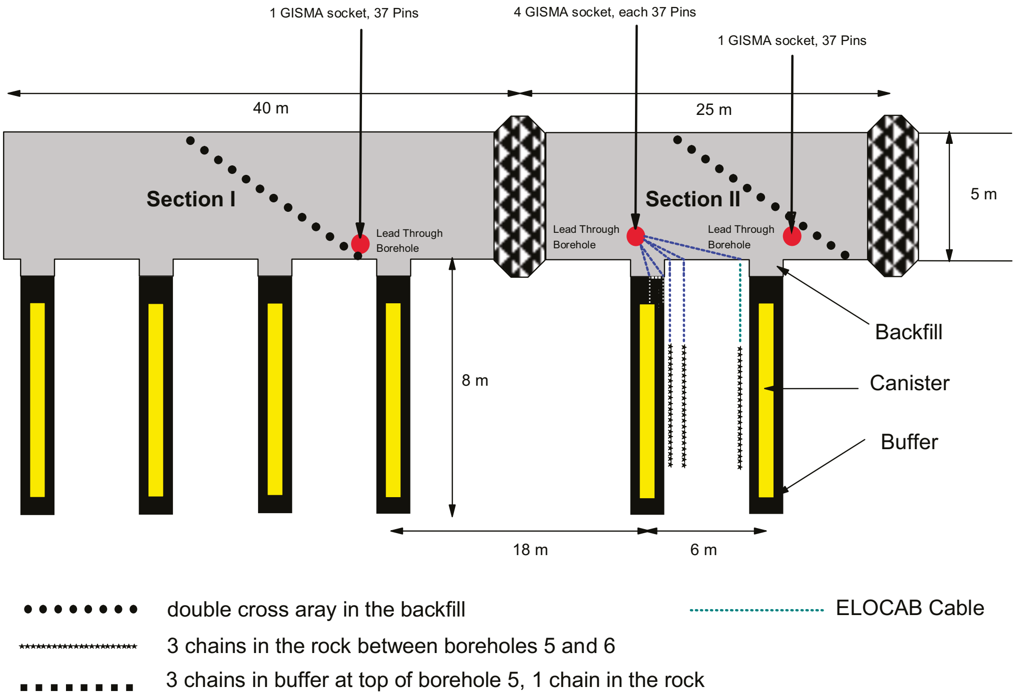


Figure 7-2. *Arrangement of electrode arrays in the Prototype Repository*

In 2008, however, a slight increase in resistivity was detected (see Figure 7-3). The respective tomogram shows a slight increase in the entire cross section and a centre of elevated resistivity above 5 Ωm near the tunnel roof, corresponding to a water content of about 18%. During 2009 the resistivity started to decrease again. The reason for this behaviour is unclear at the time being.

In Section II, the resistivity has decreased to values around 3 Ωm in the center (corresponding to a water content of 21–22%) and 2–3 Ωm near the tunnel walls. The centre region, with slightly increased resistivity, is steadily diminishing. Section II is close to saturation as well. An effect of increasing resistivity as detected in Section I did not occur.

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

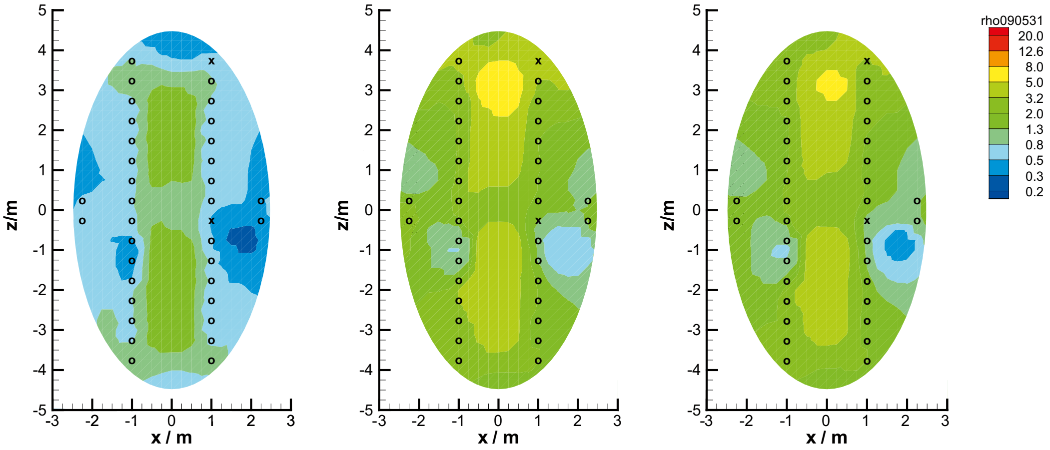


Figure 7-3. *Resistivity distributions in the backfill in Section I, November 2007 (left), September 2008 (center), and May 2009 (right).*
o: Electrodes. Colour scale in Ohmmeter.

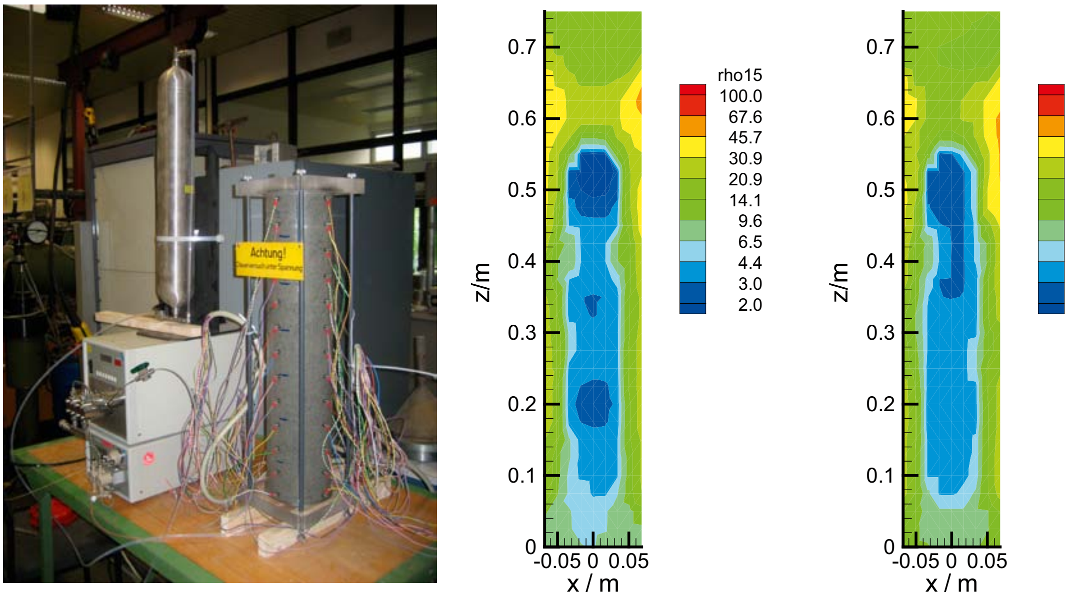


Figure 7-4. *Plexiglas tube with backfill material and electrodes (left) and resistivity tomograms obtained after flooding to 70% height (centre and right, for two longitudinal sections). Colour scale in Ohmmeter.*

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

To increase the confidence in the results of the inversions of the apparent resistivities measured in situ, laboratory experiments have been performed in which controlled progressing water uptake in drift backfill was simulated and monitored by geoelectric measurements. Original Prototype Repository backfill material with relevant initial water content was emplaced in a Plexiglas tube equipped with electrodes. After initial tomographic measurements the tubes were partially flooded from the lower end, and the geoelectric tomography measurements were repeated. Figure 7-4 shows the experimental setup and the tomograms obtained after partial flooding.

An experiment with relevant initial water content showed a very good agreement between the results of the geoelectric measurements and the water content measured on samples taken during backfill emplacement and after finishing the test. This shows that geoelectric tomography actually yields resistivity values representative for the in situ saturation conditions. The water content measurements on samples from the flooded region additionally show that 22 to 25% water content indeed mean full saturation, as was concluded from the in situ measurements.

7.3.3 Alternative Buffer Materials

In 2009 the first parcel of the alternative buffer material test was excavated. For a detailed mineralogical investigation of the materials which have been in contact with the heated steel tube, the BGR clay laboratory decided to investigate 10 out of 11 of the different materials. The 10 cm slices of each material were sampled directly at the clay-steel contact and additionally in 1, 3, 5, and 7 cm distance from the contact.

The resulting 50 samples were analysed with respect to mineralogical composition by X-ray diffraction (XRD) and infrared spectroscopy. The chemical composition was determined by X-ray fluorescence (XRF) and LECO (for C- and S-analysis). The cation exchange capacity was determined using the Cu-triethylenetetramine method and the C- and S-minerals were analysed by differential thermal analysis with mass spectrometer (DTA-MS).

The resulting significant data set proved that the different materials performed rather different. Some clays accumulated a lot of Fe derived from steel corrosion whereas others were found to be largely intact. This experiment is believed to provide particularly valuable information regarding the corrosion mechanism at the steel bentonite interface.

7.3.4 Temperature Buffer Test

In order to model the thermo-hydraulic behaviour, DBE TECHNOLOGY has simulated the coupled two-phase flow in bentonite under heating using the Tough2 code. A good fit of calculated and measured temperatures and suction values was achieved and plausible parameter sets for hydraulic and thermal calculations have been established. A sensitivity analysis was carried out in order to detect the most sensitive parameters for suction. In addition to the thermo-hydraulic modelling, the mechanical behaviour of the bentonite buffer is addressed in this report, focusing on the simulation of the impact of the swelling bentonite on the mechanical system behaviour. To this end, two different constitutive laws describing the swelling of the bentonite have been implemented into FLAC3D, and coupled thermo-hydro-mechanical simulations have been performed.

Concerning geometry the model covers one axisymmetric segment of the borehole and the surroundings, which is equivalent to a 2D axisymmetric model. The model domain as well as the model dimensions is shown in Figure 7-5.

The mesh of the model consists of 56.352 nodes. In the vicinity of the heaters, the discretisation is fine (node spacing ~ 0.1 m within a radius of 5 m). The node size increases with increasing distance from the heaters as shown in Figure 7-6. In the figure, the materials used are shown. Due to their small dimensions, the peek and the cement plate are not included in the FLAC model, in order to get small model cells and hence shorten the necessary calculation time. It is assumed that both features have negligible effect on the modelling results.

Constitutive models and parameters

Table 7-3 lists the mechanic, thermal and hydraulic constitutive models assigned to the different materials in the FLAC model. The Äspö diorite host rock and the heater and buffer system are modelled assuming a simple elastic mechanical behaviour. For the bentonite buffer, the total strain ε is a superposition of elastic strain and swelling strain:

$$\varepsilon = \varepsilon_s + \varepsilon_e$$

The heat conduction is isotropic for all materials. Water tightness is assumed for the diorite host rock and the heaters; hence, no flow boundary conditions are applied to these materials. For the remaining materials, an isotropic conductivity for fluid flow is applied.

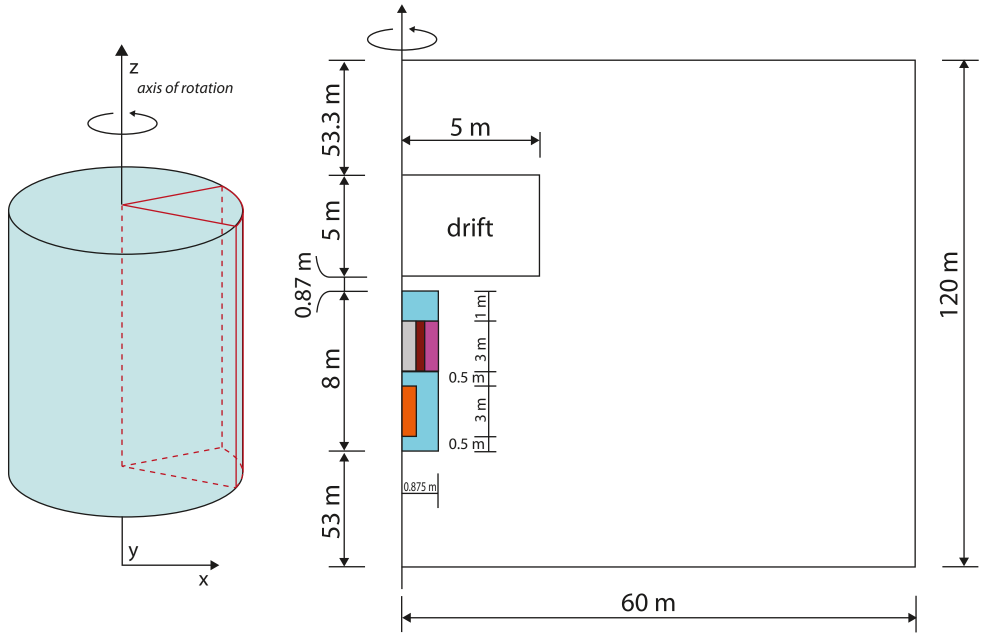


Figure 7-5. *Model domain (red border, left), model dimensions (right).*

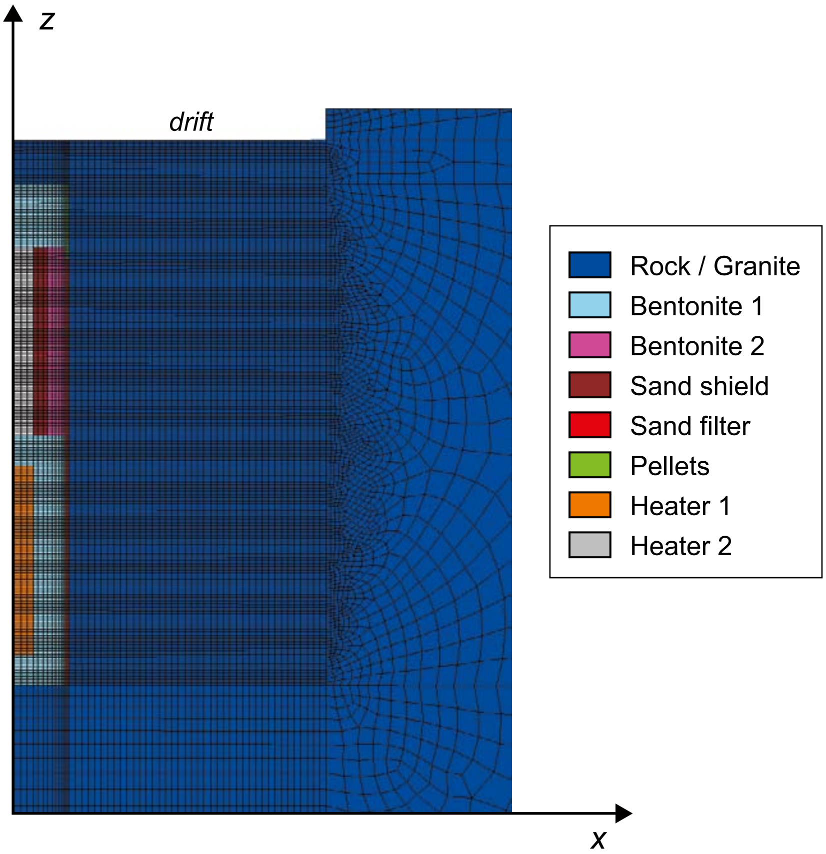


Figure 7-6. *Discretisation of the model.*

Table 7-3. Constitutive models used in FLAC3D.

Material	Mechanic	Thermal	Hydraulic
Äspö diorite	elastic	Isotropic Heat Conduction	No flow
Bentonite 1	elastic, swelling		Isotropic Darcy Flow
Bentonite 2			
Pellets	elastic		
Sand			
Sand filter			
Heater			No flow

Two different approaches for the swelling strain in the bentonite buffer are tested, both describing the swelling process phenomenologically. Both swelling laws are implemented in FLAC by a FISH-routine. The FISH-routine for the first law was written by /Konietzky 2005/, the FISH-routine for the second law is an outcome of this project.

The values of the material property parameters used in the modelling are summarised in Table 7-4 to Table 7-9 for the various materials.

1. 1-dimensional swelling law of Grob

According to Grob's law /Grob 1972/, the swelling strain is related to the actual compression stress via the logarithmic swelling law (Figure 7-7):

$$\varepsilon_s = C \cdot \log \frac{\sigma_{actual}}{\sigma_{\max}} \qquad \sigma_{actual} < \sigma_{\max}$$

$$\varepsilon_s = \varepsilon_{s,\max} \qquad \varepsilon_s > \varepsilon_{s,\max}$$

For stresses above σ_{max} the swelling strain is 0. At very low actual stresses the swelling strain, ε_s, is constrained to a maximum value, $\varepsilon_{s,max}$, in order to avoid unrealistically high swelling strains. For the sake of simplicity, the swelling is assumed to be isotropic.

2. Saturation-dependent swelling pressure

According to the swelling pressure tests (Figure 7-8), the swelling pressure σ_s is directly proportional to the degree of saturation S with σ_{sat} being the swelling pressure at saturation:

$$\sigma_s = S \cdot \sigma_{sat}$$

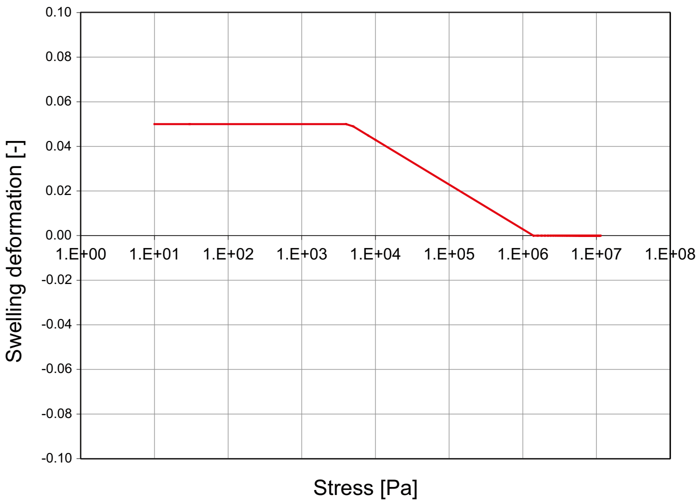


Figure 7-7. Logarithmic swelling law /Grob 1972/, material parameter set from (σ_{max} = 1.4 MPa, $\varepsilon_{s,max}$ = 0.05, C = –0.02).

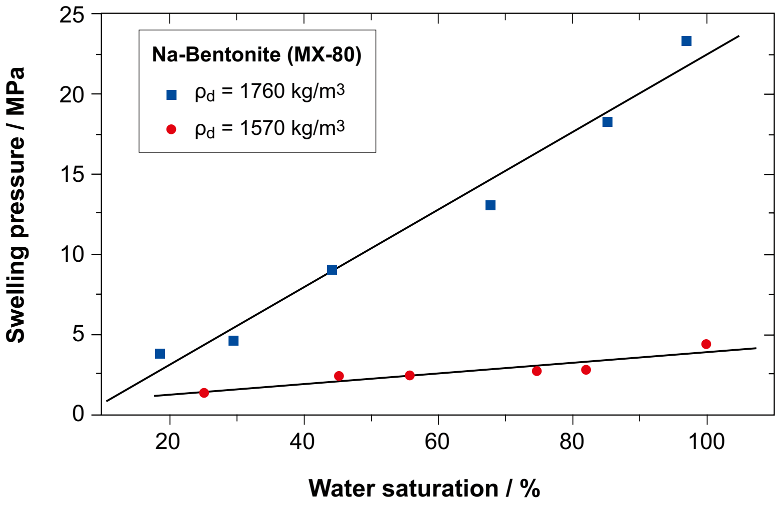


Figure 7-8. Swelling pressure as a function of the degree of water saturation for Na-bentonite with different dry densities after /Studer et al. 1984/ and /Börgesson et al. 1995/.

Äspö diorite

Table 7-4. Mechanical and thermal parameters /Fredriksson et al. 2004, Staub et al. 2004/.

Young's modulus E [GPa]	55.0
Poisson's ratio v [–]	0.26
Density ρ [kg/m^3]	2,750.0
Conductivity λ [W / (m · K)]	2.6
Heat capacity c_p [J / (kg · K)]	775
Thermal expansion coefficient α [1/°C]	$7.0\cdot10^{-6}$

Table 7-5. Hydraulic parameters /Åkesson 2006a/.

	unsaturated			
Intrinsic perme-ability K [m^2]	Kozeny's Model	$k_i = k_0 \frac{\phi^3}{(1-\phi)^2} \frac{(1-\phi_0)^2}{\phi_0^{\ 3}}$	k_0	ϕ_0
			$1\cdot10^{-30}$	0.003
Porosity n [–]	0.003			

Heater and buffer system

Table 7-6. Mechanical parameters (A) /Rautioaho and Korkiala-Tanttu 2009/, (B) /Åkesson 2006a/.

Materials	**Young's modulus *E* [MPa]**	**Poisson's ratio *v* [–] (B)**
Bentonite 1	10^2 (A)	0.2
Bentonite 2	10^2 (A)	0.2
Sand shield	55.37 (B)	0.25
Sand filter	24.93 (B)	0.25
Pellets	20 (B)	0.25
Heater (Steel)	$2.1 \cdot 10^5$ (B)	0.2

Table 7-7. Thermal conductivity of the heater and buffer system /Åkesson 2006a/.

Materials	**Law**	**Λdry [W / (m · K)]**	**Λsat [W / (m · K)]**
Bentonite 1	$\lambda = \lambda_{sat}^{\ S} \cdot \lambda_{dry}^{\ (1-S)}$	0.3	1.3
Bentonite 2		0.3	1.3
Sand shield		0.6	1.7
Sand filter		0.6	1.7
Pellets		0.1	1.0
Heater (Steel)		50.16	50.16

Table 7-8. Heat capacity, density and thermal expansion coefficient of the heater and buffer system /Åkesson 2006a, Börgesson 1992, Schneider 1994/.

Materials	**Heat capacity c_p [J / (kg · K)]**	**Density ρ [kg/m^3]**	**Thermal expansion coefficient α [1 / °C]**
Bentonite 1	1,091	2,000	$3\cdot10^{-5}$
Bentonite 2	1,091	2,000	$3\cdot10^{-5}$
Sand shield	900	1,800	$1.2\cdot10^{-5}$
Sand filter	900	1,800	$1.2\cdot10^{-5}$
Pellets	1,091	1,800	$2.5\cdot10^{-5}$
Heater (Steel)	460	7,850	$1.2\cdot10^{-5}$

Table 7-9. Hydraulic parameters /Åkesson 2006a/.

Materials	Intrinsic permeability K [m²]			Porosity [–]
	Kozeny's Model	k_0	ϕ_0	
Bentonite 1	$k_i = k_0 \dfrac{\phi^3}{(1-\phi)^2}\dfrac{(1-\phi_0)^2}{\phi_0^{\ 3}}$	$0.32 \cdot 10^{-20}$	0.389	0.389
Bentonite 2		$0.32 \cdot 10^{-20}$	0.368	0.368
Sand shield		$2.00 \cdot 10^{-15}$	0.30	0.300
Sand filter		$2.00 \cdot 10^{-15}$	0.36	0.360
Pellets		$2.00 \cdot 10^{-19}$	0.5684	0.568

Initial conditions

For the initial stress state at the test site, which is located ~460 m below the ground surface, isotropic conditions are assumed: σV = σH = σh ~ 14 MPa. Table 7-10 includes the initial thermal and hydraulic conditions. A significant suction is exerted by the buffer system.

Boundary Conditions

Mechanical and thermal boundary conditions

The mechanical boundary conditions are shown in Figure 7-9. The movement of grid-points at the bottom of the model and at the radial plane is prevented by fixing the displacement in all directions to zero. At the heater borehole axis, grid points can only move along the z-axis. At the top of the model, the grid points are free to move but the behaviour is controlled by the introduced overburden load of ~12.4 MPa.

As shown in the sketch to the right, at the tangential model planes a zero normal velocity allows only for a movement within the respective tangential plane. The temperature is fixed to 20°C at all model edges, except for the longitudinal axis of the heater borehole. There, the temperature is free to change.

Heater power

A power of 1,500 – 1,600 W was applied to the heaters. The heating scheme is described in /Goudarzi et al. 2008/. Most heating interruptions due to heater failure lasted only a few hours, the heating interruption at heater 1 on 6th June 2003 (t = 72.79 d) lasted almost 3 days.

Water inflow to the sand shield

During the first 377 days the sand filter was pressurised only through the lower injection points, while the upper injection points were open to the atmosphere. After 377 days also the upper injection points were pressurised and none of the injection points were open to the atmosphere. The injection pressures which were applied in the FLAC model are shown in Figure 7-10.

Table 7-10. Initial hydraulic conditions with T = 20°C /Åkesson 2006a/.

Materials	Porewater pressure [MPa]	Saturation
Bentonite 1	–47.5	0.798
Bentonite 2	–47.5	0.798
Sand shield	–62.5	0.0563
Sand filter	–62.5	0.0584
Rock	0.1	1.0
Pellets	–2.03	0.211
Heater	0.1	0.0

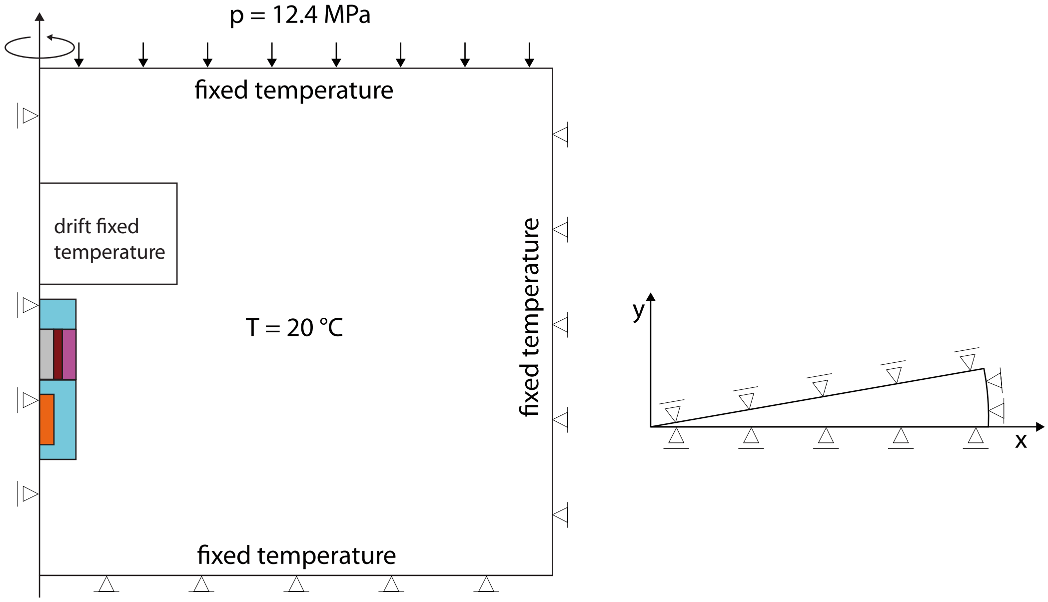


Figure 7-9. Displacement boundary conditions and fixed temperature boundary condition at a temperature of 20°C.

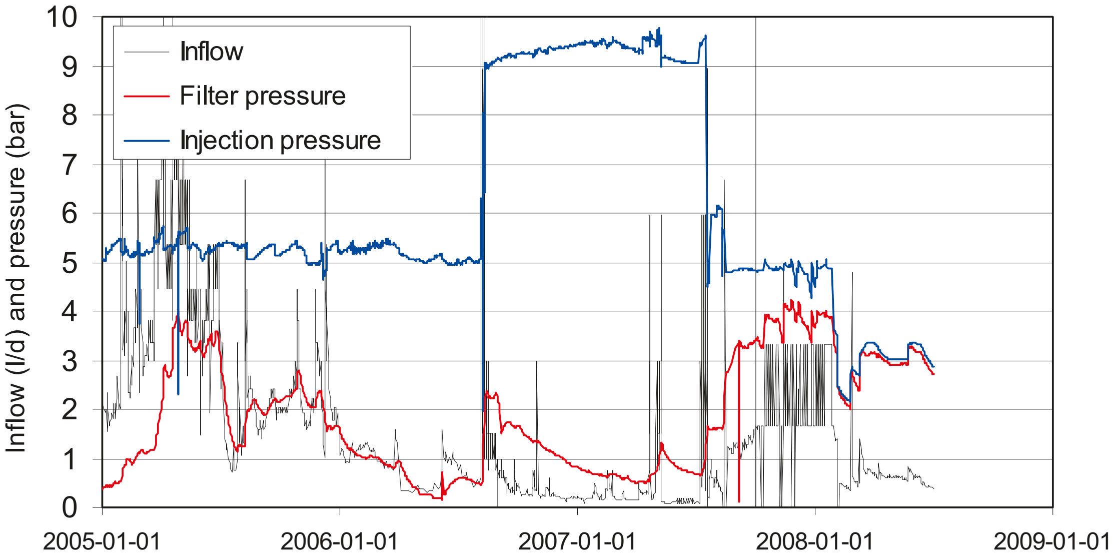


Figure 7-10. Development of relative pressures and inflow since day 568 (second hydraulic test) /Goudarzi et al. 2008/.

Model calibration

The constitutive laws for bentonite swelling have been implemented successfully and a couple of test runs have been performed to ensure a proper output.

At present, the model is being calibrated, with special focus on the swelling parameters. Figure 7-11 shows the radial stress at the observation point PB202 and the corresponding model results obtained from the very first runs for the two different swelling approaches and for different parameter sets of the Grob's law. Since there are no bentonite swelling parameters known for the used swelling laws, the parameters are currently being modified to fit the measured values.

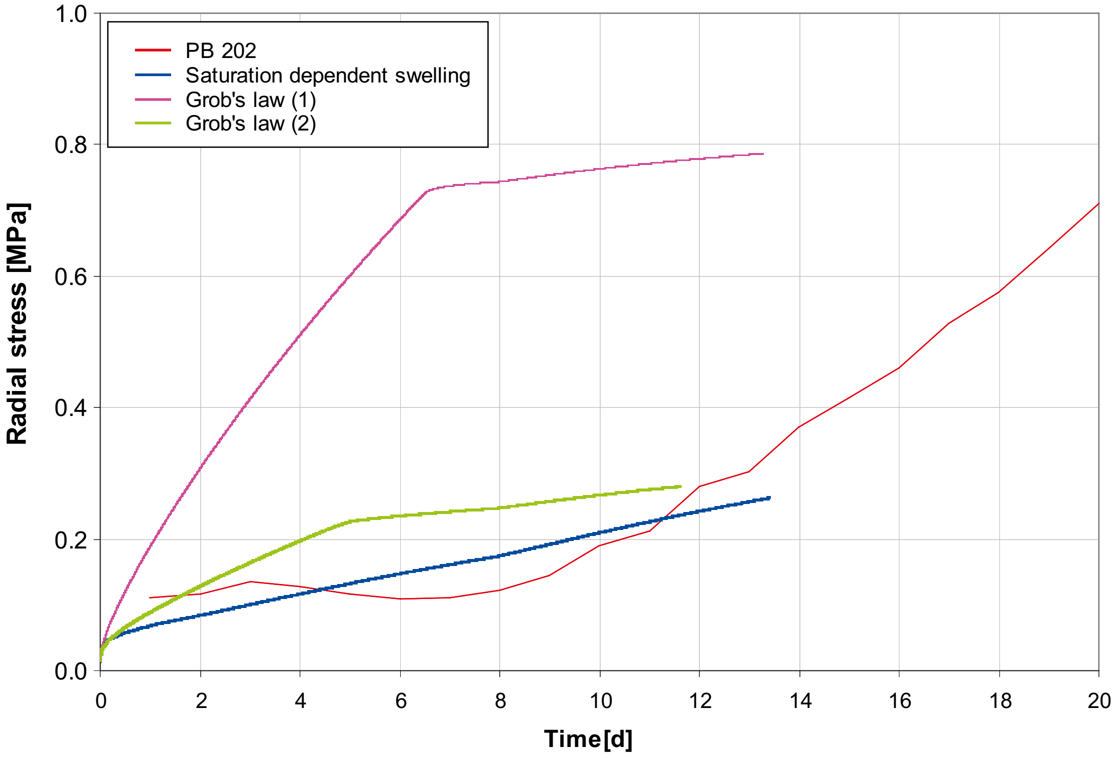


Figure 7-11. *Radial stress for different model variants, comparison to the measured.*

7.3.5 Task Force on Engineered Barrier Systems

BGR participated in task 1 (THM-tests) and task 2 (gas migration tests) of Benchmark 1 (Laboratory Tests). In 2009 the calculations of the Isothermal Test and the Buffer /Container Experiment in Benchmark 2 were documented in an International Progress Report /Nowak and Kunz 2009/. The work on the Canister Retrieval Test in Benchmark 2 was continued. Though this task is only about the Canister Retrieval Test, the nearby Temperature Buffer Test was included in the 3D model and used in the 3D-THM-coupled simulations. The results will be reported in 2010.

GRS contributed to the Buffer/Container Experiment and Isothermal Test in Benchmark 2. The results of measurements performed over a 6 year period were not satisfactorily reproduced by the calculations using the code VIPER. There were several attempts to improve model performance by adapting the vapour flow model to the special properties of bentonite-sand mixtures, by extensive check of the code VIPER for errors in the equations, and a tentative implementation of a balance equation for water based on two-phase flow theory. However, it should be noted, though, that the two-phase flow equations without considering advection can be transformed into Fick’s second law using a variable diffusion coefficient.

Inspired by the work of the ‘chemical group’ of the EBS Task Force, a diffusive migration of interlayer water according to self-diffusivity was assumed. The respective coefficient depends on water content and increases with the amount of hydrate layers at the interlayer cations. The balance equation was extended accordingly to a double-continuum model and implemented in the code VIPER, which lead to a decisive improvement of the model results without introducing new parameters that need calibration. Figure 7-12 shows the transient development of water content at three different locations in the middle plane of the buffer as well as the water content distribution as extensively measured in a post-test investigation campaign.

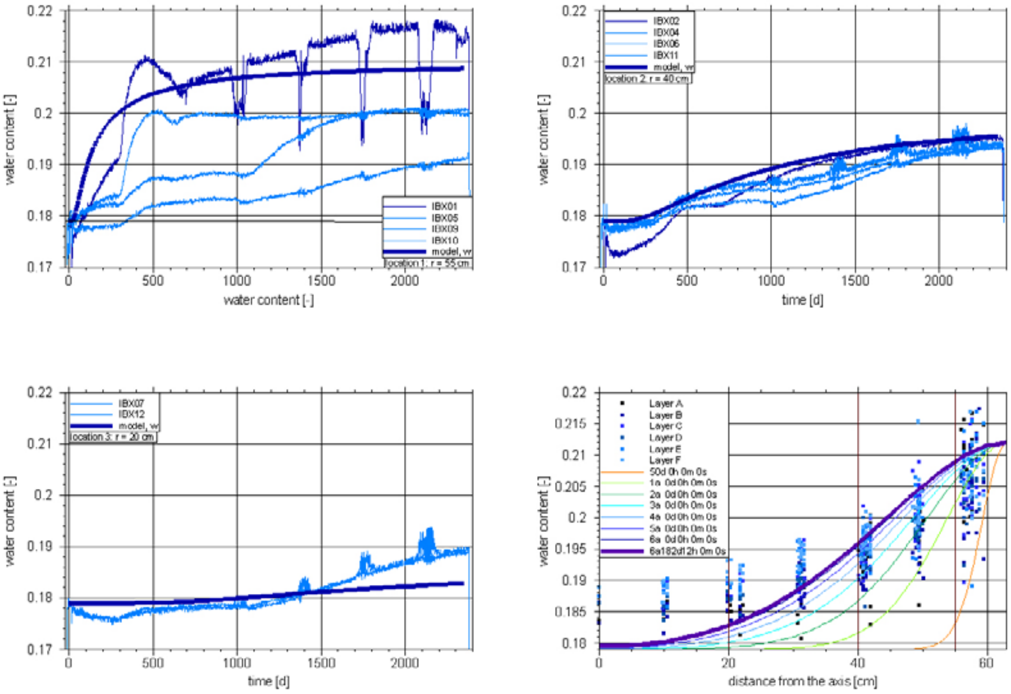


***Figure 7-12.** Results from in situ measurements and from model calculations including interlayer diffusion.*

Activities of the research group at the Ruhr-Universität Bochum (former Bauhaus University Weimar) in 2009 aimed mainly to study in terms of numerical simulation the coupled THM processes in engineered barrier and sealing systems designed for the isolation of radioactive waste. The THM experiments were performed in the Soil Mechanics Laboratory-Bauhaus University Weimar. The finite element code Code-Bright (UPC) was used for numerical solution of the considered THM coupled problems. The performed experiments were numerically simulated in order to reveal the influence of the temperature and hydraulic gradients on the distribution of temperature, mechanical stress and water content. The following tests were simulated:

1. Swelling test: Water was supplied to sand-bentonite mixture samples from the top and the measurements were done during the wetting process.
2. THM test: The soil sample was heated from below to 80°C. The features of the THM behaviour were recorded. A sensitivity analysis was carried out to identify the parameters which influence the most the response of the numerical models. Results of back analyses of the model parameters were reported and critically assessed.

Code Bright was used to study the THM behaviour of clay in terms of numerical simulations. Corresponding to the two laboratory tests considered in the present study, we performed two types of numerical simulations, namely coupled Hydro-Mechanical (HM) behaviour, and fully coupled THM numerical simulation.

Our analysis addressed the sensitivity analysis and the identification procedure via back analysis of sand-bentonite mixture model parameters. Due to the large number of parameters involved in the THM coupled models we first performed a sensitivity analysis to identify the model parameters that influence the most the modelling results. The current study explores systematic approach to model sensitivity and back analysis in case of coupled THM problems.

7.4 CRIEPI

Central Research Institute of Electric Power Industry (CRIEPI) participates mainly in modelling activities. CRIEPI has participated in the Task Force on Modelling Groundwater Flow and Transport of Solutes and performed modelling work for Task 7 and Task 8. CRIEPI has also participated in the Task Force on Engineered Barrier Systems and tackled its benchmark problems.

7.4.1 Task Force on Modelling Groundwater Flow and Transport of Solutes

CRIEPI has performed the modelling work for sub-task 7B, reduction of performance assessment uncertainty through block scale modelling of interference tests in KR14–18 at Olkiluoto, Finland. The modelled area is a 500-m-square centred on the borehole KR15. Inside the modelled volume, there are nine site scale major fracture zones (see Figure 7-13). Three major fracture zones dominating groundwater flow are modelled explicitly by using two-dimensional finite elements. On the other hand, the other major fracture zones are expressed implicitly by a smeared fracture model. As for background rock, small scale fractures around KR14–18 are expressed by a smeared fracture model with conditioning of realisations to borehole data. Small scale fractures and matrix in the other area are expressed by equivalent continuum model with depth dependency of the hydraulic conductivity. Figure 7-14 shows the numerical representation of our hydrostructural model and Figure 7-15 shows the finite element mesh used for numerical simulations.

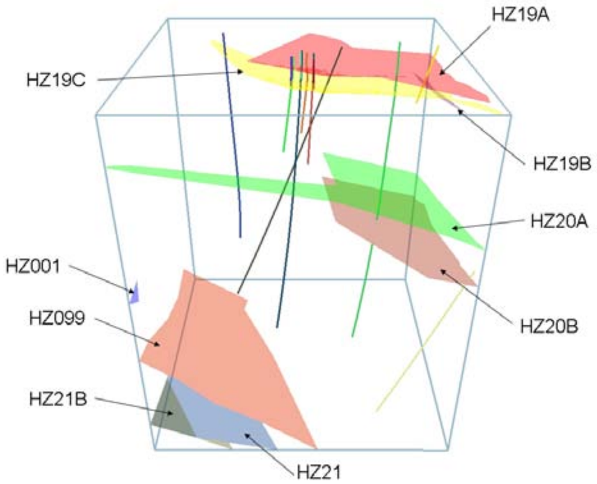


Figure 7-13. Location of major fracture zones in modelled domain.

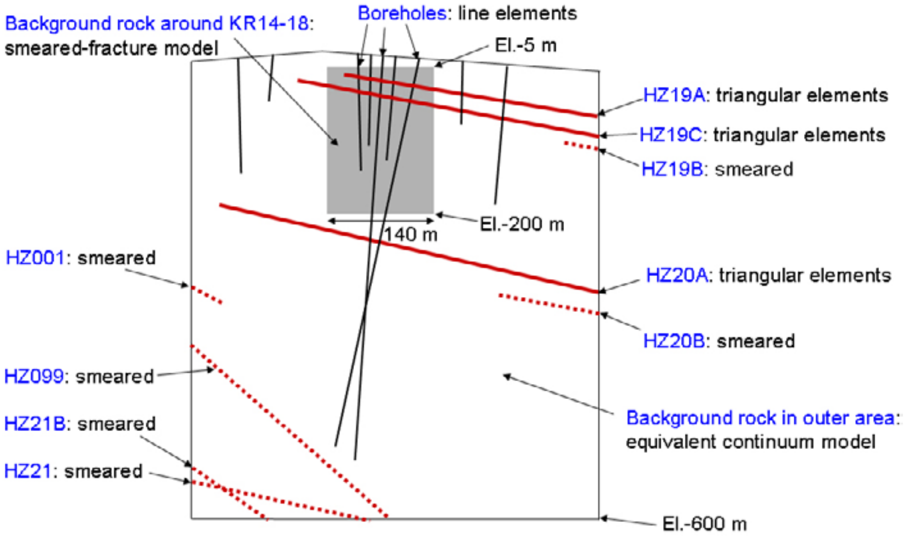
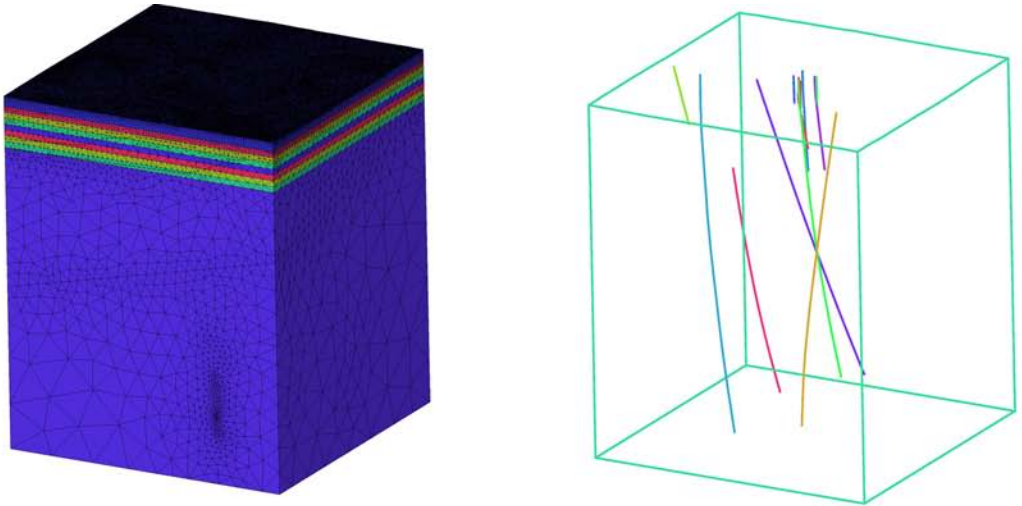
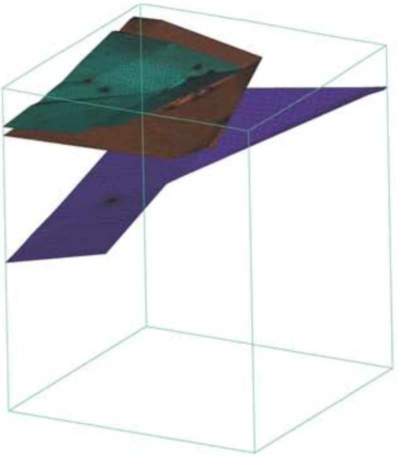


Figure 7-14. Numerical representation of hydrostructural model.

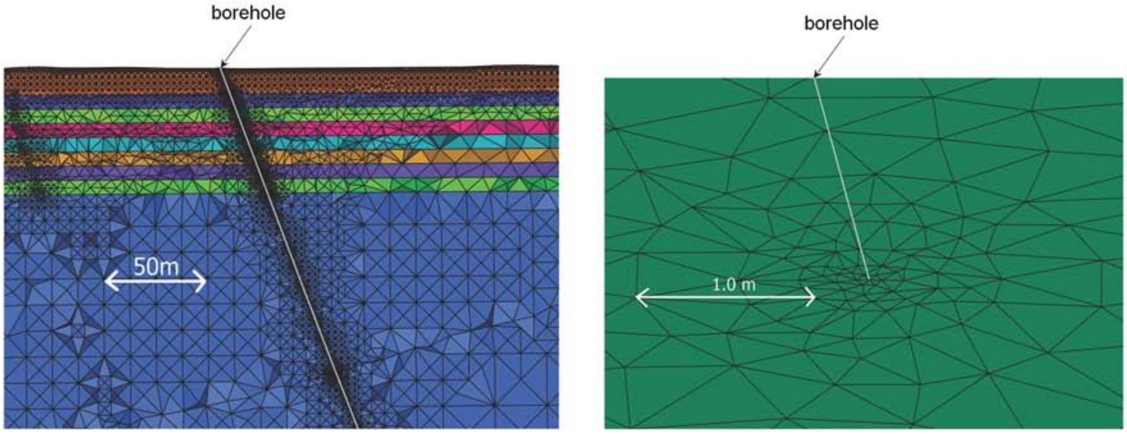


(a) Overall view

(b) Line elements



(c) Triangular elements



(d) Tetrahedral elements around a borehole

(e) Triangular elements around a borehole

Figure 7-15. *Finite element mesh for numerical simulations of sub-task 7B.*

The drawdowns and the inflow rates at pumping and observation boreholes during pumping were calculated. Figure 7-16 shows an example of the cumulative flow rate of groundwater into a pumping borehole. The calculated flow rates agree very well with the measured ones for all the pumping boreholes. The calculated inflow rates, however, do not necessarily agree with the measured ones for the observation boreholes. Figure 7-17 shows the drawdowns in the observation boreholes. The calculated drawdowns roughly correspond to the measured ones. For PA interest, the travel paths of particles starting from the nine points at 100 meters below the ground surface were also calculated under natural conditions. Figure 7-18 shows the trajectory lines of the particles. The trajectory lines are divided into two groups according to their directions.

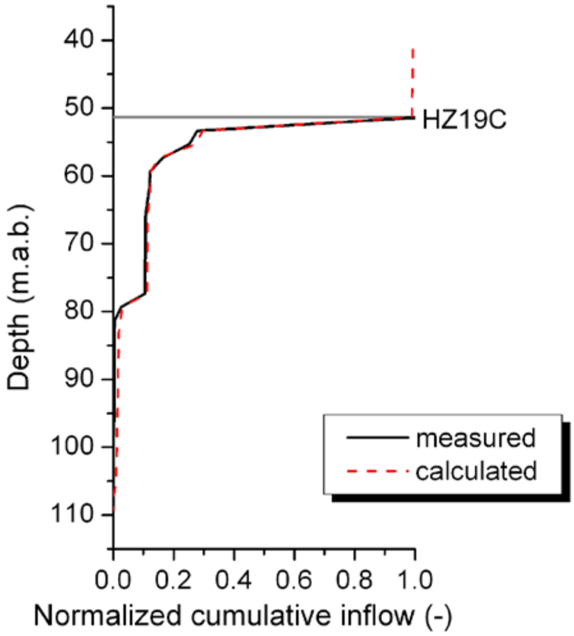


***Figure 7-16.** An example of cumulative flow rate of groundwater into a pumping borehole.*

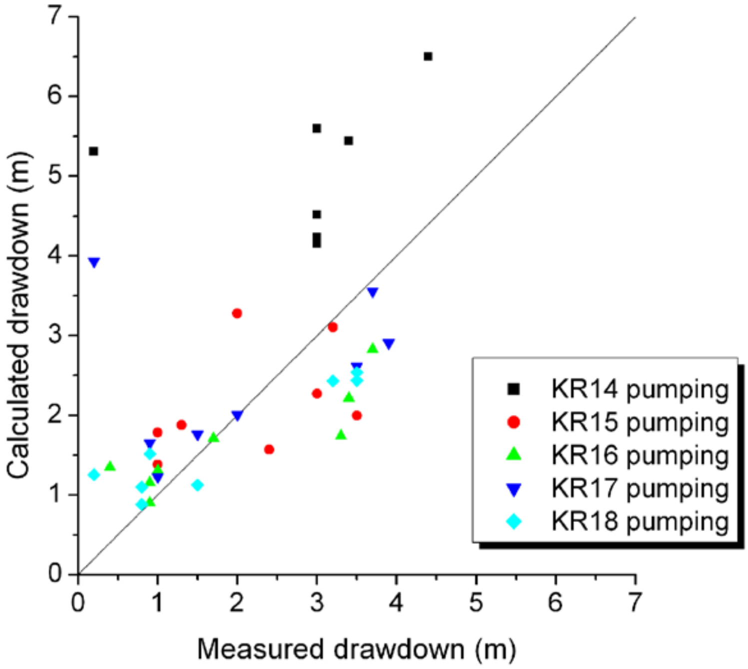


***Figure 7-17.** Drawdown in the observation boreholes during pumping tests.*

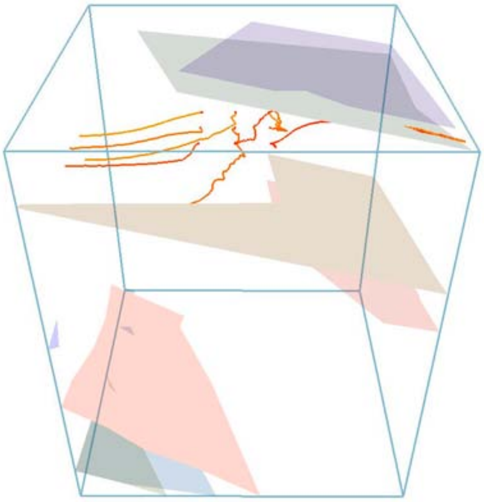


Figure 7-18. *Trajectory lines of particles starting from points at a level of 100 meters below the ground surface.*

CRIEPI has started the modelling work also for Task 8. The aim of Task 8 is to improve the knowledge of the bedrock-bentonite interface with regard to groundwater. CRIEPI conducted an initial scoping calculation, which contains two simplified and generic two-dimensional groundwater flow problems.

The geometry and finite element mesh of the initial scoping simulation are shown in Figure 7-19. Intact rock, bentonite and a tunnel cross section are included in two-dimensional axisymmetric set-up. Rock fracture is included only in case 2. The initial state was reached by keeping the pore pressure at the rock wall in the tunnel and the borehole at atmospheric pressure and the outer boundary at 2 MPa. After that the installation of the bentonite was modelled through decreasing the pore pressure in the bentonite down to –100 MPa. Hydraulic properties are shown in Table 7–11.

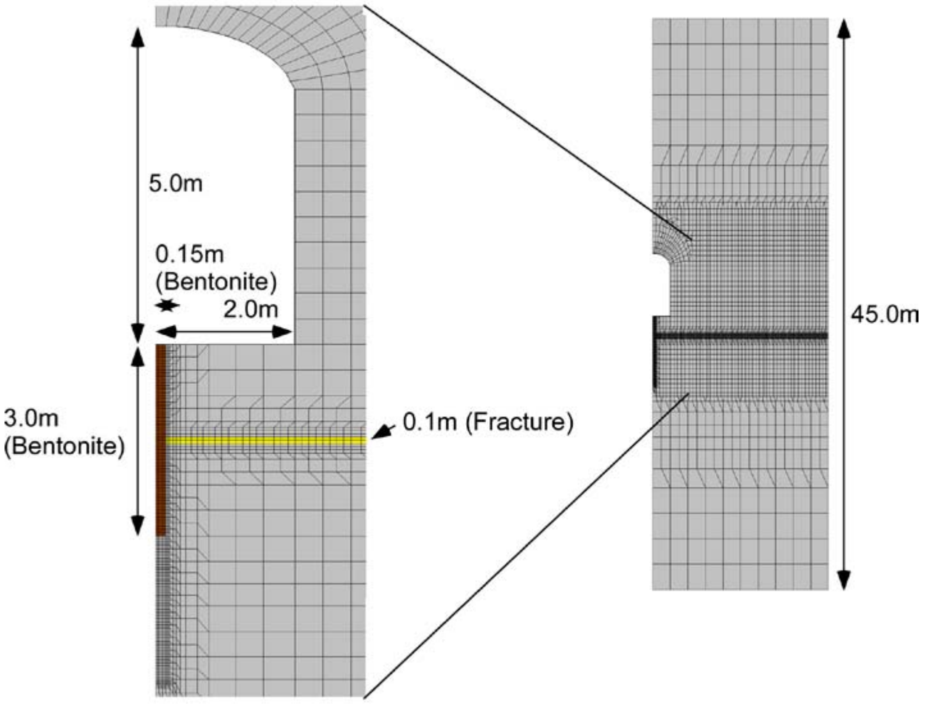


Figure 7-19. *Geometry and finite element mesh for the initial scoping calculation of Task 8.*

Table 7-11. Hydraulic properties of each material.

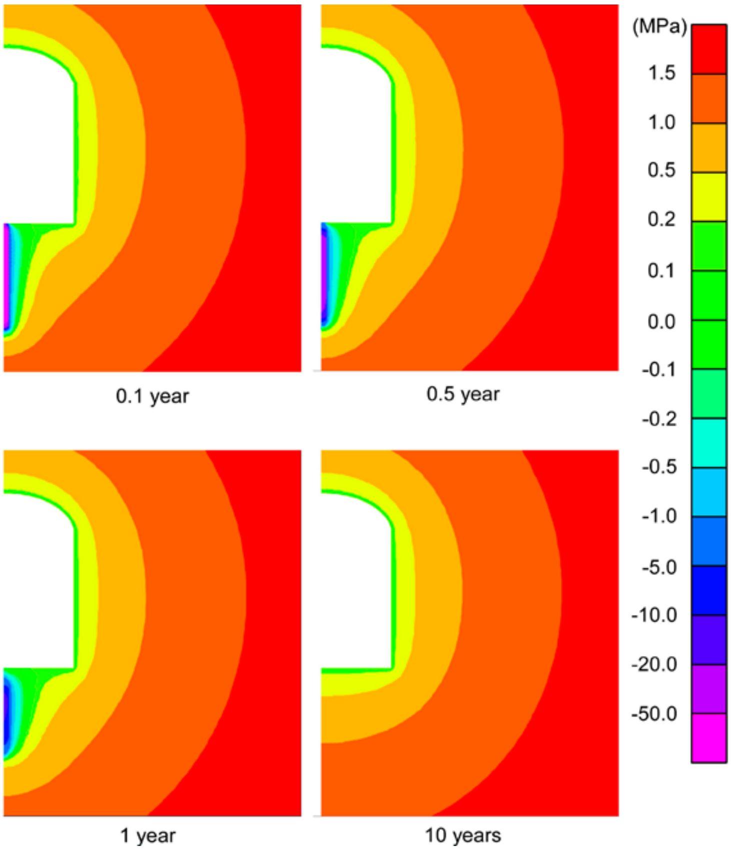
	hydraulic conductivity (m/s)	porosity	P_0 (MPa)	λ
intact rock	1.0×10^{-12}	1.0×10^{-5}	1.74	0.6
fracture	5.0×10^{-9}	1.0×10^{-3}	1.74	0.6
bentonite	2.4×10^{-13}	0.44	9.23	0.3

Retention curve $S = \left[1 + \left(\frac{P_g - P_l}{P_0} \right)^{\frac{1}{1-\lambda}} \right]^{-\lambda}$

Relative permeability $k_r = \begin{cases} S^3 & \text{(bentonite)} \\ \sqrt{S}\left(1-(1-S^{1/\lambda})^{\lambda}\right)^2 & \text{(rock)} \end{cases}$

Contour plots of calculated pore pressure are shown in Figure 7-20 (case 1) and Figure 7-21 (case 2). In case 2, water infiltration from the rock fracture is fast and saturation was completed in 1 year, while it took 1.5 years in case 1. The unsaturated zone appeared in intact rock close to the bentonite in both cases.

CRIEPI will update the calculation with the progress of the future BRIE experiment.



0.1 year

0.5 year

1 year

10 years

Figure 7-20. Contour plots of pore pressure in rock (case 1).

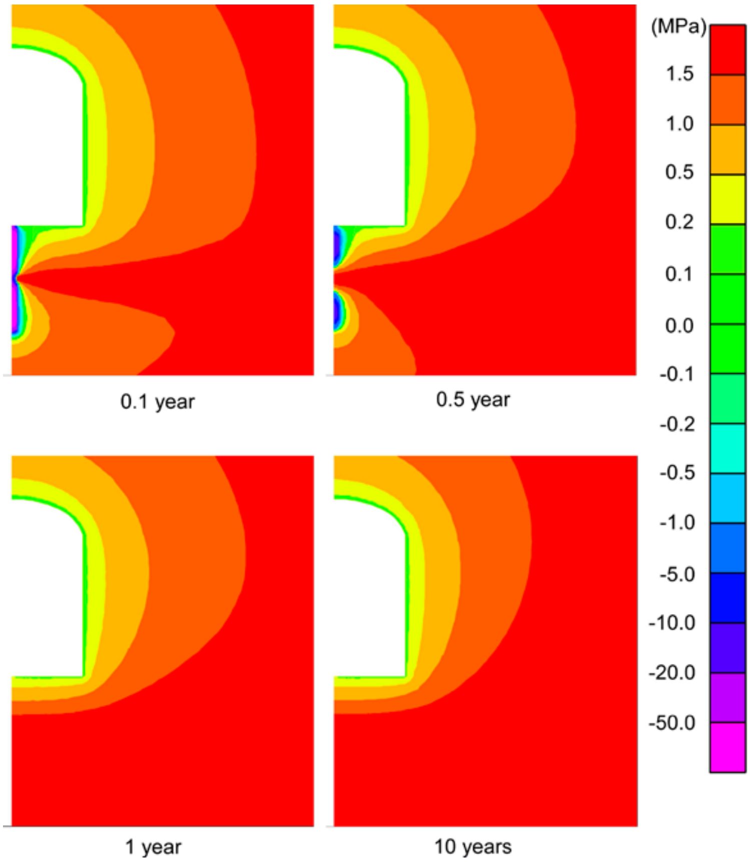


***Figure 7-21.** Contour plots of pore pressure in rock (case 2).*

7.4.2 Task Force on Engineered Barrier Systems

CRIEPI has been developing the thermal-hydrological-mechanical (THM) coupling code "LOSTUF" for evaluating the phenomena that will occur around the engineered barrier system. In 2009, Benchmark 2 was carried out, and LOSTUF was applied to the Canister Retrieval Test (CRT).

The CRT at Äspö HRL was started to demonstrate the capability to retrieve deposited nuclear waste if a better disposal solution is found. The CRT has also been used to record the THM process carefully besides proving the possibility for retrieval of the canisters. This makes it very suitable for modellers to investigate theories used in their simulations, since the calculated results can be checked against experimental data. The CRT consisted of an electric heater installed in bentonite blocks and bentonite rings in a 8.55 m deep by 1.76 m diameter borehole in the tunnel floor. A concrete plug and nine rock anchors were overlaid the bentonite to provide a vertical restraint against swelling.

There are three suggested tasks in the modelling of the CRT. The first task is a pure thermal problem for the temperature field in the surroundings of the CRT and TBT experiments, which is an optional task. CRIEPI did not conduct this task. In two other tasks, THM processes in the CRT experiment were studied. In the second task, the buffer at canister mid-height is modelled in detail. The simulation for this task had been finished in 2008. The third task is simulation of the entire experiment. The finite element mesh for the entire model is shown in Figure 7-22. This model includes four types of compacted bentonites, which are bentonite blocks, rings, bricks and pellets, whose initial dry densities are quite different. An inner slot between canister and bentonite and the surrounding rock mass are also included. The rock anchors on the top of the plug concrete are modelled by spring elements. An interesting subject in this task is how well the mechanical homogenisation process by swelling is simulated.

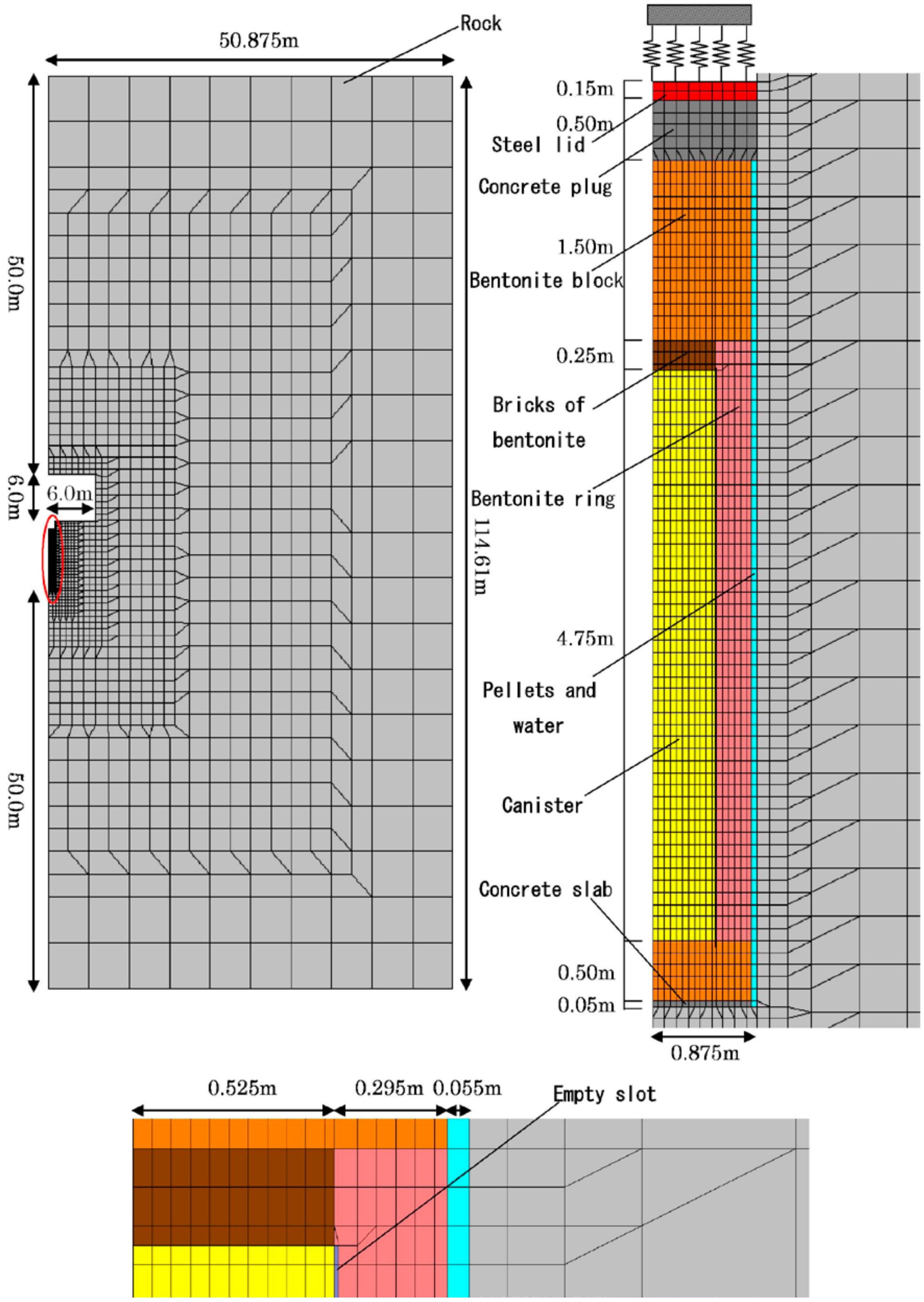


Figure 7-22. *Finite element mesh for the entire CRT experiment.*

For the third task, Figure 7-23 shows the output positions. Canister mid-height is picked up and the numbers indicates the distance from the centre axis of the canister. Figure 7-24 displays the temperature evolution in line plots, showing the results of simulation, and dotted plots showing the measured data. The simulation reproduces the temperatures very well. Figure 7-25 shows the reduction of suction in the entire period of the experiment. Simulated water infiltration is slower than measurement especially in the region near the canister. Figure 7-26 shows the vertical total pressure evolution as the total pressure increases with swelling of bentonite, the simulated increase of total pressure being larger and faster than the measured data. Figure 7-27 shows the dry density profile in buffer on the canister mid-height. Simulation can reproduce the tendency of homogenisation process with swelling of bentonite, but simulated final dry density of bentonite ring part is a little larger than the experimental results. Since the swelling pressure of bentonite is strongly dependent on its dry density, we must improve the swelling deformation model. More investigation is required in the determination of hydraulic properties and swelling model of bentonite. We will continue to investigate them in the third task in 2010.

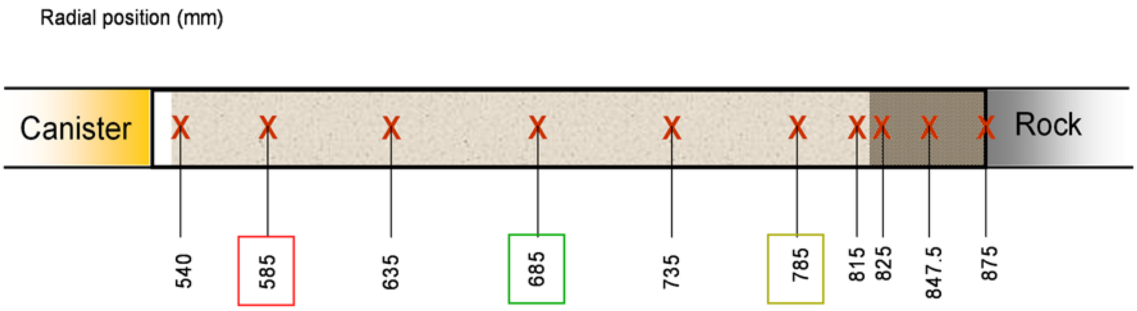


Figure 7-23. *Output positions in the buffer on canister mid-height.*

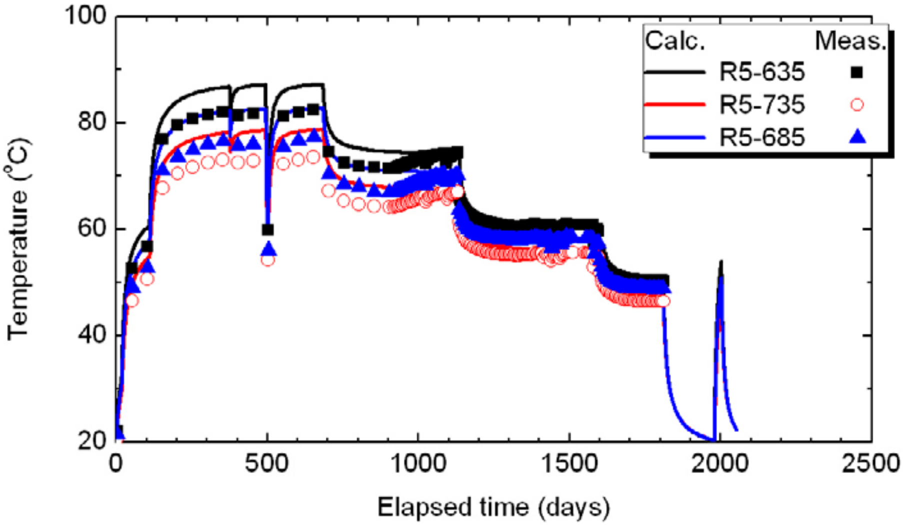


Figure 7-24. *Temperature evolution in the buffer on canister mid-height.*

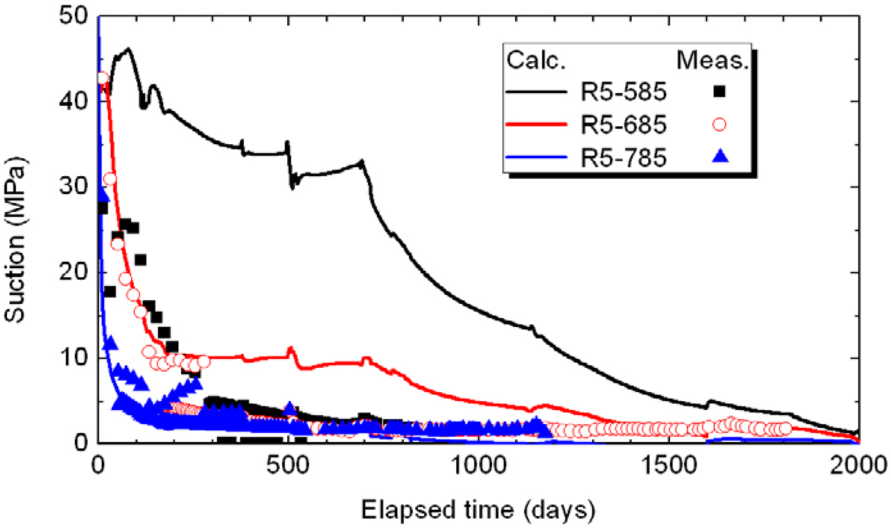


Figure 7-25. Suction reduction process.

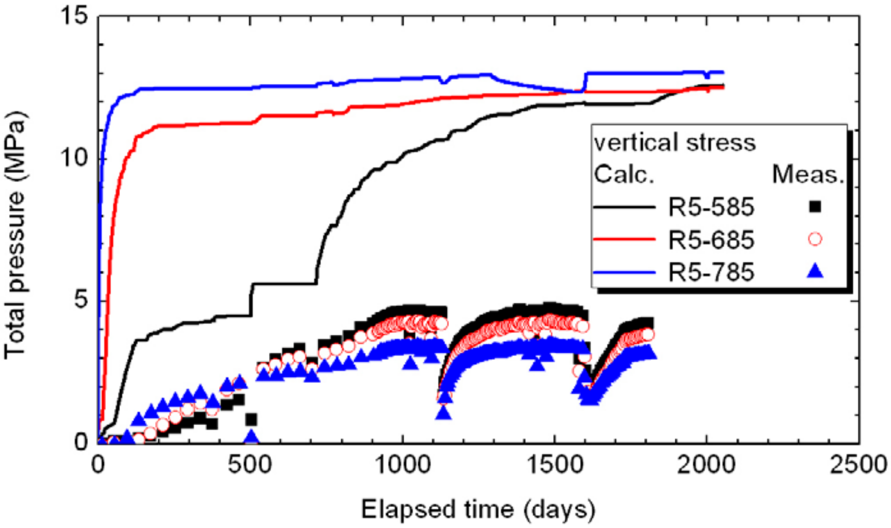


Figure 7-26. Total pressure evolution.

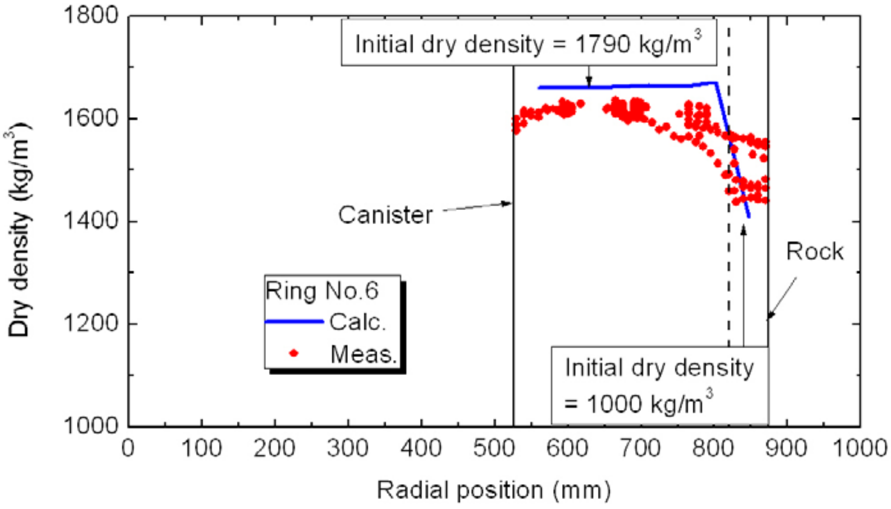


Figure 7-27. Distribution of dry density.

7.5 Japan Atomic Energy Agency – JAEA

The role of Japan Atomic Energy Agency (JAEA) in the Äspö HRL directly contributes to JAEA's mission as providing technical basis for repository site characterisation, safety assessment, and regulation in Japan. The Äspö HRL provides practical information that directly benefits JAEA's research and development activities in Japan.

JAEA research objectives at Äspö HRL during 2009 included the following:

- Improve understanding of site characterisation technologies, particularly flow logging and hydraulic interference.
- Improve understanding of flow and transport in fractured rock.
- Improve methodologies to assess uncertainty of hydrogeological model.
- Improve understanding of underground research laboratory experiments and priorities.

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

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

JAEA participation in the Äspö Task Force on Groundwater Flow and Transport of Solutes during 2009 focused on modelling for sub-tasks 7B and 7C, pressure and flow response test at Olkiluoto, Finland. JAEA's goals from participating in Task 7 include:

- An improved understanding of site characterisation.
- The reduction of uncertainty for hydrogeologic model by pressure response and flow response data measured by Posiva flow log during pumping tests.
- Assessment of uncertainty of performance measures relevant to the safety assessment evaluated by the hydrogeologic model.

The results will contribute to both site assessment and safety analysis methodologies in Japan.

During 2009, JAEA continued the development of hydrogeologic modelling for sub-task 7B, presenting a deterministic major fault zone model which focuses on the rock block scale, within the Island-scale framework characterised in the sub-task 7A. JAEA also initiated modelling for sub-task 7C at the scale of several tens of meters, focussing on flow and transport in the single fracture. Heterogeneous distribution of fracture aperture, transmissivity and transport properties in a single fracture around the tunnel are considered.

During 2009, JAEA participated in a workshop meeting in Lund, Sweden, on the 28th – 29th of January to present the modelling strategies and preliminary modelling results with simplified fault zone model for sub-task 7B. The discrete fracture network model for modelling background fractures was added to the simplified fault zone model. Results of the analyses performed and initial conceptual modelling for sub-task 7C were presented at the 25th Äspö Task Force Meeting in Mizunami, Japan, on the 14th–16th of October, 2009, hosted by JAEA.

Sub-task 7B – Hydrogeologic modelling at rock block scale

Sub-task 7B considers a region of approximately 500×500 m surrounding boreholes KR14–18 at the Olkiluoto site in Finland. The fundamental objectives of the task are to:

- Quantify the reduction of uncertainty in the properties of the fracture network.
- Assess the Posiva Flow-logging (PFL) data when analysing the rock mass and fractures.

The JAEA developed a FracMan® discrete fracture network (DFN) model for sub-task 7B combining the following elements:

- **Larger structures** such as major fault zones, modelled with a fixed (deterministic) geometry and calibrated hydraulic properties.
- **Background fractures**, represented by a stochastic discrete fracture network (DFN) model.

Larger structures ("Major Water Conducting Features") in the JAEA model were initially based on those specified in the data distribution from Posiva. In addition, JAEA utilised a derivative analysis of transient cross hole interference test data to understand the hydraulic properties and connectivity of hydraulically larger structures, such as faults and fractures. Based on this analysis, JAEA developed an updated model for the larger structures. This model was compared to the baseline hydrostructural model developed by Posiva using the residual sum of squared errors normalised by number of compared points as:

$$\frac{\sum(measured - simulated)^2}{n-1}$$

where, "measured" and "simulated" indicate measured head response and flow response, simulated head response and flow response.

Figure 7-28 shows the larger structures model proposed by JAEA, and boundary conditions. The top surface is specified as constant head matching with the elevation of ground surface. The sides of the model are also specified as constant head with average head set based on the surface elevation. The base of the model is assumed as a no-flow boundary. Open boreholes and packer sections were modelled using the FracMan® "group flux" boundary condition. These boundary conditions assume zero hydraulic resistance within packer intervals or open boreholes, such that heads are the same throughout the open borehole.

The population of background fractures among the fault zones was estimated by JAEA from a statistical analysis of the Posiva database of water conducting fractures identified at KR14–18 boreholes by PFL. Because the focus of sub-task 7B is above fault zone HZ20A, data below HZ20A at each borehole was eliminated from this analysis.

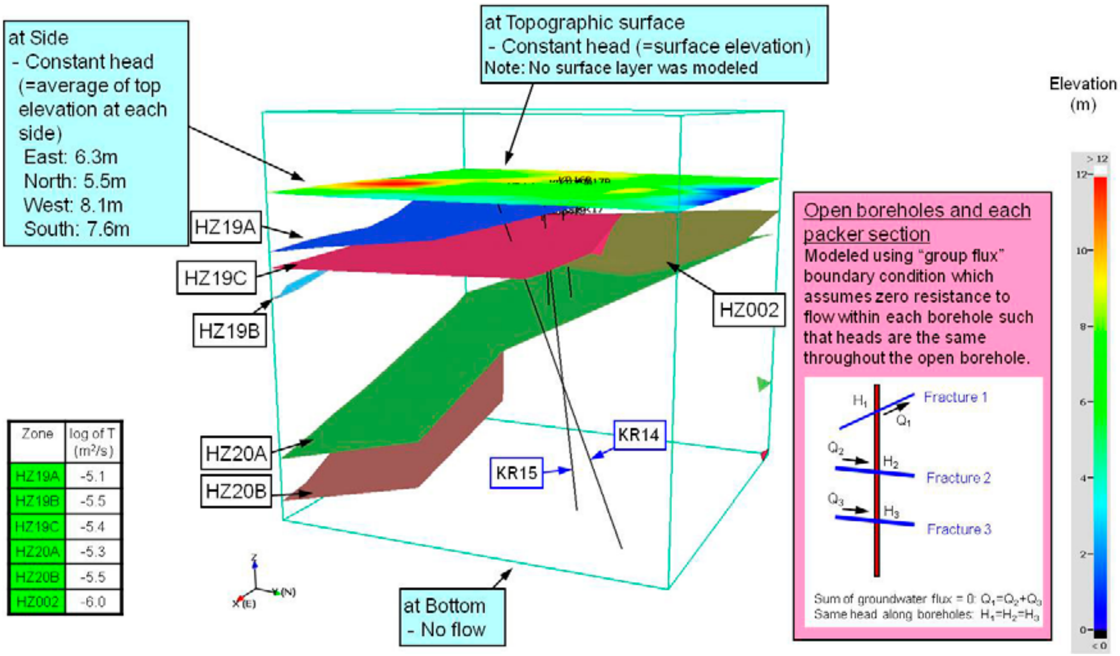
Table 7-12 summarises the derived parameters for the population of background water conducting fractures. Because there are no fracture size data measured for each water conductive fracture, the following empirical correlation found in sub-task 6C between transmissivity, T, and size, L, is used for estimating the size distribution /Dershowitz et al. 2003/.

$$T = 5\times10^{-10} \times L^{1.386} \text{ m}^2/\text{s}$$

An example of the background fracture population generated in modelling region is shown in Figure 7-29.

Table 7-12. Estimated stochastic model of background water conducting fractures identified by PFL.

	Value	Comment
Intensity P32	0.30	Assumes Fisher distribution
Intensity P10	0.23	Conductive fractures identified by PFL
Wang Conversion Factor C31	1.3	Wang (2005)
Mean Pole (Trend, Plunge)	229,78	Sub-horizontal
with Fisher K	4.7	Moderately concentrated
Fisher K-S Goodness of Fit	74%	A very good fit
Transmissivity (Mean, StDev, Min)	-8, 0.8 $\log_{10}$ m^2/s	Lognormal Distribution
Size (Mean, StDev), *L*	31 m, 67 m	Lognormal Distribution, based on Task 6C empirical correlation to Transmissivity, *T* $T= 5\cdot10^{-10} \times L^{1.386}$



at Side
- Constant head (=average of top elevation at each side)
East: 6.3m
North: 5.5m
West: 8.1m
South: 7.6m

at Topographic surface
- Constant head (=surface elevation)
Note: No surface layer was modeled

at Bottom
- No flow

Open boreholes and each packer section

Modeled using "group flux" boundary condition which assumes zero resistance to flow within each borehole such that heads are the same throughout the open borehole.

Sum of groundwater flux = 0: $Q_1=Q_2+Q_3$
Same head along boreholes: $H_1=H_2=H_3$

Figure 7-28. The most plausible model for major water conducting features proposed by JAEA, and boundary conditions.

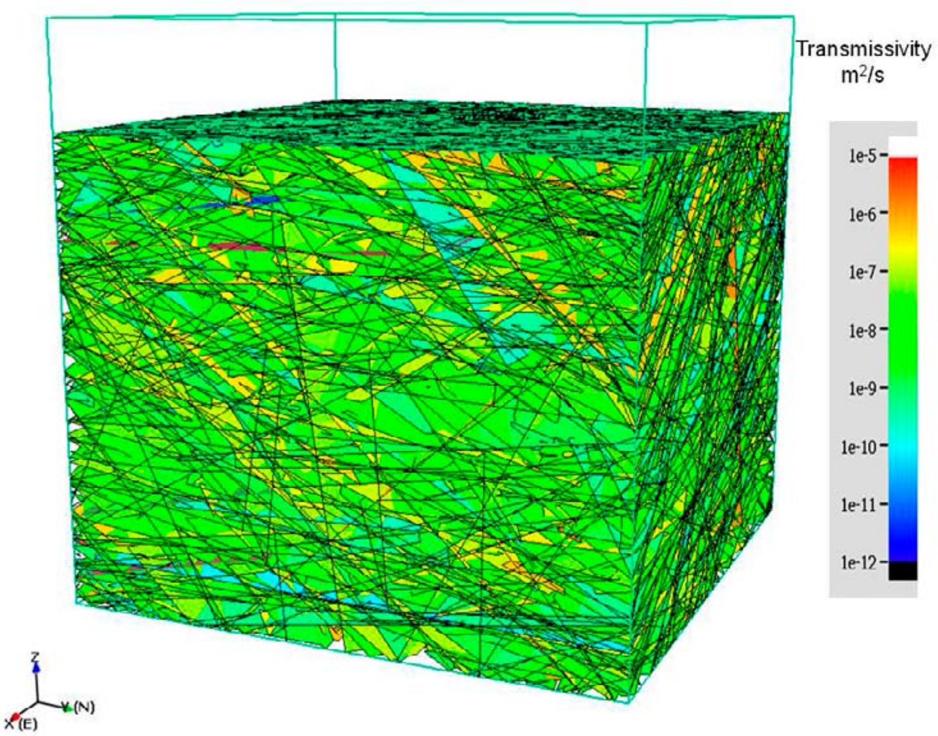


Figure 7-29. An example of background fracture network model generated in the modelling region, 500×500×500 m.

A major purpose of sub-task 7B is to improve the understanding of uncertainty. This was achieved by comparing five stochastic realisations of the background fracture population. Figure 7-30 shows an average hydraulic conductivity in 500 m scale of model block at the different realisations and in the different directions.

Figure 7-31 presents an example of the results from sub-task 7B simulations carried out to understand the role of the larger structures and stochastic background fractures on the flow response to KR14 pumping. The flow response was calculated from the difference between groundwater flow rate along each borehole during pumping and non-pumping (undisturbed phase). Simulations are able to reproduce the major flow responses; however, the match is better without the stochastic background fracture population. The background fracture network model tends to cause the model to overestimate hydraulic responses. However, since the background fracture population is based directly on PFL measurements, it is assumed that this overestimation may be a consequence of stochastic variability between realisations. In support of this, Figure 7-31 illustrates that some realisations can reproduce similar response as measured at the specific boreholes. On the other hand, the pressure responses could more easily be calibrated for a model containing only the larger structures.

JAEA carried out an evaluation of model calibration technology for sub-task 7B, in two steps. In the first step, JAEA calibrated bulk parameters such as average transmissivity of fractures, in order to shift the average model behaviours to match to pressure responses. In the second step, JAEA calibrate more heterogeneous hydraulic pathways by varying the properties of the background fracture population realisation. JAEA plans to extend this calibration study during 2010.

Important lessons from JAEA's 2009 efforts on sub-task 7B include the following:

- Development of an accurate and defensible hydrostructural model of larger structures (Major Water Conducting Features) should be a high priority. Derivative plot analysis of pressure interference tests is very useful tool to conceptualise the major water conducting features.
- It is important to define the properties of the background fracture population from a data set from which the larger structures have been removed. If possible, site investigation is also required to discriminate the effects of major water conducting features when testing at minor zones.
- There is a need to develop improved measures for comparing complex, heterogeneously connected fractured rock mass models to interference test results. JAEA has proposed the use of residual sum of squared errors as one of the performance indices; however, this measure is not sufficient to fully understand the differences between models and measurements.
- For the sub-task 7B rock mass, it was possible to match the majority of pressure and flow responses based on effective fracture hydrogeologic properties, using a single, isotropic value of transmissivity and storativity per fracture.
- Understanding of the larger structures in the hydrostructural model was most important to match pressure and flow responses from hydraulic interference tests.
- While effective fracture hydrogeologic properties are sufficient for hydraulic interference tests, heterogeneous connectivity of minor fractures and/or in-plane heterogeneity of the larger structures needs to be modelled with greater accuracy to match the minor flow responses measured by PFL.

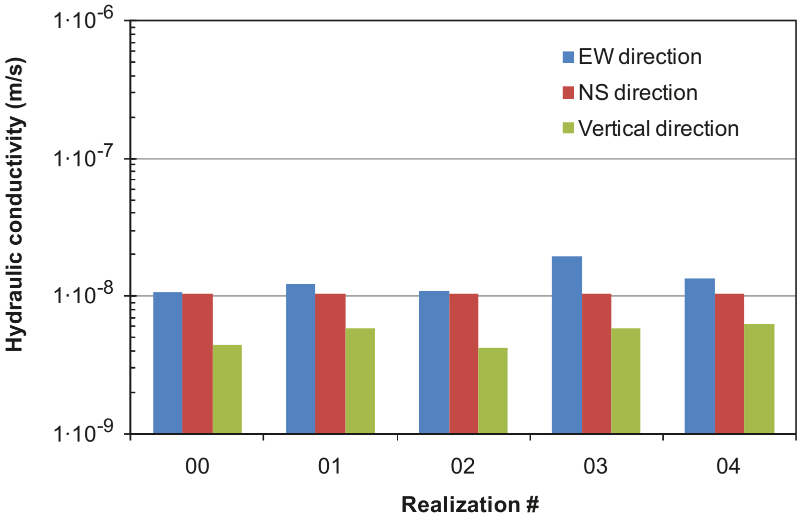


Figure 7-30. *Average hydraulic conductivity of background fracture rock at 500×500×500 m scale, five realisation results.*

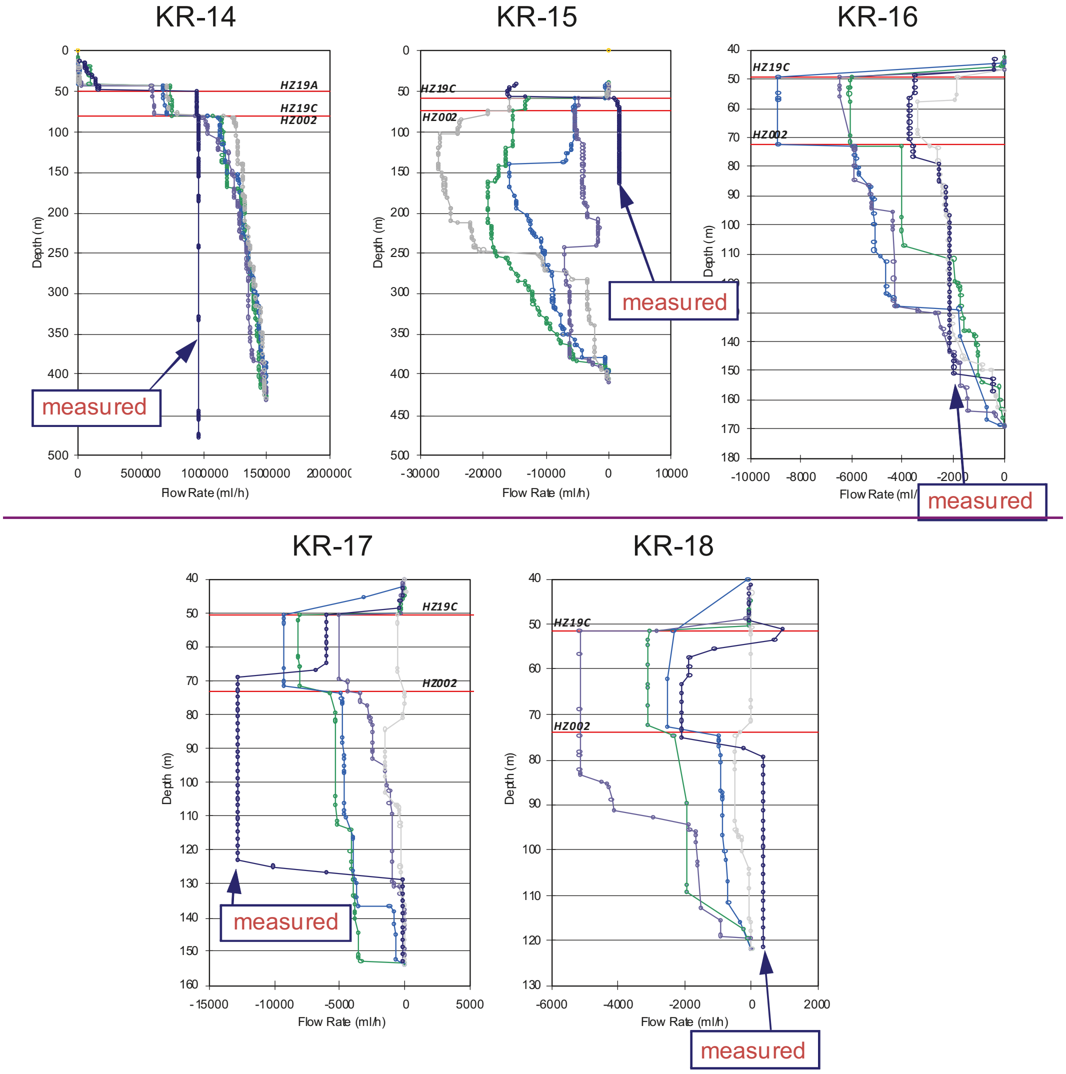


Figure 7-31. *The comparison of flow response during KR14 pumping between simulated results (results from realisations) and measured data (blue).*

Sub-task 7C – Hydrogeologic modelling at single fracture scale across the shafts

Sub-task 7C focuses on three single fractures. The single fractures were defined and characterised from mapping and testing of pilot boreholes and walls of three raised bore shafts at the ONKALO facility at Olikluoto, Finland. The three fractures were selected because they represent a class of low transmissivity fractures which are important for performance assessment, yet have only limited characterisation using conventional hydrogeological test methods. Fractures are estimated to have transmissivity values of approximately $1 \cdot 10^{-9}$, $1 \cdot 10^{-10}$, and $1 \cdot 10^{-11}$ m^2/s. Sub-task 7C includes the following four steps:

- Parameterised and justified microstructural model for three fractures, based on data set provided by Posiva and on generic information.
- Simulation of flow patterns in low transmissivity fractures and calibrating by comparing with 11 single borehole PFL tests, 12 special PFL tests with adjacent open holes ("cross-hole" PFL) tests.
- Simulation of pattern of inflow to shaft as measured on disposable diaper panels, so-called nappy experiment.
- Evaluation of uncertainty of flow in a single fracture.

During 2009, JAEA initiated development of a conceptual model for sub-task 7C, and carried out demonstration flow and transport simulations. JAEA's conceptual model combines:

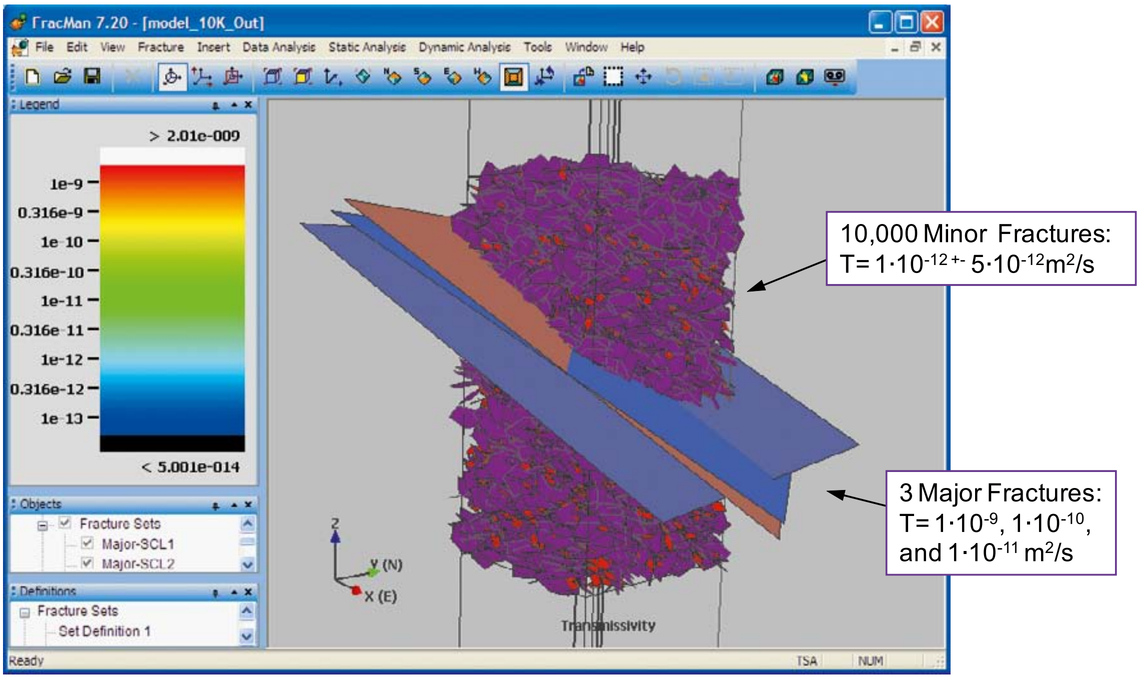
- An example of the Deterministic single fractures for each of the three defined fractures.
- Stochastic background fractures, representing the smaller PFL responses observed.
- A spatial pattern of in-plane aperture, transmissivity, and storativity heterogeneity on each fracture, including both the deterministic fractures and the stochastic background fractures.

JAEA's conceptual model is illustrated in Figure 7-32. During 2009, there was very limited data available to characterise in-plane heterogeneity for these fractures. JAEA derived a fracture roughness pattern by combining generic correlations between fracture roughness measured (Joint Roughness Coefficient: JRC) and aperture distributions measured at the borehole, with the distribution of fracture transmissivities measured by PFL. JAEA implemented this using the FracMan® Projection onto Convex Sets /Menke 1991/ fractal model. An example POCS roughness pattern is shown in Figure 7-33. This POCS pattern matches PFL based transmissivities at borehole intersections, and a fractal pattern of aperture based on JRC roughness measurements.

Figure 7-34 illustrates an example simulation of PFL measurements using the preliminary JAEA conceptual model for sub-task 7C. The model is a purely forward model, based on preliminary roughness models, and has not been calibrated to the PFL measurements shown. Nevertheless, the model shows an ability to match many (but not all) of the PFL flows from both deterministic and stochastic background fractures.

7.5.2 Alternative Buffer Materials

JAEA received the first parcel (i.e., parcel 1; one year test sample under temperature at 130°C) from SKB in June 2009. Several analyses (e.g., X-ray diffraction) have been conducted with the aim to identify mineralogical changes in the Japanese bentonite (one of eleven clay materials used in the ABM-test parcels). Preliminary results of analysis will be obtained in March 2010.



10,000 Minor Fractures: $T = 1 \cdot 10^{-12} \pm 5 \cdot 10^{-12} m^2/s$

3 Major Fractures: $T = 1 \cdot 10^{-9}$, $1 \cdot 10^{-10}$, and $1 \cdot 10^{-11}$ m^2/s

Figure 7-32. *An example of sub-task 7C model, heterogeneous distribution of background fractures connecting the target three single fractures.*

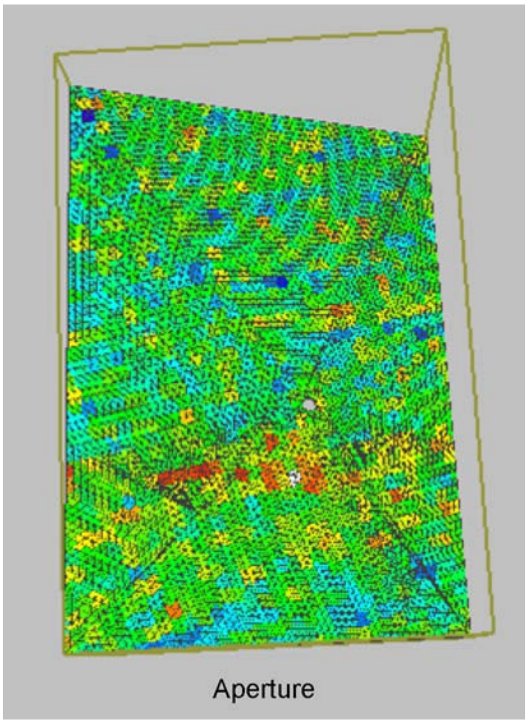


Figure 7-33. *Example POCS Fractal roughness pattern for fracture SCL-1. Scale of fracture shown is 50 m. Apertures range from 0.01 to 0.1 mm.*

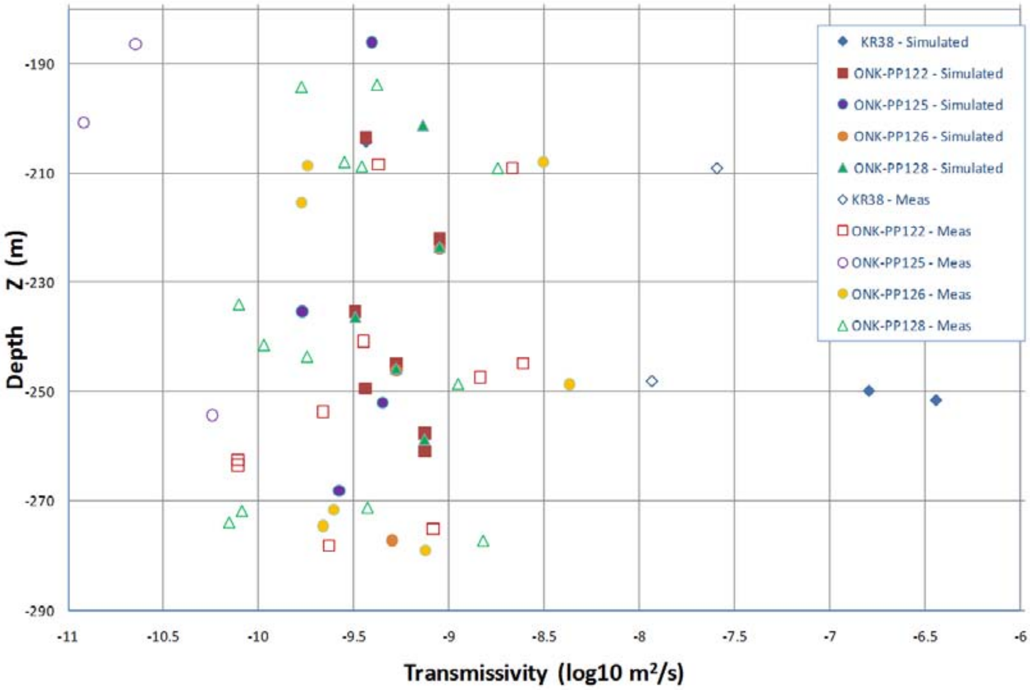


Figure 7-34. *Example of PFL simulation using fractal roughness pattern for fracture SCL-1. Results are shown for PFL measurements of boreholes KR38, PP122, PP125, PP126, and PP128. Simulated transmissivities assume Doe Law /Dershowitz et al. 2003/ correlation between aperture and transmissivity. Solid symbols are measurements, open symbols are simulated. Locations for simulated measurements are stochastic – distributions with depth and level of variability are comparable between simulations and measurements.*

7.6 NWMO

In 2009, support to projects under the Äspö Project Agreement was performed on behalf of the Nuclear Waste Management Organization (NWMO) by Atomic Energy of Canada Limited (AECL), Université Laval and Intera Engineering. The results of this work are briefly described below.

7.6.1 Colloid Transport Project

The goal of the Colloid Transport Project is to gain insight into the potential and significance of erosion of clay-based buffer and backfill materials if dilute groundwater is able to reach a deep geological repository, such as in a hypothetical glacial melt water intrusion scenario. This experiment is being undertaken collaboratively with SKB in support of their bentonite colloid program and also the in situ Colloid Formation and Migration (CFM) experiment being planned at the Swiss Grimsel test site.

In 2008, a series of laboratory-scale bentonite erosion and colloid transport experiments were conducted in a Plexiglas fracture with a consistent aperture of either 5 mm or 1 mm. The results were used to plan the 2009 Quarried Block (QB) experiments, which were conducted in a 1×1 m natural granite fracture with a known and detailed aperture distribution. The experimental plan included:

- Characterising the transport properties of the Quarried Block (QB) fracture with a series of solute tracer tests to provide a benchmark for colloid transport modelling and for assessing the impact of aperture modification associated with bentonite expansion and transport.
- Placing compacted, MX-80, bentonite plugs in both a large aperture and small aperture zone of the QB fracture, each plug being prepared with fluorescent yellow-green or red, 200 nm, latex colloids as tracers.
- Complete erosion experiment in a dipole flow field (44 mL/h) using synthetic Grimsel water as a proxy for glacial melt water, while analysing elution water for bentonite and latex tracer.
- Repeat selected solute tracer tests after the bentonite erosion experiment to determine whether eroded bentonite has altered transport within the QB.
- Complete post-test analyses of the fracture surfaces to visualise extent of bentonite erosion from each plug.

The direction of fracture slope plays an important role in determining the direction of bentonite movement, as shown in Figure 7-35 and as observed during the 2008 mock-up tests. Even though the flow rate, imposed during the erosion experiment, was higher than what would be expected under natural conditions, based on post-test sampling, almost all of the original bentonite remained in or adjacent to the borehole, as illustrated in Figure 7-35. Although limited, the extent of bentonite expansion and movement into the fracture was sufficient to alter the nature of tracer transport in the fracture as determined from comparing pre- and post-experiment tracer tests. Finally, the results of the Quarried Block erosion test indicate that in water containing millimolar amounts of dissolved salts (representative of glacial melt water), the bentonite that expands into an open fracture is likely to form stable deposits that do not release significant concentrations of bentonite colloids.

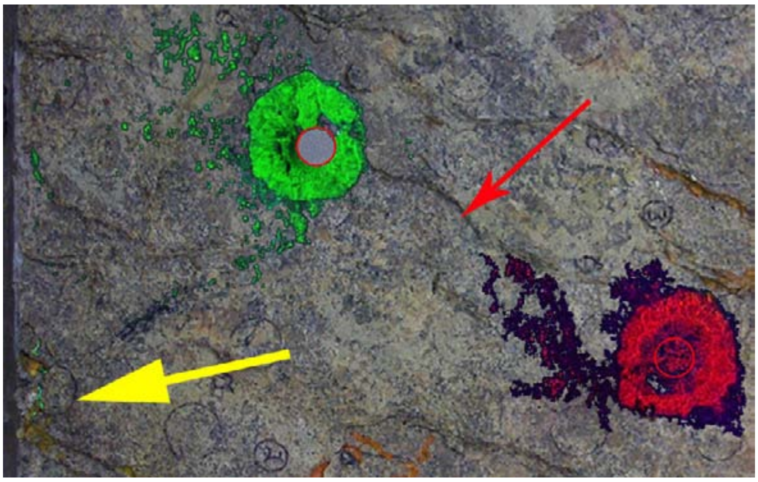


Figure 7-35. *Close up of L1 and L3, fluorescence marks extent of bentonite movement superimposed on the bottom fracture surface. Red circles show extent of bentonite plugs (38 mm diameter) before saturation and expansion, yellow arrow shows dip direction and red arrow indicates the approximate flow direction.*

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

A modelling team from the Université Laval is participating in Task 7, which involves the numerical modelling of hydraulic responses in the fractured crystalline rock environment located on Olkiluoto in Finland. A large data set is available associated with investigations for Posiva's Onkalo underground rock characterisation facility.

Work conducted in 2009 focused on fluid flow modelling within sub-task 7B, which focuses on an area of approximately 400 m × 400 m surrounding boreholes KR14–KR18. The main goals of sub-task 7B were to quantify the reduction of uncertainty in the properties of the fracture network and to further assess the contribution of Posiva Flow Log (PFL) data for rock mass characterisation. Specific goals were to develop a conceptual model for the fractured rock and to perform forward and inverse modelling to reproduce the natural groundwater flow field and the hydraulic responses observed during pumping tests conducted in boreholes KR14 and KR18.

The 2009 modelling activities for sub-task 7B included implementing a geostatistical approach (T PROGS) characterised by a transitional probability model of categorical facies based on Markov chains to represent the fractured rock mass between the major fracture zones. Transmissive fractures identified with the PFL tool were used to define the fractured rock facies (Figure 7-35). The hydraulic response to pumping in the presence of open and sealed-off observation boreholes was simulated (Figure 7-36) and automatic model calibration was performed using HydroGeoSphere and PEST, respectively. The conceptual model was adjusted to improve the match between observed and simulated hydraulic heads by testing different boundary conditions and by adding discrete fractures (Figure 7-36).

The main outcome of this work is the demonstration that PFL measurements are suitable to define rock facies using the geostatistical approach adopted here, and that they are also extremely useful to improve model calibration. In particular, if PFL values are integrated as targets for model calibration together with head values, the uncertainty of model estimated parameters, which is evaluated from 95% linear confidence intervals, is reduced and the interpretation of inverse modelling results is more reliable. This result is the achievement of one of the main goals of sub-task 7B, which was to explore how PFL measurements could reduce uncertainty in models as compared to models calibrated with only head measurements.

Since the overall strategy of Task 7 is to progress from the Olkiluoto site-scale to a much smaller scale, upcoming sub-task 7C will consider small sub-volumes surrounding three ventilation shafts of Onkalo. The main goal is to use PFL data to characterise low transmissivity fractures.

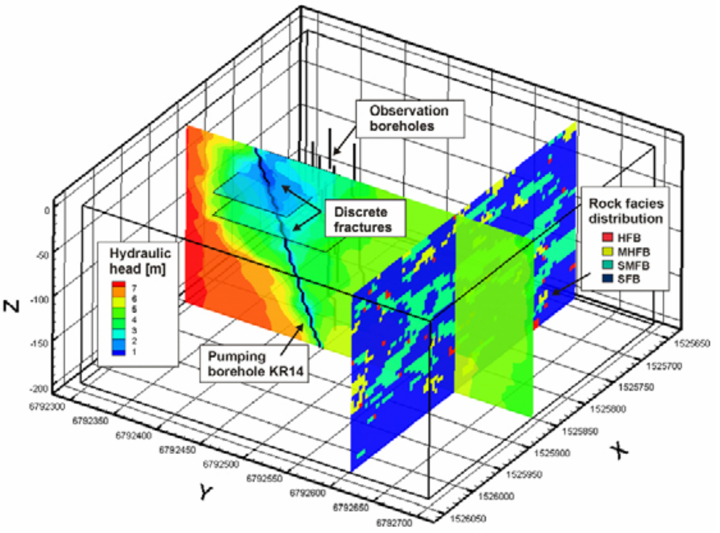


Figure 7-36. Two orthogonal slices within the 3D model show the fractured rock facies and the hydraulic head contours during pumping in KR14. Two horizontal discrete fractures and location of observation boreholes are also shown.

7.6.3 Large Scale Gas Injection Test

NWMO is providing modelling support for the Large Scale Gas Ingestion Test (Lasgit) using the Tough2 code modified with pressure-dependent permeability and capillary pressure to simulate micro-fracturing. In 2009, Lasgit modelling work continued the simulation of the preliminary gas injection tests conducted in 2007, and focused on understanding of gas transport processes. The experimental data show evidence of hydromechanical processes, particularly, some localised hydraulic fracturing in the bentonite or possibly hydraulically induced separation between the bentonite and the canister wall, but the system seems to recover and reseal rapidly after such events. However, the results of the gas tests are difficult to model due to very likely incomplete water resaturation of the bentonite that could create preferential gas flow pathways in low saturation zones, and some unknown initial and boundary conditions particularly near the rock and canister walls. In 2010, the modelling work will focus on simulating the preliminary gas injection tests conducted in 2009. These gas tests will provide improved data for modelling, hopefully to resolve the 2009 modelling difficulties. In addition, the Lasgit model will be further refined to improve definition of important model parameters, including boundary and initial conditions, and model calibration.

7.6.4 Task Force on Engineered Barrier Systems

NMWO is participating in the Task Force on Engineering Barrier systems, with respect to the THM modelling task. In 2009, the Canadian modelling team from AECL performed a modelling study using CODE_BRIGHT on the Canister Retrieval Test in Benchmark 2 /Guo 2009/. Thermal responses were successfully modelled for the bentonite materials and the granite using either the coupled TH model or coupled THM model as demonstrated in Figure 7-37. The hydraulic response could also be modelled using coupled models. The trends of mechanical response development could be captured in the simulations, however, there were some difficulties in obtaining a good match. When a high porewater pressure boundary was applied to bentonite materials, there were some difficulties with convergence in coupled THM modelling because greater porewater pressure can cause greater tensile stress in the bentonite materials.

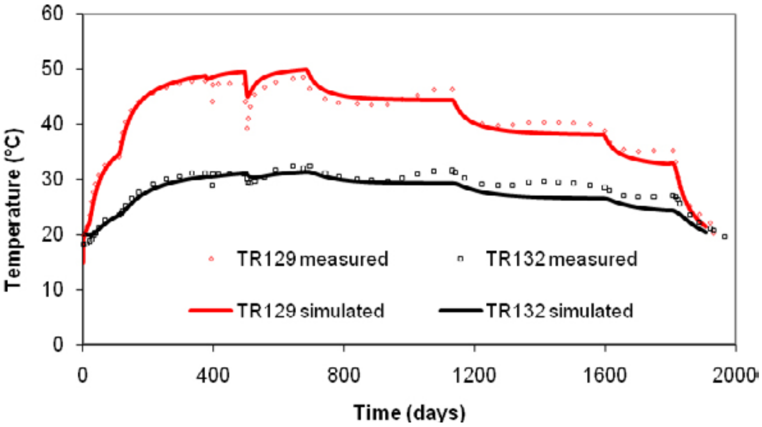


Figure 7-37. *Comparison of simulated temperatures with measurements at different locations in the rock (TR129 and TR132).*

7.7 Posiva

Posiva's co-operation with SKB continues with the new co-operation agreement signed in the autumn of 2006. The focus of the co-operation will be on encapsulation and repository technology and on bedrock investigations.

Posiva also contributed to several of the research projects within Natural barriers. The implementation and construction of the underground rock characterisation facility Onkalo at Olkiluoto in Finland give possibilities to co-operate within the research and development of underground construction technology. The organisation is participating in the following projects:

- Task Force on Modelling of Groundwater Flow and Transport of Solutes.
- Long Term Test of Buffer Materials.
- Alternative Buffer Materials.
- KBS-3 Method with Horizontal Emplacement.
- Large Scale Gas Injection Test.
- Task Force on Engineered Barrier Systems.
- Bentonite laboratory.

Posiva's co-operation is divided between Äspö HRL activities and more generic work that can lead to demonstrations in Äspö HRL. The work performed during 2009 is described below.

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

In 2009, Posiva prepared an Äspö HRL International Technical Document which reported Posiva's modelling effort for sub-task 7A1 that considered the long term pumping test in borehole KR24 in 2004. In the study it was found that the presence of the open drill holes has a clear effect on the head field both during the pumping and without pumping. The most valuable approach to use PFL-data was found to be to consider the changes in PFL-measurement which were caused by pumping at KR24. In conclusion, the PFL-results do give valuable information about the connectivities between the open monitoring drill holes and the pumped drill hole KR24. Moreover, the calibration exercise based on the Kalman filtering ensemble (automatic calibration) clearly demonstrated that the consideration of the PFL data enables the reduction of the variance probability distributions (uncertainty) much more effectively than the calibration based on the head data alone, although there also were cases were just a little change took place. As a particular result the calibration of the Kalman filtering ensemble showed strong indication that the surface connection of HZ19C, one of the most significant hydrogeological zones at the site, was restricted. Main achievements concerning the Olkiluoto site from site characterisation perspective is that the data from pumping test suggests that there is a highly conductive zone (HZ19C) which connects KR24 to the observation drill holes.

In 2009, the work on sub-task 7B modelling on the interference experiment that was carried out in early 2002 in boreholes OL-KR14 to OL-KR18 was continued. The modelling was based on the hydrogeological fracture network model implemented in the FEFTRA/VINTAGE code. With respect to the hydrogeological observables in the case without borehole pumping, the model showed a little sensitivity to various model parameters (e.g., correlation between fracture size and transmissivity).

7.7.2 Long Term Test of Buffer Material

Posiva's task in this project is to study the chemical conditions developing in the bentonite. The task is carried out at VTT. In 2009 the final report on the A2 test parcel was completed including also Posiva's contribution to the work. No new test parcels were retrieved during the year.

7.7.3 Alternative Buffer Materials

During the year 2009 Posiva participated in the studies of the first retrieved parcel of ABM by the work carried out at VTT and B+Tech. The clay materials of interest in the Posiva's studies were MX-80, Deponit, Asha and Friedland Clay. The studies included determination of clay density, water content, microstructure by XRD and SAXS, porewater pH and Eh, CEC and exchangeable cations, dissolvable anions (Cl^-, SO_4^{2-}), material mineralogy by XRD, FTIR and selective extractions, material chemistry by LOI, ICP-AES, Fe^{2+}/Fe^{3+}-ratio and Leco-C and –S. In addition changes in hydro-mechanical properties were studied by measurements on swelling pressure and hydraulic conductivity.

7.7.4 KBS-3 Method with Horizontal Emplacement

SKB and Posiva are engaged in an R&D programme with the overall aim to investigate whether KBS-3H can be regarded as a viable alternative to KBS-3V. The project is jointly executed by SKB and Posiva and has a common steering group. The present stage is the complementary study stage, 2008–2010, where the target is to further develop the KBS-3H description, solve a number of design issues, carry out component tests in the field and select a reference design for KBS-3H. The next stage including further KBS-3H description updates and full-scale sub system tests will also be planned.

Posiva's recourses are involved in all parts of the project and a Finnish sub-project manager is leading the extensive design work aimed at selecting a reference design. A Finnish sub-project manager is also leading the safety case studies focused on alternative materials and their impact on the safety function of the buffer. Fe, Ti and Cu are studied as possible materials for the Supercontainer, plugs and other structural components. The work also includes setting up long-term safety requirements for the development of the design.

7.7.5 Large Scale Gas Injection Test

The second hydration stage was started at the beginning of the year 2008. This will be reported in the forthcoming summary report of the year 2008 activities. Once having finalised this stage, a second gas injection stage was started at the latter half of the year 2009. The related issues have been pursued further within an EU project, FORGE.

7.7.6 Task Force on Engineered Barrier Systems

The objective of the Task Force on Engineered Barrier Systems is to develop methods and tools for THMC analyses of buffer and backfill. The objective for the year 2009 was to finalise the work related to simulation of benchmark cases and initiating C-benchmark analyses.

Regarding THM simulations development of a continuum thermodynamical description of an arbitrary mixture was continued. The prediction capability of the method appeared similar to the other methods used in EBS Task force while the theoretical basis still needs further development.

Considering chemical aspects, the development of benchmark cases was contributed and later simulations of benchmark case measurement setups were committed.

7.7.7 Sealing of Tunnel at Great Depth

Posiva participated in the project "Sealing of tunnel at Great Depth" mainly by having a representative in the reference group for the project.

7.7.8 Bentonite laboratory

Backfill studies continued at Äspö laboratory and Posiva participated to the project "Impact of water inflow in backfilled deposition tunnels" implemented in half scale steel tunnel in Bentonite laboratory. Posiva's role was to participate to the planning and follow of the test set ups. The project will be reported during 2010.

7.8 Nagra

The Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle, Nagra, has the task to provide scientific and technical basis for the safe disposal of radioactive waste in Switzerland. Nagra has had agreements with SKB for participation in Äspö HRL since 1994 to include mutual co-operation and participation in Äspö HRL and Grimsel Test Site projects. The last agreement expired 2003 and Nagra has now left the central and active core of participants.

Nevertheless, Nagra supports the Äspö activities and participates in specific tasks. Nagra had supplied various bentonite samples for the Alternative Buffer Materials Test. After the successful overcoring of the first of the three sets, Nagra could retrieve its bentonite samples in summer 2009. These samples are being investigated for different aspects such as rock mechanics, mineralogy, chemistry of the porewater etc at different research institutes in Switzerland. The work will be concluded in 2010 and the results will be summarised in a working report. Nagra has also participated in the modelling meetings and in the meetings of sub-group for the geochemical aspects within the EBS Task Force.

7.9 RAWRA

Radioactive Waste Repository Authority, RAWRA, was established in 1997 and has the mission to ensure the safe disposal of existing and future radioactive waste in the Czech Republic and to guarantee fulfilment of the requirements for the protection of humans and the environment from the adverse impacts of such waste. RAWRA became a participant in the Task Force on Engineered Barrier Systems in 2005 and participates also in the Alternative Buffer Materials project.

Task Force on Engineered Barrier Systems Nuclear Research Institute, contractor of RAWRA, has continued to do an experiment series for better understanding of the gas migration process.

A set of experiments has been continued by Nuclear research Institute with two types of bentonite having different properties; measured data have been described and analysed. The data only have confirmed complexity of migration process and presence of chaotic components in the gas migration process, so the creation of a universal model for simulating laboratory experiments presents a formidable task. Several simple models for estimation of this problem have been created in GoldSim environment on the basis of these data. Two-phase flow model in Tough2 was under development. In the next period, additional experiments will be started for deeper understanding of the process of gas paths creation in bentonite. Alterations in the bentonite structure after breakthrough will be followed. The results of the experiments should help in breakthrough process modelling. There will be created models using GoldSim and Tough2 code for simulating laboratory experiments and for simulating gas migration process in deep geological repository.

Technical university of Liberec (TUL) team, one of contractors of RAWRA, participated in 2009 in the "Task force on EBS", in modelling of AECL's "Buffer contained experiment", in situ thermo-hydro-mechanical test. Their own simulation code ISERIT was used for calculation of heat conduction and water distribution. Continuation of these activities is expected. The simulation code will be further developed to cover a larger group of physical phenomena and more general input data. Either the BCE experiment will be recalculated to get better fit and/or other experiments, e.g. CRT in Äspö, in the Task force EBS. It is also planned to continue the progress in combining the simulation code with an inverse problem solution algorithm (automatic calibration).

The third contractor of RAWRA, CEG of technical University in Prague, continued with evaluation of Canister Retrieval Test. The results from especially developed model were compared to experimental inputs. The model will also be used for evaluations of the experiments related to the project MockUP-CZ.

8 Literature

8.1 References

Albrecht-Gary A-M, Blanc S, Rochel N, Ocakatan A Z, Abdallah M A, 1994. Bacterial iron transport: coordination properties of pyoverdine PaA, a peptidic siderophore of Pseudomonas aeruginosa. Inorganic Chemistry, 33, pp 6391–6402.

Anderson C R, Pedersen K, 2003. In situ growth of Gallionella biofilms and partitionating of lanthanids and actinides between biological material and ferric oxyhydroxides. Geobiology, 1, pp 169–178.

Anderson C, Jakobsson A-M, Pedersen K, 2006a. Influence of in situ biofilm coverage on the radionuclide adsorption capacity of subsurface granite. Environmental Science & Technology, 41, pp 830–836.

Anderson C, Pedersen K, Jakobsson A-M, 2006b. Autoradiographic comparisons of radionuclide adsorption between subsurface anaerobic biofilms and granitic host rocks. Geomicrobiology Journal, 23, pp 15–29.

Anderson C, James R E, Chi Fru E, Kennedy C B, Pedersen K, 2006c. In situ ecological development of a bacteriogenic iron oxide-producing microbial community from a subsurface granitic rock environment. Geobiology, 4, pp 29–42.

Andersson J C, 2007. Äspö Hard Rock Laboratory. Äspö Pillar Stability Experiment, final report. Rock mass response to coupled mechanical thermal loading. SKB TR-07-01, Svensk Kärnbränslehantering AB.

Andersson P S, Wasserburg G J, Chen J H, Papanastassiou D A, Ingri J, 1995. ^{238}U–^{234}U and ^{232}Th–^{230}Th in the Baltic Sea and in river water. Earth and Planetary Science Letters 130, pp 217–234.

Andersson P, Byegård J, Billaux D, Cvetkovic V, Dershowitz W, Doe T, Hermanson J, Poteri A, Tullborg E-L, Winberg A (ed), 2007. TRUE Block Scale Continuation Project. Final report. SKB TR-06-42, Svensk Kärnbränslehantering AB.

André M, Malmström M E, Neretnieks I, 2009. Specific surface area determinations on intact drillcores and evaluation of extrapolation methods for rock matrix surfaces. Journal of Contaminant Hydrology, 110, pp 1–8.

Autio J, Johansson E, Hagros A, Anttila P, Rönnqvist P-E, Börgesson L, Sandén T, Eriksson M, Halvarsson B, Berghäll J, Kotola R, Parkkinen I, 2008. KBS-3H design description 2007. SKB R-08-44, Svensk Kärnbränslehantering AB.

Banwart S, Tullborg E-L, Pedersen K, Gustafsson E, Laaksoharju M, Nilsson A-C, Wallin B, Wikberg P, 1996. Organic carbon oxidation induced by large-scale shallow water intrusion into a vertical fracture zone at the Äspö Hard Rock Laboratory (Sweden). Journal of Contaminant Hydrology, 21, pp 115–125.

Barcena I, Garcia-Sineriz J-L, 2001. Äspö Hard Rock Laboratory. Prototype repository. System for canisters displacement tracking. SKB IPR-02-06, Svensk Kärnbränslehantering AB.

Bath A, Milodowski A, Ruotsalainen P, Tullborg E-L, Cortés R, Aranyossy J-F, 2000. Evidence from mineralogy and geochemistry for the evolution of groundwater systems during the Quaternary for use in radioactive waste repository safety assessment (EQUIP Project). EUR 19613, European Commission.

Berlin R, Hardenby C, 2008. Äspö Hard Rock Laboratory. Laser scanning combined with digital photography. Tunnel TASQ and niche NASQ0036A at Äspö HRL. SKB IPR-08-10, Svensk Kärnbränslehantering AB.

Birgersson M, Karnland O, 2009. Ion equilibrium between montmorillonite interlayer space and an external solution – consequences for diffusional transport. Geochimica et Cosmochimica Acta, 73, pp 1908–1923.

Bono N, Röshoff K, 2003. Äspö Hard Rock Laboratory. Prototype repository. Instrumentation for stress, strain and displacement measurements in rock. SKB IPR-03-19, Svensk Kärnbränslehantering AB.

Byegård J, Johansson H, Skålberg M, Tullborg E-L, 1998. The interaction of sorbing and non-sorbing tracers with different Äspö rock types. Sorption and diffusion experiments in the laboratory scale. SKB TR-98-18, Svensk Kärnbränslehantering AB.

Börgesson L, 1992. Interaction between rock, bentonite buffer and canister. FEM calculations of some mechanical effects on the canister in different disposal concepts. SKB TR 92-30, Svensk Kärnbränslehantering AB.

Börgesson L, Sandén T, 2003. Äspö Hard Rock Laboratory. Prototype repository. Instrumentation of buffer and backfill in section II. SKB IPR-03-21, Svensk Kärnbränslehantering AB.

Börgesson L, Johannesson L-E, Sandén T, Hernelind J, 1995. Modelling of the physical behaviour of water saturated clay barriers. Laboratory tests, material models and finite element applications. SKB TR 95-20, Svensk Kärnbränslehantering AB.

Carlsten S, Hultgren P, Mattsson H, Stanfors R, Wahlgren C-H, 2006. Oskarshamn site investigation. Geological single-hole interpretation of KLX03, HLX26 and HLX27. SKB P-05-38, Svensk Kärnbränslehantering AB.

Chen J H, Edwards R L, Wasserburg G J, 1986. ^{238}U, ^{234}U and ^{232}Th in seawater. Earth and Planetary Science Letters, 80, pp 241–251.

Cheng H, Cvetkovic V, 2009. Evaluation of colloid transport experiments in a quarried block. In: Hyatt N C, Pickett D A, Rebak R B (eds). Scientific Basis for Nuclear Waste Management XXXII. Warrendale, PA: Materials Research Society. (Materials Research Society Symposium Proceedings 1124), pp 519–524.

Collin M, Börgesson L, 2001. Äspö Hard Rock Laboratory. Prototype repository. Instrumentation of buffer and backfill for measuring THM processes. SKB IPR-02-03, Svensk Kärnbränslehantering AB.

Cvetkovic V, 2010a. Significance of fracture rim zone heterogeneity for tracer transport in crystalline rock. Water Resources Research, 46, W03504, doi: 10.1029/2009WR007755.

Cvetkovic V, 2010b. Diffusion-controlled tracer retention in crystalline rock on the field scale. Geophysical Research Letters, 37, L13401, doi:10.1029/2010GL0434.

Cvetkovic V, Frampton A, 2010. Transport and retention from single to multiple fractures in crystalline rock at Äspo (Sweden): 2. Fracture network simulations and generic retention model. Water Resources Research, 46, W05506, doi:10.1029/2009WR008030.

Cvetkovic V, Cheng H, Byegard J, Winberg A, Tullborg E-L, Widestrand H, 2010. Transport and retention from single to multiple fractures in crystalline rock at Äspo (Sweden): 1. Evaluation of tracer test results and sensitivity analysis. Water Resources Research, 46, W05505, doi:10.1029/2009WR008013.

Degueldre C, Raabe S, Wold S, 2009. Investigations of clay colloid aggregates by scanning Xray microspectroscopy of suspensions. Applied Geochemistry, 24, pp 2015–2018.

Dershowitz W, Doe T, Uchida M, Hermanson J, 2003. Correlations between fracture size, transmissivity, and aperture. In: Culligan P, Einstein H, Whittle A (eds). Soil and Rock America 2003: proceedings of the 39th U.S. Rock Mechanics Symposium, Cambridge, Massachusetts, June 2003. Essen: Glückauf, pp 887–891.

Dubois I E, Holgersson S, Allard S, Malmstrom M E, 2009. Dependency of BET surface area on particle size for some granitic minerals. Accepted for publication in Radiochimica Acta 2010.

Duckworth D, Haycox J, Pettitt W S, 2008. Äspö Hard Rock Laboratory. Prototype Repository. Acoustic emission and ultrasonic monitoring results from deposition hole DA3545G01 in the Prototype Repository between October 2007 and March 2008. SKB IPR-09-10, Svensk Kärnbränslehantering AB.

Duckworth D, Haycox J R, Pettitt W S, 2009. Äspö Hard Rock Laboratory. Prototype Repository. Acoustic emission and ultrasonic monitoring results from deposition hole DA3545G01 in the Prototype Repository between April 2008 and September 2008. SKB IPR-09-13, Svensk Kärnbränslehantering AB.

Edén P, Björklund A, 1993. Hydrogeochemistry of river waters in Fennoscandia. Aqua Fennica, 23, pp 125–142.

Eriksson S, 2007. Äspö Hard Rock Laboratory. Prototype Repository. Analysis of microorganisms, gases, and water chemistry in buffer and backfill, 2004–2007. SKB IPR-08-01, Svensk Kärnbränslehantering AB.

Essén S A, Johnsson A, Bylund D, Pedersen K, Lundström U S, 2007. Siderophore production by Pseudomonas stutzeri under aerobic and anaerobic conditions. Applied and Environmental Microbiology, 73, pp 5857–5864.

Fredriksson A, Staub I, Outters N, 2004. Äspö Pillar Stability Experiment. Final 2D coupled thermo-mechanical modelling. SKB R-04-02, Svensk Kärnbränslehantering AB.

García-García S, Degueldre C, Wold S, Frick S, 2009a. Determining pseudo-equilibrium of montmorillonite colloids in generation and sedimentation experiments as a function of ionic strength, cationic form, and elevation. Journal of Colloid and Interface Science, 335, pp 54–61.

García-García S, Wold S, Jonsson M, 2009b. Effect of temperature on the stability of colloidal montmorillonite particles at different pH and ionic strength. Applied Clay Science, 43, pp 21–26.

Goudarzi R, Johannesson L-E, 2009. Äspö Hard Rock Laboratory. Prototype Repository. Sensors data report. (Period 010917–090601). Report No: 21. IPR-09-17, Svensk Kärnbränslehantering AB.

Goudarzi R, Åkesson M, Hökmark H, 2008. Äspö Hard Rock Laboratory. Temperature Buffer Test. Sensors data report. (Period 030326-080701). Report No: 12. SKB IPR-09-04, Svensk Kärnbränslehantering AB.

Grenier C, Bernard-Michel G, Benabderrahmane H, 2009. Evaluation of retention properties of a semi-synthetic fractured block from modelling at performance assessment time scales (Äspö Hard Rock Laboratory, Sweden). Hydrogeology Journal, 17, pp 1051–1066.

Grob H, 1972. Schwelldruck am Beispiel des Belchentunnels. In: Lama R D (ed). Proceedings of the International Symposium on Underground Openings, Lucerne, Switzerland, pp 99–119.

Guo R, 2009. Coupled thermal-hydraulic-mechanical modelling of the canister retrieval test. NWMO TR-2009-31, Nuclear Waste Management Organization, Canada.

Gustafson G, Gylling B, Selroos J-O, 2009. The Äspö Task Fortce on groundwater flow and transport of solutes: bridging the gap between site characterization and performance assessment for radioactive waste disposal in fractured rocks. Hydrogeology Journal, 17, pp 1031–1033.

Hakami E, Wang W, 2005. Äspö Hard Rock Laboratory. TRUE-1 Continuation Project. Fault rock zones characterisation. Characterisation and quantification of resin-impregnated fault rock pore space using image analysis. SKB IPR-05-40, Svensk Kärnbränslehantering AB.

Hallbeck L, Pedersen K, 2008a. Characterization of microbial processes in deep aquifers of the Fennoscandian Shield. Applied Geochemistry, 23, pp 1796–1819.

Hallbeck L, Pedersen K, 2008b. Explorative analysis of microbes, colloids, and gases together with microbial modelling. Site description model, SDM-Site Laxemar. R-08-109, Svensk Kärnbränslehantering AB.

Hallbeck L, Pedersen K, 2008c. Explorative analysis of microbes, colloids and gases. SDM-Site Forsmark. R-08-85, Svensk Kärnbränslehantering AB.

Hardenby C, Sigurdsson O, Hernqvist L, Bockgård N, 2008. Äspö Hard Rock Laboratory. The TASS-tunnel project "Sealing of tunnel at great depth". Geology and hydrogeology – Results from the pre-investigations based on the boreholes Kl0010B01, Kl0014B01 and Kl0016B01. SKB IPR-08-18, Svensk Kärnbränslehantering AB.

Harrington J F, Horseman S T, 2003. Gas migration in KBS-3 buffer bentonite. Sensitivity of test parameters to experimental boundary conditions. SKB TR-03-02, Svensk Kärbränslehantering AB.

Haveman S A, Pedersen K, 2002. Microbially mediated redox processes in natural analogues for radioactive waste. Journal of Contaminant Hydrology, 55, pp 161–174.

Hodgkinson D P, Benabderrahmane H, Elert M, Hautojärvi A, Selroos J-O, Tanaka Y, Uchida M, 2009. An overview of Task 6 of the Äspö Task Force: modelling groundwater and solute transport: improved understanding of radionuclide transport in fractured rock. Hydrogeology Journal, 17, pp 1035–1049.

Holmboe M, Wold S, Jonsson M, García-García S, 2009. Effects of γ-irradiation on the stability of colloidal Na^+-Montmorillonite dispersions. Applied Clay Science, 43, pp 86–90.

Hultgren P, 2008. Äspö Hard Rock Laboratory. A comparative study of tunnel mapping results from the Äspö TBM and drill and blast tunnels. SKB P-08-102, Svensk Kärnbränslehantering AB.

Hökmark H, Ledesma A, Lassabatere T, Fälth B, Börgesson L, Robinet J C, Sellali N, Sémété P, 2007. Modelling heat and moisture transport in the ANDRA/SKB temperature buffer test. Physics and Chemistry of the Earth, Parts A/B/C, 32, pp 753–766.

Jansson M, 2009. Bentonite erosion. Laboratory studies. SKB TR-09-33, Svensk Kärnbränslehantering AB.

Johnsson A, Arlinger J, Pedersen K, Ödegaard-Jensen A, Albinsson Y, 2006. Solid-aqueous phase partitioning of radionuclides by complexing compounds excreted by subsurface bacteria. Geomicrobiology Journal, 23, pp 621–630.

Karnland O, Olsson S, Dueck A, Birgersson M, Nilsson U, Hernan-Håkansson T, Pedersen K, Nilsson S, Eriksen T, Rosborg B, 2009. Long term test of buffer material at the Äspö Hard Rock Laboratory, LOT project. Final report on the A2 test parcel. SKB TR-09-29, Svensk Kärnbränslehantering AB.

Kyle J E, Eydal H S C, Ferris F G, Pedersen K, 2008. Viruses in granitic groundwater from 69 to 450 m depth of the Äspö Hard Rock Laboratory, Sweden. The ISME Journal, 2, pp 571–574.

Ledesma A, Jacinto A, Velasco M, 2006. Temperature Buffer Test. ENRESA contribution. Final report. CIMNE-UPC, DM Iberia.

Ledesma A, Jacinto A, 2007. Modelling Andra experiment "Temperature Buffer Test". Final report 2007. CIMNE-UPC.

Löfvendahl R, 1987. Dissolved uranium in the Baltic Sea. Marine Chemistry, 21, pp 213–227.

Menke W, 1991. Applications of the POCS inversion method to interpolating topography and other geophysical fields. Geophysical Research Letters, 18, pp 435–438.

Milodowski A E, Tullborg E-L, Buil B, Gomez P, Turrero M-J, Haszeldine S, England G, Gillespie M R, Torres T, Ortiz J E, Zacharias J, Silar J, Chvatal M, Strnad L, Sebek O, Bouch J E, Chenery S R N, Chenery C A, Shepherd T J, McKervey J A, 2005. Application of mineralogical, petrological and geochemical tools for evaluating the palaeohydrogeological evolution of the PADAMOT study sites. Harwell: UK Nirex Ltd. (PADAMOT Project Technical Report WP2).

Moll H, Glorius, M, Bernhard G, Johnsson A, Pedersen, K, Schäfer M, Budzikiewicz H, 2008. Characterization of pyoverdins secreted by a subsurface strain of Pseudomonas fluorescens and their interactions with uranium(VI). Geomicrobiology Journal, 25, pp 157–166.

Moll H, Glorius M, Barkleit A, Rossberg A, Bernhard G, 2009. The mobilization of actinides by microbial ligands taking into consideration the final storage of nuclear waste – interactions of selected actinides U(VI), Cm(III), and Np(V) with pyoverdins secreted by Pseudomonas fluorescens and related model compounds. Technical Report FZD-522, Forschungszentrum Dresden-Rossendorf, Germany.

Moreno L, Crawford J, 2009. Can we use tracer tests to obtain data for performance assessment of repositories for nuclear waste? Hydrogeology Journal, 17, pp 1067–1080.

Neretnieks I, 1982. Leach rates of high level waste and spent fuel. Limiting rates as determined by backfill and bedrock conditions. In: Lutze W (ed). Scientific basis for nuclear waste management V: proceedings of the Materials research society fifth International symposium on the scientific basis for nuclear waste management, Berlin, Germany, 7–10 June 1982. New York: North-Holland. (Materials Research Society Symposium Proceedings 11), pp 559–568.

Neretnieks I, Andersson J C, 2009. Characterization of spalling fragments to obtain data for flow and solute transport in damaged zones. In: Rock characterisation,modelling and engineering design methods: proceedings for the. International Symposium on Rock Mechanics (SINOROCK 2009), University of Hong Kong, 19–22 May 2009.

Nielsen M E, Pedersen K, Fisk M R, Istok J D, 2006. Microbial nitrate respiration of lactate at in situ conditions in ground water from a granitic aquifer situated 450 m underground. Geobiology, 4, pp 43–52.

Nowak T, Kunz H, 2009. Äspö Hard Rock Laboratory. Äspö Task Force on Engineered Barrier System. Modelling of THM-coupled processes for benchmark 2.1.1 and 2.1.2 with the code GeoSys/RockFlow. SKB IPR-09-14, Svensk Kärnbränslehantering AB.

Parkhurst D L, Appelo C A J, 1999. User's guide to PHREEQC (version 2): a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. Denver, Co: U.S. Geological Survey. (Water-resources investigations report 99-4259).

Pedersen K, 2000. Äspö Hard Rock Laboratory. The microbe site. Drilling, instrumentation and characterisation. SKB IPR-00-36, Svensk Kärnbränslehantering AB.

Pedersen K, 2002. Microbial processes in the disposal of high level radioactive waste 500 m underground in Fennoscandian shield rocks. In: Keith-Roach M J, Livens F R (eds). Interactions of microorganisms with radionuclides. Amsterdam: Elsevier, pp 279–311.

Pedersen K, 2005a. Äspö Hard Rock Laboratory. The MICROBE framework. Site descriptions, instrumentation, and characterization, Äspö Hard Rock Laboratory. SKB IPR-05-05, Svensk Kärnbränslehantering AB.

Pedersen K, 2005b. Äspö Hard Rock Laboratory. MICROBE. Analysis of microorganisms and gases in MICROBE groundwater over time during MINICAN drainage of the MICROBE water conducting zone. SKB IPR-05-29, Svensk Kärnbränslehantering AB.

Pedersen K, Albinsson Y, 1991. Effect of cell number, pH and lanthanide concentration on the sorption of promethium by Shewanella putrefaciens. Radiochima Acta, 54, pp 91–95.

Pedersen K, Albinsson Y, 1992. Possible effects of bacteria on trace element migration in crystalline bed-rock. Radiochima Acta, 58/59, pp 365–369.

Pedersen K, Arlinger J, Hallbeck A, Hallbeck L, Eriksson S, Johansson J, 2008. Numbers, biomass and cultivable diversity of microbial populations relate to depth and borehole-specific conditions in groundwater from depths of 4–450 m in Olkiluoto, Finland. The ISME Journal, 2, pp 760–775.

Poteri A, 2009. Retention properties of flow paths in fractured rock. Hydrogeology Journal, 17, pp 1081–1092.

Puigdomenech I, Sandén T, 2001. Äspö Hard Rock Laboratory. Prototype repository. Instrumentation for gas and water sampling in buffer and backfill. Tunnel section I. SKB IPR-01-62, Svensk Kärnbränslehantering AB.

Rautioaho E, Korkiala-Tanttu L, 2009. Betomap: survey of bentonite and tunnel backfill knowledge – State-of-the-art. VTT Working Papers 133, VTT Technical Research Centre of Finland.

Rhén I, Forsmark T, Magnusson J, Alm P, 2003. Äspö Hard Rock Laboratory. Prototype repository. Hydrogelogical, hydrochemical, hydromechanical and temperature measurements in boreholes during the operation phase of the Prototype Repository Tunnel section II. SKB IPR-03-22, Svensk Kärnbränslehantering AB.

Roos M, Åström M, 2005. Hydrochemistry of rivers in an acid sulphate soil hotspot area in western Finland. Agricultural and Food Science, 14, pp 24–33.

Rothfuchs T, Hartwig L, Komischke M, Miehe R, Wieczorek K, 2003. Äspö Hard Rock Laboratory. Prototype repository. Instrumentation for resistivity measurements in buffer backfill and rock in section II. SKB IPR-03-48, Svensk Kärnbränslehantering AB.

Schneider K J, 1994. Bautabellen für Ingenieure: mit europäischen und nationalen Vorschriften. 11. Aufl. Düsseldorf: Werner.

SKB, 2001. Forsknings-, utvecklings- och demonstrationsprogram för ett KBS-3-förvar med horisontell deponering. SKB R-01-55, Svensk Kärnbränslehantering AB.

SKB, 2007. RD&D-Programme 2007. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste. SKB TR-07-12, Svensk Kärnbränslehantering AB.

SKB, 2008. Horizontal deposition of canisters for spent nuclear fuel. Summary of the KBS-3H project 2004–2007. SKB TR-08-03, Svensk Kärnbränslehantering AB.

SKB, 2009a. Äspö Hard Rock Laboratory. Planning report for 2009. SKB IPR-09-05 Svensk Kärnbränslehantering AB.

SKB, 2009b. Äspö Hard Rock Laboratory. Status report January – April 2009. SKB IPR-09-15, Svensk Kärnbränslehantering AB.

SKB, 2009c. Äspö Hard Rock Laboratory. Status report May – August 2009. SKB IPR-09-18, Svensk Kärnbränslehantering AB.

SKB, 2010. Äspö Hard Rock Laboratory. Status Report October – December 2009. SKB IPR-10-09, Svensk Kärnbränslehantering AB.

Smart N R, Rance A P, 2009. Miniature canister corrosion experiment – results of operations to May 2008. SKB TR-09-20, Svensk Kärnbränslehantering AB.

Smellie J A T, Waberg H N, Frape S K, 2003. Matrix fluid chemistry experiment. Final report. June 1998 – March 2003. SKB TR-03-18, Svensk Kärnbränslehantering AB.

Smith P, Neall F, Snellman M, Pastina B, Hjerpe T, Nordman H, Johnson L, 2008. Safety assessment for a KBS-3H spent nuclear fuel repository at Olkiluoto. Summary report. SKB R-08-39, Svensk Kärnbränslehantering AB.

Staub I, Anderson J C, Magnor B, 2004. Äspö Pillar Stability Experiment. Geology and properties of the rock in TASQ. SKB R-04-01, Svensk Kärnbränslehantering AB.

Studer J, Ammann W, Meier P, Müller C, Glauser E, 1984. Verfüllen und Versiegeln von Stollen, Schächten und Bohrlöchern. Band 1. Band 2: Anhänge. Nagra Technischer Bericht NTB 84-33, National Cooperative for the Disposal of Radioactive Waste, Switzerland.

Uchida M, Dershowitz W, Lee G, Shuttle D, 2009. An empirical probabilistic approach for constraining the uncertainty of long-term solute transport predictions in fractured rock using in situ tracer experiments. Hydrogeology Journal, 17, pp 1093–1110.

Vilks P, Miller N H, 2009. Bentonite and latex colloid migration experiments in a granite fracture on a metre scale to evaluate effects of particle size and flow velocity. NWMO TR-2009-26, Nuclear Waste Management Organization, Canada.

Wass E, Nyberg G, 2009. Äspö Hard Rock Laboratory. Hydro Monitoring Program. Report for 2008. SKB IPR-09-11, Svensk Kärnbränslehantering AB.

Zazzi Å, 2009. Chlorite: geochemical properties, dissolution kinetics and Ni(II) sorption. Ph. D. thesis. KTH Chemical Science and Engineering, Royal Institute of Technology, Stockholm. (TRITA-CHE Report 2009:9).

Zolezzi F, Haycox J R, Pettitt W S, 2008. Äspö Hard Rock Laboratory. Prototype repository. Acoustic emission and ultrasonic monitoring results from deposition hole DA3545G01 in the Prototype repository between April 2007 and September 2007. SKB IPR-09-03, Svensk Kärnbränslehantering AB.

Åkesson M (ed), 2006a. Äspö Hard Rock Laboratory. Temperature Buffer Test. Evaluation modelling – field test. SKB IPR-06-10, Svensk Kärnbränslehantering AB.

Åkesson M (ed), 2006b. Äspö Hard Rock Laboratory. Temperature Buffer Test. Evaluation modelling – mock-up Test. SKB IPR-06-11, Svensk Kärnbränslehantering AB.

Åkesson M (ed), 2008. Äspö Hard Rock Laboratory. Temperature Buffer Test. Evaluation modelling. TBT_3 Mock-up test. SKB IPR-08-09, Svensk Kärnbränslehantering AB.

Åkesson M, Jacinto A C, Gatabin C, Sanchez M, Ledesma A, 2009. Bentonite THM behaviour at high temperatures: experimental and numerical analysis. Géotechnique, 59, pp 307–318.

8.2 List of papers and articles published 2009

The Microbe Laboratory

Eydal H S C, Jägevall S, Hermansson M, Pedersen K, 2009. Bacteriophage lytic to Desulfovibrio aespoeensis isolated from deep groundwater. The ISME Journal, 3, pp 1139–1147.

Pedersen K, 2009. The deep intraterrestrial biosphere. International Continental Drilling Program (ICDP) workshop: integration of deep biosphere research into terrestrial drilling operations. Potsdam, Germany, 27–29 September 2009.

In Situ Corrosion Testing of Miniature Canisters

Smart N R, Rance A P, 2009. Miniature canister corrosion experiment – results of operations to May 2008. SKB TR-09-20, Svensk Kärnbränslehantering AB.

BMWi

Barkleit A, Moll H, Bernhard G, 2009. Complexation of uranium(VI) with peptidoglycan. Dalton Transactions, 2009, pp 5379–5385.

Moll H, Barkleit A, Bernhard G, 2009. A comparative complexation study on Np(V) inter-actions with bacterial cell wall compartments and bioligands secreted by microbes. Lecture at the 4th Asia-Pacific Symposium on Radiochemistry (APSORC' 09), Napa, California, 29 November – 4 December 2009. APSORC' 09, Book of abstracts, p 32.

Moll H, Glorius M, Johnsson A, Schäfer M, Budzikiewicz H, Pedersen K, Bernhard G, 2010. Neptunium (V) complexation by natural pyoverdins and related model compounds. Radiochimica Acta, 98, pp 571–576.

Moll H, Glorius M, Barkleit A, Rossberg A, Bernhard G, 2009. The mobilization of actinides by microbial ligands taking into consideration the final storage of nuclear waste – interactions of selected actinides U(VI), Cm(III), and Np(V) with pyoverdins secreted by Pseudomonas fluorescens and related model compounds. Technical Report FZD-522, Forschungszentrum Dresden-Rossendorf, Germany.

True Block Scale Continuation

Cvetkovic V, 2010a. Significance of fracture rim zone heterogeneity for tracer transport in crystalline rock. Water Resources Research, W03504, doi:10.1029/2009WR007755.

Cvetkovic V, 2010b. Diffusion-controlled tracer retention in crystalline rock on the field scale. Geophysical Research Letters, 37, L13401, doi:10.1029/2010GL0434.

Cvetkovic V, Frampton A, 2010. Transport and retention from single to multiple fractures in crystalline rock at Äspö (Sweden): 2. Fracture network simulations and generic retention model. Water Resources Research, 46, W05506, doi: 10.1029/2009WR008030.

Cvetkovic V, Cheng H, Byegard J, Winberg A, Tullborg E-L, Widestrand H, 2010. Transport and retention from single to multiple fractures in crystalline rock at Äspö (Sweden): 1. Evaluation of tracer test results and sensitivity analysis. Water Resources Research, 46, W055505, doi: 10.1029/2009WR008013.

Gustafson G, Gylling B, Selroos J-O, 2009. The Äspö Task Force on groundwater flow and transport of solutes: bridging the gap between site characterization and performance assessment for radioactive waste disposal in fractured rocks. Hydrogeology Journal, 17, pp 1031–1033.

Colloid Transport Project

Cheng H, Cvetkovic V, 2009. Evaluation of colloid transport experiments in a quarried block. In: Hyatt N C, Pickett D A, Rebak R B (eds). Scientific Basis for Nuclear Waste Management XXXII. Warrendale, PA: Materials Research Society. (Materials Research Society Symposium Proceedings 1124), pp 519–524.

Degueldre C, Raabe S, Wold S, 2009. Investigations of clay colloid aggregates by scanning X-ray microspectroscopy of suspensions. Applied Geochemistry, 24, pp 2015–2018.

García-García S, Degueldre C, Wold S, Frick S, 2009a. Determining pseudo-equilibrium of montmorillonite colloids in generation and sedimentation experiments as a function of ionic strength, cationic form, and elevation. Journal of Colloid and Interface Science, 335, pp 54–61.

García-García S, Wold S, Jonsson M, 2009b. Effect of temperature on the stability of colloidal montmorillonite particles at different pH and ionic strength. Applied Clay Science, 43, pp 21–26.

Holmboe M, Wold S, Jonsson M, García-García S, 2009. Effects of γ-irradiation on the stability of colloidal Na+-montmorillonite dispersion. Applied Clay Science, 43, pp 86–90.

Vilks P, Miller N H, 2009. Bentonite and latex colloid migration experiments in a granite fracture on a metre scale to evaluate effects of particle size and flow velocity. NWMO TR-2009-26, Nuclear Waste Management Organization, Canada.

Microbe Projects

Eydal H S C, Jägevall S, Hermansson M, Pedersen K, 2009. Bacteriophage lytic to Desulfovibrio aespoeensis isolated from deep groundwater. The ISME Journal, 3, 1139–1147.

Pedersen K, 2009. The deep intraterrestrial biosphere. International Continental Drilling Program (ICDP) workshop: integration of deep biosphere research into terrestrial drilling operations. Potsdam, Germany, 27–29 September 2009.

Task Force on Modelling of Groundwater Flow and Transport of Solutes

Grenier C, Bernard-Michel G, Benabderrahmane H, 2009. Evaluation of retention properties of a semi-synthetic fractured block from modelling at performance assessment time scales (Äspö Hard Rock Laboratory, Sweden). Hydrogeology Journal, 17, pp 1051–1066.

Gustafson G, Gylling B, Selroos J-O, 2009. The Äspö Task Force on groundwater flow and transport of solutes: bridging the gap between site characterization and performance assessment for radioactive waste disposal in fractured rocks. Hydrogeology Journal, 17, pp 1031–1033.

Hodgkinson D, Benabderrahmane H, Elert M, Hautojärvi A, Selroos J-O, Tanaka Y, Uchida M, 2009. An overview of Task 6 of the Äspö Task Force: modelling groundwater and solute transport: improved understanding of radionuclide transport in fractured rock. Hydrogeology Journal, 17, pp 1035–1049.

Moreno L, Crawford J, 2009. Can we use tracer tests to obtain data for performance assessment of repositories for nuclear waste? Hydrogeology Journal, 17, pp 1067–1080.

Poteri A, 2009. Retention properties of flow paths in fractured rock. Hydrogeology Journal, 17, pp 1081–1092.

Uchida M, Dershowitz W, Lee G, Shuttle D, 2009. An empirical probabilistic approach for constraining the uncertainty of long-term solute transport predictions in fractured rock using in situ tracer experiments. Hydrogeology Journal, 17, pp 1093–1110.

Temperature Buffer Test

Goudarzi R, Åkesson M, Hökmark H, 2008. Äspö Hard Rock Laboratory. Temperature Buffer Test. Sensors data report (period 030326-080701). Report No:12. SKB IPR-09-04, Svensk Kärnbränslehantering AB.

Åkesson M, Jacinto A C, Gatabin C, Sanchez M, Ledesma A, 2009. Bentonite THM behaviour at high temperatures: experimental and numerical analysis. Géotechnique, 59, pp 307–318.

Task Force on Engineered Barrier Systems

Birgersson M, Karnland O, 2009. Ion equilibrium between montmorillonite interlayer space and an external solution – consequences for diffusional transport. Geochimica et Cosmochimica Acta, 73, pp 1908–1923.

Environmental Research

Augustsson A, Bergbäck B, Åström M, 2009. Trace metals in recharge and discharge groundwaters at two sites at the Baltic coast of Sweden. Applied Geochemistry, 24, pp 1640–1652.

Fältmarsch R, Österholm P, Greger M, Åström M, 2009. Metal concentrations in oats (Avena sativa L.) grown on acid sulphate soils. Agricultural and Food Science, 18, pp 45–56.

Lavergren U, Åström M E, Falk H, Bergbäck B, 2009. Metal dispersion in groundwater in an area with natural and processed black shale – nationwide perspective and comparison with acid sulfate soils. Applied Geochemistry, 24, pp 359–369.

Lavergren U, Åström M E, Bergbäck, Holmström H, 2009. Mobility of trace elements in black shale assessed by leaching tests and sequential chemical extraction. Geochemistry: Exploration, Environment, Analysis, 9, pp 71–79.

Åström M E, Peltola P, Rönnback P, Lavergren U, Bergbäck B, Tarvainen T, Backman B, Salminen R, 2009. Uranium in surface and groundwaters in Boreal Europe. Geochemistry: Exploration, Environment, Analysis, 9, pp 51–62.

8.3 Documents published 2009

During 2009 the following reports and documents have been published in the SKB series.

International Progress Reports

Forsmark T, 2008. Äspö Hard Rock Laboratory. Prototype repository. Hydraulic tests and deformation measurements during operation phase. Test campaign 9. SKB IPR-08-22, Svensk Kärnbränslehantering AB.

SKB, 2008. Äspö Hard Rock Laboratory. Status report. July – September 2008. SKB IPR-09-02, Svensk Kärnbränslehantering AB.

Zolezzi F, Haycox J R, Pettitt W S, 2008. Äspö Hard Rock Laboratory. Acoustic emission and ultrasonic monitoring results from deposition hole DA3545G01 in the Prototype repository between April 2007 and September 2007. SKB IPR-09-03, Svensk Kärnbränslehantering AB.

Goudarzi R, Åkesson M, Hökmark H, 2008. Äspö Hard Rock Laboratory. Temperature Buffer Test. Sensors data report (period: 030326-080701). Report No:12. SKB IPR-09-04, Svensk Kärnbränslehantering AB.

SKB, 2009. Äspö Hard Rock Laboratory. Planning report for 2009. SKB IPR-09-05, Svensk Kärnbränslehantering AB.

Hardenby C, Sigurdsson O, Hernqvist L, Bockgård N, 2008. Äspö Hard Rock Laboratory. The TASS-tunnel – project "Sealing of tunnel at great depth". Geology and hydrogeology – results from the pre-investigations based on the boreholes Kl0010B01, Kl0014B01 and Kl0016B01. SKB IPR-08-18, Svensk Kärnbränslehantering AB.

Ludvigson J-E, Nordqvist R, Ekman L, Hansson K, 1999. Äspö Hard Rock Laboratory. Backfill and Plug test. Hydraulic testing of core drilled boreholes in the ZEDEX drift. SKB IPR-09-01, Svensk Kärnbränslehantering AB.

SKB, 2009. Äspö Hard Rock Laboratory. Status report October – December 2008. SKB IPR-09-06, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, 2009. Äspö Hard Rock Laboratory. Prototype repository. Sensors data report (period: 010917-081201). Report No:20. SKB IPR-09-09, Svensk Kärnbränslehantering AB.

Duckworth D, Haycox J, Pettitt W S, 2008. Äspö Hard Rock Laboratory. Prototype repository. Acoustic emission and ultrasonic monitoring results from deposition hole DA3545G01 in the Prototype repository between October 2007 and March 2008. SKB IPR-09-10, Svensk Kärnbränslehantering AB.

Hakami E, Weixing W, 2005. Äspö Hard Rock Laboratory. TRUE-1 Continuation project. Fault rock zones characterisation. Characterisation and quantification of resin-impregnated fault rock pore space using image analysis. SKB IPR-05-40, Svensk Kärnbränslehantering AB.

Morad S, Aldahan A, 2005. Äspö Hard Rock Laboratory. Petrographic and mineral-chemical evaluation of the distribution and conditions of alterations around deformation zones in granitic bedrock, Äspö HRL, Sweden. SKB IPR-05-41, Svensk Kärnbränslehantering AB.

Berlin R, Hardenby C, 2008. Äspö Hard Rock Laboratory. Laser scanning combined with digital photography. Tunnel TASQ and niche NASQ0036A at Äspö HRL. SKB IPR-08-10, Svensk Kärnbränslehantering AB.

Wass E, Nyberg G, 2009. Äspö Hard Rock Laboratory. Hydro Monitoring Program. Report for 2008. SKB IPR-09-11, Svensk Kärnbränslehantering AB.

Wegdén M, Kristiansson P, Svensson D, Sjöland A, 2007. Äspö Hard Rock Laboratory. The use of focused ion beams for structural characterisation of bentonite. A feasibility study. SKB IPR-09-12, Svensk Kärnbränslehantering AB.

Duckworth D, Haycox J, Pettitt W S, 2009. Äspö Hard Rock Laboratory. Prototype repository. Acoustic emission and ultrasonic monitoring results from deposition hole DA3545G01 in the Prototype repository between April 2008 and September 2008. SKB IPR-09-13, Svensk Kärnbränslehantering AB.

Nowak T, Kunz H, 2009. Äspö Hard Rock Laboratory. Äspö Task Force on Engineered Barrier System. Modelling of THM-coupled processes for benchmark 2.1.1 and 2.1.2 with the code GeoSys/RockFlow. SKB IPR-09-14, Svensk Kärnbränslehantering AB.

SKB, 2009. Äspö Hard Rock Laboratory. Status report. January – April 2009. SKB IPR-09-15, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, 2009. Äspö Hard Rock Laboratory. Prototype repository. Sensors data report (period: 010917-090601). Report No:21. SKB IPR-09-17, Svensk Kärnbränslehantering AB.

SKB, 2009. Äspö Hard Rock Laboratory. Status Report. May – August 2009. SKB IPR-09-18, Svensk Kärnbränslehantering AB.

Technical documents

No technical documents were published during 2009.

International technical documents

Thirteen International Technical Documents have been published during 2009.