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Äspö Hard Rock Laboratory

Annual report 2010

Svensk Kärnbränslehantering AB

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

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

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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 2010 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 of Counterforce Applied to Prevent Spalling during 2009, reporting the field experiments and delivering the recorded data to Sicada during 2010.

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 2010, work has been performed in the projects: *TRUE Block Scale Continuation* and *TRUE-1 Continuation* (writing of papers to scientific journals) 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 work with *BS TASS – Follow up of TRUE Block scale structures* in the TASS tunnel has also been initiated.

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 2010 the experimental tasks of the project has been completed.

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 2010 experiments and modelling were finalised and the results will be summarised in a final report during the next year.

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. During 2010 the experimental phase has been completed and is presently being reported and integrated with the results from the earlier Matrix Fluid Chemistry Experiment.

Radionuclide Retention Experiments are carried out with the aim to confirm results of laboratory studies in situ. The experiments are carried out in special borehole laboratories. A program has been written in Matlab to be able to follow the progress of the diffusion profile by time in the study of the *Transport Resistance at the Buffer Rock Interface*.

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, which is optimal for the understanding 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 Continuation Phase of this project has been completed.

In *Sulphide in repository conditions* the aim of the project is to study the processes behind microbial sulphide production and the regulating factors for dissolved sulphide. The analysis and evaluations from the experiments have not been completed, but some preliminary results are summarised in this report.

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. During 2010, the site was prepared and re-instrumented in order to better suite the performance of Swiw with synthetic groundwater. A number of tests were also carried out in order to further investigate the suitability of KA2858A as a test site and to optimise the test procedure prior to the main tests.

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 2010, determination of specific surface area of particle size fraction of chlorite, biotite, hornblende and apatite has been carried out using the BET-method.

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*. During 2010, for Task 7 work has mainly been performed within sub-task 7B and 7C. The work within Task 8 mainly contained updated scoping calculations. The BRIE project has started up, which has couplings to Task 8 in terms of data deliveries but also predictive modelling within the task may provide support to the experiment. BRIE also provides a possibility to compare the modelling results to the experiment. A workshop for Task 7 and 8 was held in January in Vuojoki, Finland. The 26th international Task Force meeting was held in Barcelona, Spain in May. Another Task 7 and 8 Workshop venued in Lund, Sweden in December where updated modelling results were presented and discussed.

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 the tunnel is saturated and that there is different degree of saturation in the buffer in the deposition holes. During 2010 the planning of the retrieval of the outer section of the Prototype Repository started and the work with the retrieval are organized in six sub projects. The actual removal activities will be made mainly during 2011.

The *Long Term Test of Buffer Material (Lot-experiment)* aims at validating models and hypotheses concerning physical properties in a bentonite buffer material and of related processes regarding microbiology, radionuclide transport, copper corrosion and gas transport under conditions similar to those in a KBS-3 repository. No retrieval of any test parcels were made during 2010 and the activity within the project has therefore been limited to managing the three ongoing test parcels, including the finalised reporting of the A0-package.

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. The status of the work with analyses of reference material and material from test package 1 will be described in a report that will be ready in the beginning of 2011.

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 2010 hydraulic testing of the local hydraulic conductivity of the crushed rock with the so called "CT-tubes" have started, but not yet been finished. In 2010 it was also decided to keep the project dormant for the coming years, and the activities will be kept at a very low level.

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 2010 the reporting of the buffer analyses has progressed.

The *Temperature Buffer Test* aims at improving our current understanding of the thermo-hydro-mechanical behaviour of buffers with a temperature around and above 100°C during the water saturation transient. The experiment has generated data since the start in 2003 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 2009, when all the bentonite down to Cylinder 2 were sampled and removed and core drilling was used as the method for dismantling. The base program, i.e. the determination of water content and density, has been performed in parallel to the dismantling operation, and was completed during 2010. The HM&C characterization programme was launched subsequent to the dismantling operation. The main goal is to investigate if any significant differences can be observed between exposed material and the reference material.

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 2010 the compartment plug test has continued.

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. During 2010 the test programme of Lasgit saw several stages of experimentation. The most significant stage was the completion of the gas test of filter FL903. Under the year several presentations and papers were made on Lasgit.

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. During 2010 the inflow to the tunnel has automatically been monitored and a programme for mapping of inflows has been established. Evaluation and reporting is almost completed.

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 reports on the installation and results have been published. During 2010, monitoring of the miniature canister experiment has continued and results from the project have been presented at the "4th International workshop on long-term prediction of corrosion damage in nuclear waste systems" in Bruges, Belgium, June 2010. During the year the main focus for the project has been on planning and preparing for dismantling Experiment 3.

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. During 2010 compilation and integration of the outcome of subproject 1 and 2 have been made. For subproject 3 and 4 the experiments have continued.

In the project *Concrete and Clay* the aim of the project is to increase our understanding of the processes related to degradation of low- and intermediate level waste in a cement matrix, the degradation of the cement itself through reactions with the groundwater and the interactions between the cement/groundwater and adjacent materials such as bentonite and the surrounding host rock. During 2010 the experiments in stage 1 of the project has been prepared and established in niche NASA0507A.

The purpose of the *Low pH-programme* is to develop low-pH cementations products that can be used in the final repository for spent nuclear fuel. These products would be used for sealing of fractures, grouting of rock bolts, rock support and concrete for plugs for the deposition tunnels. SKB has for many years had a close co-operation with Posiva, Finland and Numo, Japan, in this field. The work during 2010 has mainly focused on following up on and reporting the activities from 2009 with the rock bolts and rock support. During the reporting period also the preparation for over coring of the first set of rock bolts has been ongoing, as well as follows up of the corrosion experiments with carbon steel rock bolts in low-pH concrete.

In the programme *Development of End Plugs for Deposition Tunnels* SKB has performed extensive calculations of vault plugs based on data from concrete recipes with low pH-concrete. In the ongoing project regarding development of concrete plug, function, requirements and assumptions have been documented. In the programme for further development, the achievements will be broadened and more intense during the next years.

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 2010 the second phase of the Task Force on Engineered Barrier Systems (EBS) started and is a natural continuation of the modelling work in the first phase. Two Task Force meetings have been held during 2010, in Barcelona (Spain) and in Prague (Czech Republic).

Mechanical- and system engineering

At Äspö HRL and the Canister Laboratory in Oskarshamn, technologies for the final disposal of spent nuclear fuel are being developed. Established as well as new technology will be used in the final repository. The technical systems, machines and vehicles to be developed are identified and listed in the project FUMIS. A total of about 175 different objects, known today, are needed. Several projects within mechanical- and system engineering are ongoing.

SKB has a continuous need for performing heavy load transports in the ramp of the Äspö HRL. In order to perform these transports, a vehicle, called *Multi Purpose Vehicle* (MPV) has been ordered in the end of 2010. The delivery is planned to take place in March 2011.

The project *Equipment for backfilling* is performing design and testing of backfilling equipment. The simulation of a concept has shown that a robot should be able to place 220 tons of backfilling blocks per day, which is requirement for the logistics in the deep repository.

The project *Buffer emplacement* is investigating whether or not the buffer, in the shape of blocks and rings, can be placed in the deposition holes with the required degree of precision. During 2010 the steering gear of the emplacement tool was completed. A test programme is being drawn up, as well as a plan and instructions for the accomplishment of quantity and endurance tests.

The aim of the full-scale tests of the *Deposition Machine* that are being carried out with completely automated operation is to collect data and evaluate the reliability and availability of the machine and the parts of the system, as well as the service requirements under continuous operation.

In the project *Transport system for buffer and backfill material* a feasibility study aiming at finding a solution for the transportation of buffer and backfill material has been carried out during 2010. The study has included the transportation of material from the production premises to the equipment that places the buffer in the deposition hole and that installs the backfill and pellets.

The main objective with the *Logistic studies* for the final repository for spent fuel is to be able to simulate all the activities at the repository during the operational phase. A demonstration project was completed during 2010, where the purpose was to find out if suitable software is available and if it is a practical way to carry out this type of simulations. The results of the demonstrations project have been used for international information and a decision for continued work with logistic studies.

Within the project Mission control system (MCS) a prototype of a comprehensive automatic system for the management and control of transport and production logistics for the final repository will be developed. Preparatory work has been made during 2010 and formally the project was started in October 2010.

In the project Drilling Machine for Deposition Holes, SKB has used a modified TMB machine. SKB are currently following Posivas work on the subject and Posiva are expected to have a new drill available for these purposes during 2011.

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.

Äspö Hard Rock Laboratory has over the last year entered a new interesting phase in its history, for example with the excavation of the outer section of the Prototype Repository that began as scheduled at the end of November. The operation of the already ongoing experiments in the Äspö Hard Rock Laboratory has continued and some have been completed (e.g. TBT) with respect to field work. For those now remains work to analyze, evaluate and report results from the experiments. With regard to operation, maintenance and development of the facility, it has been an intense year both under and over ground. During the last period of the year has restoration work been performed underground to prepare the tunnels TASS and TASQ for coming experiments, the work to establish a geotechnical laboratory has begun and the facilities for the chemistry laboratory are expanding to increase opportunities for researchers in Nova FoU to use the Äspö Hard Rock Laboratory.

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 2010 a number of bedtests have been performed with the purpose of better describing characteristics of the bottom bed for backfill blocks which will be installed in the deposition tunnel.

The operation of the facility during 2010 has been stable, with a very high degree of availability. Work on upgrading the elevator machine has been performed as planned, and the exchange of cable ladders in the elevator shaft between the levels –340 m and –220 m has been carried out during the summer. During the planning of the excavation of the outer part of the Prototype Repository it was found that in order to do the necessary analyses a good geotechnical laboratory is required and this work has began during the year. During the autumn the work with a new water- and wastewater plant began.

The main goal for *the unit Communication Oskarshamn* is to create public acceptance for SKB, which is done in co-operations with other departments at SKB. During 2010 the three facilities in Oskarshamn were visited by 11,340 persons. Among the events and activities that took place during the year there have been a number of VIP-visits, for example President Obama's Blue Ribbon Commission on nuclear waste and representatives from the French Parliament. There have also been special summer arrangements, national events and the unit also went to schools within the municipality of Oskarshamn to meet students in the 9th grade and students in the 3rd grade of the high school.

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 programme 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 2010, thirteen 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 2010. Six of them: 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. 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. Nagra left the central and active core of participants 2003 but are nevertheless supporting the Äspö activities and participates in specific projects.

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 2010.

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. Under 2010 har fälttester inom området för att förhindra spjälkning slutförts. Rapportering av experimenten har gjorts och data har levererats till Sicada.

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* och *TRUE-1 Continuation* (framtagning av artiklar för publicering i vetenskapliga tidskrifter) och *TRUE-1 Completion* (analys av material, fokus på målsprickan, från överborrningen av två borrhål vid TRUE-1 som genomfördes under 2007).

Under 2010 har arbete utförts inom delprojekten: *TRUE Block Scale Continuation* och *TRUE-1 Continuation* (framtagning av artiklar för publicering i vetenskapliga tidskrifter) och *TRUE-1 Completion* (analys av material, fokus på målsprickan, från överborrningen av två borrhål vid TRUE-1 som genomfördes under 2007). Arbete med *BS TASS – Uppföljning av TRUE Block Scale Structure* i TASS-tunneln har också initierats.

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. Under 2010 har de experimentella uppgifterna för projektet slutförts.

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. Under 2010 har experiment och modellering slutförts och kommer att sammanfattas i en slutrapport.

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. Under 2010 har den experimentella fasen avslutats och för närvarande rapporteras och integreras dessa med resultaten från de tidigare experimenten inom Matrix Fluid Chemistry.

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. Ett program har skrivits i Matlab för att kunna följa utvecklingen av spridningsprofilen över tid i studien av *Transport Resistence at the Buffer Rock Interface*.

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 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. Fortsättningsfasen i detta projekt har nu slutförts.

I projektet *Svavelväte i förvarsliknande förhållanden* är syftet att studera processer bakom den mikrobiella produktionen av sulfider och reglerande faktorer för löst sulfid. Analyserna och utvärderingarna från experimenten har inte färdigställts, men några preliminära resultat sammanfattas i denna rapport.

Swiw-tester med syntetiskt grundvatten utgör ett komplement till testerna och studierna som utförts rörande de processer som styr fördröjningen av radionuklider i berget. Under 2010 var platsen förberedd och på nytt instrumenterad för att bättre passa Swiw-prestanda med syntetiskt grundvatten. Ett antal tester genomfördes också i syfte att ytterligare undersöka lämpligheten av KA2858A som provplats och optimera testförfarandet innan huvudtesterna.

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 2010 har bestämning av den specifika ytan av partiklar av klorit, biotit, hornblände och apatit utförts med BET-metoden.

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*”. Under 2010 har arbetet i Task 7 huvudsakligen utförts inom Task 7B och 7C som är uppdelade I flera underprojekt, s k ”Tasks”. Arbetet inom Task 8 innehåller huvudsakligen uppdaterade begränsade beräkningar. BRIE-projektet, vilket har kopplingar till Task 8 i form av uppgifter av dataleveranser, men också för progronosmodeller inom uppgiften, har under året startats och som kan ge stöd till experimentet men också ge en möjlighet att jämföra modellresultaten för experimentet. En workshop för Task 7 och 8 hölls i januari i Vuojoki, Finland. Det 26:e internationella Task Force-mötet hölls i Barcelona, Spanien i maj. Ytterligare en workshop för Task 7 och 8 hölls i december i Lund, Sverige där uppdaterade modellresultat presenterades och diskuterades.

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. Under 2010 har planeringen av återtaget av den yttre delen av Prototypförvaret börjat och arbetet med att återtaget är organiserat i sex delprojekt. Själva återhämtningen kommer att göras under 2011.

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 gjordes under 2010 och verksamheten inom projektet har därför begränsats till att förvalta de tre befintliga testpaketen.

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. Statusen för arbetet med analyser av referensmaterial och material från testpaket 1 kommer att beskrivas i en rapport som beräknas vara färdig i början av år 2011.

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 2010 var det planerat att göra tester av den hydrauliska konduktiviteten lokalt i återfyllningen med krossat berg med s k CT-rör. Dessa tester har påbörjats men är ännu inte klara. 2010 beslutades också att hålla projektet vilande under de kommande åren och verksamheten kommer att hållas på en mycket låg nivå.

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 under 2010 har rapporteringen av buffertanalyserna påbörjats.

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. Basprogrammet, dvs bestämning av vattenhalt och densitet, har genomförts parallellt med nedmonteringen och slutfördes under 2010. HM&C-karakteriseringsprogrogrammet lanserades efter nedmonteringen. Det huvudsakliga målet är att undersöka om några betydande skillnader kan observeras mellan exponerat material och referensmaterial.

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. Under 2010 har pluggtesterna fortsatt.

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. Under 2010 utfördes flera experimentstadier. Det mest betydande steget var fullbordandet av gasfiltertest FL903. Under året har flera presentationer och dokument gjorts inom projektet.

Även om ett förvar kommer att lokaliseras till ett berg av god kvalitet med låg sprickförekomst kommer injektering av berget att behövas. Målsättningen med projektet *Tätning av tunnel på stort djup* är att bekräfta att injekteringsmedlet SilicaSol 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. Under 2010 har inflödet till tunneln automatiskts övervakats och ett program för kartläggning av inflödena har fastställts. Utvärdering och rapportering är nästan klar.

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 rapporter som beskriver själva installationen och resultat som erhållits har publicerats. Under 2010 har övervakningen av miniatyrkapselförsöket fortsatt och resultaten från projektet har presenterats vid ”Den fjärde internationella workshopen om långsiktig förutsägelse av korrosionsskador i kärnavfallssystem” i Brügge, Belgien i juni 2010. Under året har den huvudsakliga inriktningen för projektet varit att planera och förbereda för nedmontering av experiment 3.

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. Under 2010 har sammanställning och integrering av resultaten av delprojekt 1 och 2 gjorts. För delprojekt 3 och 4 har försöken fortsatt.

I *“Betong- och lerprojektet”* är syftet att öka förståelsen för processer i samband med nedbrytning av låg- och medelaktivt avfall i en cementmatris, nedbrytning av cementen självt genom reaktioner med grundvattnet och växelverkan mellan cement, mark och angränsande material som bentonit och den omgivande berggrunden. Under 2010 har experimenten i etapp 1 av projektet förberetts och deponerats i nisch NASA0507A.

Syftet med "Lågt pH-programmet" är att utveckla cementprodukter med låg pH som kan användas i slutförvaret för använt kärnbränsle. Dessa produkter ska användas för tätning av frakturer, fogning av bergbultar, bergförstärkning och som betong för pluggar i deponeringstunnlarna. SKB har inom detta område under många år haft ett nära samarbete med Posiva, Finland och NUMO, Japan. Arbetet under 2010 har främst fokuserat på uppföljning av verksamheten från 2009 med bergbultar och bergförstärkning. Under rapporteringsperioden har också förberedelserna för överborrningar av den främsta uppsättningen av bergbultar pågått, samt uppföljning av korrorsionsexperimenten med bergbultar av kolspetsstål i betong med låg pH.

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. Under 2010 har den Andra fasen av arbetsgruppen för "Engineered Systems Barrier" (EBS) startat som en naturlig fortsättning av modelleringsarbetet i den första fasen. Två "Task Force"-möten har hållits under 2010, i Barcelona, Spanien och i Prag, Tjeckien.

Mekanik- och systemutveckling

Vid Äspölaboratoriet och Kapsellaboratoriet i Oskarshamn utvecklas tekniken för slutförvaring av använt kärnbränsle. Befintligt liksom ny teknik kommer att användas i slutförvaret. De tekniska systemen, maskinerna och fordonen som ska utvecklas identifieras och finns förtecknade inom projektet FUMIS. Omkring 175 olika objekt kommer att behövas. Flera projekt inom mekanik- och systemkonstruktion pågår.

SKB har ett kontinuerligt behov av att utföra tunga lasttransporter ner till Äspölaboratoriet. För att utföra dessa transporter har ett fordon kallat *Multi Purpose Vehicle (MPV)* beställts under slutet av 2010. Leveransen är planerad att äga rum i mars 2011.

Projektet "Utrustning för återfyllning" utför konstruktion och provning av återfyllningsutrustning. Simulering av ett koncept har visat att en robot ska kunna placera 220 ton återfyllningsblock per dag, vilket är kravet på logistik i djupförvaret.

Projektet *Buffertplacering* undersöker hur buffert, I form av block och ringar, kan placeras i deponeringshålen med kravställd grad av precision. Under 2010 avslutades arbetet med styrväxeln mot placering av verktyget. Ett testprogram är under utarbetande, liksom en plan och anvisningar för genomförande av kvantitet och uthållighetstester.

Syftet med fullskaliga tester av *"Deponieringsmaskinen"* som utförs med helt automatiserad drift är att samla in data och utvärdera tillförlitligheten och tillgängligheten av maskinen och delar av systemet, liksom kraven på service under kontinuerlig drift.

I projektet *Transportsystem för buffert och återfyllningsmaterial* har en genomförbarhetsstudie gjorts under 2010 i syfte att hitta en lösning för transport av buffert och återfyllningsmaterial. Studien har omfattat transport av material från produktionen och förutsättningar för den utrustning som placerar bufferten i deponeringshålet och som installerar återfyllningen och pellets.

Huvudsyftet med *Logistikstudierna* för slutförvaret för använt kärnbränsle är att kunna simulera all verksamhet i förvaret under driftfasen. Ett demonstreringsprojekt slutfördes under 2010, där syftet var att ta reda på om lämplig programvara är tillgänglig och om det är ett praktiskt sätt att genomföra denna typ av simuleringar. Resultaten av demonstrationerna i projektet har använts i internationell information och som underlag för beslut om fortsatt arbete med logistikstudier.

Inom projektet *Mission control system (MCS)* kommer en prototyp för ett omfattande automatiskt system för förvaltning och kontroll av transporter och produktionslogistik för slutförvaret att utvecklas. Förberedande arbeten har gjorts under 2010 och formellt startade projektet i oktober 2010.

I projektet *Borrmaskin för deponeringshål* har SKB använt en modifierad TMB-maskin. SKB följer för närvarande Posivas arbete i ämnet och Posiva förväntas ha en ny borr tillgänglig för detta ämne under 2011.

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. Äspölaboratoriet har under det senaste året gått in i en ny intressant fas i sin historia, tex med utgrävningen av den yttre delen av Prototypförvaret som började planeras i slutet av november. Driften av redan pågående experiment i Äspölaboratoriet har fortsatt och en del fältarbeten har avslutats (t ex TBT). För dem återstår nu arbetet med att analysera, utvärdera och rapportera resultaten från experimenten. När det gäller drift, underhåll och utveckling av anläggningen har det varit ett intensivt år både under och över jord. Under den sista perioden av året har restaureringsarbete utförts under jord för att förbereda tunnlarna TASS och TASQ för kommande experiment, arbete med att upprätta ett geotekniskt laboratorium har börjat och anläggningar för kemilaboratoriet expanderar för att öka möjligheterna för forskare från Nova FoU att använda Äspölaboratoriet.

I *Bentonitlaboratoriet* provas olika metoder och tekniker för installation av pellets och block I deponeringstunnlar och tester av rörledningar och erosion av buffert och återfyllningsmaterial utförs. Under 2010 har ett antal bäddtester utförts med syfte att bättre beskriva egenskaper av bädden som kommer att installeras i deponigeringstunneln.

Driften av anläggningen under 2010 har varit stabil med en mycket hög tillgänglighet. Arbete med att uppgradera hissen har genomförts som planerat och mellan nivåerna –340 m och –220 m har kabelstegar i schaktet bytts ut under sommaren. Under planeringen för utgrävningen av den yttre delen av Prototypförvaret konstaterades att det krävs ett bra geotekniskt laboratorium för att kunna göra de nödvändiga analyserna. Arbetet med detta har börjat under året. Under hösten har också arbetet med ett nytt reningsverk påbörjats.

Det huvudsakliga målet för enheten *Kommunikation Oskarshamn* är att skapa en allmän acceptans för SKB, vilket görs I samarbeten med andra avdelningar inom SKB. Under 2010 besöktes de tre anläggningarna i Oskarshamns av 11,340 personer. Bland de evenemang och aktiviteter som ägde rum under året har det funnits ett antal VIP-besök, till exempel president Obamas Blue Ribbon-kommission för kärnavfall och representanter från det franska parlamentet. Det har också funnits särskilda sommararrangemang, nationella evenemang och enheten har också varit ute i skolor i Oskarshamns kommun för att möta elever i årskurs 9 och i årskurs 3 på gymnasiet.

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 2010 pågick tretton projekt inom Nova FoU:s ramverk.

Internationellt samarbete

Förutom SKB har åtta organisationer från sju länder deltagit i det internationella samarbetet vid Äspölaboratoriet under 2008. 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". Nagra lämnade den centrala och aktiva kärnan av deltagare 2003, men stöder Äspölaboratoriets verksamhet och deltar i särskilda projekt.

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 the island 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.

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

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

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

The Operational phase began in 1995. A preliminary outline of the programme for this phase was given in SKB's Research, Development and Demonstration (RD&D) Programme 1992. Since then the programme has been revised every third year and the 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. The Technology department comprises five units; the Technology Staff, the Repository Technology, Encapsulation/the Canister Laboratory, Research and security and Survey Technology.

Äspö HRL is the residence of the unit *Repository Technology* 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 spent nuclear fuel and for low- and intermediate level waste.
- Develop the horizontal application of the KBS-3-method (KBS-3H).
- Perform experiments in the Äspö HRL commissioned by SKB's Research unit.
- Secure a safe and cost effective operation of the Äspö HRL.
- Prosecute comprehensive visitor services and information activities in co-operation with SKB's Communication department.

The *Repository Technology (TD)* unit is organised in four operative groups and one 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.
- *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.

Earlier were also Public relations and visitors group, TDI, a part of the Repository Technology unit. However the group were transferred to the reorganised Communications department within SKB in May 2010 and is now named Communication Oskarshamn. The group and its personnel are however still located at Äspö HRL and have a continuously close co-operation with the facility and the daily coordination of underground activities.

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

1.4 International participation in Äspö HRL

The Äspö HRL has so far attracted considerable international interest. During 2010 eight organisations from seven countries has in addition to SKB participated in the co-operation at Äspö HRL Six of them; Andra, BMWi, CRIEPI, JAEA, NWMO and Posiva together with SKB form the Äspö International Joint Committee (IJC), which is responsible for the coordination of the experimental work arising from the international participation. Numo (Nuclear Waste Management Organisation of Japan) was represented as an observer at the IJC-meeting in May, 2009 and May 2010. Nagra left the central and active core of participants 2003 but are nevertheless supporting the Äspö activities and participates in specific projects.

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.
- Korea Atomic Energy Research Institute, Kaeri, Korea

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.

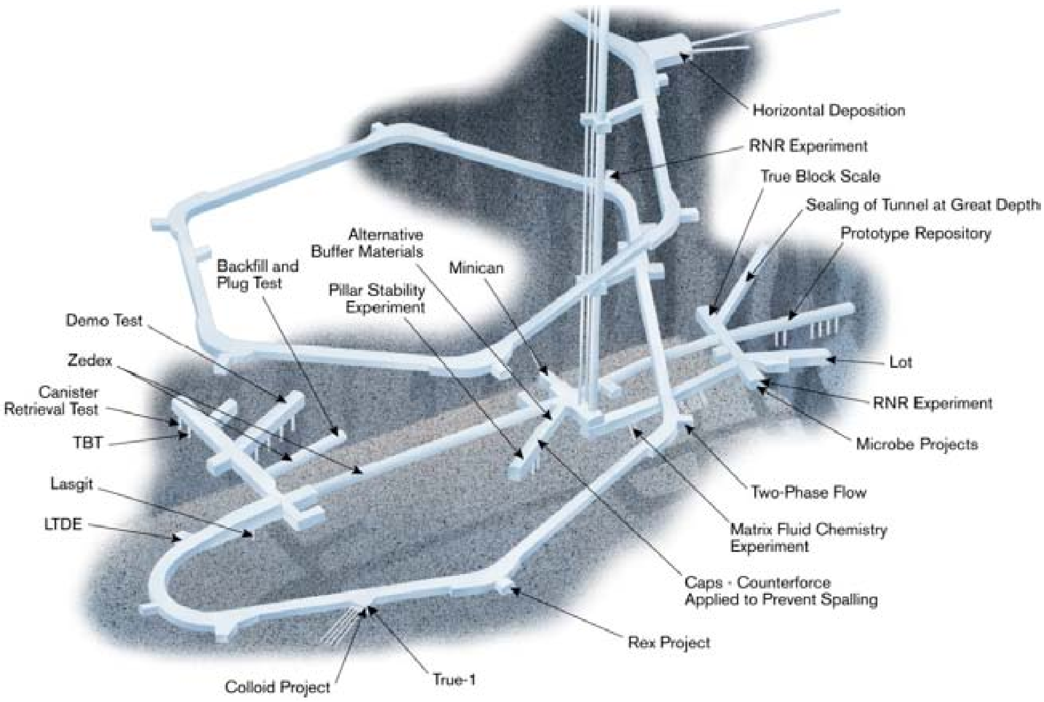


Figure 1-2. Allocation of experimental sites from –220 m to –460 m level.

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 2010/ 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 2010. In addition, the progress in the projects during the year has also been reported in three Status Reports.

Joint international work at Äspö HRL, as well as data and evaluations for specific experiments and tasks, have been reported in Äspö International Progress Report series. In the future other report series will be used for this information. 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 2010 are in this report described in seven 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.
- Mechanical- and system engineering – developing of technologies for the final disposal of spent nuclear fuel.
- Äspö facility – operation, maintenance, data management, monitoring, communication 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. Laser scanning combined with digital photography has been used to obtain e.g. the tunnel geometries, 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), see Section 2.2. 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.

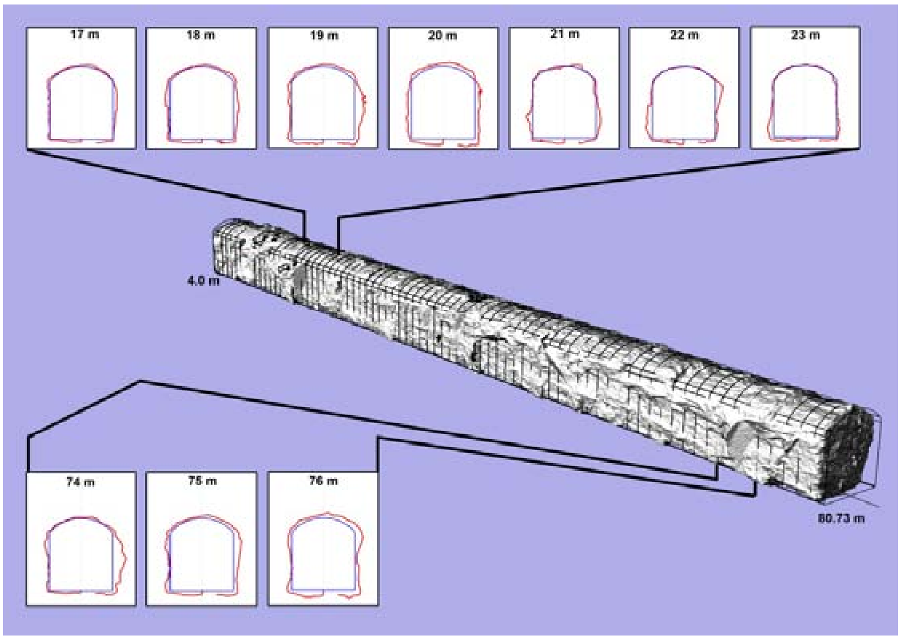


Figure 2-1. *Triangulated model of the TASS-tunnel based on intensity laser scans. Topography of the tunnel surfaces and some theoretical cross sections (blue) compared to the real contour (red). (Model created for SKB in 2010 by P. Kinnbom, PKM Innovation AB).*

2.2 Äspö site descriptive model

Background and objectives

One main task within the geoscientific field is the development of an Äspö Site Descriptive Model (SDM) integrating the information from the fields of geology, hydrogeology and geochemistry, see Figure 2-2. The present, most updated descriptive model of the Äspö site includes data collected up to 2002 and was published in a series of reports in 2005 /Berglund et al. 2003, Vidstrand 2003, Laaksoharju and Gurban 2003, Hakami 2003/.

The SDM provides basic geoscientific data to support predictions and planning of experiments performed in Äspö HRL. The aim is also to ensure high quality experiments and measurements related to geosciences.

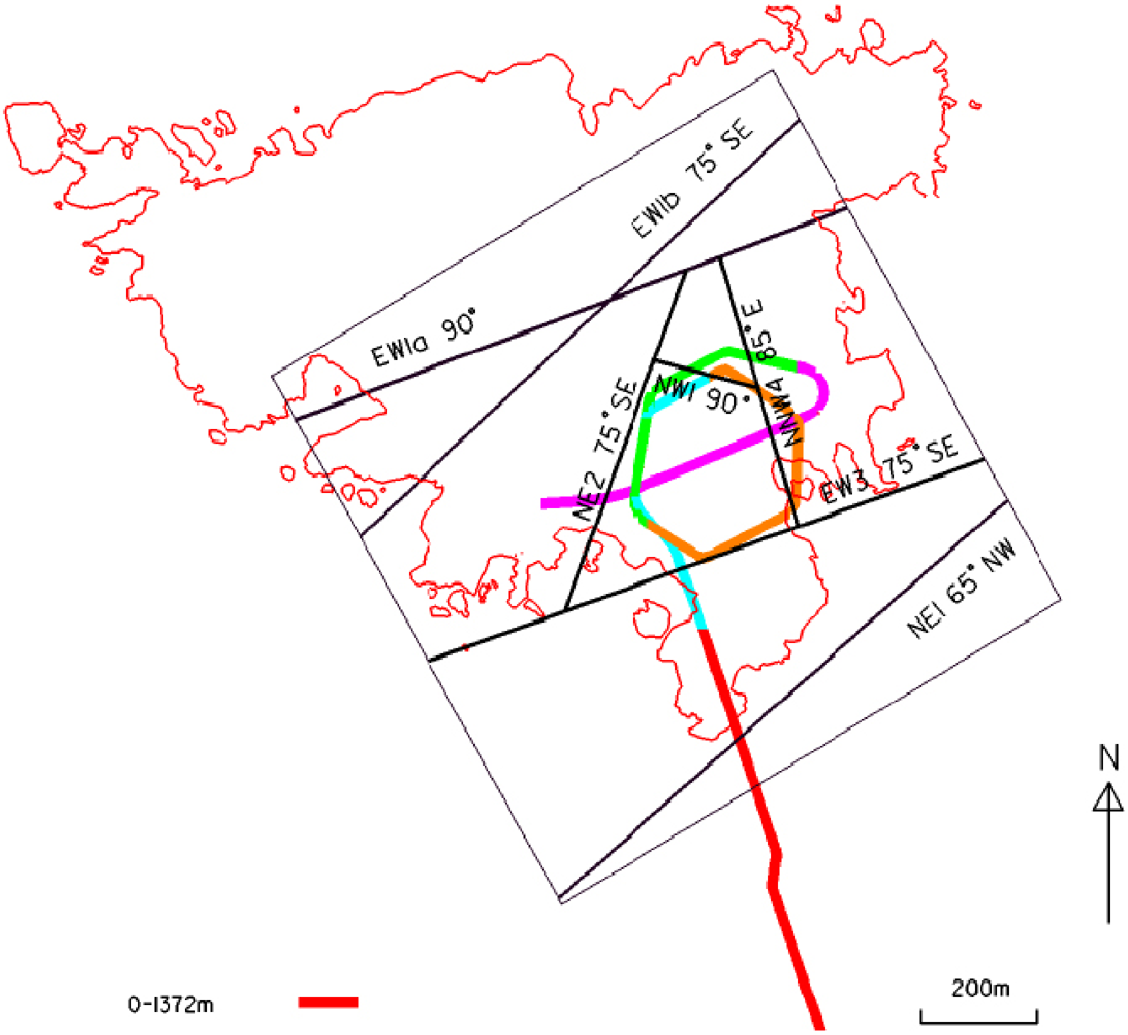


Figure 2-2. Modelling work to help understand the geological, hydrogeological and geochemical conditions of the Äspö site area.

Objectives

- Describe the geoscientific conditions in Äspö HRL with the SDM methodology used for the Site Investigations (geology, hydrogeology, hydrogeochemistry, rock mechanics, and thermal conditions).
- The SDM models should be detailed enough to make scooping calculations for selection of sites for future experiments.
- Give data for detailed investigations in connection with investigations before excavation of a new tunnel in Äspö HRL as well as give experience for modelling in connection with excavation of the final repository.
- Try to establish models in different scales and to further develop methods for modelling for planning of the excavation of the final repository.
- Educate own personnel in SDM methodology to be used in future SDM modelling for safety assessment.

Experimental concept

- The nomenclature used for the different disciplines and for the structures in different scales should be the same.
- The description should be integrated between the different disciplines.
- The connections between the disciplines should be identified and described.
- The modelling methodology used for Laxemar and Forsmark should be used.
- The modelling should be applied for use in close coordination with tunnelling.

Results

The report concerning the detailed 3D structural geological and hydrogeological model of the –450 m level is delivered for print /Markström et al. 2010/. The model is based on available data from earlier investigations.

Geological single hole interpretation on five surface based boreholes and eight boreholes drilled from the tunnel has been performed. Hydrogeological single hole interpretation was performed as well. Lineament interpretation based on ground surface magnetic measurements performed 1988 and topographic data has been performed, see Figure 2-3. All water conductive fractures and water conductive deformation zones have been plotted in different sections along the tunnel. Hydrogeochemical monitoring data has been analyzed. Explorative analysis of the major components has been and is currently being done. Plots of Cl, Mg, $\delta^{18}O$ versus depth and time during and after the tunnel construction have been performed. Multivariate Mixing and Mass balance (M3) modelling modelling has been used to determine end members and what reactions that needs to be modelled in PhreeqC.

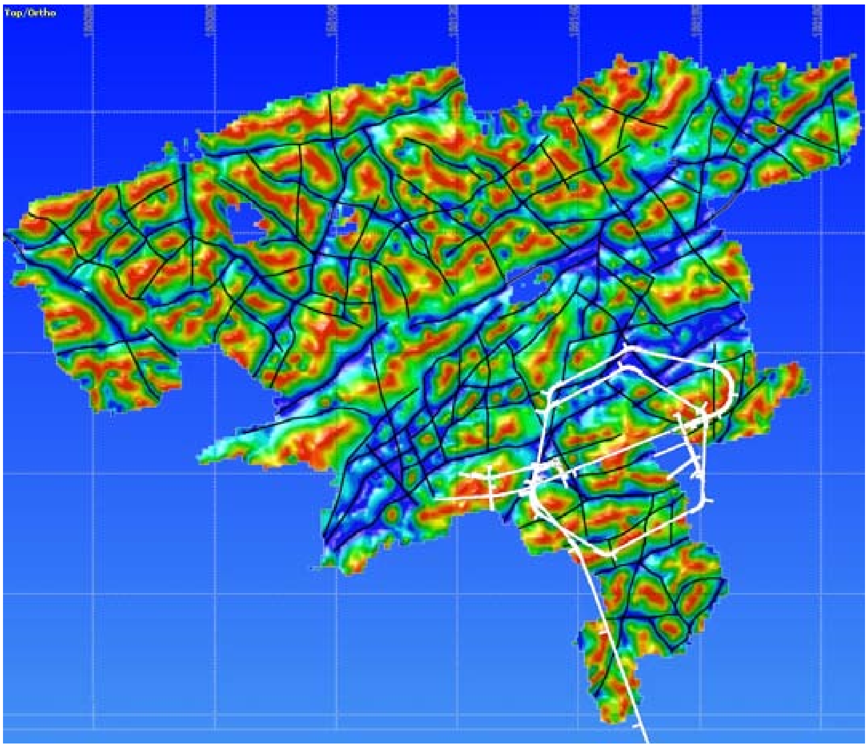


Figure 2-3. Lineament interpretation of ground surface magnetic measurements performed in 1988 /Nisca and Triumf 1989/.

2.3 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 three-dimensional 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 2.3.2.

2.3.1 Geological mapping and modelling

Background and objectives

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

Experimental concept

Understand the geological properties of rock types, fractures and deformation zones of the Äspö HRL rock volume as an input for Äspö SDM modelling.

Results

The report concerning the geological mapping of the TASS-tunnel has been adjusted after being on review. The report concerning modelling of water bearing fractures at the –450 m level is now in print. /Markström et al. 2010/. A method description (SKB MD 143.007) concerning the handling and sampling of drill cores has been updated. The sorting and labelling of digitized photos from the deposition holes and minor tunnels continues. The digitizing and database entry of old geological mapping into the TMS-system (Tunnel Mapping System) continues. For example all the deposition holes from the TASK-tunnel have been completed.

The orientations of fractures and deformation zones in the Äspö HRL have been plotted in stereo and rose diagrams. The plots show fractures plus deformation zones, only fractures or deformation zones, only water bearing or dry fractures/deformation zones. The diagrams represent the total tunnel system or the tunnel system divided into sections. The work is now completed.

The drawing summarizing the geological mapping of all the Äspö-tunnels has been up-dated to include the mapping of new tunnels and the colors used in the new rock type nomenclature. Some errors were discovered in the TMS (Tunnel Mapping System). These errors have been corrected. This resulted also in a check up on rock types and change of rock type names in parts of the TASA-tunnel.

The core storage at Äspö HRL was emptied and the core-boxes transported to the storage facilities in the town of Oskarshamn. The Äspö core storage has now been rebuilt, but occupies a smaller area since parts of the original area will be used for other purposes.

Core logging of the drill cores from the boreholes KO0014G01, KO0015G01, KO0017G01, KO0018G01 and KO0020G01 for the planned project called Brie (Buffer-rock interaction experiment) in the TASO-tunnel has been performed.

The expansion plans of Äspö HRL have continued and a preliminary site for a new tunnel has been decided.

2.3.2 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 should 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.

Experimental concept

Develop and implement a new characterisation tool for geological mapping and modelling and to obtain e.g. tunnel geometries in Äspö HRL as well as implement a working tool to be adapted at the final repository.

Results

The previous year SKB 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. The company Ergodata that developed the software Boremap has been chosen to develop the mapping module in RoCS. So far only a rather primitive test program has been presented, but the work is on-going. The Austrian company 3G Software & Measurement (3GSM) has delivered the hardware and software for the photogrammetry part of RoCS. A course was held at Äspö HRL during the fall 2010 about how to handle the hardware as well as the software (see Figure 2-4). New battery powered LED-lamps/floodlights have been purchased by SKB to ensure good illumination during the field work in the tunnels.

Figure 2-4. Photogrammetry course at Äspö HRL. Here how to handle the field equipment – digital camera, tripod, floodlights etc in the TASS-tunnel (to the left) and in the TASA-tunnel (to the right). Photo: C. Hardenby.

2.4 Hydrogeology

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 reason is 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.

Objectives

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 to ensure they are performed with high quality.
- Provide hydrogeological support to active and planned experiments at Äspö HRL.

Experimental concept

Maintain and develop the understanding of the hydrogeological properties and processes of the Äspö site as well as of the hydrogeological characterisation and analysis methodology.

Results

The primary results have been achieved with the data compilation and analysis in the framework of the Äspö SDM and in supporting various experiments.

2.4.1 Hydro monitoring programme

Background

The hydro monitoring programme is an important part of the hydrogeological research and a support to the experiments undertaken in the Äspö HRL. 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 system comprise measuring groundwater level and pressure, level in the sea and in a lake, flow and temperature on one creek as well as metrological parameters at Äspö.

Objectives

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 validation exercises, including the comparison of predicted head with actual head.

Experimental concept

Understanding of the hydraulic connectivity of the site and its geoscientific processes by long term measurements of various hydrogeological variables.

Results

The hydrogeological monitoring system has been performing well and the monitoring points in the tunnels have been maintained. The monitoring system has provided continuous support for the experiments in their planning and execution and for the tunnel activities. A review of potential supporting and corrective measures for the surface borehole has been performed. The refurbished borehole KAS03 was brought on-line and was taken in to operation. Figure 2-5 shows a typical housing of monitoring equipment as exemplified with container at borehole KAS04. The monitoring is reported every four month period through quality control documents and on an annual basis, describing the measurement system and basic results. Results of the monitoring activities are found in the annual report for the monitoring year 2009 /Wass and Nyberg 2010/.

Figure 2-5. Typical housing of monitoring equipment as exemplified with container at borehole KAS04.

2.5 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.

Experimental concept

Understand the hydrogeochemical properties of the Äspö HRL rock volume and groundwater mixing conditions as an input for Äspö SDM modelling.

Results

Parts of the monitoring programme from the site investigations at Oskarshamn have been transferred into the monitoring programme for Äspö. The monitoring programme has been modified to satisfy the needs for Äspö SDM, such as boundary conditions which resulted in a reduced programme with a careful selection of sampling parameters. Further on, the installations of the new sampling equipment in five percussion boreholes (HLX01, HLX08, HMJ01, HAV14 and HLX27) have been completed. This is done to better support the sampling of the shallow water at Laxemar and Ävrö.

During the year sampling of surface water, soil tubes, precipitation have been performed at regular intervals except cored- and percussion boreholes.

2.5.1 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 obtained from boreholes drilled from the ground surface and from the tunnel. At the beginning of the operational phase, sampling was replaced by a groundwater chemistry monitoring programme, 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, within the rock mass, the hydrogeochemical changes are taking place and at what time stationary conditions are established.

During 2011 the programme will be modified to better serve the on-going activities. A revision of older boreholes will be implemented and/or new boreholes will be considered, especially in connection to the planned expansion of the HRL.

Experimental concept

Understand the groundwater chemistry and its evolution.

Results

The yearly monitoring campaign for 2010 started December 2010 and was planned to run through January 2011. In situ measurements of pH, EC and temperature are always performed before sampling take place. Water samples will be taken from varying depths in the Äspö HRL and hopefully also from some boreholes drilled from the surface; KAS03 and KAS09. Last year they were not instrumented. In addition, all projects at Äspö HRL can request additional sampling of their sites to be coordinated within the monitoring programme.

Groundwater fluctuations due to different project activities, such as drilling and blasting during construction of a new tunnel next year may cause indirect changes in groundwater pressure and flow, and thus also in groundwater chemistry Therefore the monitoring programme will be performed more than once during 2011 depending on access to important boreholes.

2.6 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.

A project called Caps (Counterforce Applied to Prevent Spalling) comprising field tests in Äspö HRL and numerical modelling is ongoing and is described in the section below.

2.6.1 Counterforce applied to prevent spalling

Background and objectives

The field experiment within Counterforce Applied to Prevent Spalling (Caps) has been initiated as a demonstration experiment 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 the 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.

The field experiment includes four pairs of heated half-scale KBS-3 holes and is carried out as a series of demonstration tests in the TASQ-tunnel at Äspö HRL.

Each test consists of two heating holes of 0.5 m diameter and 4 m depth separated by a 0.7 m pillar, which are surrounded by a number of boreholes for installation of temperature gauges.

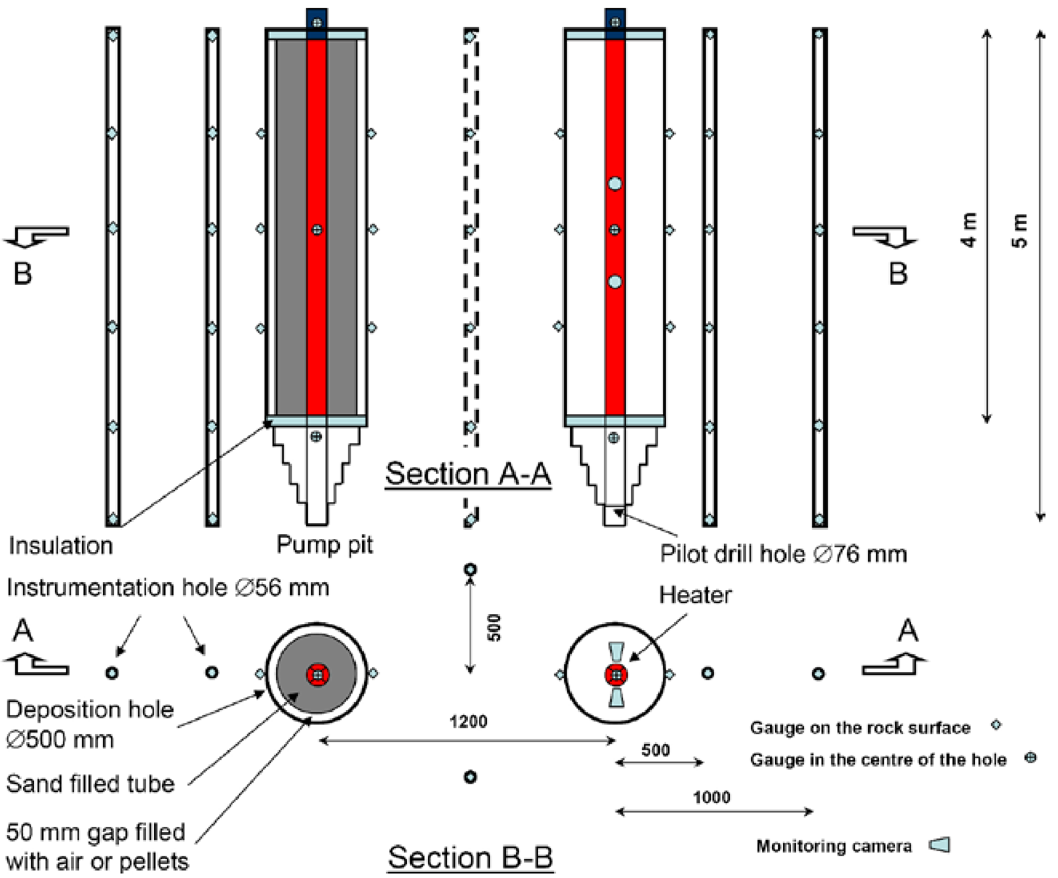
The first step in the testing sequence includes heating of one pair of open holes to ensure that spalling will occur and can be observed in the test holes. The next step includes heating and observation of spalling in separate pair of holes. A 50 mm gap created between a large inner tube and the borehole wall is filled with a loosely placed pellets substitute. The final step is a complementary test that is carried out to address questions that arise during the previous tests.

Experimental concept

Understand the geomechanical properties of the rock mass, fractures and deformation zones and stresses as well as spalling around deformation zones.

Results

The field experiment is finished and reported. The first heating test was initiated at the end of August 2008 and the final test was finished at the end of May 2009. The recorded data has been delivered to Sicada. The final report of the project was printed in July 2010 /Glamheden et al. 2010/. A paper entitled *"Thermal spalling in a field experiment in hard rock"* was approved for presentation at the conference *"Rock mechanics in the Nordic countries 2010"* in Oslo in June.



Configuration of the test holes and the positioning of instruments in the experiments in the TASQ-tunnel as original design with one open and one pellet filled hole. In reality the tests have been performed in two pairs of open holes and two pairs of pellet filled holes.

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 development 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 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 2010, the ongoing experiments and projects within Natural barriers were:

- Tracer Retention Understanding Experiments.
- Long Term Sorption Diffusion Experiment.
- Colloid Transport Project.
- Microbe Experiments.
- Matrix Fluid Chemistry Continuation.
- Radionuclide Retention Experiments.
- Padamot.
- Investigation of Sulphide Production Processes in Groundwater.
- Fe-Oxides in Fractures.
- Swiw-tests with Synthetic Groundwater.
- Äspö Model for Radionuclide Sorption.
- Task Force on Groundwater Flow and Transport of Solutes.

3.2 Tracer retention understanding experiments

Objectives

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.

After an interlude of site investigations and site modelling, finalisation of the principal components of the TRUE Programme – TRUE-1 Continuation and TRUE Block Scale Continuation are near their conclusion. In the aftermath, a project following up on the interpreted extensions of select TRUE Block Scale structures in the TASS tunnel has been initiated.

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.

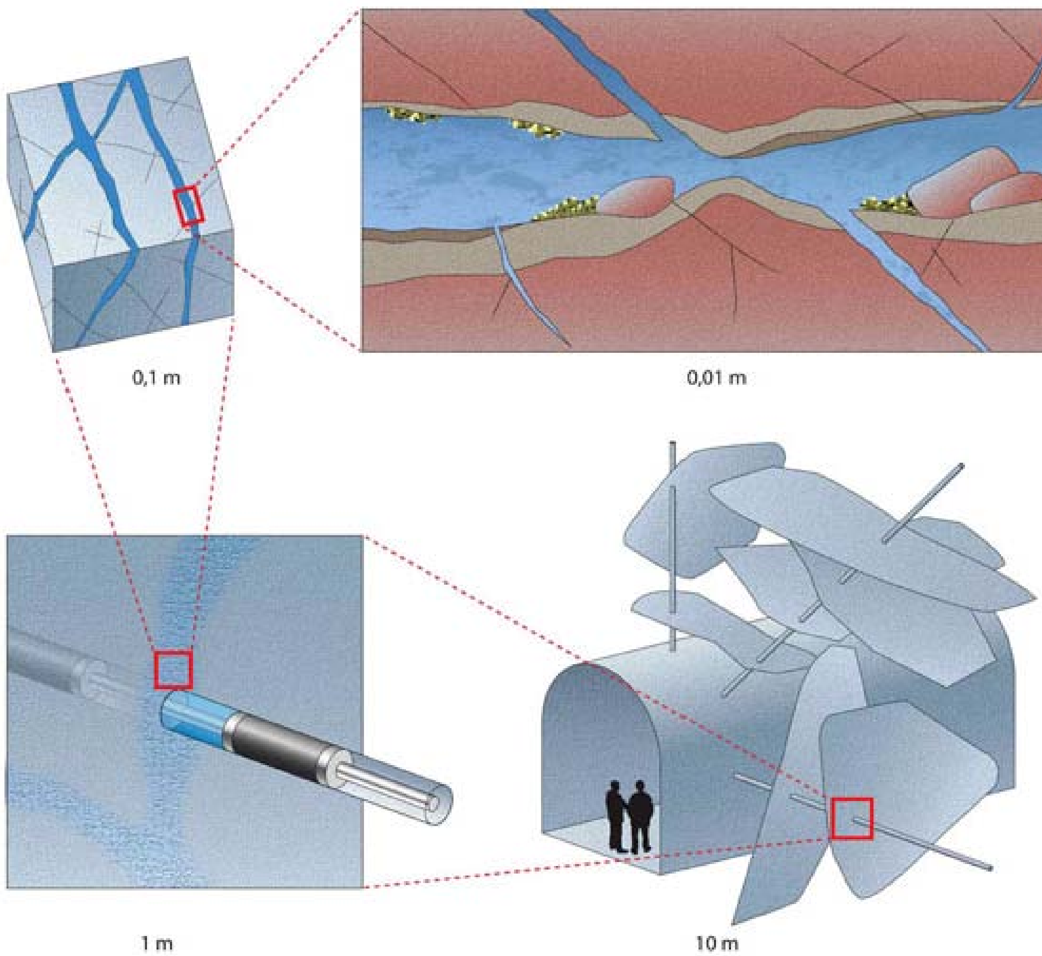


Figure 3-1. *Schematic representation of transport scales addressed in the TRUE programme.*

3.2.1 True block scale continuation (BS3)

Background

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 peer-reviewed papers published in high-ranked scientific journals.

Results

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 network simulations were published in Water Resources Research during the year /Cvetkovic et al. 2010, Cvetkovic and Frampton 2010/. Furthermore, a third paper, providing an assessment of the role of enhanced porosity in the rock wall immediately adjacent to a conductive fracture, applicable both to detailed and block scales, was published by /Cvetkovic 2010a/. The principal task during 2010 was completion and submission of an overall synthesis paper directed to a high-ranked scientific journal. This paper was seconded by a supporting paper directed to Geophysical Research Letters /Cvetkovic 2010b/ elucidating the ability of the TRUE experiments to provide firm evidence of in situ diffusion-controlled retention at multiple scales.

The principal findings presented in the Geophysical Research Letters paper were that (i) normalised peak arrival time and relative fractional arrival times inferred from tracer test data, provide robust, complementary measures for characterising field scale retention properties; (ii) these measures are shown to be comparable between the two test sites located 200 m apart in the crystalline rock of the Äspö HRL, indicating that a consistent effective representation of retention properties on large scales is possible; (iii) retention in crystalline rock should be a priori assumed diffusion-controlled where the bounding values of DELTA can be estimated reasonably well based on independent information. As shown by work done, the uncertainty range for DELTA based on information independent of tracer tests is large for predicting the outcome of any individual tracer test. This uncertainly may be further reduced by combining additional information on structural and hydrodynamic properties, combined with flow and transport modelling.

The high-profiled paper set out to answer the question "*Would crystalline bedrock sufficiently contain radionuclide release from a high-level nuclear waste repository?*" In the paper a model is presented for estimating the efficiency of a crystalline rock formation to contain radionuclides that relies on recent experimental and theoretical advances. Results show robust features of radioactive isotope retention over a wide range of spatial scales and sorption affinities, indicating consistency in the conceptualisation of field and laboratory scale transport experiments. The main implication is that field-scale transport of radioactive (metal) isotopes, serving as proxies for actinides in the crystalline bedrock, can be verified by combining independent information with a relatively simple conceptual model. The paper was submitted to the journal Science, but was rejected due to Science's stringent space limitations and the specialised nature of the paper.

3.2.2 True-1 Continuation

Background

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 3.2.4) Additional activities include: (a) test of the developed epoxy resin technology to fault rock zones distributed in the access tunnel of the Äspö HRL (Fault Rock Zones Characterisation project), (b) laboratory sorption experiments for the purpose of establishing K_d-values for altered wall rock (rim zone) and fault gouge, (c) writing of scientific papers related to the TRUE-1 project. Of the listed components item (c) is completed, whereas reporting of the preceding two activities have been finalised durting the year.

Objectives and scope

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.

During the year the final report of the Fault Rock Zones Characterisation project /Winberg 2010/ has been completed. Similarly, the report reporting the results of the sorption and leaching experiments involving different tracers and rim zone and fault gouge materials /Byegård and Tullborg 2010/ has been finalised.

Results

Sorption and leaching experiments on rim zone and fault gouge materials

Select conclusions include:

- The sorption coefficients determined in this work follow the relative order, i.e. $Na^+ < Ca^{2+} \approx Sr^{2+} < Rb^+ \approx Ba^{2+} < Cs^+$, observed in earlier laboratory investigations mainly focusing on non-altered rock material from the Äspö HRL (e.g. /Byegård et al. 1998/). In this work the Mn^{2+} and Ra^{2+} tracers have also been included, where the sorption of the Mn^{2+} tracer has been found to be, for the majority of the fault gouge materials studied, more strongly sorbing than e.g. Cs^+. The K_d for Ra^{2+} is for all cases studied (with one exception) highest in comparison with all other tracers studied.
- Fault gouge material has been identified as a strongly sorbing material; in most cases the K_d for these materials are found to be more than 1–2 order of magnitude higher than the corresponding rim zone material at the same sampling location. This is an indication that, at least for short term *in situ* experiment, the retention may be governed by the interaction with fault gouge material in direct contact with the flowing water in the studied flow path, as proposed by e.g. /Andersson et al. 2004/.

- There is a pronounced heterogeneity in the sorption for the fault gouge material as noticed from variable results on material from different locations in the same geological structure.
- Regarding the sorption of gouge material as a function of measured BET surface area, the correlation is rather poor. One can also observe that high sorption of one tracer does no necessary imply that high sorption of other tracers is to be expected; an observation which probably can be explained by the heterogeneity in the mineralogical composition of the materials (and structures) studied.
- The concept of extrapolation of sorption results of different size fractions to a process consisting of a combination of outer surface sorption (K_a) together with inner surface sorption (K_d) has been tested. The extrapolation gives high uncertainties for the extrapolated K_d and for one case the extrapolation gives a negative value. Model calculations using the time dependence in the batch sorption experiment show poor conceptual agreement to an inner-outer surface model which therefore raises doubt in the validity of this sorption model.
- Concerning the Cation Exchange Capacity (CEC) determinations, it is indicated that the ISO 13536 method (saturation with Ba^{2+} followed by desorption with Mg^{2+}) is not sensitive enough for measurements of rock material. The newly established method ISO 23470 (saturation with Co-hexamine) gave results that were in agreement with the sorption results and is proposed as a method much more suitable for measurement of CEC for rock material.

Fault Rock Zones Characterisation project

The principal conclusions from the image-based analysis, primarily of the impregnated structure at 2430 m, are the following:

- An indirect estimate of porosity from image analysis is obtained as the sum of epoxy-filled area of a defined image area divided by the total area. This implies that the apparent porosity measure is a "bulk" value, which most likely is lower that the "true" in situ porosity. The porosity values obtained range from c. 11–70%, depending on degree of resolution of the imagery. Porosity obtained by conventional techniques has been obtained for (non-epoxy impregnated) fault gouge material from 1/596 m (zone NE-2) indicating average porosity between 12–14%-vol, cf. Section 6.1. Comparative calibrations between image-based and conventional porosity determinations have not been possible while undisturbed and non-impregnated (by epoxy) samples are required for such comparisons. The latter situation is inherent while it is very difficult to sample these types of structures with conventional core drilling. In conclusion, given the dependence on image resolution the image-based apparent porosities may at best be regarded as ball-park relative measures of porosity of complete fault zones. The method employed does not allow firm quantification of fault gouge porosity for the samples analysed in this study. However, the values of apparent porosity for fault gouge obtained in this study comply with the lower end of the interval suggested by /Mazurek et al. 1996/.
- The information obtained from the current study, both descriptive geometrical information, and quantitative information is not in conflict with the decametre conceptual microstructural models, applicable to Äspö HRL conditions, devised by /Mazurek et al. 1996, Andersson et al. 2002, Dershowitz et al. 2003/. The information provides opportunity for introducing additional detail in the microstructural model. In fact, there is information and potential for reconstructing microstructural models (fracture network models) in 3D. The latter has not been pursued as part of this study

3.2.3 BS TASS – Follow-up of TRUE Block scale structures in the TASS tunnel

Background

The TRUE Block Scale project /Winberg et al. 2002, Andersson et al. 2007/ had as its principal aim to investigate the retention of radionuclides in fractured rock at depth in the Äspö HRL. The experiment involved an extensive site characterisation of the 3D geometries and properties of conductive structures resulting in a deterministic hydrostructural model. This model formed the basis for packing off selected intervals in the boreholes, facilitating performance of comprehensive tracer experiments using radioactive tracers, producing a basis for assessing the retention of radioactive tracers in the studied flow paths.

The project Sealing of Tunnel at Great Depth, cf. Section 4.10, involved construction of an 80 m long tunnel (the TASS tunnel) at repository depth at the Äspö HRL with the principal aim of demonstrating the ability to seal a tunnel at repository depth. The tunnel was preceded by drilling of three pilot boreholes along the tunnel perimeter. The tunnel development featured pre-grouting using low alkaline cement-based grouts and Silica sol resin.

The performed site descriptive modelling at Forsmark /SKB 2008/ and Laxemar /SKB 2009/ involved DFN-based hydraulic modelling where the stochastically assigned transmissivity of modelled fractures was assumed constant across their extent. This analysis and subsequent safety analysis identified a need for an improved description of the heterogeneity of material properties, mainly transmissivity, of modelled fractures.

The new project (BS TASS) makes use of the possibility to investigate selected relevant TRUE Block Scale structures in the TASS tunnel further, and associated pilot boreholes. This provides an opportunity to observe in the tunnel structures involved in the tracer experiments and to assess the heterogeneity in structure properties across a larger extent of the structure and allows assessment of heterogeneity at different scales of observation. Of particular interest is the validity of information collected in a pilot borehole for a tunnel, relative to information collected along the corresponding tunnel interface on the tunnel wall. This has bearing on the detailed site investigations. Inferences made in the study have relevance to the detailed site characterisation to be carried out in conjunction with construction of a repository at Forsmark.

Objectives

Geometrical, structural-geological, mineralogical and hydraulic analysis of select TRUE Block Scale structures, as observed in pilot boreholes for the TASS tunnel and the TASS tunnel itself, with the aim of describing the geological and hydraulic heterogeneity of the structures. The hydraulic analysis include studies of pressure responses during pilot drilling and analysis of variability of hydraulic properties as collected in the TASS tunnel pilot boreholes and the TRUE Block Scale characterisation boreholes. The study will result in improved descriptions of the structures studied. The results of the study can be used in the planning of detailed investigations at the selected repository site at Forsmark.

Experimental concept

The work include revisit of the drill cores from the TRUE Block Scale Project and detailed structure-geological and mineralogical mapping of the TASS pilot boreholes using photographic records of the studied intercepts as mapping platforms. The analysis of drill cores is followed by photographic documentation (ordinary light (including high dynamic range (HDR)) and UV light) of the structure intercept in the tunnel. Existing tunnel mapping and laser scanning results are used as reference and base material for detailed tunnel mapping. Samples are taken from intercepts in the core and in the tunnel for mineralogy and geochemical analysis. Existing hydraulic pressure records and hydraulic test results from existing boreholes are used to infer the intercepts in boreholes/tunnel and the variability in hydraulic characteristics. The produced photography can possibly be plugged in as detailed information superimposed on already produced RoCS and laser scanning mapping.

Results

The field work carried out in early December 2010 included remapping of intercepts with Structures #20 and in part #22, as observed in TRUE Block Scale and TASS pilot boreholes, employing the descriptors employed in the site descriptive modelling. The structural-geological and mineralogical mapping has been made using one common photographic platform. Subsequently, detailed mapping of the Structure #20 and tentative mapping of Structure #22 was conducted in the tunnel. The mapping of Structure #20 was made in transects, similar to core mapping, along remnants of blastholes visible on the tunnel wall which provide geometric reference. Interpolation of geometrical and structural characteristics is facilitated by the added information provided by the ordinary light and UV photography. Samples of the Structure #20 intercepts for fracture mineralogical analysis have been collected from the drillcores as well as from the tunnel. Assessment of hydraulic pressure information from existing boreholes has been made, and hydraulic test data have been compiled. Evaluation of the collected information is under way.

3.2.4 True-1 Completion

Background

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 caesium.
- 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 image 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

All field tests, experiments and analysis within the project are completed. During 2010 the work has been focused on evaluations and writing of reports covering the three major parts of the project; tracer tests, epoxy injection with overcoring and analyses of core material. None of the reports are yet printed but exists in advanced drafts. Overall, the project has not been carried out according to plan during 2010 due to the engagement of project members in other more prioritized SKB projects. Accordingly, the summarizing report that was planned for 2010 has not yet been initiated.

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 (6 ½ 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

The experiment is focussed on both matrix rock and 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 circumferences of the two boreholes, Figure 3-2. A core stub with the natural fracture surface is isolated in the bottom of the large diameter telescoped borehole. In addition a small diameter extension is drilled through the core stub into the intact undisturbed rock beyond the target fracture. A cocktail of non-sorbing and sorbing tracers is circulated in the test sections for a period of 6 ½ months after which the borehole is over-cored, and extracted rock analysed for tracer penetration and fixation.

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 (high purity germanium) detectors are 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 (3 of 1 mm, 3 of 3 mm, 3 of 5 mm, and so on) 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.

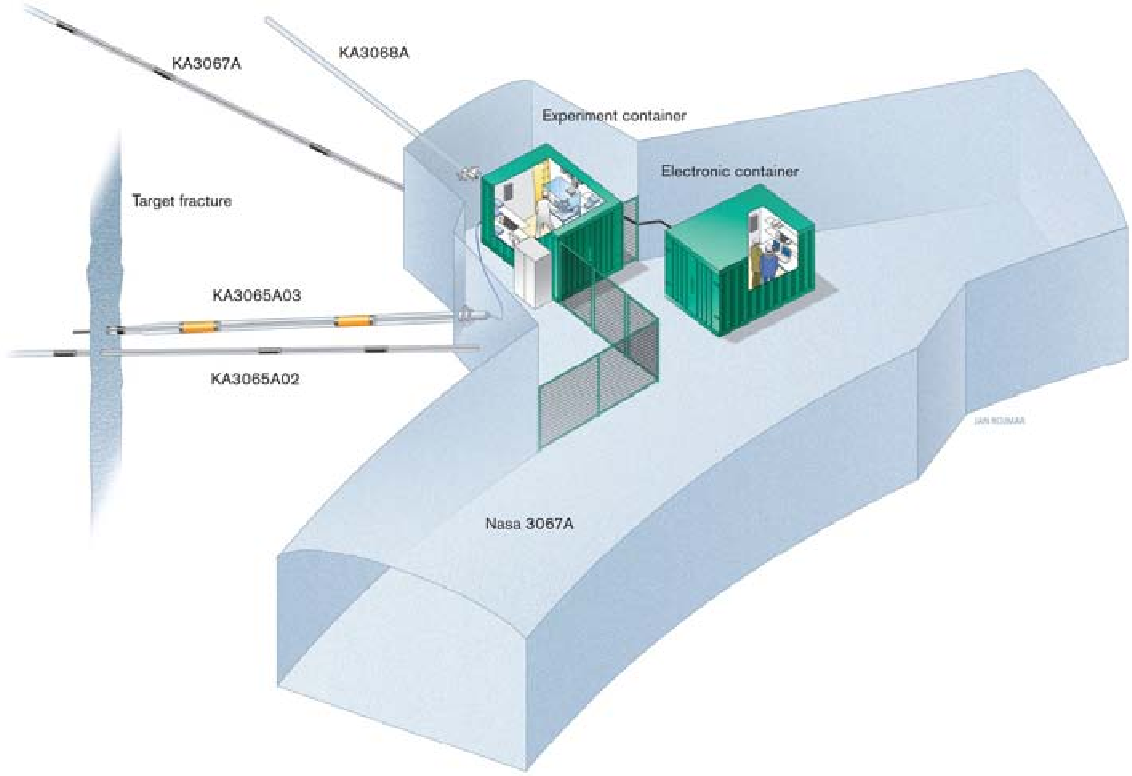


Figure 3-2. *Schematic view of the LTDE-SD experiment layout at niche NASA 3067A at the –410 m level in Äspö HRL.*

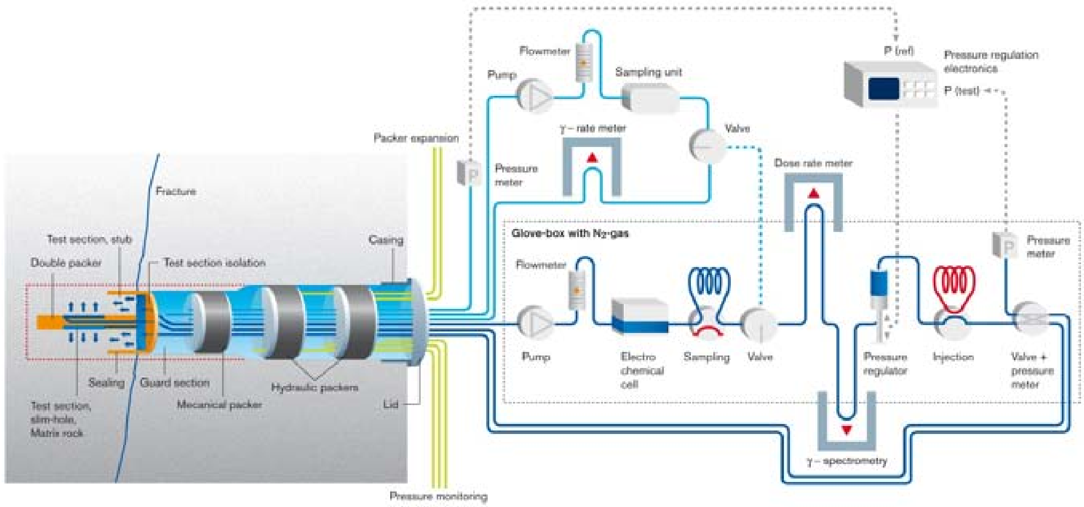


Figure 3-3. *LTDE-SD experimental set-up in the experimental borehole KA3065A03 including the hydraulic pressure control system and the water circulation system for the test-sections in front of natural fracture and in matrix rock.*

Results

The experimental tasks of the project are completed. Data have been printed into data tables for further delivery to SKB data base Sicada. A first draft report is compiled for the laboratory batch sorption tests and sorption/diffusion tests with intact rock pieces from the experimental site. Evaluation, modelling and reporting of the in situ experiment water phase and rock samples is in its final stages. Printed reports are foreseen early in 2011.

A general conclusion is that there is a good qualitative agreement of the results from the in situ experiment to the behavior of the tracers predicted from the LTDE-SD laboratory programme and also to the general knowledge of the tracer behavior. Figure 3-4 shows autoradiographs exemplifying sorption sites in matrix rock (sample cores D5 and D7), in pore space in grain boundaries as well as to biotite, chlorite and titanite minerals. For the very weakly-sorbing and non-sorbing tracers (e.g. Na-22 and Cl-36) very low concentrations of the tracers are found in the first slices closest to the rock/water boundary. The concentrations decrease comparatively slowly by depth into inner part of the rock. The moderately sorbing tracers (e.g. Cs-137, Ni-63 and Ba-133) are present in quite high concentration in the first slices and, for the most cases, decrease to a level 3–4 order of magnitudes lower than the surface concentration already after 3–4 slices, i.e. 3–6 mm depth. For the very strongly sorbing tracer, e.g. Gd-153, activities can only be measured in the first slices. The results can therefore be regarded as confirmation of a combined sorption/diffusion process taking place in the rock which is dependent on the sorption parameters (diffusivity and sorption).

Estimations of sorption coefficient (Kd) have been made using different techniques as; only the measurements of tracer concentration in the water phase, only penetration profile data, as well as combination of both. The technique where only the measurement of the aqueous phase is used gives the highest Kd-values of the different methods. It has been indicated that, especially for strongly

a)

b)

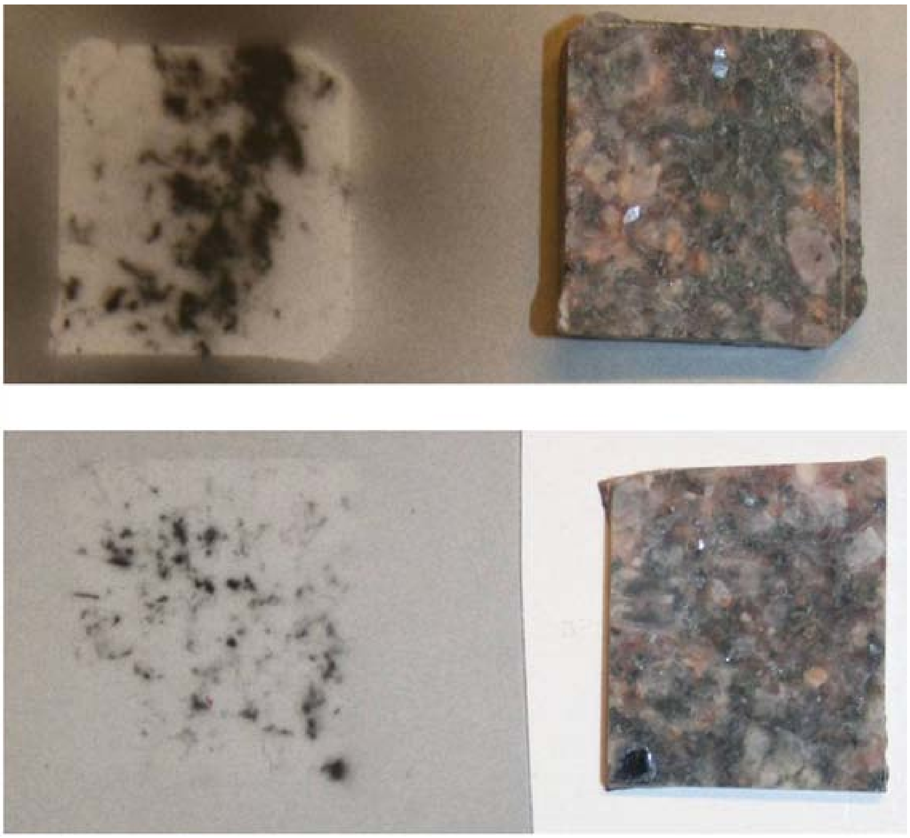


Figure 3-4. *a) Autoradiograph of rock slice D5 to the left; and its corresponding photo to the right. The black areas are interpreted to correspond to primarily biotite as well as pore space in grain boundaries; b) slice D7 where the blackening are interpreted to correspond mainly to mineral aggregate with biotite, chlorite and titanite.*

sorbing tracers, there is an influence of losses in the aqueous phase not directly proven to be rock-water interactions which could be identified as a source of overestimations. The technique that is associated to the lowest Kd-values is the homogenous porosity model using only the penetration profile data. The fact that the penetration depth is much higher than what should be expected from homogeneous sorption (in most cases shorter than mm) makes it necessary to apply a low Kd in order to explain that diffusion curves of e.g. Cs prolonging up to ~1 cm into the rock can be found. These low Kd-values cannot reproduce the actual loss of tracer observed for the aqueous phase which is an indication that this technique is suspected to underestimate the real Kd. Combining this observation to the results of the modelling using only the water phase results, it is thus quite obvious that there is a conceptual uncertainty applying a homogeneous matrix diffusion sorption concept in the scale of the experiment. The most robust concept seems to be to combine the measured concentrations in the aqueous phase and measured concentration in the rock samples close to the rock water boundary. The estimated Kd for selected tracers are presented in Table 3-1. The trivalent lanthanide Gd and the tetravalent Hf, proposed analogues to tri- and tetravalent actinides, shows typically high Kd-values. Also the mono- and divalent cations Cs, Ni, Cd and Ra are within expected Kd ranges.

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 then involved. The project also aims 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 the case of a leaking montmorillonite 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 is in the finalisation stage. 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 to take place in 2011. 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 test under varying conditions are performed as well as colloidal characterisation in the laboratory. Transport experiments in fracture filling material are performed to try to quantify the retardation mechanisms of colloids during transport. Also analysis of colloid concentrations in samples from transport experiments in Grimsel, are performed. Modelling efforts are ongoing, where retention now can be included in the models whereas the aim is to separate the retention into the physical and chemical process such as filtration, sorption and sedimentation.

Table 3-1. Sorption coefficient Kd (m^3/kg) for selected tracers obtained from LTDE-SD in situ experiment by combining aqueous phase and rock sample data.

Tracer	Minimum	Maximum
$^{137}Cs^{+}$	4.0×10^{-4}	9.0×10^{-3}
$^{63}Ni^{2+}$	7.0×10^{-4}	2.0×10^{-3}
$^{109}Cd^{2+}$	2.0×10^{-4}	2.0×10^{-3}
$^{226}Ra^{2+}$	4.0×10^{-4}	4.0×10^{-3}
$^{153}Gd^{(III)}$	3.0×10^{-3}	1.0×10^{-1}
$^{175}Hf^{(IV)}$	1.0×10^{-2}	3.0×10^{-2}

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.
- To determine the structure of montmorillonite colloids equilibrated in different waters.
- To determine in what groundwater conditions montmorillonite colloids as well as natural colloids are stable.
- To study colloid transport in different types of fractures and in different types of waters to understand the impact of aperture distribution, fracture mineral surfaces, fracture filling minerals, colloid size distribution and colloid surface charge density and colloid structure.
- To study the impact of the presence of montmorillonite and humic colloids on actinide transport in water bearing fractures.
- To 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

Experiments are performed in different scales from laboratory scale to in situ scale. The experiments are performed to study:

- Colloid generation.
- Colloid erosion.
- Colloid transport in fractures with varying characteristics.
- Colloid attachment to different fracture minerals.
- Colloid stability in varying groundwater conditions.

Results

During 2010 experiments and modelling were finalised and will be summarized in the final report that is now under construction and will be finished in a first draft in March 2011. The final report will include the experimental and modelling work from both the Colloid Dipole project 2005–2008 and Colloid Transport project 2008–2010.

One doctoral thesis by Sandra Garcia Garcia was published during 2010 with a number of experimental studies performed in the two projects with the title *"Generation, stability and migration of montmorillonite colloids in aqueous systems"*. The thesis includes studies of colloid sorption to fracture filling minerals and transport of latex and montmorillonite colloids through fracture filling minerals from Äspö, which are still not published but are finalised in a manuscript which is soon to be sent in to a scientific journal for publication. The colloid sorption to fracture minerals shows that attachment of colloids to the mineral surfaces is significant even in unfavourable conditions i.e. when both the colloids and the mineral surfaces are negatively charged. Minerals with the point of zero charge closer to the pH in which the experiments have been performed, have a higher tendency to attract negatively charged colloids. Colloids with a less negative zeta-potential have a higher tendency to attach to the minerals. This is in accordance with that the interaction is electrostatic. Transport experiments with latex and montmorillonite colloids in columns with the same minerals as used in the sorption experiments indicated that the retention in the system could be predicted by using the sorption data. Worth to notice was that the sorption experiments were performed in such a way that the colloids were stuck in the structure both by sorption and by physical hindrance in roughness on the mineral surfaces.

The stability of montmorillonite colloids in exposed γ-irradiation was shown to be more stable than their non irradiated counterparts. The effect has been further investigated, and one part of the explanation for the enhanced stability is the increasing ratio of Fe^{2+}/ Fe^{3+} with irradiation giving a higher negative nettocharge increasing the colloid stability.

Montmorillonite colloid transport experiments have been conducted in well characterized fractures in bore cores from Äspö. The colloids were not stabile due to that the fracture surfaces were too fresh and Ca^{2+} inducing aggregation and further sedimentation of the colloids. The ambition was to suty actinide mobility in the presence of montmorillonite colloids, however, these experiments were not feasible to the stability problems.

Modelling strategies for colloid transport and bentonite erosion in situ experiments to be performed at Grimsel in the CFM-project has been developed and the models are continuously being calibrated against experimental data.

Results from the project are now summarized in a final report as well as in scientific articles soon to be submitted for publication.

3.5 Microbe projects

Microbial processes

Microbial processes comprise the decomposition and the production of organic molecules with different electron donors, energy sources and electron acceptors. Organic carbon, including methane, and reduced inorganic molecules, including hydrogen, are possible electron donors and energy sources for microbial processes in the groundwater systems surrounding a repository. During the microbial oxidation of these energy sources, micro-organisms preferentially reduce electron acceptors in a particular order as shown in Figure 3-5. First oxygen, and thereafter nitrate, manganese, iron, sulphate, sulphur and carbon dioxide are reduced. Simultaneously, fermentative processes supply the metabolising micro-organisms with, for example, hydrogen and short-chain organic acids such as acetate. As the solubility of oxygen in water is low, and because oxygen is the preferred electron

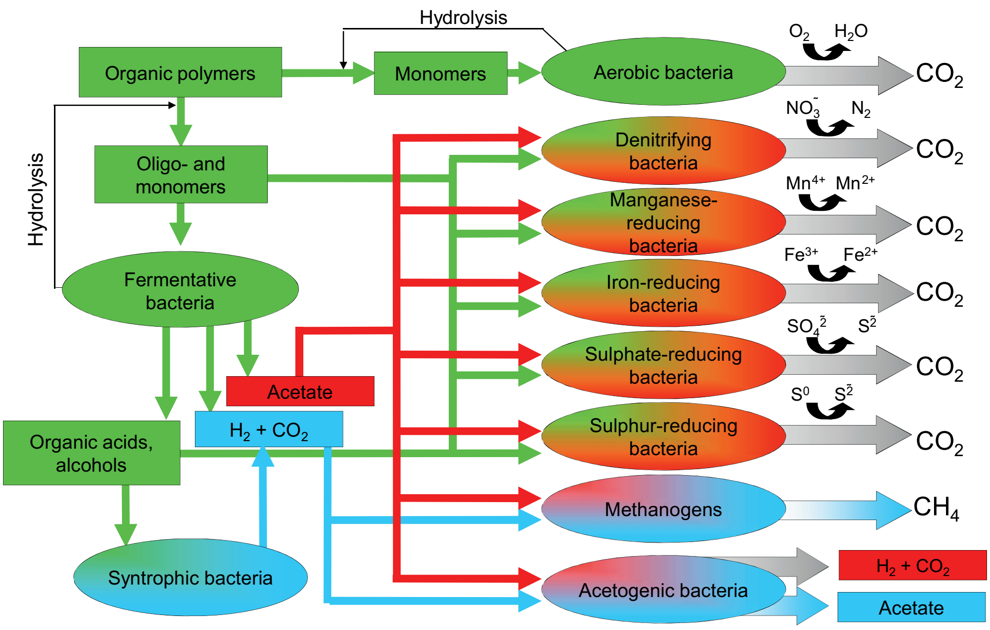


Figure 3-5. Possible pathways for the flow of carbon in the subterranean repository environment. Organic carbon (green and red) is respired to carbon dioxide with oxygen (black/grey), if present, or else fermentation (green) and anaerobic respiration (black/grey) occurs with an array of different electron acceptors. Autotrophic processes (blue) generate methane and acetate from carbon dioxide and hydrogen.

acceptor of many bacteria that utilise organic compounds in shallow groundwater, anaerobic environments and processes usually dominate at depth in the repository environment. The reduction of microbial electron acceptors may significantly alter the groundwater composition and influence fracture minerals. Dissolved nitrate is reduced to dinitrogen and nitrogen dioxide which dissolves in groundwater, solid manganese and iron oxides in fracture minerals are reduced to dissolved species, and the sulphur in sulphate is reduced to sulphide. In addition, the metabolic processes of some autotrophic micro-organisms produce organic carbon, such as acetate, from the inorganic gases carbon dioxide and hydrogen, while other micro-organisms produce methane from these gases; all microbial processes generally lower the redox potential, E_h.

The microbe research initiative

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 need to be tested in a repository like environment. The reasons are several. Firstly, at repository depth, the hydrostatic pressure reaches close to 50 bars, a setting that is very difficult to reproduce in the microbiology laboratory. The high pressure will influence chemical equilibrium and the content of dissolved gases. Secondly, the geochemical environment of deep groundwater, on which microbial life depends and 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 2008, 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 discussed above resulted in the construction and set-up of an underground laboratory in the Äspö HRL tunnel /Pedersen 2000/. The site was denoted the MICROBE laboratory and it was situated at the –450 m level in the F-tunnel.

Three specific microbial process areas of importance for proper repository functions were selected to be studied at the MICROBE laboratory within separate projects. They were: microbial effects on the chemical stability, including the redox potential of deep groundwater environments (MICORED), bio-mobilisation of radionuclides (MICOMIG), bio-immobilisation of radionuclides (MICOMIG). The MICROBE projects have been executed in series for a total of 11 years since drilling of the MICROBE boreholes during 1999 until the end of 2010. At present, there is no planned continuation.

3.5.1 Micored

Background

Micro-organisms can have an important influence on the chemical situation in groundwater /Haveman and Pedersen 2002/. Especially, they may execute reactions that stabilise the redox potential in groundwater at a low and, therefore, beneficial level for the repository. It is hypothesised that hydrogen from deep geological processes contributes to the redox stability of deep groundwater via microbial turnover of this gas. Hydrogen, and possibly also carbon mono-oxide and methane energy metabolisms will generate secondary metabolites such as ferrous iron, sulphide, acetate and complex organic carbon compounds. These species buffer towards a low redox potential and will help to reduce possibly introduced oxygen /Banwart et al. 1994/. The groundwater systems utilized in the MICROBE laboratory have microbial populations that are reproducible in numbers and species distribution over time under stable hydrological conditions as exemplified in Figure 3-6. There was a disturbance in the numbers of sulphate reducing bacteria at about 500 days caused by an adjacent drilling activity as described elsewhere /Pedersen 2005b/. All the physiological groups of micro-organisms described in Figure 3-5 can execute an influence on the redox potential. 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 at the MICROBE laboratory made it very well suited for research on the influence of these micro-organisms on the evolution and stability of redox potential in groundwater.

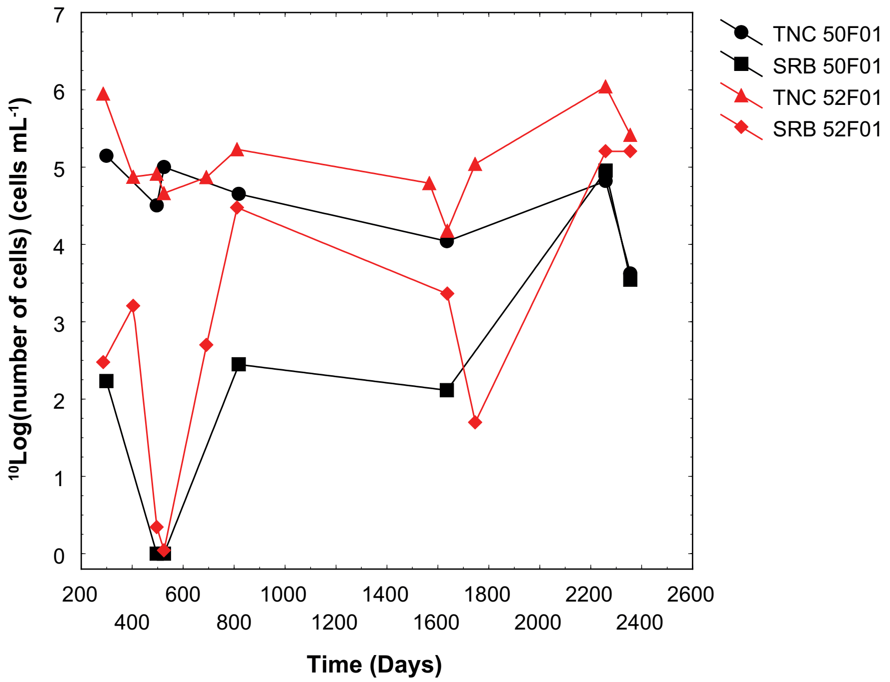


Figure 3-6. *The total number of cells (TNC) and the most probable number of sulphate reducing bacteria (SRB) observed over time since 2004-01-01 in groundwater from the MICROBE boreholes KJ0050F01 and KJ0052F01.*

Objectives

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

Experimental concept

The MICROBE laboratory was situated at the –450 m level in the F-tunnel. A laboratory container was 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 were connected to the MICROBE laboratory via 1/8" (poly-ether-ether-ketone) PEEK tubing. The boreholes were equipped with metal free packer systems that allow controlled circulation of groundwater via respective fracture /Pedersen 2000/. The laboratory was equipped with six circulation systems, each could offer a total of 2112 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. Alternatively, they could be equipped with a total of 450 g (per four flow cells) crushed rock material in the size fraction 3–4 mm. Three systems were metal free made of PEEK and three systems were made of stainless steel. The systems operated at pressures around 20 to 25 bars. The flow through the flow cells was adjusted to 25–30 ml per minute, which corresponded to a flow rate over the surfaces of about 1 mm per second. Temperature was controlled and kept close to the in situ temperature at around 15–18°C. Remote alarms and a survey system were 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 2008/.

In the so called open mode groundwater was circulated from the aquifer to biofilms that developed on the surfaces in the flow cells and back to the aquifer. The circulation systems with these biofilms could be isolated from the aquifers in a so called closed mode and groundwater with indigenous microbes was then circulated through the flow cells without contact with the aquifer. When the systems were changed to the closed mode, the in situ pressure, and the anaerobic and reduced conditions were kept as in the open mode. During 2010, the flow cells contained crushed rock for biofilms support and each circulation system was installed with two pairs of pressure resistant, on line microelectrodes (diameter 0.5 mm), one measurement and one reference electrode in each pair, for measurement of the redox potential (Figure 3-7).These systems were used to investigate the effect of hydrogen on microbial processes coupled to redox measurements under *is situ* groundwater conditions. The experiments were denoted series 3 and series 4. In series 3, the influence of varying hydrogen concentrations on microbial activity and sulphide production was investigated for 65 days. In series 4, immediately following upon series 3, the influence of consecutive pulses of oxygen on the redox potential was studied.

Figure 3-7. *Two pairs of pressure resistant redox electrodes installed on-line on the circulating groundwater in one of the stainless steel circulation systems.*

Results

The investigations of the influence of hydrogen on microbial activity, analysed as sulphide production were performed on microbial populations from both KJ0050F01 and KJ0052F01 in PEEK or stainless steel circulation systems. In general, microbial sulphide production rates were much larger with micro-organisms from the KJ0052F01 groundwater compared to groundwater from KJ0050F01. Here, some results from the stainless steel systems with KJ0052F01 groundwater are presented. The produced amount of sulphide was dependent on the added amount of hydrogen and increased with increasing hydrogen concentration (Figure 3-8 A-). After build-up of sulphide in the three systems, the effect from five pulses of oxygen (~0.5 mM per pulse) on the redox potential was followed. Initially, there were some technical problems with the redox measurements, but they were solved and unbroken data series were obtained from around day 40 until end of the experiments after 110 days (Figure 3-8 A–B–D). The redox potentials of all three systems were intermittently influenced by the oxygen pulses, but they generally recovered the redox potential they had before the pulse after a couple of days. The 10 mM hydrogen system showed the most rapid recovery followed by the 1 and 0.1 mM hydrogen systems. It was also found that the 10 mM hydrogen system had a much lower redox potential than the other two systems. The two pairs of redox electrodes per circulation system reproduced redox readings excellently with small discrepancies, except for the pairs in the 0.1 mM hydrogen system where the response to oxygen was 150 mV larger for one of the electrode pairs compared to its companion electrode pair. Still this difference was not very large. In addition to redox potential and sulphide, several other parameters were analysed as well. They were: pH, sulphate, acetate, dissolved organic carbon, total number of micro-organisms, and the content of the dissolved gases hydrogen, helium, oxygen, nitrogen, carbon monoxide, carbon dioxide and methane. Detailed interpretation and analysis of the data is presently ongoing and will be published during 2011.

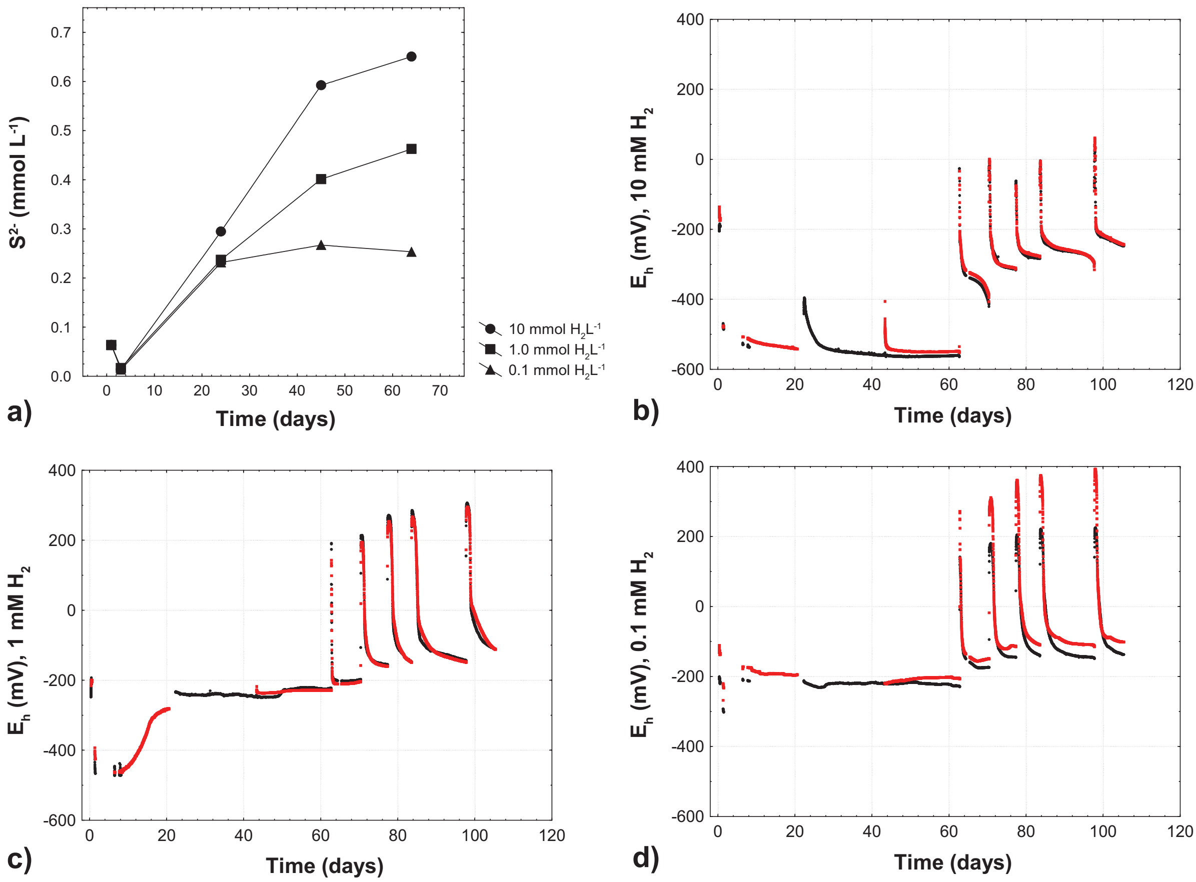


Figure 3-8 A–D. *The production of sulphide in stainless steel circulation systems with microbial populations from KJ0052F01 as a function of different start concentrations of hydrogen gas (A). After 65 days of sulphide production, five consecutive pulses of oxygen (~0.5 mM per pulse) were made to the three hydrogen added systems (B–D) and the corresponding redox potential was registered. The red and black symbols show data from two in-line redox electrode pairs.*

Detailed evaluation is on-going, but some preliminary conclusions seem safe to draw.

- Microbial groundwater populations appeared to be specific in numbers and diversity relative to the aquifer investigated.
- Microbial populations produced sulphide via the reduction of sulphate with dissolved hydrogen gas as electron donor. The amount of sulphide produced increased with the amount of added dissolved hydrogen gas.
- The pressure resistant microelectrodes reproduced well, were sensitive to oxygen and delivered stable data over a period of 110 days.
- Hydrogen is a strong redox buffering agent, possibly via microbial processes that produce redox controlling by-products such as sulphide and ferrous iron.

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, 2010/.

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.

Biofilms in aquifers will influence the retention processes of radionuclides in groundwater. Research results indicate that these surfaces adsorb up to 50% of these radionuclides in natural conditions with K_a (m) approaching 10^5 and 10^6 for Co and Pm respectively. The formation of colloids accounted for a further 20% to 40% of aqueous Co and Pm complexation. Anaerobic biofilms and rock surfaces share similar adsorption capacities for Pm but not for Co. The studied biofilms seemed to isolate the rock surface from the groundwater as diffusion to the rock surface must first proceed through the biofilms. This possible suppression of adsorption by biofilms motivated further research. Until now this biofilm effect had been observed only with one biofilm type in one MICROBE laboratory circulation. The analysis of fracture surfaces obtained during drilling at 1362 m tunnel length in the Äspö tunnel showed that microbial biofilms form also on natural fracture surfaces, making effects from biofilms on radionuclides more likely.

The objectives of Micomig are:

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

Results

There has not been any experimental activity within the MICOMIG project during 2010.

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.

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 3-9) 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

The experimental phase of this continuation project has been completed and is presently being reported and integrated with the results from the earlier Matrix Fluid Chemistry Experiment.

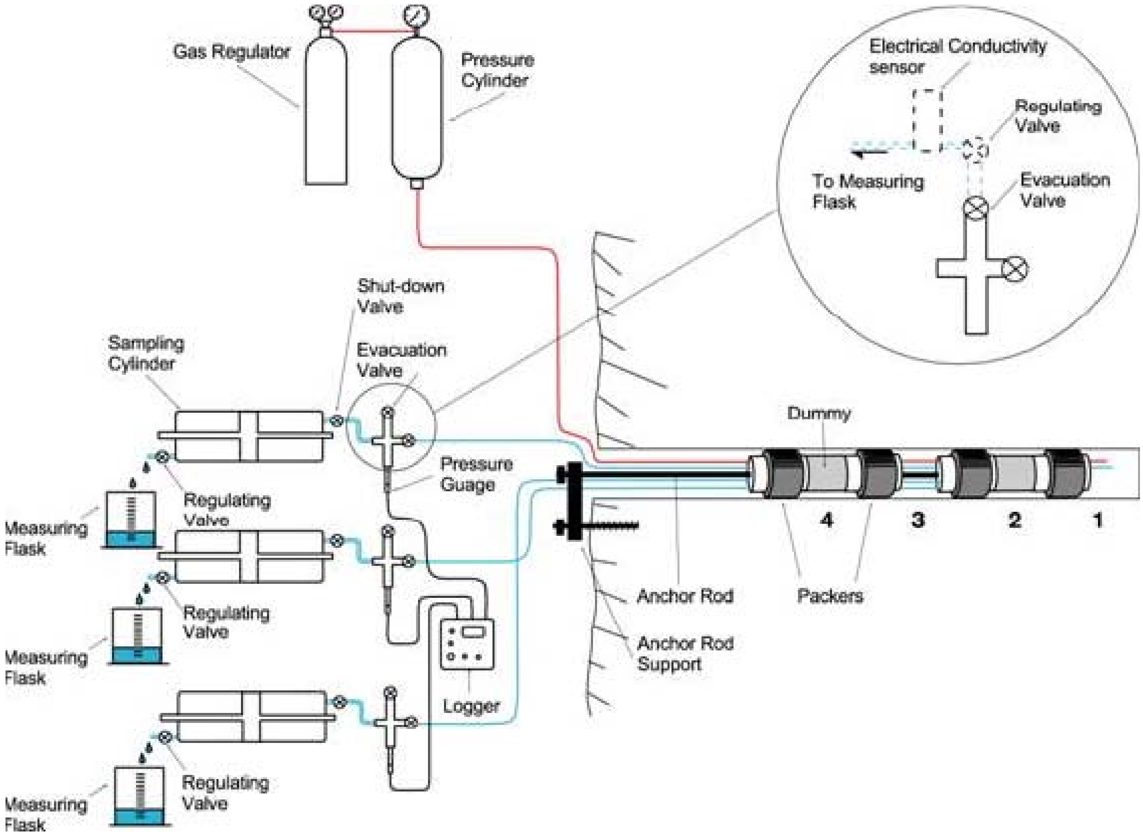


Figure 3-9. Matrix Fluid Chemistry experimental set-up. Borehole Sections 2 and 4 were selected to collect matrix fluid and Sections 1–4 were continuously monitored for pressure.

3.7 Radionuclide retention experiments

Background

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.

Objectives

- To prove the concept Q-equivalents is valid.
- To verify that 94% of the transport resistance in due to the diffusional resistance in the small cross section area of the fissures in the bedrock.

Experimental concept

An artificial fracture is used where a container is situated at one side of the fracture. Water is pumped through the fracture perpendicular to the container. The container is filled with some material (crushed rock or bentonite or glass beads) and a dye is used as tracer.

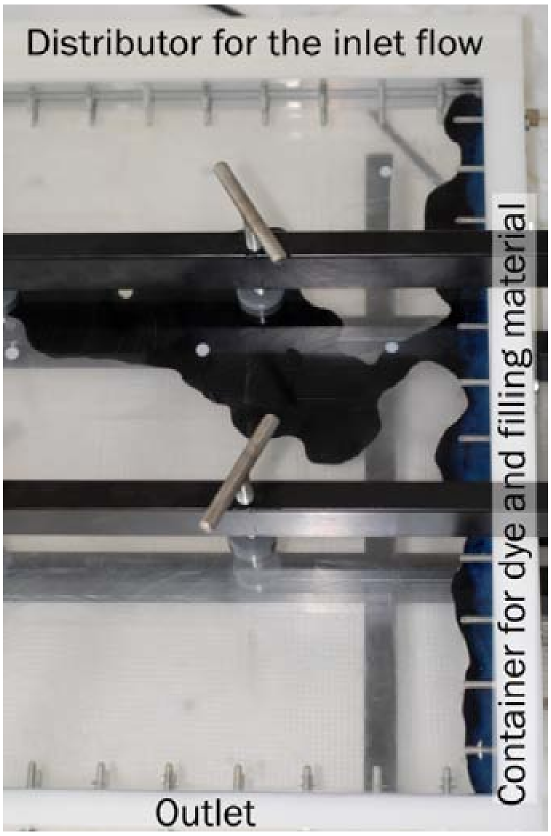


Figure 3-10. In the first experiment indigo was used as dye. As can be seen, the solubility of the dye is very high and the container was soon drained from dye.

Results

Six different attempts were performed in the fracture. None of them were successful. Attempts with a dye which – as it turned out – had too high solubility, the container was filled with too much bentonite so that when it was water saturated it had penetrated too far out in the fracture. Several tests were performed where the dye escaped from the container as solid grains and in the last (most promising) micro-organisms started to grow. Some attempts were performed to study the dissolution rate of the dye that looked most promising for the experiments. In June SKB decided to terminate the project due to lack of results. The work was performed as described in Äspö HRL Planning Report 2010.

3.7.1 Transport resistance at the buffer rock interface

Background and objectives

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

The transport resistance (sometimes called Qeq) 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 diffusional resistance in the small cross section area of the fissures in the bedrock." The aim of the Transport Resistance at Buffer-Rock Interface project is to perform studies to verify the magnitude of this resistance.

Experimental concept

A variable aperture slit has been made by pressing two glass sheets with uneven surfaces together. A dye is allowed to diffuse upward in the slit. The progression of the diffusion is followed by taking pictures at regular intervals. A light box (Microlight) is placed behind the slit to ensure even and constant lightning conditions. A calibration slit is placed next to the variable aperture slit. The calibration slit is filled with dye of the same concentration as in the variable aperture slit chamber. The calibration slit has 0 mm aperture at the bottom and 1.00 mm at 100 mm height. By comparing the light transmission in the calibration slit with the same in the variable aperture slit (completely filled with dye) the variable aperture between the uneven glass sheets can be determined.

Results

Figure 3-11 shows the equipment at the end of the introductory experiment. Visual inspection of the equipment during and after the introductory experiment showed that air bubbles had formed inside the variable aperture slit. This is due to leakage of air into the equipment.

The topography of the variable slit was determined by analysing a picture of the variable slit completely filled with dye and of the calibration slit using Matlab. A calibration curve for transmissivity versus colour intensity was generated. The topography of the variable slit used in the scoping experiment is showed in Figure 3-12.

A program was also written in Matlab to be able to follow the progress of the diffusion profile by time. The evaluation of the introductory experiment showed that the dye chamber needs to be enlarged.

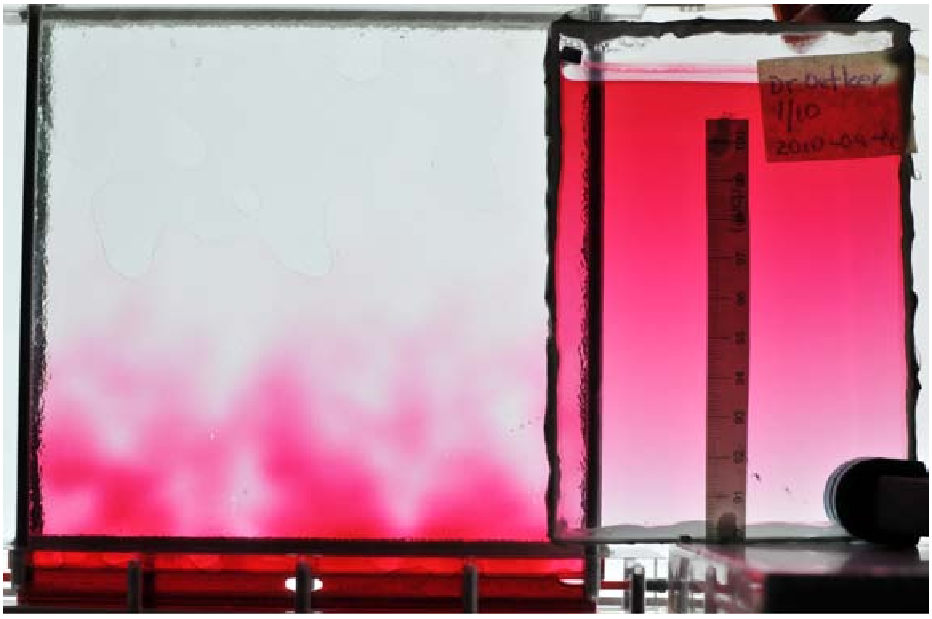


__Figure 3-11.__ Picture of the variable slit at the end of the experiment (after 60 days).

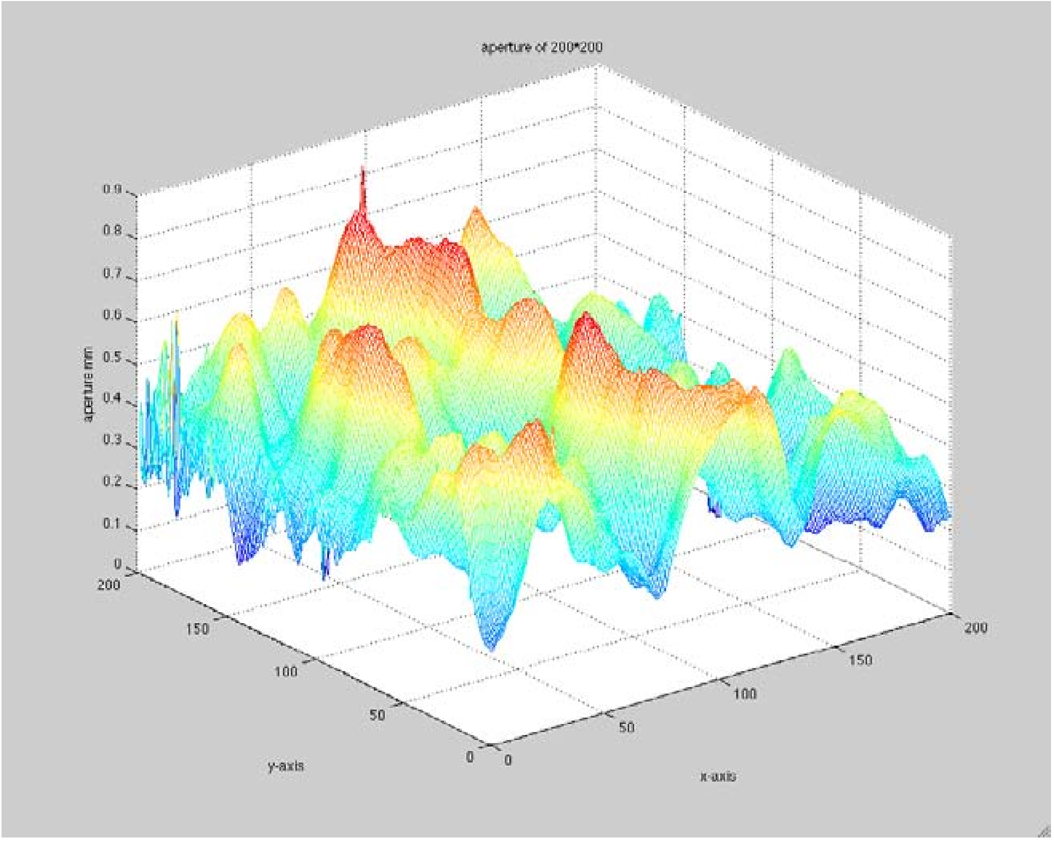


Figure 3-12. *Topography of the variable slit.*

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. Two different EC-founded 3-year projects have been devoted to this issue; EQUIP (Evidences from Quaternary Infills for Palaeohydrogeology) 1997–2000 and subsequently Padamot (Palaeohydrogeological Data Analysis and Model Testing) 2002–2005. 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 glaciations. 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 objectives for the Padamot Continuation 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.
- Focus on the use of these analyses for determination of the redox conditions during glacial and postglacial time.
- Summarise the experiences of palaeohydrogeological studies carried out at Äspö.

Experimental concept

The basic idea has been to sample open fractures from the surface and down to ca 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 micm) fractions was split into three (and if possible four) parts, see Figure 3-13. Two for USD analyses (bulk series uranium 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 consists of quartz, K-felspar, albite, chlorite, calcite and clay minerals of mixed layer clay type. U contents in the samples varied from 6 to 27 ppm.

All six samples were analysed for U and Th content by ALS Scandinavia AB at the ‘Analytica’ laboratory in Luleå. Bulk uranium series analyses (USD) were applied on all six samples by 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 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, U and Th contents were analysed on these samples by a third laboratory.

Figure 3-13. *Photo of sample from a fracture zone at 196.55–196.75 m in KAS 17.*

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 U mobilisation to U deposition. Only the uppermost sample (19.6 m) indicates U mobilisation caused by oxidative leaching. However, this sample also has the highest U content (around 25 ppm) suggesting older U precipitation (before the last 1 Ma). Recent deposition was obvious in sample 20.38 m whereas sample 20.3 showed much less influence of recent redistribution, once again underlining the inhomogeneity in the bedrock fracture system. The deepest samples, 156 and 196 m, show activity ratios approaching equilibrium, whereas sample 102 m shows U deposition, considered older than the last deglaciation.

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) cf Figure 3-15 and shifts from U mobilisation to U deposition can take place within a very short distance, depending on changes in groundwater flow and chemistry (maybe annual variations).

Important conclusions from the study are that:

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 a very 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 select samples as soon as possible following drilling, and thereafter protect the samples from water, acid and long exposure to the atmosphere, is therefore optimal. This knowledge has been used in a new sampling of drill core material from a new drilled borehole at SFR, Forsmark. Three samples have been put in PVC bags which are then flushed with nitrogen and then vacuum sealed directly following drilling, and are thereafter transported to Helsinki University where they are now stored in oxygen free atmosphere within a glove-box, until analyses will be performed, hopefully this spring (Figure 3-14.)

Figure 3-14. *One example of drillcore sampling handling (KFR 106 at SFR, Forsmark).*

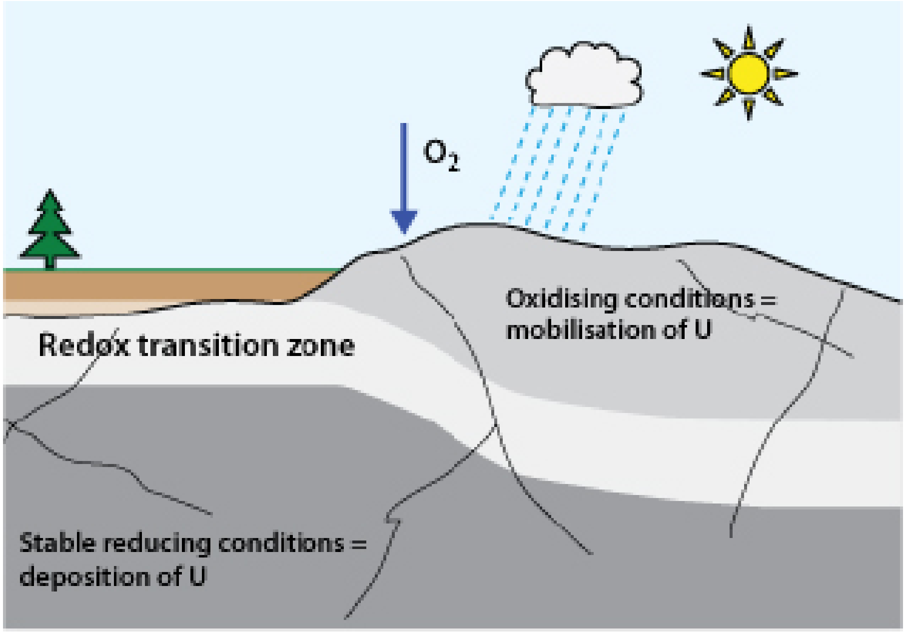


Figure 3-15. *Oxygen entering the bedrock via recharge water will be consumed by organic and inorganic processes along the bedrock fractures. This transition can be detected by studies of uranium and uranium isotopes.*

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 extraction scheme used can be simplified: The original 4 steps, i.e. 1) ammonium acetate, 2) Tamm's oxalate, 3) 6 M HCl, and 4) dissolution of the residual with aqua regia, can be replaced by the following two steps procedure: A) Leaching steps 1 and 2 are replaced by extraction with 1M ammonium acetate-0.05 EDTA solution (buffered to pH 4.8 with acetic acid) B) 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. The new knowledge is presently applied on drillcores material from Greenland (the GAP project). However, a challenge with these samples are the drillcores quality (no triple-tube analyses are available so far).

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

The continuation phase of this project has been completed and will be reported. This report, together with earlier published reports, will be combined and published as a separate SKB Technical Report in 2011.

3.10 Sulphide in repository conditions

Background

In a repository, knowledge of the groundwater sulphide concentration and its variability is important, since sulphide affects the stability of the copper canister. During the early pre-investigations at Äspö, the site investigations at Laxemar and Forsmark, and the subsequent monitoring programmes, variations in sulphide concentration were obtained. It has been discussed whether drilling and pumping activities and/or installation of monitoring equipment might influence the sulphide concentration.

Metabolism of either dissolved organic carbon molecules, or the gases methane and hydrogen by sulphate reducing bacteria may generate sulphide in deep groundwater systems. Methane and hydrogen are formed in deep geological processes, but hydrogen may also be produced in corrosion processes of metals. Organic carbon molecules may be produced as acetate by acetogenic bacteria from hydrogen and carbon dioxide, but may also exist in equipment materials such as plastics and rubber.

Observations from a previous investigation of sulphide concentration in a core-drilled borehole at Laxemar and results from hydrochemical monitoring in several boreholes in Forsmark suggest that the sulphide concentration decreases as the section water is discharged and the fraction of formation water increases /Rosdahl et al. 2010, Nilsson et al. 2010/. In periods between pumping, the sulphide concentration is restored to the original and the decrease in sulphide concentration with discharged water volume is reproducible when conducting the pumping under similar conditions (pumping rate, time etc).

During the investigations at Laxemar it was also discovered that the upper part of the equipment (the so called water standpipes) that are in contact both with the atmosphere and the section water, might influence the quality of water samples collected from the section. The water in the standpipes are in contact with the equipment for pumping and sampling and was found to contain several milligrams of dissolved organic carbon and sulphide. It is likely that surface water (and dissolved organic material) can reach the standpipe and in some cases the section water through leakage between couplings and packers. In addition, activities in the borehole sections, such as measurements of the groundwater level and chemical monitoring, might cause organic constituents to be transported from the ground surface to the section water by pressure gradients, mixing, diffusion and gravity.

Objectives

The aim of this project is to study the processes behind microbial sulphide production and the regulating factors for dissolved sulphide. This includes investigations on whether bacteria can use some carbon based components in equipment materials and additives as a source of energy in the process of reducing sulphate to sulphide. The overall aim is to be able to predict the expected variability of the sulphide concentration in a repository environment.

Experimental concept

The conceptual idea is to follow the build-up of sulphide in a borehole section. A suitable place for conducting the experiment is Äspö HRL, since the location underground facilitates sampling of dissolved gas and in addition the installed equipment does not include water standpipes.

A circulation system for study of sulphide production processes in a packed-off borehole section was assembled (see Figure 3-16). The section water is circulated under maintained pressure using a circulation pump located outside the borehole. Tubing ending at the two ends of the section enables circulation / mixing of water before small volumes of water samples are collected and analysed as time-series. The analytical programme includes sulphide and other chemical compounds, microorganisms and dissolved gases. In addition, analyses of stable isotopes and stable isotopes in gases are performed in order to determine reaction pathways and origin of reactants and products.

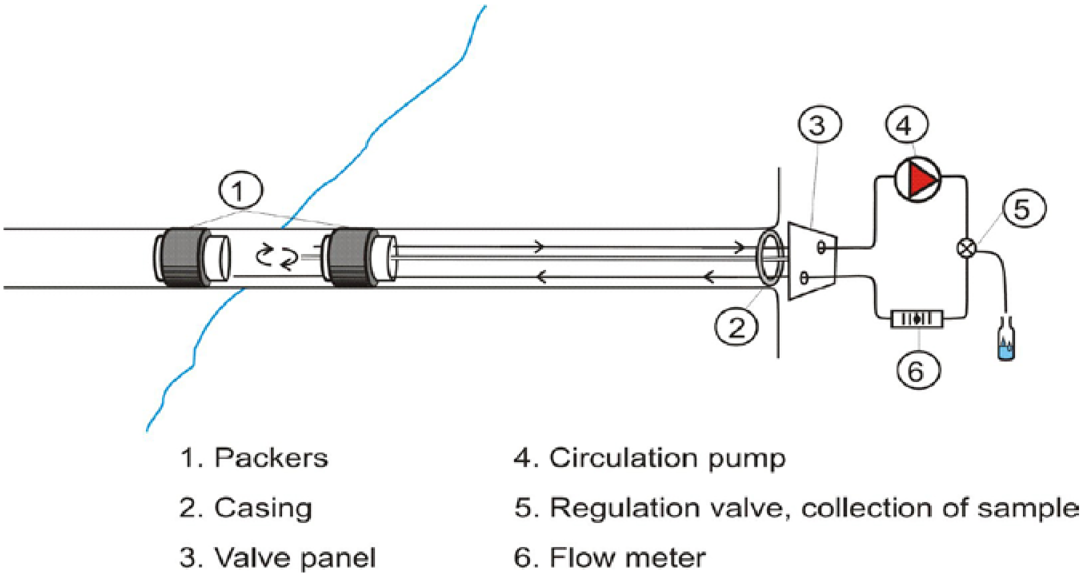


Figure 3-16. *A schematic picture illustrating circulation of groundwater in a packed-off borehole section. The circulation pump and flow meter are located outside the borehole. The distance between casing and investigated section is about 30 meters.*

Results

The analyses and evaluation from the experiments have not been completed. However, preliminary results from the circulation experiments can be summarised as follows;

- The concentration of sulphide and sulphate reducing bacteria increase with time when water in a packed-off section is circulated and small volumes of water are collected for analyses.
- Discharge of water from the section (increased water volume from the fractures) results in a decrease in sulphide concentration and sulphate reducing bacteria.
- The results suggest that each packed-off section has its own specific sulphide concentration and possibly also composition of bacteria.
- The concentrations of acetate and other dissolved organic carbon constituents and dissolved gaseous compounds are more or less constant with time, which may indicate a steady-state situation with respect to production and consumption of components.

After completion of the circulation experiment the transmissivity of the fractures will be determined in a dilution experiment. This will allow assessing the natural flow of water and transport of dissolved components from fractures to the section in time periods between pumping.

In a consecutive investigation the borehole equipment (tubing, packers, pipe strings) will be dismantled and after being visually inspected for any disintegration of plastic material and indications of corrosion, etc, samples will be collected and analysed for organic carbon content, biofilms, sulphide complexes, plastic softeners and corrosion products.

Further investigations will include investigations on composition of gases in the rock matrix, diffusion rates and transport of gas between rock matrix and water-bearing fractures. Also, studies of sulphide minerals in fractures will be conducted.

3.11 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 chloride, sodium, calcium replaced by nitrate, lithium, magnesium. Besides, in order to compare to a normal Swiw test, both sorbing and non-sorbing 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 (chloride, sodium and calcium) 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

Borehole KA2858A was in December 2009 selected as the primary test site candidate for performing Swiw tests with synthetic groundwater. During 2010, the site was prepared and re-instrumented in order to better suite the performance of Swiw with synthetic groundwater. A number of tests were also carried out in order to further investigate the suitability of KA2858A as a test site and to optimise the test procedure prior to the main tests.

Several tests with the tracer dilution method indicated a low groundwater flow in the test section. Three Swiw pre-tests with a conservative tracer resulted in a high tracer recovery and that a larger injection volume and a longer waiting period could be used in the main tests than originally planned for, which could be beneficial for the Swiw test evaluation. The low groundwater flow, high tracer recovery and possibility to use a relatively large injection volume and long waiting period all indicates that KA2858A is a suitable test site for Swiw with synthetic groundwater.

The first of the two Swiw main tests, without a waiting period, was carried out during November. The second main test, with a waiting period, was finalised in December 2010. The main tests were performed without any major complications considered to affect the end result. However, no final results in terms of breakthrough curves are presently available.

3.12 Äspö model for radionuclide sorption

Background

Today, geochemical retention of radionuclides in the granitic environment is commonly assessed using K_d-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.

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.
- To 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.
- With support from the results of activities linked to both objectives, as well as literature data, formulate and parameterise predictive models for radionuclide sorption on Äspö rock material and to test the models against small-scale laboratory experiments.

Experimental concept

The project is divided into four research activities

1. Preparatory studies.
2. Surface area dependency of sorption.
3. Localisation of sorption.
4. 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 at Äspö. The concept follows the CA approach, where the behaviours of the individual pure minerals are studied and the knowledge synthesized into a prediction of the behaviour of the full rock sample. During 2010, focus has been on determining the specific surface area and porosity as a function of particle size of a number of minerals that are important constituents of granite. The determinations were carried out using the BET-methodology (method developed Brunauer-Emmet-Teller, /Brunauer et al. 1938/) for specific surface and the BJH-methodology (method developed by Barrett, Joyner and Halenda, /Barrett et al. 1951/) for porosity, where nitrogen or krypton gas was adsorbed onto the sample at low temperature. The instrument is a Micromeritics ASAP 2020, see Figure 3-17.

Further focus has been on characterising the mineral samples and the particle size fractions obtained by crushing parts of the specimens mechanically (first by hammer and then by an agate pestle and mortar; Figure 3-18). A bigger chunk of each of the minerals was used as an example of a less mechanically disturbed sample.

Figure 3-17. *Instrument for making surface area and porosity determinations.*

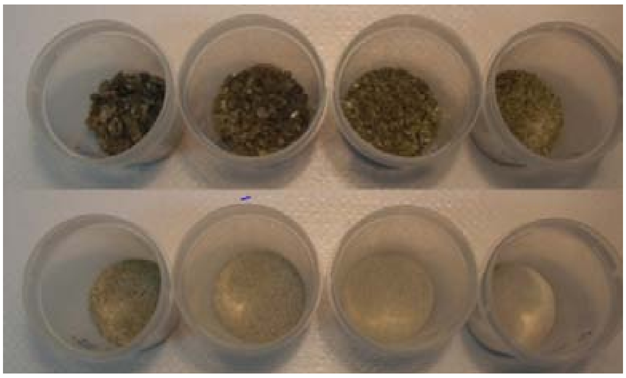


Figure 3-18. *Different particle size fractions of labradorite used in the experiments.*

Results

During 2010, determination of specific surface area of particle size fractions of chlorite, biotite, hornblende, and apatite has been carried out using the BET-method. Furthermore, the porosity of some of the samples has been determined. Focus has also been on characterising the mineral specimen and the particle size fractions. Figure 3-19 summarises the central information obtained.

Figure 3-19a and b shows the nominal chemical composition and general crystal structure of the mineral, respectively. Figure 3-19c shows a photograph of each of the hand specimen used in the experiments whereas Figure 3-19d shows a Scanning Electron Microscopy image of the 0.5–1.0 mm size fraction at rather low magnification. The broken squares in Figure 3-19d indicate the sieve sizes used to delimit the particle size fraction. For all the minerals, the particle form is more parallelepipedic than spherical or cubic. This implies that one dimension of the particle can be significantly larger than the aperture of the sieve, which is also observed for all of the minerals. Figure 3-19e, finally, shows the specific surface area as measured by the BET-method, using Kr-gas adsorption, versus the inverse of the representative particle size as given by the sieve aperture cut-offs. The insert to Figure 3-19e magnifies the plot for large particles, thereby highlighting results for the bigger, sawed chunk of the mineral.

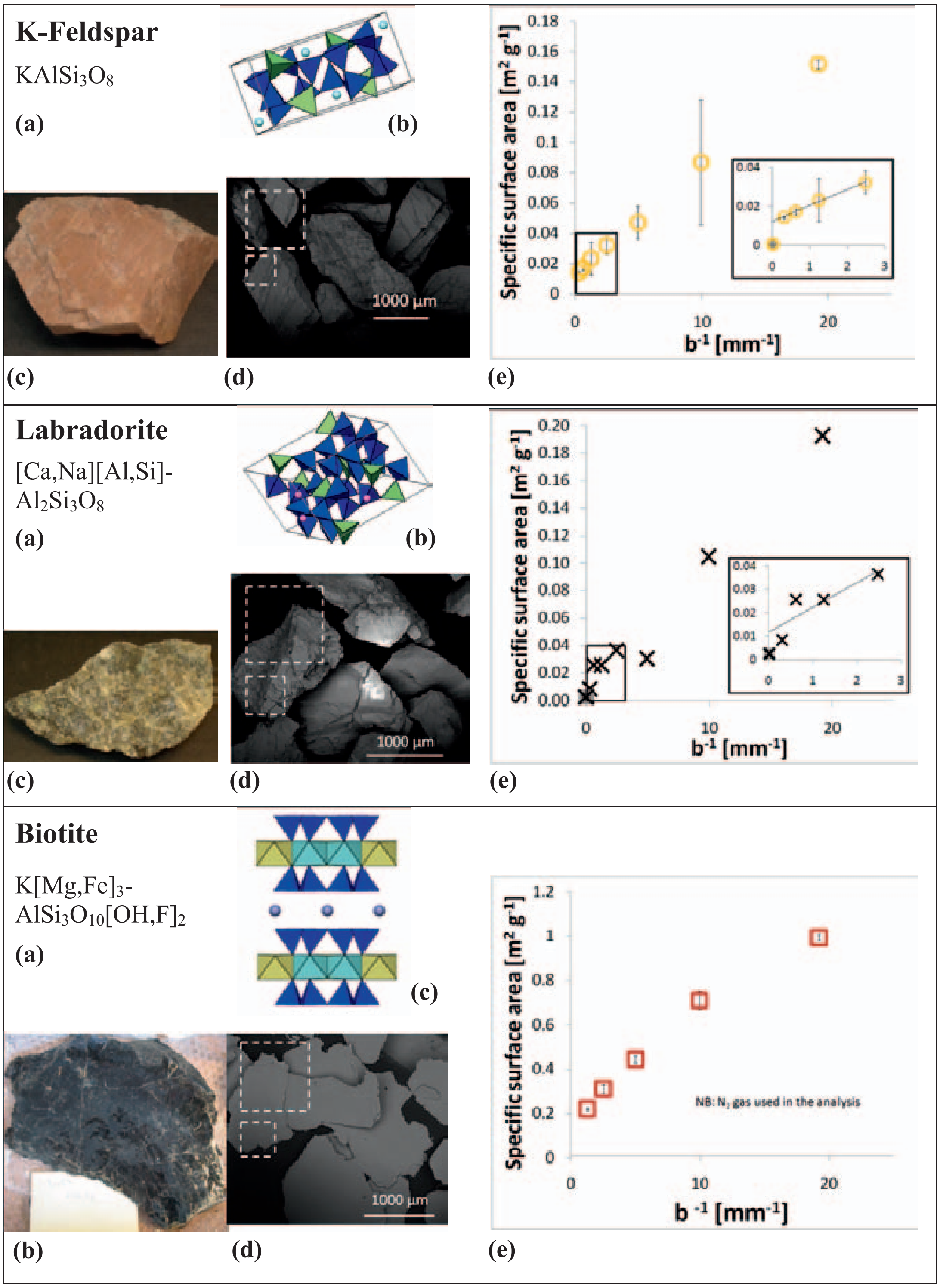


Figure 3-19. *Mineral characteristics and specific surface area as function of the inverse of the representative particle size. For each mineral **(a)** Mineral name and nominal chemical composition; **(b)** general crystal structure; **(c)** photograph of a chunk of the specimen used in the experiments (generally ca 5–20 cm pieces) prior to removal of impurities; **(d)** SEM image of 0.5–1.0 mm size fraction of the mineral. The broken square indicate the size of the sieves used to delimit the size fraction; **(e)** experimentally determined specific surface area [m^2 g^{-1}] as function of the inverse of the characteristic particle size [mm^{-1}] from BET-measurements using krypton gas absorption. N.B. vertical error bars (often hardly visible) represent one standard deviation from replicate measurements. **Insert:** Magnification for larger particles. The grey shaded marker (K-feldspar, chlorite, magnetite, labradorite and hornblende) shows analytical data of a larger chunk (usually 5–10 cm) of the material. For K-feldspar, the value is an upper estimate, as the actual value was below the detection limit of the analytical method. For hornblende, a smaller chunk (~1 cm) of material was used. For apatite and biotite, no analytical result is yet available for a bigger chunk. **N.B.** Preliminary results.*

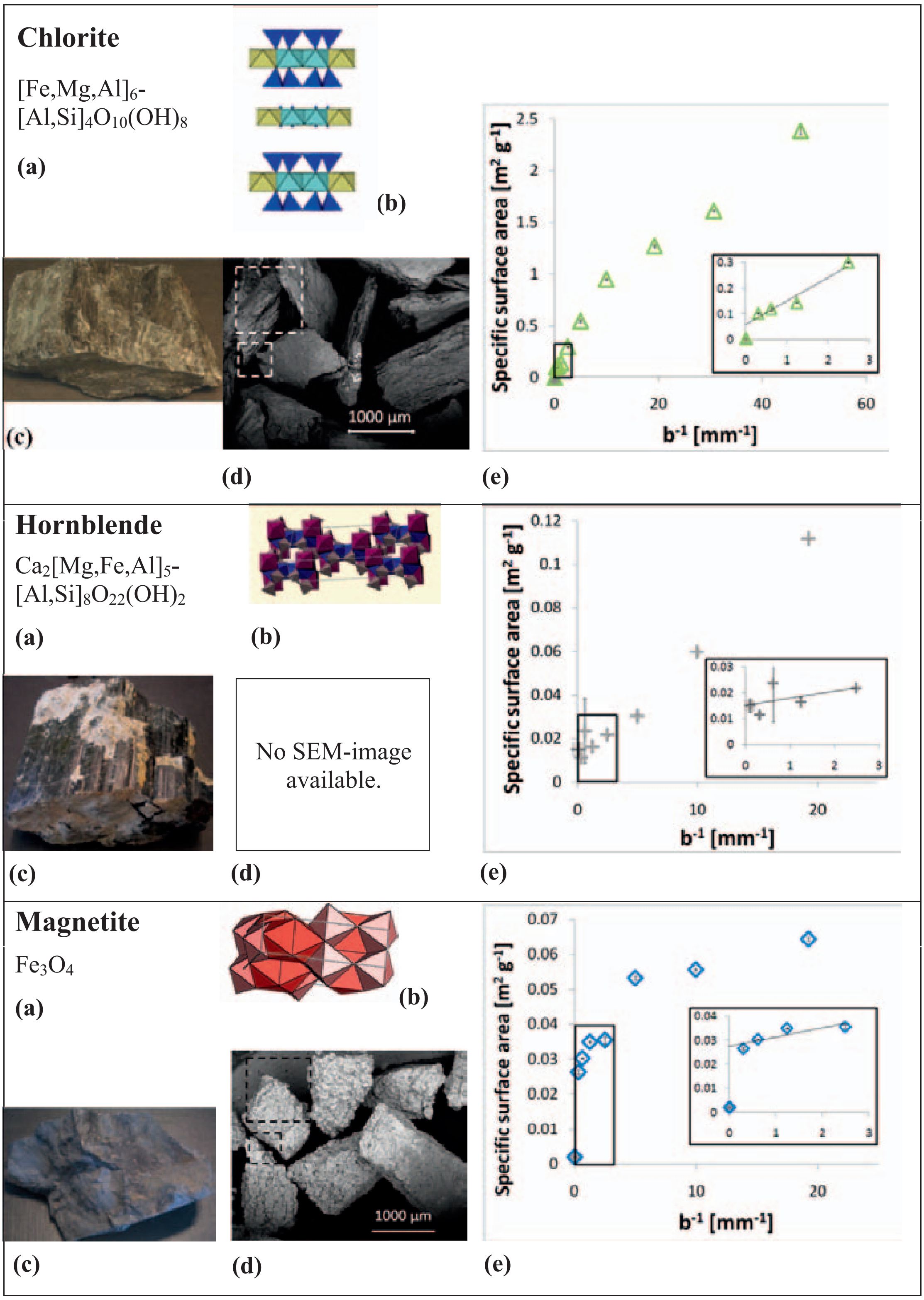


Figure 3-19. *Continued.*

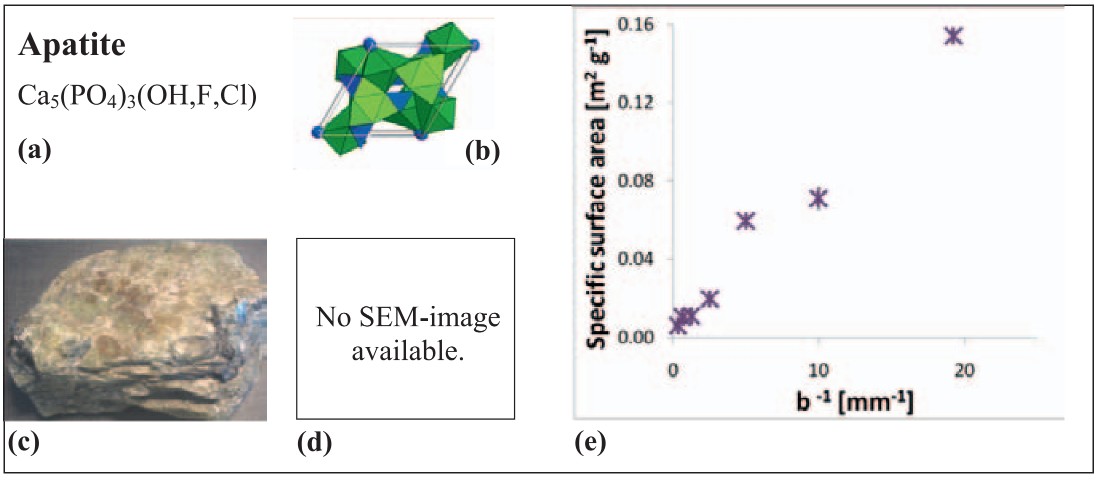


Figure 3-19. *Continued.*

Particle form, morphology and size distribution

Selected particle size fractions of the mineral samples have been characterised by Scanning Electron Microscopy (SEM; see Figure 3-19d) and by a particle analyzer (PartAn 3001L and multi-imaging-software PartAn 3D). In the latter method, the particles are stroboscopically photographed while they fall. Figure 3-19d indicates that the minerals, as expected, have different forms, belonging to different crystal habits. For example, biotite and chlorite have thin, micaceous, particles, whereas the feldspars (labradorite and K-feldspar) are stubbier. Whereas, the biotite surface if comparably smooth, the surface of magnetite is rough.

Figure 3-20 shows SEM images of biotite from the size fraction 75–125 µm size fraction at different magnifications as an example of results from this part of the investigation. Figure 3-20a shows the typical thin micaceous particles, yielding an almost two dimensional, rhomboidal form of the biotite particles. It is noteworthy that the unequal lengths of the sides of the particles allows one dimension of the particle to be larger than the cutoff size of the sieve used to delimit the particle size fraction (indicated as broken squares top left in the figure). Figure 3-20b shows that although the form is largely rhomboidal, the particle has an irregular form and frayed edges. Figure 3-20c shows that the biotite surface (basal plane) is dominantly smooth with few features, dominantly occurring at the edges of the particle. Finally, Figure 3-20d shows the layered structure of the biotite, the frayed edges of the particle and presence of few fine particles on the basal plane. Systematic evaluation of all of the SEM results is ongoing.

Specific surface area

In the literature, it has been suggested that determination of the specific surface area through the use of the BET-method may yield disagreeing results from analyses using different analytical gases. Comparison of results from N_2(g) or Kr(g) adsorption over different particle sizes showed to be similar for many of the minerals studied in this project (Figure 3-21). However, as the detection limit is approached for larger particles, higher values are generally obtained from the use of N_2. The use of Kr was found to yield a lower detection limit and better reproducibility, as has also previously been reported in the literature.

Figure 3-22 shows a conceptualisation of a cubic particle with surface roughness and defects marked on only two of its sides and with a schematic representation of the pore structure along an arbitrary plane within the particle. As the figure indicates, the outer geometric surface area is just part of the total, exposed surface area. BET-measurements of the surface area will cover the geometric surface area, including surface features leading to roughness, and the inner surfaces of pores that go through the particle and blind pores, connected to one of the edges of the particle and any associated dead-end porosity. Surfaces of enclosed porosity will not be available for the adsorbing gas, and is thus excluded from the measurable area of the particle.

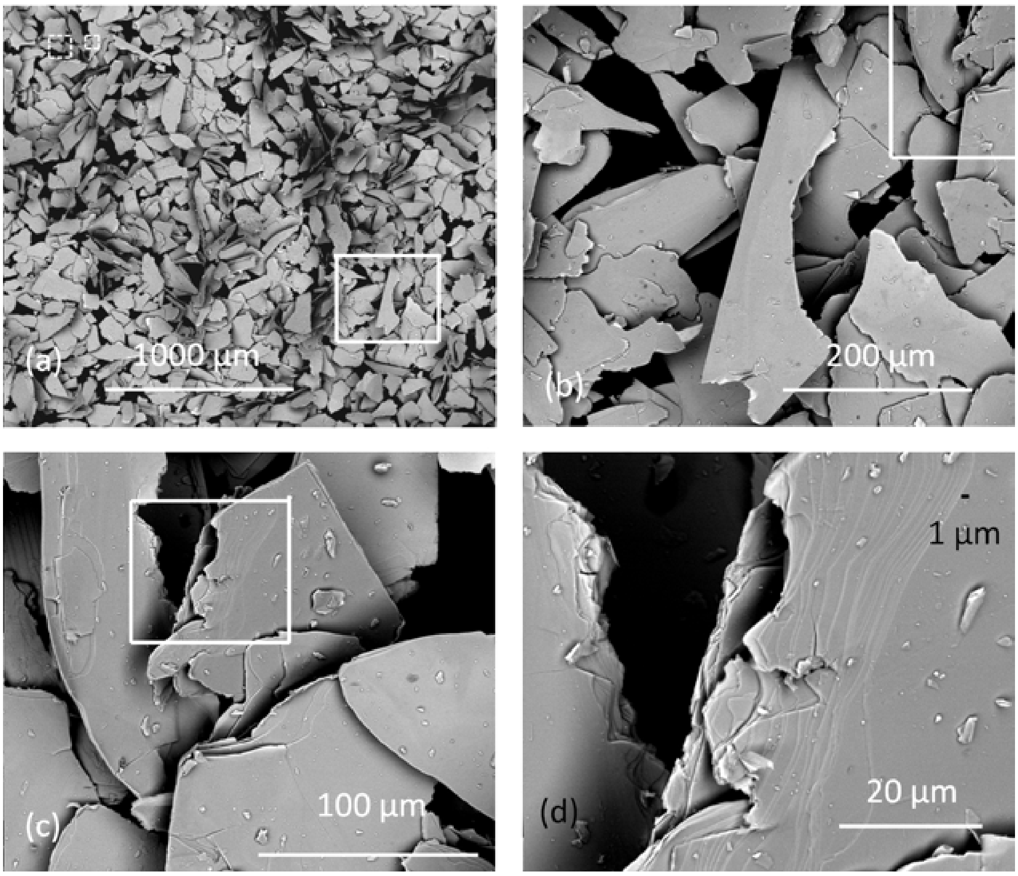


Figure 3-20. *Scanning electron microscopy images of biotite from the size fraction 75–125 µm in different magnifications. The broken squares in (a) show the sieve sizes used to delimit the size fraction. The full-drawn squares in (a)–(c) mark the position of the next image at larger magnification. N.B. Preliminary results.*

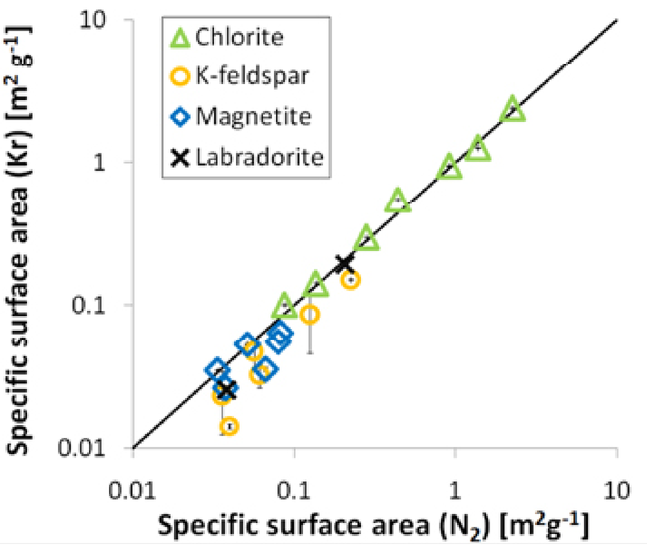


Figure 3-21. *Specific surface area as determined from Kr(g) sorption as function of the area determined from N_2(g) adsorption for four minerals. N.B. Logarithmic scale. Preliminary results.*

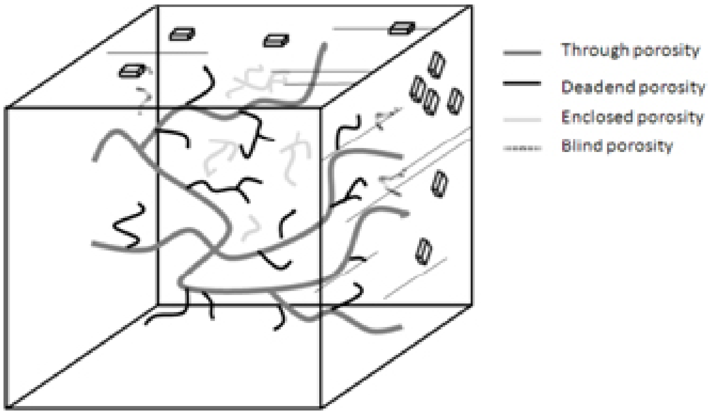


Figure 3-22. *Schematic conceptualisation of the pore system in a mineral particle (one plane) including through, dead-end, enclosed and blind porosity. On two of the sides of the cubic particle, surface features contributing to roughness, are symbolically marked by fine particles/kinks/pits and fractures/steps.*

/André et al. 2009/ hypothesized for granite, that a disturbed zone at the particle edge is developed during particle size reduction by mechanical means, leading to an increased internal surface area in the outer part of the particle. They proposed a model for the particle size dependence of the specific surface area based on the behaviour of granitic samples and assuming spherical particles. Furthermore, they showed that large chunks of granite had much lower specific surface area than would be predicted by extrapolation of specific surface areas of granite powder from size fractions commonly used in laboratory experiments for sorption /André et al. 2008, 2009/.

In this project, the model of /André et al. 2009/ was extended to cover parallelepipedic particles with sides a, b and c (compare typical particles forms in Figure 3-19d and 3-20). For an assemblage of geometrically similar particles with a=lb and b=mc ($0 \le m \le 1$; $l \ge 1$), the specific surface area, SSA, was expressed as a function of the particle size through:

For $c \le 2\delta$

$$SSA_{tot} = \frac{2\lambda\beta}{b\rho} + \frac{\alpha_{\text{int}}}{\rho} + \frac{\alpha_{dist}}{\rho} \tag{3-1a}$$

For $c > 2\delta$

$$SSA_{tot} = \frac{2\lambda\beta}{b\rho} + \frac{\alpha_{\text{int}}}{\rho} + \frac{\alpha_{dist}}{\rho}\left[2\frac{\delta}{b}\left(1+\frac{1}{l}+\frac{1}{m}\right)-\left(2\frac{\delta}{b}\right)^2\left(\frac{1}{lm}+\frac{1}{l}+\frac{1}{m}\right)+\left(2\frac{\delta}{b}\right)^3\frac{1}{lm}\right] \tag{3-1b}$$

where β [-] is a form factor $\beta = 1+l^{-1}+m^{-1}$, λ [-] is the surface roughness, ρ [g m^{-3}] is the density of the mineral, δ [m] is the thickness of the disturbed zone, and α [m^2 m^{-3}] is the internal surface area, with "int" and "dist" representing "internal" and "disturbed zone", respectively.

In Equation 3-1, b [-] is the representative size of the particle size, the inverse of which is obtained from $b_{rep}^{-1} = \frac{4\cdot(b_2^3 - b_1^3)}{3\cdot(b_2^4 - b_1^4)}$ for a rectangular distribution of the particle sizes between the lower and upper sieve cutoffs, b_1 and b_2.

As shown in Figure 3-19e, the specific surface area of the crushed minerals in this study generally followed the predictions of Equation 3-1, with a linear trend (Equation 3-1a) of SSA with b^{-1} for small particles and a negative deviation from this for larger particles (Equation 3-1b). However, for a few cases, no considerable deviation of larger particles to the linearity depicted in Equation 3-1a was observed (hornblende, K-feldspar and apatite) or the data split into several, seemingly linear regions (magnetite and chlorite). Detailed interpretation of this data is ongoing.

The specific surface area of the larger chunks is currently addressed. So far, measurements have yielded considerably lower values than expected from extrapolations of values for the crushed material (see grey symbols in inserts to Figure 3-19e). In accordance to the results of /André et al. 2008, 2009/, this indicates a possible overprediction of the available surface area and thus sorption from small-scale sorption experiments using crushed material. Moreover, as discussed by /Dubois et al. 2010a, b/, a considerable part of the exposed surface area is seemingly made available through the mechanical treatment of the material, and may have other characteristics than that intrinsically present. This may affect the applicability of radionuclide sorption results from small scale experiments to field situations.

Porosity

Biotite, chlorite, K-feldspar, and magnetite were selected for porosity determinations and found to be mesoporous (compare Figure 3-22) from established N_2 adsorption/desorption isotherms. The specific pore volume was found to decrease with increasing particle size (Figure 3-23). The preliminary results in Figure 3-23 indicates that the mesoporosity differs with up to 1–2 orders of magnitude between the various minerals for any given particle size less than 1 mm, with higher values for chlorite and biotite than for magnetite and K-feldspar, which presumably is related to their different crystal structure and mineral habit of these two groups of minerals (compare Figure 3-19). Generally, the obtained pore size from this preliminary assessment fell within the range 100–300 Å for most of the particle sizes analysed and there was in most cases no clear dependence of the pore size on the particle size (data not shown).

Porosity as determined by mercury intrusion was generally found to be much larger than that shown in Figure 3-23. Possibly, this may be related to the presence of large macropores not detected by N_2 adsorption/desorption. Further analysis of the porosity data is ongoing. Determination of porosity of the larger, sawed chunks of material is aimed for, but found difficult, due to the low porosity of these samples.

Literature data on the sorption of radionuclides to granitic minerals

A literature review aiming at identifying available surface complexation and ion-exchange models for the sorption of radionuclides to be used in the sorption experiments of this project onto relevant, granitic minerals has been carried out (data not shown). It was found that high quality information in terms of ready-to-use models was extremely scarce. For some combinations of radionuclides-minerals, systematic experimental data was available so that models potentially may be derived from this existing data within the project. However, in some cases even such experimental data was not found.

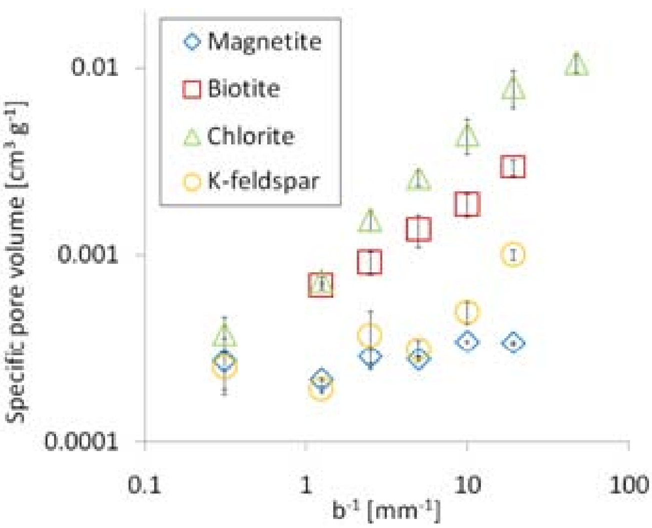


Figure 3-23. *Specific pore volume as determined by N_2 adsorption/desorption as function of inverse of the representative particle size. Error bars represent the standard deviation in replicate determinations. N.B. Logarithmic scale. Preliminary results.*

Further discrimination of the expected importance of different minerals to the overall sorption of the selected radionuclides to granite will be attempted through the use of the identified data. Results of this discrimination will help to identify further research needs within the project and to focus the planned sorption experiments.

Conclusions

In summary, the results obtained within the project during 2010 indicate that there are important variations in specific surface area and porosity between different minerals that are major constituents of granite and/or minerals that can be expected to dominate the sorption of radionuclides (e.g. K-feldspar, plagioclase, biotite, chlorite, and magnetite). Moreover, both specific surface area and porosity vary greatly for any of the studied minerals over the range of particle sizes investigated. This indicates the exposure of considerable amount of surfaces originally not present, through the mechanical reduction of particle size. For a mechanically less disturbed chunk of material, the specific surface area was generally found to be lower than predicted from the crushed material. This indicates that the radionuclide sorption for intact rocks and minerals may be greatly overestimated if it is based on a simple linear extrapolation of data from laboratory experiments with crushed material. Furthermore, this suggests that sorption of radionuclides in experiments using crushed material may be dominated by the properties of fresh surfaces, not originally present in the rock or mineral. During 2011, batch and indiffusion experiments with radionuclides within this project will test these hypotheses.

3.13 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 organization 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, with the exception Task 7, are utilized 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 (ongoing).

Objectives

The Äspö Task Force is a forum for the organizations 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

During 2010, for Task 7 work has mainly been performed within subtask 7B (rock block scale) and 7C (deposition hole scale) that is divided into several sub-tasks. The Task 8 work mainly contained updated scoping calculations. The BRIE project has started up, which has couplings to Task 8 in terms of data deliveries but also predictive modelling within the task may provide support to the experiment, and also provide a possibility to compare the modelling results to the experiment.

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 Vuojoki, Finland.

The 26th International Task Force meeting was held in Barcelona, Spain in May. The presentations were mainly addressing modelling results on sub-tasks 7B and 7C. In addition, updated 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. A joint session with the Task Force on Engineered Barriers was held to discuss processes in the interaction between the rock and the bentonite in deposition holes. The minutes of this venue have been distributed to the Task Force.

Another, Task 7 and 8 Workshop venued in Lund, Sweden December 2010, and updated modelling results were presented and discussed. The description and the status of the specific modelling sub-tasks within Task 7 and 8 are given in Table 3-2.

Table 3-2. Descriptions and status (within brackets) of the specific sub-tasks in Task 7 and 8.

7	**Reduction of performance assessment uncertainty through modelling of hydraulic tests at Olkiluoto, Finland.**
7A	Long-term pumping experiment. (Final results of sub-task 7A1 and 7A2 are reported as ITDs).
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. (Final results presented at 26th Task Force meeting).
7C	Here focus is on deposition hole scale issues, resolving geomechanics, buffers, and hydraulic views of fractures. (Updated results presented at Task 7 and 8 Workshop in December).
8	**Interaction between engineered and natural barriers.**
8A	Initial scoping calculation (Results presented at the 26th Task Force meeting).
8B	Scoping calculation (Updated results presented at Task 7 and 8 Workshop in December).

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 2010, 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.
- Concrete and Clay.
- Low pH-programme.
- Development of End Plugs for Deposition Tunnels.
- 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 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.

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 and 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 temperature of the buffer. 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.

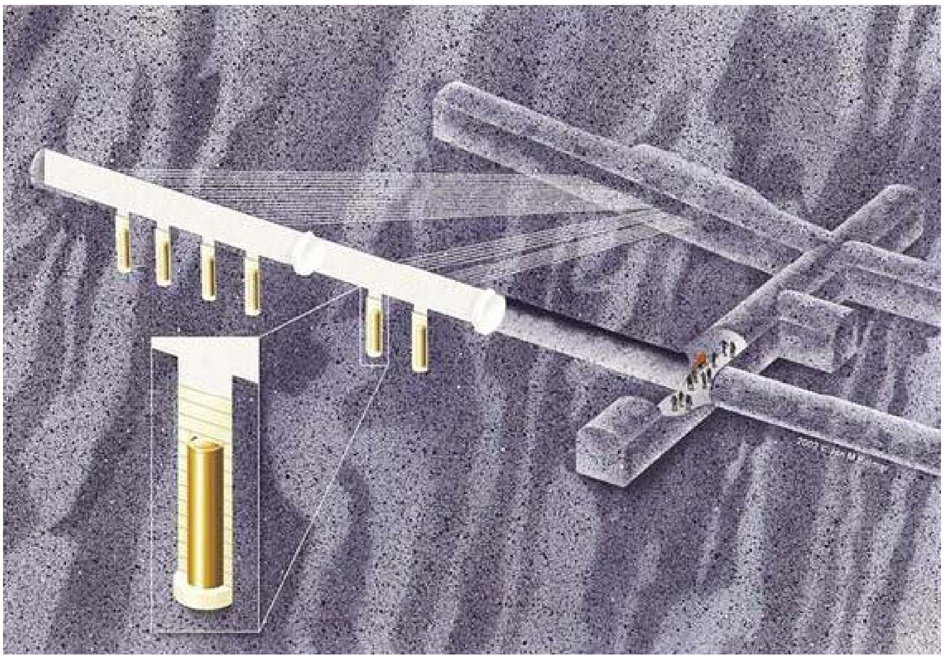


Figure 4-1. *Schematic view of the layout of the Prototype Repository (not to scale).*

It is decided that the outer test section will be decommissioned during 2011 after approximately seven years of water uptake of the buffer and backfill. 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.

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 the cables to the installed heater in 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 1160W. A data report covering the period 17th September 2001 up to 1st June 2010 is available /Goudarzi and Johannesson 2010/.

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 2002, Rhén et al. 2003/. The transducers measure the temperature, the pore pressure and the total pressure in different part of the test area. The water saturation process is recorded by measuring the relative humidity in the pore system of the backfill and the buffer, which can be converted to total suction.

Furthermore transducers were installed for recording the displacement of the canisters in deposition hole 3 and 6. 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.

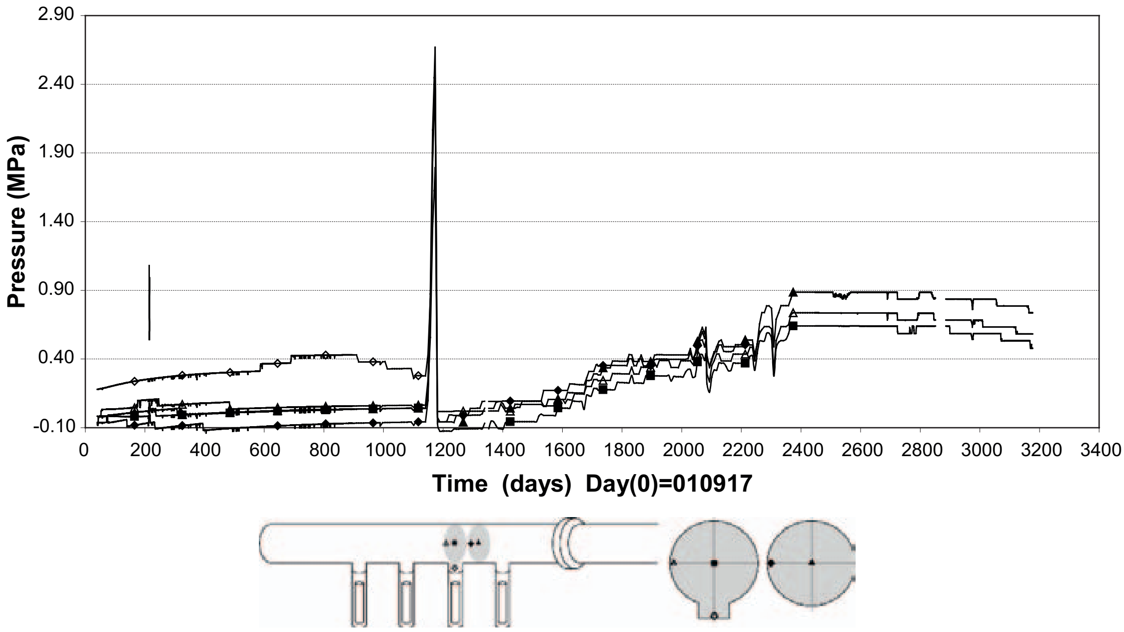


Figure 4-2. *Examples of measured total pressure in the backfill around deposition hole 3 (17th September 2001 to 1st June 2010).*

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 been published yet.

Furthermore, the third tracer dilution campaign during the Prototype Repository operation period was performed in January 2010. The purpose was to estimate the groundwater flows and hydraulic gradients in the boreholes vicinity and will function as a reference for comparison with results from modelling and prior assumptions. The test campaign consisted of tracer dilution tests in 13 different borehole sections. Each test consisted of approximately 15–55 min tracer injection time and about 1–3 days dilution test time depending on the transmissivity of the test section. The data interpretation also included estimates of the local hydraulic gradients in the vicinity of the borehole sections. A report from the preformed tests has 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 reported two times per year. 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.

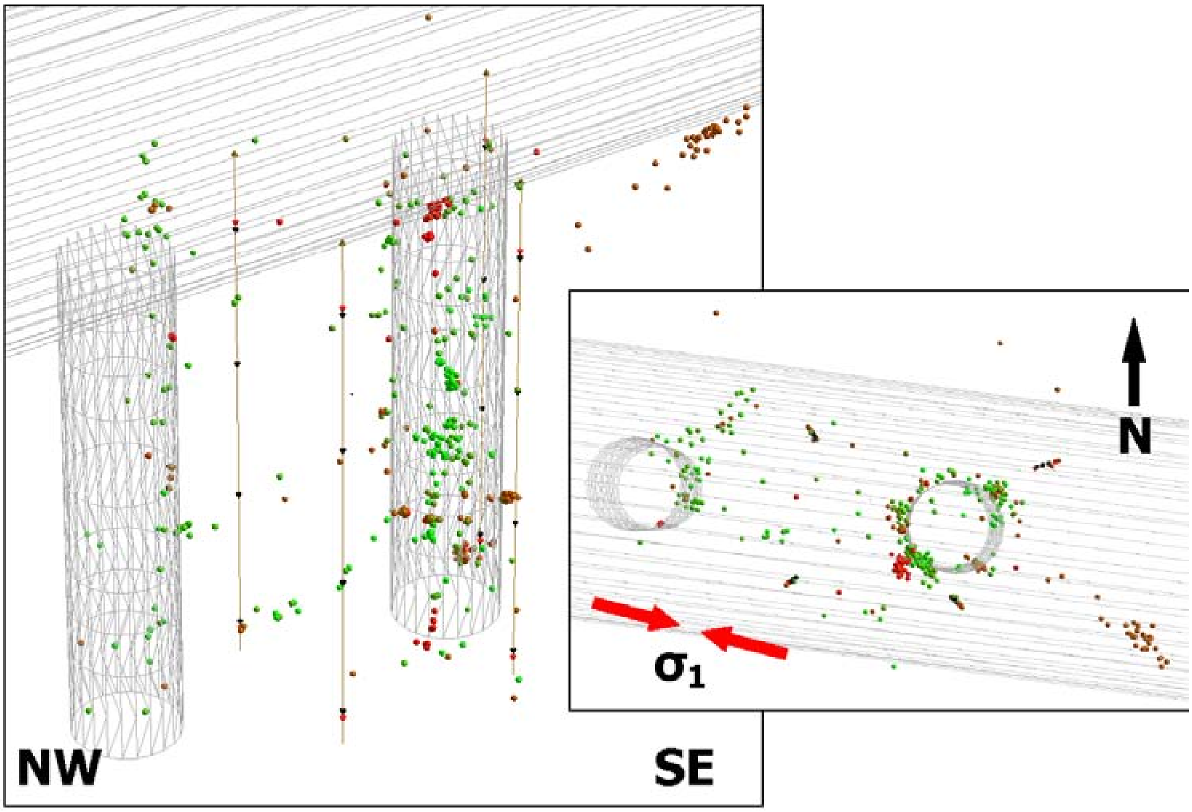


Figure 4-3. Projections of all AEs located during the heating phase (20th March 2003 to 31st March 2010). In total there have been 910 events over the last seven years of monitoring (events are scaled by time: green early and red late).

Equipment for taking gas and water samples both in buffer and backfill have been installed /Puigdomenech and Sandén 2001/. A report where analyses of micro-organisms, gases and chemistry in buffer and backfill during 2004–2007 are described has been published /Eriksson 2008/. New gas and water samples have been taken during 2009–2010. The results from these tests have been reported but not published yet.

The saturation of the buffer in the 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. The measured total pressure varies between 0 and 11 MPa. The sensors measuring 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.

Hydration 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 the both sections of the tunnel is saturated.

Opening and retrieval of the outer section

The planning of the retrieval of the outer section of the Prototype Repository started during 2010 and objectives of this part of the project are as follows:

- To acquire an image of density and water saturation of buffer and backfilling of the outer section of the trial. This is achieved by extensive sampling of buffer and backfill.
- It is also important to find out how the contact between buffer-backfill and backfill-tunnel wall appears after more than 7 years wetting. These parts of the buffer and backfill can be studied in more detail during progress of the retrieval.
- Measurements made of the rock around the two deposition holes indicate that changes have occurred in the rock mass. After removing the backfill, buffer and canister the rock in and around the deposition holes can be studied to confirm or reject these measurements.
- The canister has been subjected to high swelling pressures by the buffer. These pressures can have changed the position and also the shape of the canister. It is therefore important to determine the position and shape of the canister after the wetting period.
- During a short period of the trial the outer plug has been subjected to high pressure, about 2 MPa. If possible any damage and changes to the plug should be recorded.
- Biological and chemical activity in the buffer and backfill have been measured during the progress of the trial by sampling of water and gas. Samples will be taken to verify these measurements if possible during progress of the retrieval.
- During progress of the trial the buffer has become saturated by water from the surrounding rock. Furthermore, it has been subjected to high temperatures during a long period. This can possibly affect properties of the buffer material. Tests will be made on samples taken from this trial with the object of studying possible changes in the bentonite.
- Equipment for studying corrosion of copper in the buffer has been installed in one of the holes (hole 5). Measurements from this equipment will be complemented by sampling from the buffer with the object of studying possible corrosion.

The work with the retrieval of the outer section has been organized in six sub projects according to Figure 4-4 below. Project planes for each of the sub projects have been written and approved during 2010. Most of the planned field work will be made during 2011 but the breaching of the outer plug started in December 2010. The plug will be removed mechanically by core drilling and hydraulic demolition, see Figure 4-5. This work was preceded by four core-boreholes where the contact surface between concrete and rock can be studied.

Before breaching the plug, a number of reference measurements were performed:

- Estimation of the plug tightness and filter (geotextile) permeability.
- Measuring the corrosion rate of copper electrodes installed in deposition holes 1 and 5.
- Gas and microbiology sampling.
- Water sampling from the rock surrounding Prototype Repository.

Work has started to compile Activity plans for the extensive examination programme of backfill, buffer, sensors, canisters and bedrock. The actual removal activities will be made mainly during 2011. Laboratory examinations will be made during 2011–2012. Reporting will be made during 2013. Subsequent modelling of buffer and backfill will be made in the project EBS-Task Force.

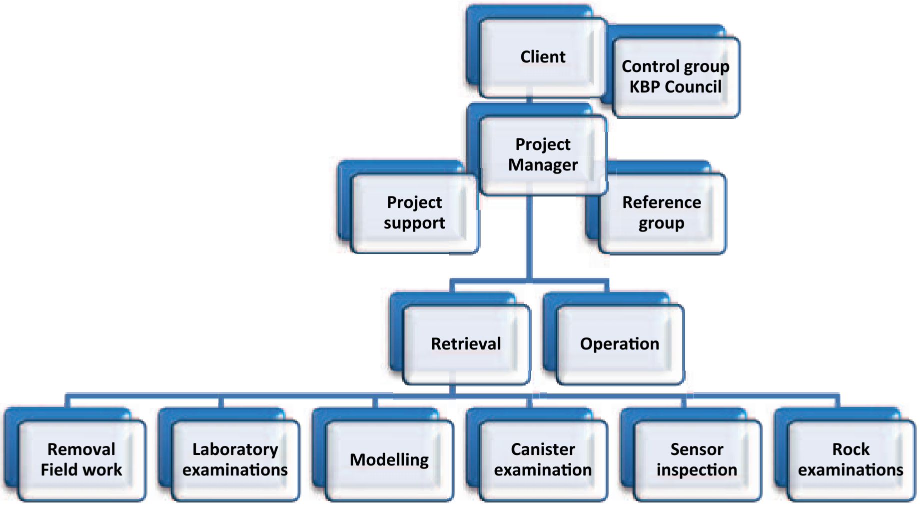


Figure 4-4. *Organisation chart for the project.*

Figure 4-5. *The outer plug in the Prototype Repository in December 2010 with the core drilled holes.*

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 induce a temperature increase in the bentonite buffer, and initially also 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.

Originally, the Lot project also aimed at testing materials and techniques which could be used in 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 approximately 300 mm and a depth of 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.

Results

No retrieval of any test parcel was made during 2010, and the activity within the Lot project was therefore limited to managing the three ongoing test parcels, finalising the A0 report, and presenting the Lot project concept and results at conferences in Nantes and Sapporo.

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	Reported
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	> 10	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.

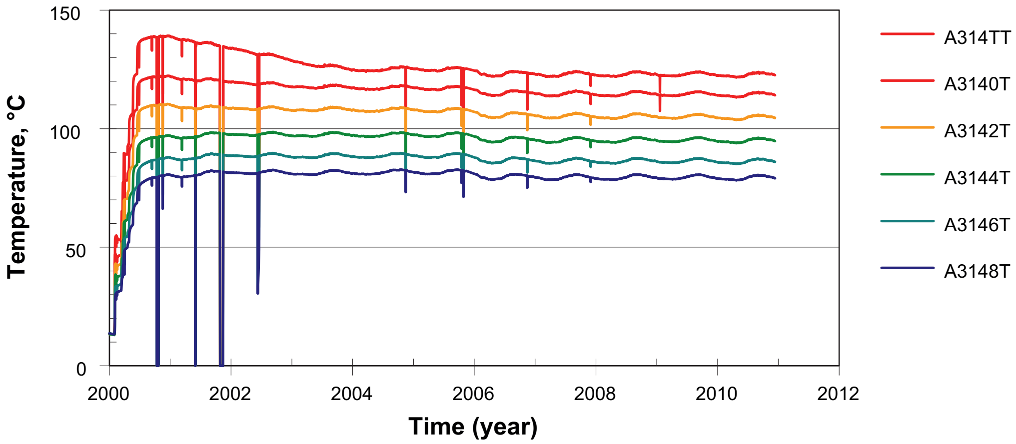


Figure 4-6. *Temperature evolution in the warmest section in test parcel A3 during the ten years of operation. A314TT (uppermost curve) indicate the temperature at canister surface, and the following curves indicate the temperatures in the bentonite close to the canister and successively closer to the rock (A3148T).*

The three remaining heating tests have now been running for ten years. The power has been close to 500 W in the two standard test parcels (T ~90°C) and close to 750 W in the adverse condition tests (T ~130°C). Figure 4-6 shows the temperature evolution during the 10 years of operation in the hottest section in one of the test parcels (Lot A3). No significant problems are reported for any parcel and a sufficient amount of sensors are still functioning.

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. 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 4-7. The target temperature in all three parcels is 130°C. Parcel 1 was retrieved after about 1.5 years operation at the target temperature, parcel 2 is planned to be retrieved 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 artificially wetted if it at some point is found necessary.

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

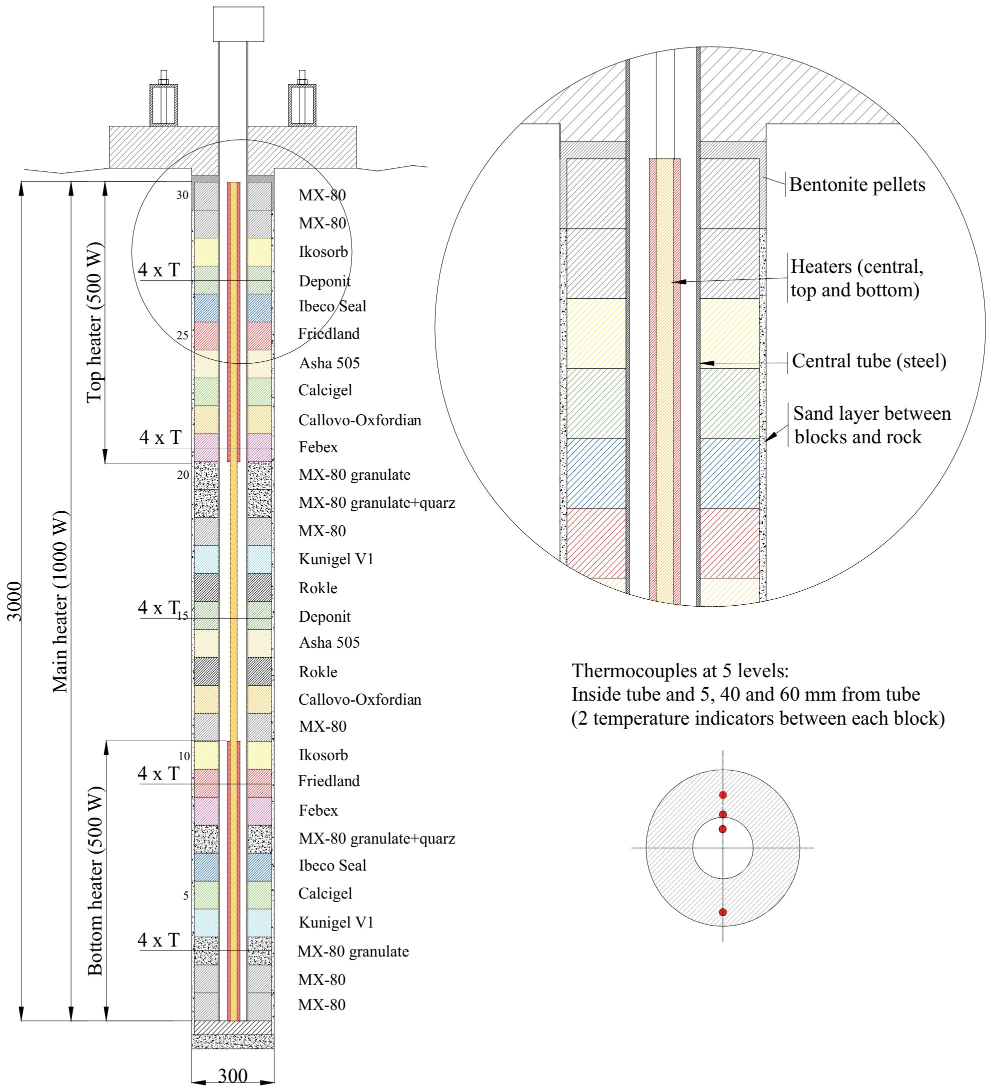


Figure 4-7. *Cross section showing the experimental set-up in the ABM test. The picture also shows the block configuration in test parcel 1.*

Results

Test parcel 1 was retrieved in May 2009, thirty months after installation and after about eighteen months of 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 300 mm, 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. 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.

A report describing the status of the work with analyses of reference material and material from test package 1 will be ready in the beginning of 2011.

4.5 Backfill and plug test

Background and objectives

The Backfill and Plug Test include 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 4-8 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.

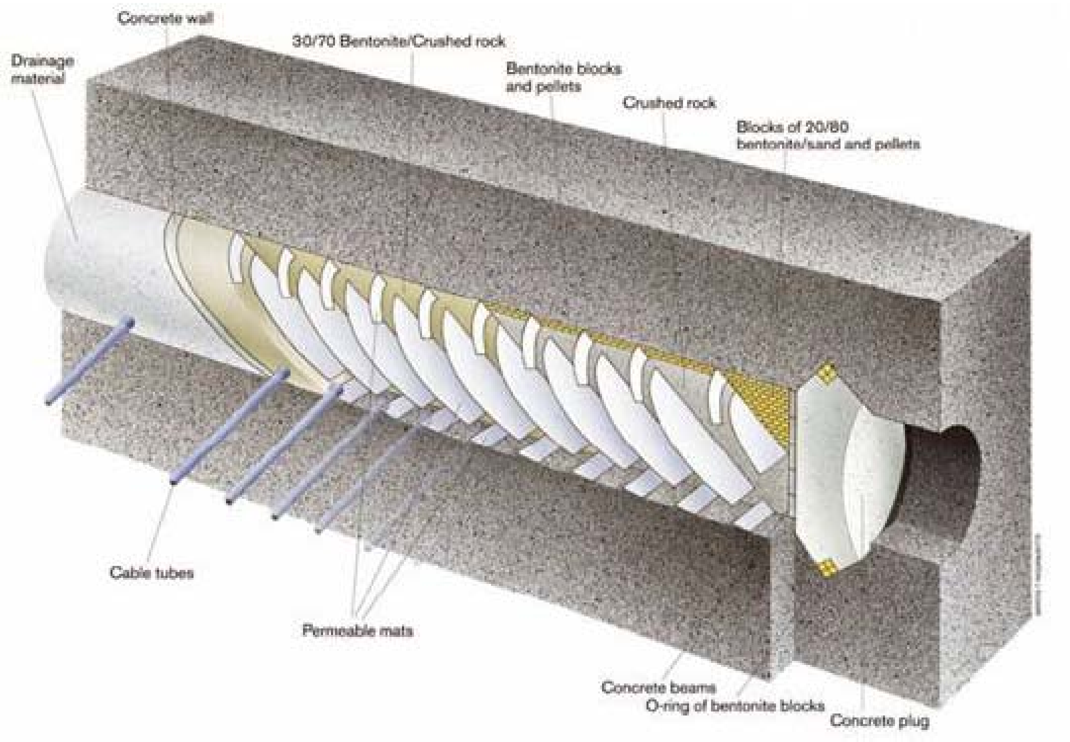


Figure 4-8. *Illustration of the experimental set-up of the Backfill and Plug Test.*

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 2010 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 have been logged. Measurement of leakage of water through the plug has continued.

In 2010 it was decided to keep the project dormant for the coming years. The activities will be kept at a very low level, with continued data collection, maintenance of equipment, supervision of the test and reporting of measured water pressure, water flow and total pressure.

4.6 Canister retrieval test

Background

According to the Swedish KBS-3 concept for disposal of high-level radioactive waste, the spent fuel will be stored in copper canisters embedded in bentonite buffers in vertical emplacement boreholes at a depth of ~500 m in crystalline bedrock. When water saturated, the confined buffer generate a considerable pressure due to the swelling ability of the bentonite clay and the material become tight. In the KBS-3 concept this swelling ability is an imporatnt reason for chosing bentonite as buffer material.

If a canister embedded in a fully water saturated bentonite buffer was to be retrieved, however, the swelling property could pose a problem since the canister will be held firmly by the buffer.

Objectives

The main objective of the Canister Retrieval Test is to demonstrate the retrieval technique for deposit canisters of KBS-3 design when the buffer is fully saturated and, consequently, full swelling pressure prevails.

Secondary objectives are to monitor the thermal, hydraulic and mechanical processes in the bentonite buffer during saturation and to analyze the buffer properties after excavation of the experiment.

Experimental concept

Two full-scale deposition holes have been drilled at the –420 m level for studies of the drilling process and the rock mechanical consequences of drilling the holes. A canister equipped with heaters, bentonite blocks and pellets were installed in one of the holes in 2000. The hole was sealed with a vertically displaceable plug, the heaters were turned on and an artificial water supply controlled the water inflow at the deposition hole wall.

The experiment was running for more than five years with continuous measurements of the wetting process, temperature, stresses and strains. In January 2006 the retrieval phase was initiated and the canister was successfully retrieved in May 2006. The retrieval technique was tested on the lower part of the buffer, whereas samples were taken from the upper half. The samples were then analyzed to give information about the buffer which had been subjected to the simulated "repository conditions".

Results

The reporting of the buffer analyses has progressed during 2010. The work aims at investigating if there have been any changes in the material characteristics by comparing properties of samples retrieved from the CRT buffer with the properties of reference material. An article, where results of the buffer analyses will be presented, is in progress. The article is intended to be presented in a scientific journal to make the findings of the buffer analyses public. Also, in parallel, a more detailed report is written on the findings of the buffer analyses.

Numerical studies of the homogenization process in the CRT experiment, where simulations are verified against experimental data was presented at *"Clays in Natural & Engineered Barriers for Radioactive Waste Confinement"* (Nantes, 29th March – 1st April, 2010). Also, a manuscript "*Homogenization of engineered barriers, simulations verified against Canister Retrieval Test data*" of the material presented at the conference, has been accepted for publication in the proceedings and is presently in the review-process.

4.7 Temperature buffer test

Background and objectives

The Temperature Buffer Test (TBT) is a joint project between SKB/Andra and supported by Enresa (modelling) and DBE (instrumentation). The Temperature Buffer Test aims at improving the understanding of the thermo-hydro-mechanical (THM) 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. The experiment was installed during the spring of 2003.

Apart from the general focus on THM behaviour, a number of additional aims were defined in 2007: i) gas migration, ii) retrievability of heaters and iii) THMC-processes. The gas test was not however carried out since it was shown that the buffer around the sand shield (see below) was not sufficiently tight. In order to promote mineralogical alteration processes in the lower package, the thermal output from the lower heater was significantly increased at the end of 2007 (see below).

The test was dismantled during the winter of 2009/2010.

Experimental concept

The test has been carried out at the –420 m level in Äspö HRL in a 8 m deep and 1.75 m diameter deposition hole, with two heaters (3 m long, 0.6 m diameter), surrounded by four cylinders and 12 rings of compacted MX-80 bentonite. On the top, there was a confining concrete plug and a steel lid anchored with 9 rods (Figure 4-9). Two buffer arrangements have been investigated: the lower heater was surrounded by bentonite in the usual way, whereas the upper heater was surrounded by a ring of sand. The latter has acted as a thermal protection for the bentonite, and as an important component for the retrievability.

The canisters were heated with 1,500 W power from day 15 to day 1171, when the power was raised to 1600 W. This was a compensation for the termination of the neighbouring Canister Retrieval Test (CRT). Around day 1700 the power was raised by steps to 2000 W in the lower heater and reduced to 1000 W in the upper heater. The heating was terminated on day 2347 in August 2009. The temperature distribution prior to this event is shown in Figure 4-10. At this time the temperature on the mid-section of the lower heater was 155 ºC. The corresponding value for the upper heater was 86 ºC.

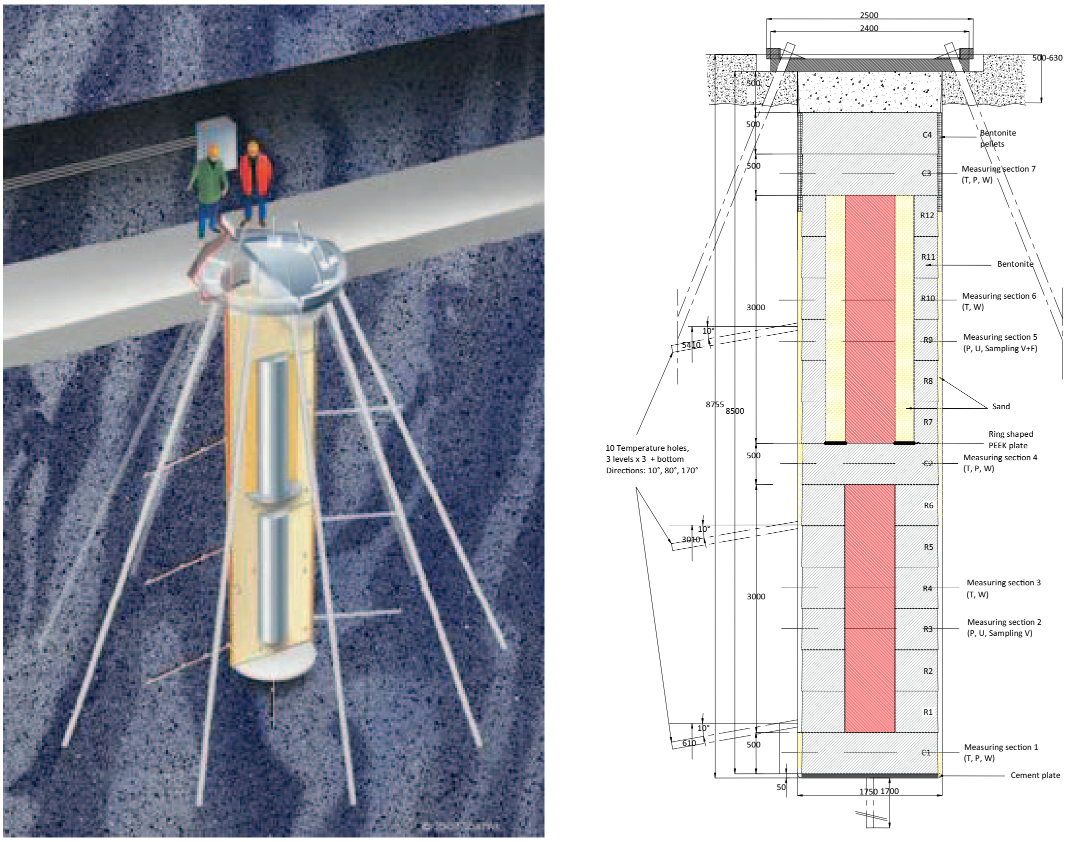


Figure 4-9. Principle design and experimental set-up of the Temperature Buffer Test.

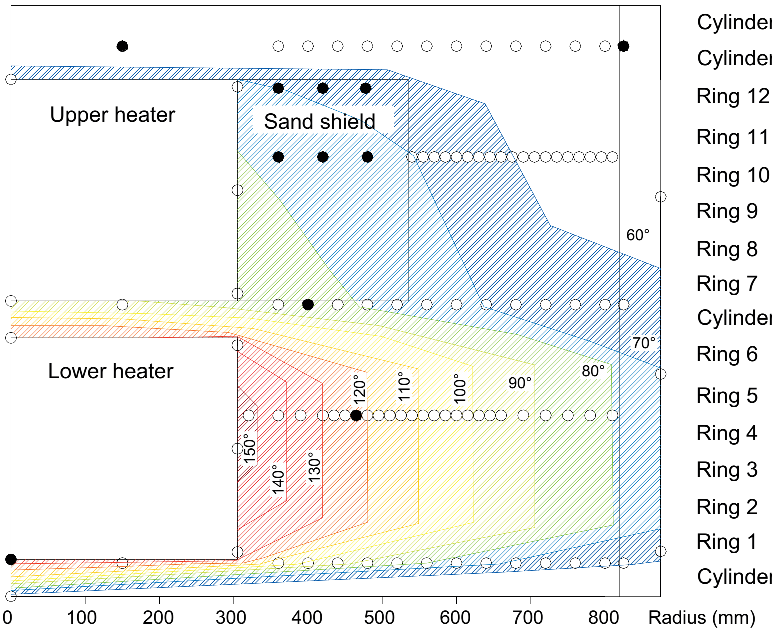


Figure 4-10. Temperature distribution at August 16 2009. Rings indicate sensor positions. Filled rings indicate sensors out of order.

The following measurements have been made in the bentonite: temperature was measured in 92 points, total pressure in 29 points, pore water pressure in 8 points and relative humidity in 35 points. The following additional measurements have been made: temperature was measured in 40 points in the rock, in 11 points on the surface of each heater and in 6 points inside each heater. The force on the confining plug was measured in 3 of the 9 rods and its vertical displacement was measured in three points. The water inflow and water pressure in the outer sand filter was also measured.

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/ and through evaluation and numerical modelling of parallel lab-scale mock-up tests /Åkesson 2006b, 2008, Åkesson et al. 2009, Ledesma et al. 2006/. With access to the data from the dismantling operation, the THM modelling of the field test was resumed at the end of 2010. The plan is to continue with and finalise this modelling during the first half of 2011.

Dismantling operation

During the last two months of 2009, the upper package of the test (i.e. Cylinder 3 and 4, Ring 7 to Ring 12, as well as the upper heater and the sand shield) was sampled and removed. The dismantling operation of the lower package began in the beginning of 2010 with the sampling and removal of Cylinder 2 and was completed at the end of April 2010 with the sampling and removal of Cylinder 1.

One important goal with the dismantling operation was to obtain different types of samples. Bentonite *cores* were devoted for the so-called base programme (see below). Large pieces of bentonite, so-called *big sectors*, were devoted for the HM&C (hydro-mechanical and chemical) programme. Finally, there was an interest to obtain different types of interface samples in which bentonite were in contact with sand, iron or concrete. An example of such an interface sample is shown in Figure 4-11. The experiment was also documented in different aspects: measurements of the coordinate (height or radius) of different interfaces (between bentonite blocks and between bentonite and sand); verification of sensor positions and retrieval of sensors for subsequent function control; and through documentation of the operation through photography.

***Figure 4-11.** Lifting of Heater 1 with attached bentonite material from Ring 1. This material constitutes an undisturbed bentonite-iron interface sample.*

The main method to sample and partition the bentonite blocks was with the use of handheld coring machines. Two machines were used in parallel. The plan was to take Ø50 mm cores that spanned over the entire height of the bentonite blocks, i.e. approx. 500 mm. For each block a coring scheme was specified according to which cores were to be taken in four directions (32, 122, 212 and 302°) at 50 mm intervals (see Figure 4-12). The two big sectors were "cut" through stitch drilling from each block representing the entire radial distribution in two directions: 32 and 212°. In order to obtain samples close to the rock wall and the lower heater, so called *end sectors* were taken, either through stitch drilling, or through cutting bigger pieces with hand saw. In the lower part of the experiment, it was found to be beneficial to make a circular stitch drill around the heater which enabled the sampling of suitable pieces close to the heater. All samples were packaged in evacuated aluminium laminate foil bags.

Characterization programmes

The base program, i.e. the determination of water content and density, has been performed in parallel to the dismantling operation, and was completed during 2010. The cores taken from the bentonite blocks were cut in smaller samples before the analysis. The cutting was made according to the following plan: From each core from the 122° and 302° directions, a sample was taken at one depth (50 mm). From each core from the 32° direction, samples were taken at *five* depths (50, 150, 250, 350 and 450 mm). From each core from the 212° direction a sample was at one depth (50 mm), which in turn was divided in two samples thereby representing a radial width of 25 mm. Finally, the end sectors were cut in samples with a radial width of 10 mm. The water content of the bentonite was determined by drying a sample at a temperature of 105°C for 24 h and the bulk density was determined by weighing a sample both in the air and immerged in paraffin oil with known density. Examples of the results from this program are shown in Figure 4-13 and 4-14. The void ratio of the bentonite had increased compared to the initial state, especially close to the sand filter, but tended to decrease slightly close to the heater. The degree of saturation close to the sand filter was 100%, while the degree of saturation in the central part of the block is slightly below 95%. The lowest degree of saturation could be observed approx. 70 mm from the surface of the heater.

The HM&C characterization program was launched subsequent to the dismantling operation. Exposed material from the experiment (i.e. samples taken at 100 mm radial distance in Ring 4) and reference material is tested and analyzed. The following physical properties are determined for the material (test technique within brackets): hydraulic conductivity (oedometer), swelling pressure (oedometer), unconfined compression strength (mechanical press), shear strength (triaxial cell) and retention

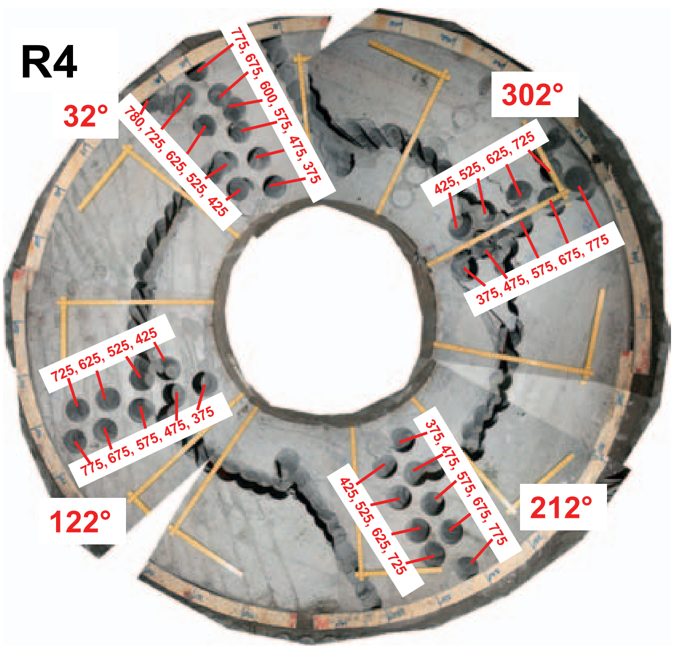


Figure 4-12. *Cores sampled from Ring 4.*

properties (jar method). The following mineralogical properties (methods within brackets) is determined: anion analysis in water solution (IC), element content in the bulk and clay fraction material (ICP/AES+MS+EGA), cation exchange capacity (CEC, Cu-trien method) and exchangeable cations (exchange with NH_4, ICP-AES), mineralogical composition in bulk and clay (XRD), mineralogical composition in bulk and clay (FTIR), element distribution and microstructure (SEM and STEM), iron oxidation state (Mössbauer spectroscopy). The main goal is to investigate if any significant differences can be observed between exposed material and the reference material. The plan is to continue with and finalise these analyses during the first half of 2011.

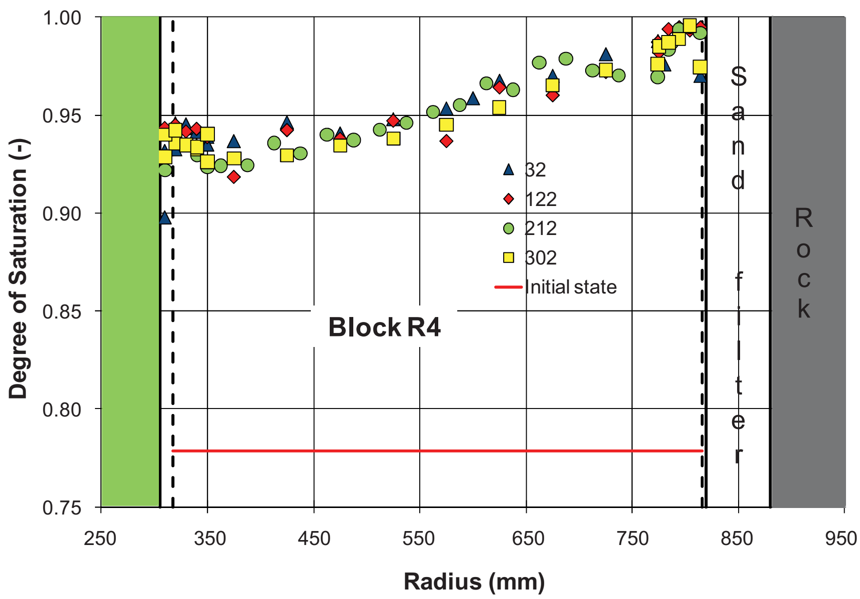


Figure 4-13. Radial distribution of degree of saturation in four different directions at 50 mm depth. Results from measurements of water content and density in Ring 4.

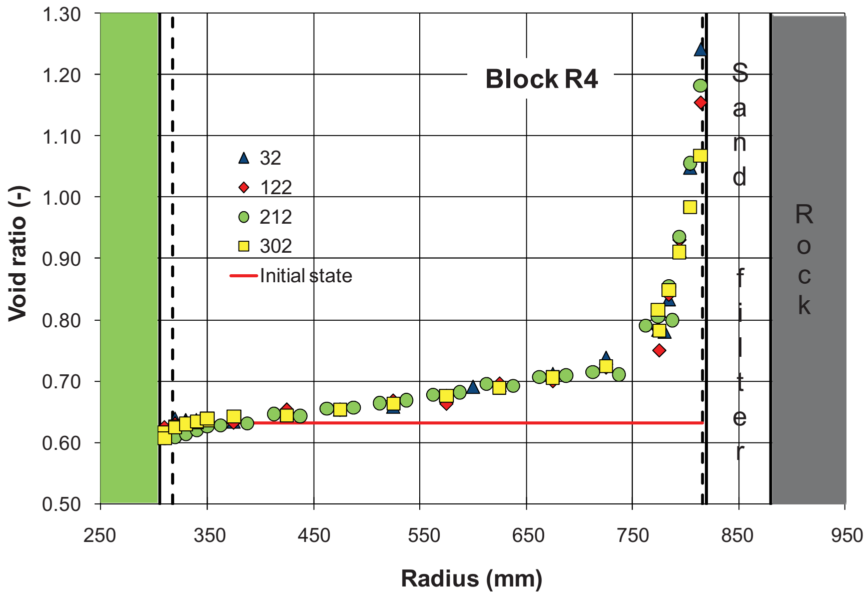


Figure 4-14. Radial distribution of void ratio in four different directions at 50 mm depth. Results from measurements of water content and density in Ring 4.

4.8 KBS-3 Method with horizontal emplacement

Background and objectives

This project studies the possibility to modify the KBS-3 reference method with its single canisters in vertical deposition holes, KBS-3V, by using long horizontal deposition holes with multiple canister positions, KBS-3H.

One reason for proposing this change is that the deposition tunnels in the KBS-3V design are not needed if the canisters are disposed in long horizontal deposition holes. The excavated rock volume and hence the amount of backfill can then be considerably reduced. In turn this reduces the environmental impact during the construction of the repository as well as construction costs.

The site for demonstrations of the method is located at the –220 m level. A 25·15 m niche with a height of about 8 m forms the work area.

A fundamental part of the KBS-3H design is the horizontal deposition holes, two such holes have been excavated; one short with a length of about 15 m (DA1622A01) and one long with a length of about 95 m (DA1619A02). The short hole has been used primarily to test the compartment plug used in the KBS-3H concept and the long hole has been used to test the deposition equipment and a specialised post grouting equipment (Mega Packer).

The project is a joint project between SKB and Posiva. The present phase of the project is: *"Complementary studies of horizontal emplacement KBS-3H"*. The main goal of the complementary studies (2008–2010) is to develop the KBS-3H solution to such a state that a decision on full-scale testing and demonstration can be made. The results from this project phase will be presented in the report *"Summary of KBS-3H complementary studies phase 2008–2010"* (in preparation).

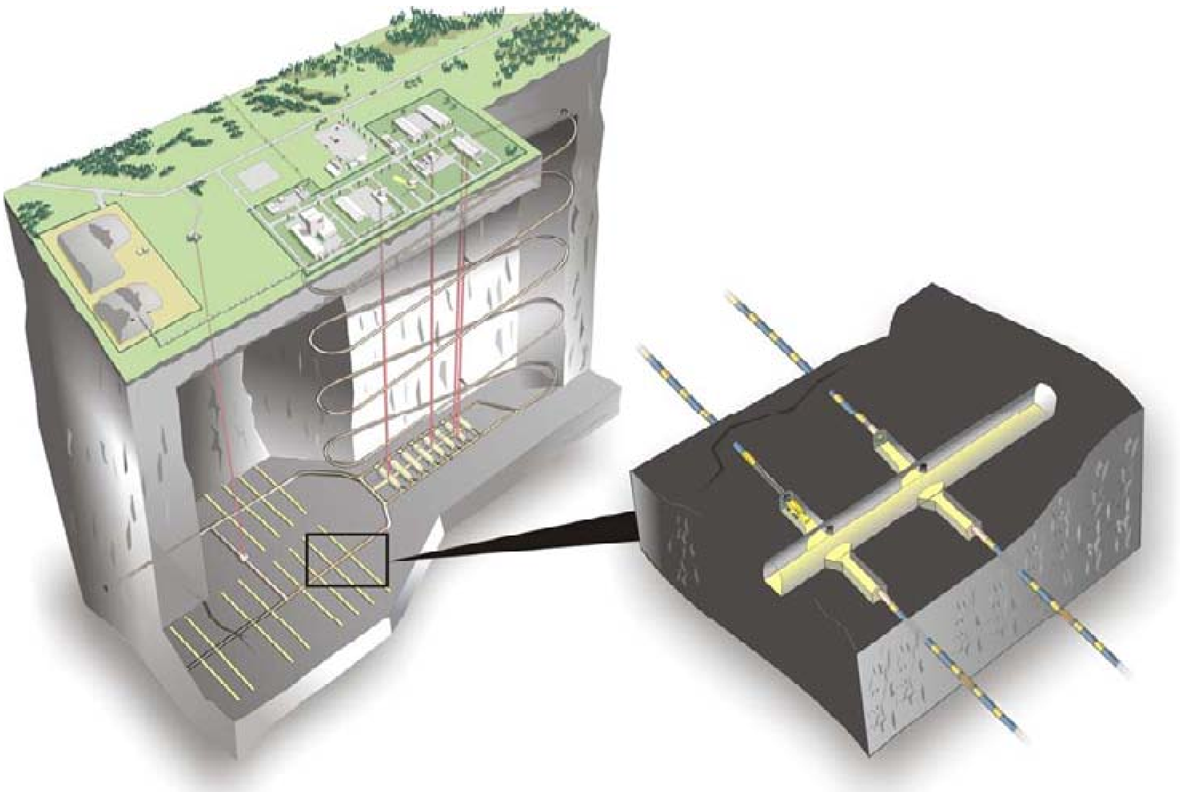


Figure 4-15. *Schematic figure of the KBS-3H repository with the horizontal deposition tunnels magnified to the right.*

Results

During the year the compartment plug test has continued. The initial test in the end of 2009 showed that the compartment plug fulfils the 0.1 L/min leakage criterion at 5 MPa if the concrete casting is grouted with SilicaSol. To further test the concept the third phase of the compartment plug test was initiated. In this test the void behind the plug is filled with bentonite pellets. The third test was started in January and initially no significant changes compared to test 2 (without pellets) were found. Leakage through the plug was unaltered at 0.002 L/min during steady state and the rock leakage (water leakage into the rock volume from the test void) was at the same level (1 L/min approximately). After a 30 day pellet maturing time the rock leakage was however reduced significantly and at 60 days operation time the leakage was very low, approximately 0.003 L/min compared to the initial 1L/min rock leakage. The test was in operation for a total of 9 months during which both plug leakage and rock leakage was stable at these low levels. Apart from having verified the compartment plug functionality this also illustrates the pellet ability to seal water bearing fractures at 5 MPa pressure.

The ending of the compartment plug test finalises the test at the –220 meter level planned within the current KBS-3H project phase. At the end of the third test a high pressure plug failure test was planned. Before the test was started the pressure system malfunctioned which resulted in deformation of the compartment plug, the failure test was therefore cancelled.

The deposit machine has been run during the year and evaluation work regarding required upgrades has been carried out. The main focus has been on the software (the control system) but possible mechanical upgrades have also been identified. The aim of the machine upgrade planned for an upcoming project phase is to raise the quality and address identified issues with the machine to ensure a robust deposition process.

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 420 m depth in the Äspö HRL.

The multiple barrier concepts are 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, for example, corrosion of the iron insert, could potentially affect the buffer performance in three ways:

- Permanent pathways in the buffer could form at gas breakthrough. This could potentially lead to a loss of the diffusion barrier.
- If gas cannot 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, 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 in filter FL903 (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 in filter FL903 (Stage 4, day 1430–2064). In late 2010 attention moved from the lower array filter (FL903) to the upper array. Stage 5 started on day 2073 and is still ongoing.

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:

- 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 (Figure 4-16). A deposition hole, 8.5 m deep and 1.8 m 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.

***Figure 4-16.** The Large scale gas injection test at the –420 m level in Äspö HRL.*

In the field laboratory 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

During 2010 (day 1795 – day 2159) the test programme of Lasgit saw several stages of experimentation. The most significant stage was the completion of the gas test of filter FL903, which was started on the 28th May 2009 (day 1577) and stopped on day 1964. This was followed by a hydraulic test in filter FL903 and recovery stage. From day 2073 onwards the test programme concentrated on an upper level canister filter.

Figure 4-17 shows the evolution of injection gas pressure and flow into the clay. As seen, the system continually over- and under-shoots as the pressure changes with time, as previously reported for laboratory experiments. Neon is the gas injection medium so that leakage to the host rock can be monitored.

The final gas injection stage was initiated on day 1742 (12th November, 2009) with a slow gas injection rate of 500 micro litres per hour. As can be seen in Figure 4-17 and as with previous steps, gas entry into the clay was immediate, as expected. Pressure continued to rise until it reached a maximum of 5,860 kPa after 25 days of gas injection, when gas entry into the buffer resulted in a reduction of gas pressure.

At approximately day 1810 flow into the clay increased for a second time, resulting in a drop of pressure in filter FL903 of about 300 kPa. Gas flow reduced and pressure in FL903 slowly increased once more to return to approximately 5,600 kPa by day 1830, where once again pressure slowly decayed to 5,520 kPa (over- and under-shooting).

Gas flow into the clay increased for a third time, with a major flux pulse on day 1853. This resulted in a considerable loss of filter pressure, which was aided by a leaking valve on the injection pump. On day 1864 the valve was closed fully and the pressure in FL903 began to rise. While this event was not planned, it is effectively a pressure shut-in test and gave the opportunity to observe whether a gas peak similar to the gas breakthrough on day 1767 of 5,860 kPa would occur. As seen the gas pressure peaked at a pressure of approximately 5,600 kPa and did not correspond with a significant peak in flow into the clay. Following the peak, gas pressure reached an asymptote of 5,210 kPa.

It was seen that the pressure in one of the pore-pressure sensors within the bentonite buffer, namely UB902, greatly increased on day 1783 from 420 kPa to 4,590 kPa. The response of the sensor thereafter coincides with the observations of the gas pressure and flow in the injection filter FL903. This indicates that gas propagated to this point in the system.

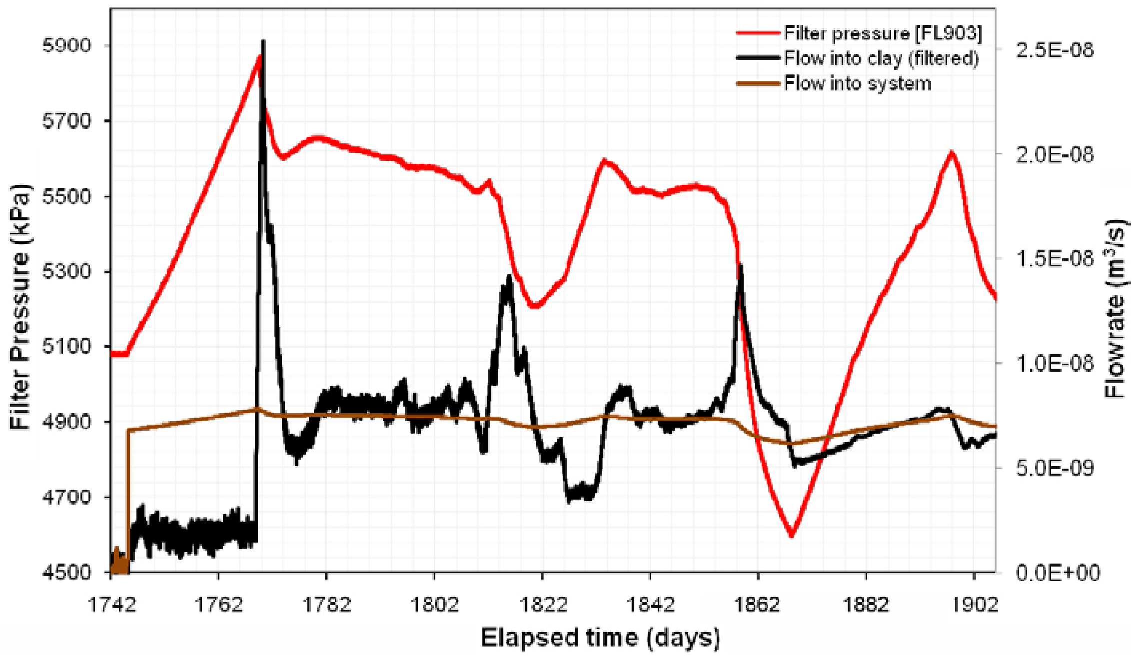


Figure 4-17. *The evolution of the injection gas pressure and the flow into the clay. The start of gas flow into the clay occurred at 5,830 kPa and the maximum gas pressure experienced was 5,860 kPa.*

The highly instrumented Lasgit experiment has shown that gas has propagated within the deposition hole. Significant pressure changes have been observed in several of the pressure and stress sensors, giving insight into the direction and propagation of the gas, as well as the hydromechanical response of the buffer system. As with the previous gas test in 2007, propagation has been in a downwards direction. However, the extended period of gas injection post-break through has shown that gas continues to move around the system and has propagated to a number of locations. The complete propagation history shows that gas injected at filter FL903 reached filter FL901 (by-passing filters FL902 and FL904 in the process) and then gas migrated downwards towards the bottom of the deposition hole.

The decision was taken to stop gas injection on day 1907 (25^{th} April 2010) and the system underwent a 54-day period of gas shut-in. This was followed by a hydraulic constant head test in filter FL903, the results of which are shown in Figure 4-18. A similar curve is seen in the test results before and after the second gas test. This shows that the gas testing has had little effect on the hydraulic properties of the bentonite buffer. Comparing the hydraulic head tests for the two gas tests conducted shows that the buffer has continued to hydrate and mature, as seen by reduction in hydraulic conductivity and specific storage.

Neon gas sampling in the pressure relief holes following the completion of the hydraulic constant head testing showed that Neon was now present outside of the Lasgit deposition hole.

The focus of experimentation moved to the upper canister array of filters from day 2073 onwards in preparation for a detailed gas test in 2011. Previous gas testing has been conducted in a canister filter on the lower array, namely filter FL903. The rationale for testing an upper filter is this allows comparisons to be made for filter diameter, different stress and hydration state and position within the deposition hole.

Filter FL912 was selected as it has the largest contrast in filter diameter size compared with filter FL903. The hydraulic testing of this filter was started on day 2073, with pore pressure increased to 4.5 MPa. It became immediately obvious that the filter pressure of FU912 was mirrored by filter FU909. The system was quickly shut-off and the two filters were allowed to leak-off to back-ground pressures. The rate of leakage was identical for both filters, even though they are different diameters. All data shows that the two filters were in direct communication. Short-circuiting by the calibration line or through the control board can be ruled out, suggesting that the communication is through the bentonite buffer. It should be noted that water pumped into the system was small, suggesting that the short-circuit is not through a large void.

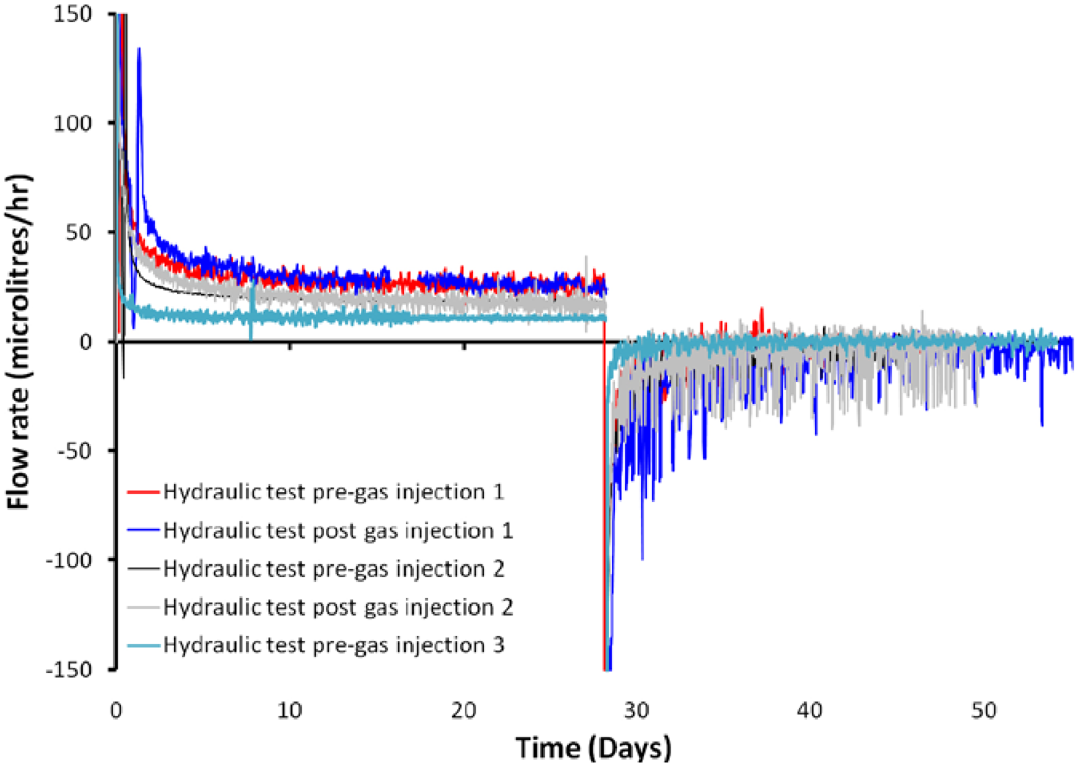


Figure 4-18. *The result for constant head tests conducted before and after the two gas injection tests conducted in filter FL903 and the hydraulic head test conducted before the gas test in filter FU910.*

It was decided to abandon using filter FU912 and filter FU910 was selected instead. This filter is still smaller than FL903; 25 mm diameter compared with 50 mm for FL903. Filter FU910 did not show any issues of communication with other filters.

A hydraulic constant head test was successfully conducted in filter FU910 and was completed during December, as shown in Figure 4-18. The form of the hydraulic data shows that filter FU910 has a lower hydraulic conductivity and lower specific storage compared with filter FL903.

During 2010 several presentations and papers were made on Lasgit (see references). A PhD student started in January 2010 at the Geoenvironmental Research Centre at Cardiff University. The study is titled *"Large-scale data visualisation, event identification and numerical simulation for gas migration experiments in high-level nuclear waste disposal."*

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. SilicaSol, 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 SilicaSol 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 SilicaSol 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

The inflow to the tunnel is being automatically monitored and a programme for mapping of inflows established. The monitoring and mapping is for the time being considered a prioritised task.

Evaluation and reporting is almost completed. The project has provided ample data and further evaluation may be carried out in new projects.

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 will be exposed for several years in boreholes in the Äspö HRL. Defects have been deliberately introduced into the outer copper shell 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 product 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 31.5 cm have been set up in five boreholes 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 is 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 defects in the outer copper shell, in a range of different orientations. The canisters are mounted in electrically insulated support cages (Figure 4-20), which contain bentonite clay of two different densities. 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. 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 will be monitored using strain gauges to monitor any expansion effects. The redox potential, Eh, 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.

The experiments are continuously monitored to measure the following parameters:

- Corrosion potential of the model canister, cast iron and copper.
- Electrochemical potential of gold, platinum and a mixed metal oxide Eh probe.
- Corrosion rate of cast iron and copper, using linear polarisation resistance, AC impedance and electrochemical noise.
- Strain on the surface of two of the model canisters.

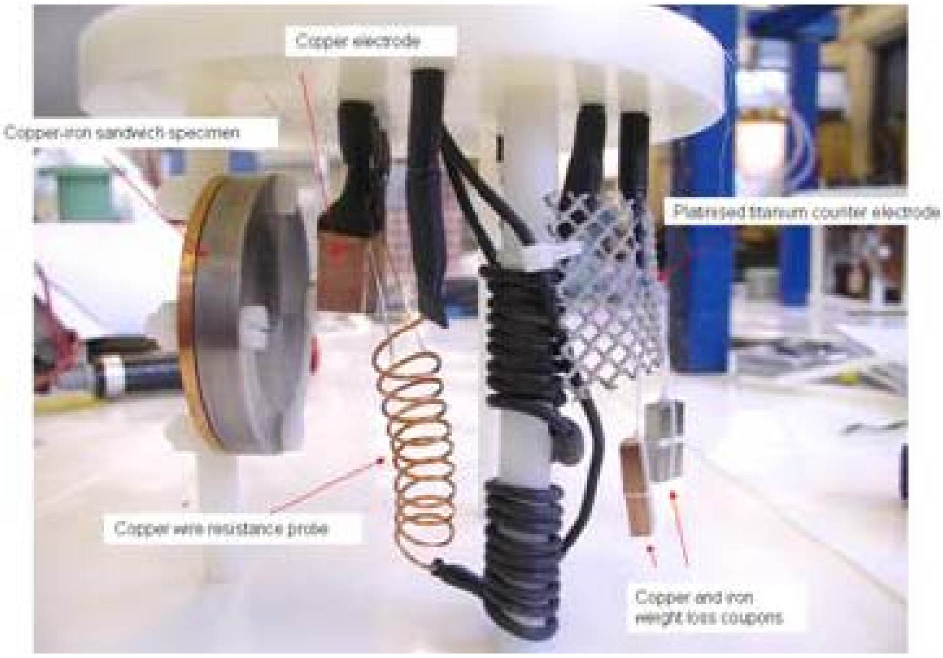


Figure 4-19. *Test electrodes inside support cage around model canister experiments.*

Figure 4-20. *Model canister being lowered into support cage containing bentonite pellets in annulus.*

Regular water samples are taken from within the support cages to monitor the development of the local chemistry. The experiments will remain in situ for several years, after which they will be dismantled and the evolution of the corrosion front inside the canister will be analysed.

Results

During 2010, monitoring of the miniature canister experiments has continued. Data are being collected for the corrosion rate of copper and iron electrodes, and electrochemical potentials for a range of electrodes, including Eh, iron and copper. In addition, strain gauge data are being collected for two of the canisters.

Results from the project have been presented at the "4th International workshop on long-term prediction of corrosion damage in nuclear waste systems" in Bruges, Belgium, June 2010.

The highlights of the results obtained to date are as follows:

- Water analyses have shown an increased concentration of iron 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). Water samples were taken for analysis during December 2010 and these samples will be analyzed for gas and microbial content in 2011.
- The measured Eh values are comparable to published literature values and show a fall in Eh with time as any residual oxygen is consumed, 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 rate values for the copper electrodes were initially comparable to those in the published literature, but since then they have increased in the experiments with bentonite present, but not in the experiment without bentonite. It is not clear what is causing the increase in these measurements and whether or not it is a genuine result. The electrochemically measured corrosion rates of the cast iron electrodes have also increased over the course of the experiments. The corrosion rates of copper measured using alternative techniques, such as the electrical resistance of copper wires, have yielded much lower corrosion rate values. The extent of corrosion of both copper and cast iron will be confirmed by weight loss measurements when the experiments are dismantled.

During 2010 the project's main focus has been on planning and preparing for dismantling Experiment 3. Detailed analysis of this experiment will be carried out to characterize (i) the overall extent of corrosion (i.e. the integrated corrosion rate over the whole exposure period), (ii) the form of any corrosion of the model canister and the test coupons, and (iii) the condition of the surrounding bentonite.

4.12 Cleaning and sealing of investigation boreholes

Background and objectives

Phase 4 of the project has four subprojects:

1. Characterization and planning of borehole plugging.
2. Performance and Quality assessment.
3. Sealing of large-diameter holes.
4. Interaction of clay and concrete plugs.

The specific goal of Subproject 1 was to characterize and plan plugging of boreholes so that the impact of the seals on the overall hydraulic performance of the repository rock can be evaluated. The work was confined to deal with certain "reference holes" as a basis of development of a general programme for planning and realizing of borehole plugging, considering also cost issues.

The aim of Subproject 2 was to quantify the role of seals in boreholes selected in Subproject 1.

Subproject 3 concerns testing of techniques for sealing large diameter holes.

Subproject 4 deals with physical and chemical interaction of clay and concrete seals in boreholes.

The purpose of Subproject 3, conducted in 2010, was to investigate how large-diameter holes can be sealed under field conditions using techniques worked out in the preceding Subprojects. The aim of Subproject 4, also conducted in 2010, had the same purpose as an earlier planned investigation of clay/concrete interaction in a deep hole (OL-KR-24) at Olkiluoto. This test was cancelled, however, which put focus on the Äspö tests. The primary aim was to investigate what chemical and mineralogical changes had taken place and how they affected the geotechnical properties.

Experimental concept

Subproject 3

Two techniques for constructing clay seals were investigated, i.e. filling of pellets in very soft clay (mud), and installing highly compacted clay blocks. The latter technique was found to be superior and was selected for the field experiments. The slightly inclined 300 mm diameter holes, which are located near the ramp at Section 2950, are intersected by a series of water-bearing fractures, which required development of a technique for discharging water in the course of installing the seals. Two clay seals of Couronne type (Figure 4-21), implying stacking of highly compacted clay blocks around a central copper tube that served to discharge water flowing in from below, were installed and concrete cast to fill the space between them and on the top of the respective holes.

Subproject 4

The two about 5 m long, vertical holes had been sealed with clay over which concrete had been cast, the holes being in place for about 3 years. Rock containing one of the sealed holes was extracted by slot drilling and samples taken for analysis in Germany and Sweden.

Results

Subproject 1 and 2

Compilation and integration of the outcome of these subprojects have been made in 2010 and the final report of the entire project Phase 4 will be complete in early 2011.

Subproject 3

The study demonstrated that severe conditions with respect to inflow of water into the holes to be sealed could be managed but hydraulic conditions on other sites can be more demanding and require other means of discharging water and anchoring the plug seals. It is therefore not possible to define a standard procedure for installing plug components and further investigations of how large-diameter holes can be sealed, especially in deeper holes, are recommended. The overall outcome of the experiments was deemed to be successful and serves as an example of how the methods worked out in the preceding phases can be implemented.

Subproject 4

The holes contained clay seals of Basic type, i.e. clay-filled perforated copper tubes, upon which concrete of low-pH type had been cast and focus was on investigating whether mineralogical and chemical changes had occurred in the contacting seals and if they had an impact on their geotechnical properties. It was concluded that the changes were insignificant in the limited period of time. The major conclusions drawn from the analyses were:

1. There is clear evidence that the bentonite continued to swell and infiltrate the concrete plug after filling of the borehole. Clay is detected both along the contact between the plug and the granite wall as well as interleaved within the bottom of the concrete fill.
2. Chemical alteration of the cement mineral phases at the clay-concrete contact released some quantities of Ca and K, with bivalent ions partly replacing Na in the interlayer of the montmorillonite in the clay plug directly contacting concrete. Composition analyses of the montmorillonite particles by analytical electron microscopy indicate a permanent decrease in the interlayer charge at the top of the clay plug caused by octahedral exchange of metals (possibly Al^{3+} replacing Mg^{2+}). Calculated cation exchange capacity (CEC) values indicate that this parameter was reduced by as much as 50% compared to the raw bentonite material.
3. The cement has clearly been altered in contact with the clay plug and has lost a significant part of its material strength. In addition to the leaching of Ca and K, the neocrystallization of a fibrous Ca-Si phase had occurred along with the formation of some amorphous components. Dissolution is the probable mechanism of cement weakening in the plug.

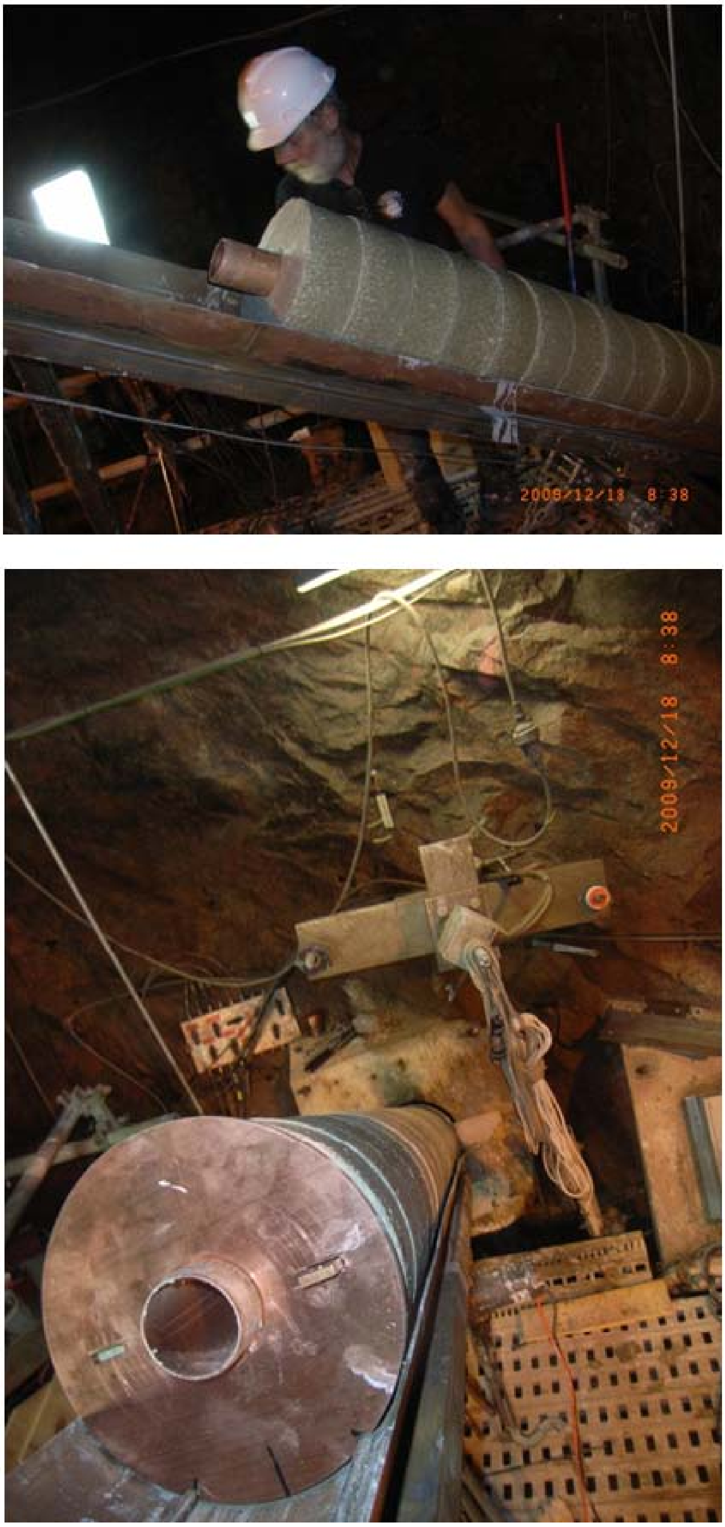


__Figure 4-21.__ Placement of clay blocks. Upper: Funnel for letting the blocks slide down. Lower: Block column with copper plate and attached central tube passing through.

4.13 Concrete and clay

Background

Concrete and other cement based materials are important components in repositories for low and intermediate level waste. Their mechanical and chemical properties make them suitable for the use both as a construction material in the repository as well as for the solidification of many different types of waste. Cement based materials are also known for their retention capabilities making them suitable as barrier materials to prevent the release of radionuclides from a repository.

In the repository the cement will come in contact with the ground water and the soluble compounds in the cement such as NaOH, KOH, $Ca(OH)_2$ and the CSH-gel will be dissolved. In the long term this will alter the chemical and physical properties of the cement but also the composition of the ground water whose alkalinity will increase.

In the repository, also the waste itself will react with compounds in the pore water and transform/ decompose. For instance, the metals will corrode under anaerobic conditions forming solid or soluble corrosion products under the release of hydrogen gas whereas the organic waste can be expected to decompose into CO_2 and CH_4 as well as into other more complex molecules. Some of these are known to be very strong complexing agents that can enhance the transport of the radio nuclides out of the repository.

Objectives

The aim of this project is to increase our understanding of the processes related to the degradation of low- and intermediate level waste in a cement matrix, the degradation of the cement itself through reactions with the ground water and the interactions between the cement/ ground water and adjacent materials such as bentonite and the surrounding host rock.

Experimental concept

During 2010, 2011 and 2012 a total of about 15 experiments will be prepared and deposited at different sites in the Äspö laboratory. The experiments have different objectives and can be divided into four different groups:

- Studies of the degradation of different waste forms in a cementitious environment.
- Studies of the degradation of cementitious materials under repository conditions.
- Studies of the evolution of a high-pH plume in the bedrock surrounding the deposition hole.
- Interactions between the cement and the surrounding materials such as the bedrock and the bentonite.

The specimens are cast into cylinders with a diameter of 300 mm and a length of one meter in the Bentonite Laboratory as shown in Figure 4-22. The cylinders are then transported to the experimental site where they are deposited in a Ø 350 mm hole in the tunnel floor. Typically 3 cylinders are deposited on top of each other in each hole. After deposition, the space between the cylinders and the surrounding bedrock is filled with sand and finally the deposition hole is sealed to avoid contact between the specimens and surface water. One of the experiments will be cast directly in the deposition hole. The aim of this particular experiment is to investigate the degradation of the waste and the cement under dry repository conditions.

Altogether the project is expected to run for up to 30 years but according to present plans the first experiments will be retrieved and analyzed already after 3–5 years. Experiments will then be retrieved at regular intervals and only a few will be left for the entire 30 year period.

Results

During 2010 the experiments in stage 1 of this project has been prepared and deposited in niche NASA0507A, see Figure 4-23. The aim of these experiments is to study the degradation of metals such as aluminium, iron, steel and zinc and organic materials such as paper, rubber, cotton etc in a cement matrix. The first specimens will be retrieved and analysed in 2015–2017 whereas the last will remain deposited until somewhere between the years 2030–2040.

***Figure 4-22.** Casting of the waste containing cylinders.*

***Figure 4-23.** Emplacement of the cylinders.*

4.14 Low pH-programme

Background and objectives

The purpose of this programme is to develop low-pH cementations products that can be used in the final repository for spent nuclear fuel. These products would be used for sealing of fractures, grouting of rock bolts, rock support and concrete for plugs for the deposition tunnels.

SKB has for many years had a close co-operation with Posiva (Finland) and Numo (Japan) in this field. The main focus of the low-pH programme during 2008 and 2009 has mainly been on developing formulas for low-pH concrete to be used for construction of the sealing plugs for the deposition tunnels. In 2009 new field tests with rock bolts and shotcrete for rock support was performed at Äspö.

Figure 4-24. *Filed test with low-pH shotcrete at Äspö HRL.*

Experimental concept

During 2009 SKB performed field test with low-pH grout for rock bolts at Äspö HRL. In total, 20 bolts have been installed. These bolts will be monitored and over-cored after 1, 2, 5 and 10 years for evaluation of the behaviour of the low-pH grout but also corrosion of the rock bolts.

An international project for standardisation of pH measuring started mid 2008 as a joint project with the following participating organisations: SKB, Posiva, NAGRA, ENRESA, NUMO and JAEA.

Results

The work during 2010 has mainly been focused on following up the activities from 2009 with the rock bolts and rock support. The design work of the plugs for the deposition tunnels in the final repository for spent fuel has required additional investigation about material parameters of the low-pH concrete.

The main activity during the reporting period has been the preparation of an official report of the work performed during 2009. The report is expected to be ready in mid 2011. During the reporting period also the preparation for over coring of the first set of rock bolts has been ongoing, as well as follows up of the corrosion experiments with carbon steel rock bolts in low-pH concrete.

The work within the pH-project has been ongoing during the reporting period. In February pH-measurements had been performed in nine laboratories in six different countries. Analysis of the results was done during March and April and an interim report was presented mid April.

In June 2010 "real" samples of low pH-products have been prepared by four members of the consortium. The pH-measurements were done during September in the same laboratories as in the previous phase. The analysis of the results and reporting of this second phase was ongoing up to the later part of 2010. The pH-project is expected to be finished during the second half of 2011.

4.15 Development of end plugs for deposition tunnels

Background

SKB has performed extensive calculations of vault plugs based on data from concrete recipes with low pH-concrete. In view of the fact that low pH-concrete shrinks more than standard concrete, there are risks that the reinforcement can cause a lot of smaller cracks. Reinforcement corrosion and time-saving during installation are further reasons to test a concrete plug that is **not** reinforced in coming full-scale test. Vault plug without reinforcement has been analysed in comprehensive crack and stress calculations but the results need to be verified in a full scale test. Calculations of friction plug have also been executed and reported.

In the ongoing project regarding development of concrete plug, function, requirements and assumptions have been documented. A risk analysis of the different plug variants has also been performed. An evaluation based on the foundation of the two construction alternatives indicated clearly that the vault plug is the most appropriate alternative.

Seal liability is an important parameter for the plug, even if the main task is to work as a holding up construction against the backfilling in the deposition tunnel. The plug shall initially (approx. 100 years) prevent water flow through the plug and in the interface between rock and concrete. This will reduce the risk of erosion of backfill and buffer.

Objectives

In the programme for further development, the achievements will be broadened and more intense during the next years. The objective is to test the design in a full-scale test during 2012. To manage this and to make the tests meaningful, the following objectives have been set up:

- The plug system requirements need to be analysed and determined.
- Modelling and tests of bentonite sealing, filter and drainage to be able to guarantee function.
- Concrete recipe shall, if possible, be adapted to the requirements and conditions for the plug. Some parameters, like shrinkage, tensile strength and creeping should be tested further.
- Control method with regard to the sealing ability of the plug has to be developed.
- Rock excavation method for the plug has to be suited to industrial conditions.

Experimental concept

A pilot study of the planned full scale experiment 2012 has been approved in August 2010. A preliminary sketch of the planned instrumentation has been performed and the test arrangements will be further discussed and determined as the planning of the trial is intensified during 2011. A suitable localisation at repository depth for the full-scale trial is handled in consultation with the project Expansion of Äspö HRL 2011–2012.

Results

SKB has signed a Project Agreement with Posiva Oy for co-operation in the following plug development areas; Requirements and methods for control, Modelling of sealing, filter and drainage as well as Rock excavation methods.

During 2010 the factual basis has been compiled, documenting the most appropriate plug-design. In addition, a number of design drawings and construction documents have been prepared. A section sketch is presented in Figure 4-25. The R-report will be published before summer 2011.

The results will be handed over to the project *System Design of Plug for deposition tunnels*. This project will refine the design criteria and perform tests and modelling of the filter, bentonite sealing and drainage. In addition, the design will be adjusted to production-related conditions by further analysis of concrete behaviour and studies of the most appropriate way to make the rock excavation for a plug. These aspects will also be studied in the full-scale trial 2012.

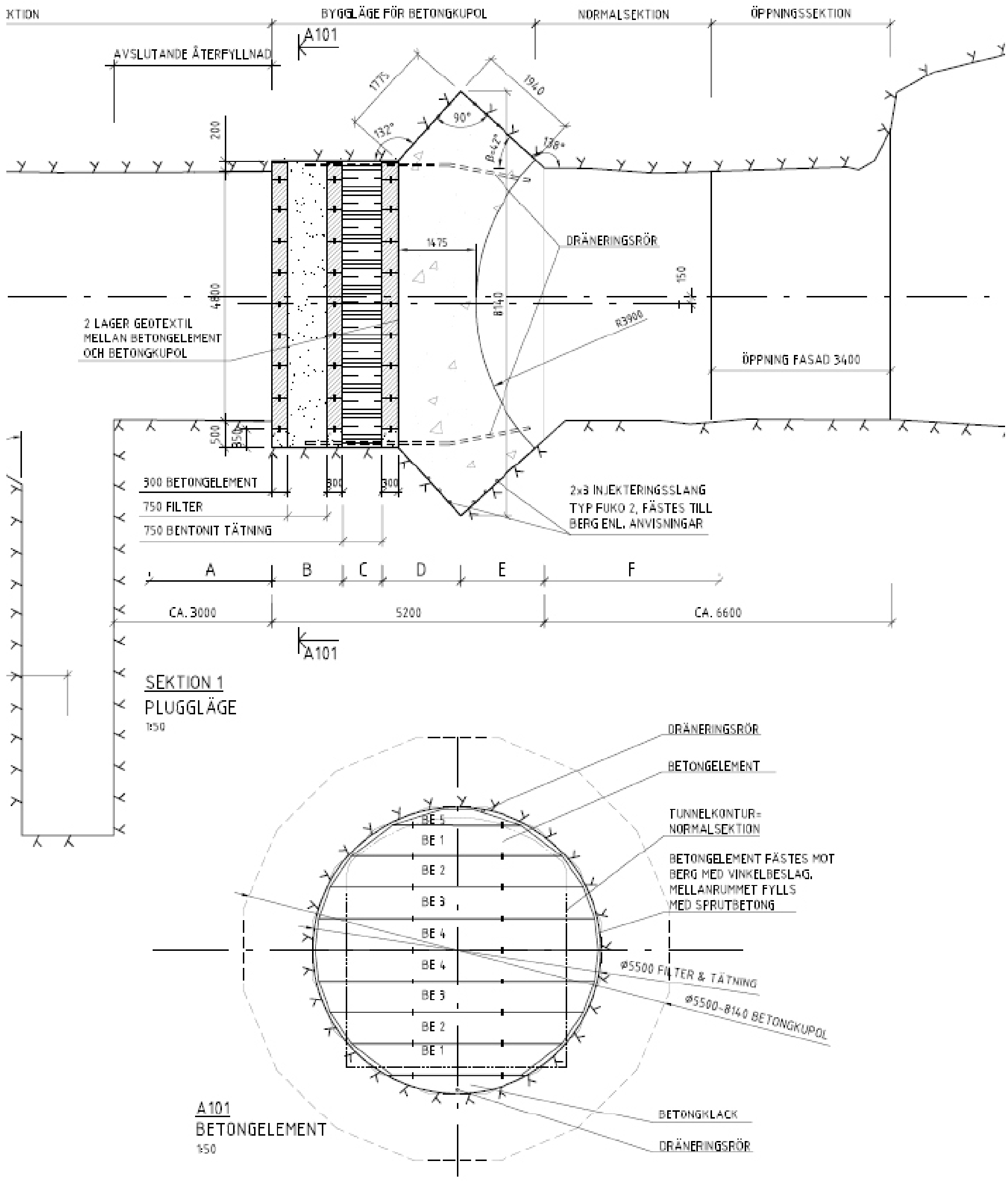


Figure 4-25. *Several design drawings and construction documents that has been prepared. The figure shows a horizontal section sketch.*

4.16 Task force on engineered barrier systems

Background

The second phase of The Task Force on Engineered Barrier Systems (EBS) started in 2010 and is a natural continuation of the modelling work in the first phase. The first phase included a number of THM (thermo-hydro-mechanical) tasks for modelling both well-defined laboratory tests and large scale field tests such as the two Canadian URL tests (Buffer/Container Experiment and Isothermal Test) and the Swedish Caniste Retrieval Test at Äspö HRL. In the first phase the Task Force was also enlarged to two groups, one treating the original THM issues and one group concentrating on geochemical issues. The two Task Force groups have a common secretariat, but separate chairmen.

Objectives

THM

The objectives of the work of the THM group of the EBS 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).

Geochemistry

The objectives of the work of the geochemical group 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.

THM

All defined tasks of the first phase 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.

Geochemistry

SKB (Clay Technology, Amphos21), Nagra (University of Bern, Madrid), Posiva (VTT), and RAWRA (NRI) 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 phase 1 of 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 2010; one in Barcelona (Spain) in May and one in Prague (Czech Republic) in November. For information about performed work within the different tasks by the international organisations, see Chapter 8.

The first phase of the Task Force was concluded and the second phase started in 2010.

THM

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. Altogether 8 modelling teams are working with this Benchmark. 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. Two reports are still missing to conclude Task 2.

New tasks for phase 2

The second phase includes so far the following tasks:

1. Sensitivity analysis.
2. Homogenisation.
3. Task 8 (common with TF Groundwater Flow).
4. Prototype Repository.

Participating organisations in phase 2 are besides SKB at present BMWi (Germany), CRIEPI (Japan), Nagra (Switzerland), Posiva (Finland), NWMO (Canada) and RAWRA (Czech Republic). All together 10–15 modelling teams are foreseen to participate in phase 2.

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.

The task description of this task is still under preparation.

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 hydro-geology group. The main project goals are the following:

- 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). The task description has been delivered. This task is divided into several subtasks and the modelling has started 2010.

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.

The task description is still under preparation.

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.

A prediction of the state of the outer section of the Prototype Repository (mainly in the buffer in the deposition holes) and capturing the THM processes during operation are the main goals of the assignment. A proposal for a solution strategy has been developed for the assignment. The suggested strategy has three "steps", where each step defines a "sub assignment" which might be interesting to study on its own. The three sub assignments in the proposed solution strategy are:

1. Modelling of the water inflow in the repository before installation. (To calibrate the hydraulic conductivities in the surrounding rock mass.)
2. Modelling of the thermal and hydraulic processes after installation, during the operational phase. (To determine suitable boundary conditions for the models used in the next sub assignment.)
3. Modelling of the THM-processes in the outer section (concentrating on hole 6) during the operational phase and predict the state at the excavation taking place during 2011.

SKB team 1 has developed a model for sub assignment 1 and is in the process of developing a model of sub assignment 2.

Geochemistry

During the year, the University of Bern (Nagra), Universidad Autonoma de Madrid (Nagra), Clay Technology (SKB), Amphos21 (SKB), VTT (Posiva), Grüner (Posiva), Czech Nuclear Research Institute (Rawra) have contributed to the C-part activity.

The following issues have been dealt with during 2010.

Modelling work:

Three experimental data sets on montmorillonite systems have so far been presented to use for benchmark calculations: (1) salt diffusion, (2) gypsum dissolution and sulphate diffusion, and (3) calcium/sodium exchange of montmorillonite in compacted state.

During the year, Clay Technology has presented (continued) work performed on both data set 1) and 3). Focus has been on comparison between applying the ion-equilibrium or the multi-porosity approach to compacted bentonite.

Amphos21 have presented modelling of the saturation phase of the A2-parcel of the LOT test at Äspö HRL. The model involves gaseous, liquid and solid phases, temperature gradients, and both advective and diffusive transport. The main focus of the modelling was on the redistributed sulphate in the hot parts of the A2 parcel, as well as on the chloride inventory. Modelling of Äspö field test experiments will be further addressed in the second phase of the Task Force.

Universidad Autonoma de Madrid has presented modelling of the core infiltration test performed on MX-80 bentonite at university of Bern. The experiment has been modelled using both Phreeqc and Crunchflow, utilizing the multi porosity approach with DDL-theory features. Results from the core infiltration test will soon be made available within the Task Force as a benchmark data set.

The Czech Nuclear Research Institute has presented pore water calculations made on MX-80 and Rokle bentonite using Phreeqc.

An extension of the ion equilibrium approach to pressure and water flow responses due to externally applied water pressure gradients were presented by Clay Technology. It was shown that central concepts such as Darcy's law for water flow and the effective stress equation can be derived for compacted bentonite by considering only the water chemical potential. The theory was successfully applied to the UniBern core infiltration test and to Clay Technology water flow experiments showing non-linear flow and pressure response. This is an attempt to bridge the two Task Force issues.

Clay Technology presented further molecular dynamic simulations of the montmorillonite/water system which illuminates the concepts of Donnan equilibrium, friction and colloidal coagulation due to ion-ion correlation effects in Ca-montmorillonite.

Code development:

Carl Steefel, creator of the reactive transport code Crunchflow, presented the newly implemented diffuse double layer feature of Crunchflow at the Speyer workshop. He also gave a short hands-on demonstration of how to work with the code.

Presentation of additional experimental work:

The analysis of cations and anions in the first parcel of the Äspö HRL field test Alternative Buffer Materials (ABM) was presented and compared to earlier results of the LOT A2 parcel.

Two distinctive features were observed in the ABM parcel: 1) Chloride concentrations were significantly lower than in the ground water and were negatively correlated with bentonite quality and density. These observations are in complete agreement with the theory of Donnan equilibrium 2) Major internal diffusion was observed of the charge compensating cations, suggesting that interlayer diffusivity is the major transport mechanism.

UniBern presented initial results form a second core infiltration test, performed at ~140°C.

Czech Nuclear Research Institute presented mineralogical analyses of the Rockle bentonite. The data is proposed as a benchmark data set.

5 Mechanical- and system engineering

5.1 General

At Äspö HRL and the Canister Laboratory in Oskarshamn, technologies for the final disposal of spent nuclear fuel are being developed. Established as well as new technology will be used in the final repository. When it comes to mechanical- and system engineering, well known standard objects with secured function will be used to the fullest possible extent. With standard equipment as a basis, needed adjustments, modifications and adaptations can be made for the intended function. Where no standard objects are available, new technical development will be necessary.

5.2 Technical development at Äspö HRL

The technical systems, machines and vehicles to be developed are identified and listed in the project FUMIS. Preliminary plans for this development are drawn up.

A total of about 175 different objects, known today, are needed. The preliminary plans for these objects point out the start and finish time for development to have each object ready in time for operation. The plans also include time for development and tests of necessary prototypes. Also a model for cost calculation of modifying and development of objects is developed.

Several projects within mechanical- and system engineering are ongoing and the activities in some of the projects are described in the text below.

Multi purpose vehicle

SKB has a continuous need for performing heavy load transports in the ramp of the Äspö HRL. In order to perform these transports, a vehicle, called Multi Purpose Vehicle (MPV) has been ordered. The vehicle will also be used as a technical development platform for various systems and as a prototype for the future ramp vehicle for the deep repository.

To perform tendering and ordering of the vehicle, a project was initialised during the spring and has resulted in advertisement on the European homepage of Simap Information on public procurement. The order was placed in the beginning of December 2010 with the Italian company Cometto, and the delivery is planned to take place in March 2011.

Multi purpose vehicle.

Equipment for backfilling

The project is performing design and testing of backfilling equipment. The simulation of a concept has shown that a robot should be able to place 220 tons of backfilling blocks per day, which is a requirement for the logistics in the deep repository. A simulation of the robot placing the backfill is now being made. A rack mounted laser to check and measure the result of backfilling with the robot is being purchased.

Future work includes building and testing a prototype of the handling equipment, which will consist of a platform and an industrial robot with a vacuum tool. Testing will be performed both at the Bentonite Laboratory and at the –420 m-level.

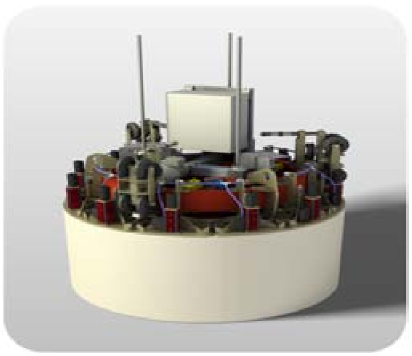
Backfilling equipment.

Buffer emplacement

This project is investigating whether or not the buffer, in the shape of blocks and rings, can be placed in the deposition holes with the required degree of precision.

The tool uses vacuum to lift the bentonite rings and has been functioning well in the laboratory. Minor adjustments need to be made on the crane for final tests to be performed. The buffer rings used for testing were too porous and were easily breaking and vacuum could not be achieved on the damaged rings. The rings have been repaired and can be used for the present. Damage may occur again and affect the tests so new rings will be produced.

During 2010 the steering gear of the emplacement tool was completed. A test programme is being drawn up, as well as a plan and instructions for the accomplishment of quantity and endurance tests. The test programme describes the hoists that are to be made both in design, number, sequence and how the tests are documented. Performance of the tests will start in 2011.



Lifting tool for buffer emplacement.

Deposition machine

The aim of the full-scale tests that are being carried out with completely automated operation is to collect data and evaluate the reliability and availability of the machine and the parts of the system, as well as the service requirements under continuous operation.

The tests have been initiated and product information on the deposition machine was developed. A remote connection has been installed and Navitec System are now using the remote connection for maintenance and fine tuning of the software. A UPS (uninterruptible power supply) has been installed for the screens in the driver cabin.

The data collected from the first campaign of the full scale tests are to be analysed and a requirement specification for a test server (SCADA) will be produced. A SCADA will be acquired and the full scale tests will continue during the next few months.

Deposition machine.

Transport system for buffer and backfill material

A feasibility study aiming at finding a solution for the transportation of buffer and backfill material has been carried out during 2010. The study has included the transportation of material from the production premises to the equipment that places the buffer in the deposition hole and that installs the backfill and the pellets. The feasibility study has determined a concept, which equipment to be used and a preliminary analysis has been made regarding human factors. An intern report of the feasibility study has been produced.

The main final objective of the project is to deliver an autonomous remotely operated transport system for material from the production premises to the deposition hole and the backfill of the deposition tunnels.

The intention was for the feasibility study to pass into a project, but for the moment the project has been put on ice.

Logistics study

The main objective with the logistic studies for the final repository for spent fuel is to be able to simulate all the activities at the repository during the operational phase, both rock excavation and the emplacement of buffer, canister, backfill and sealing of the deposition tunnel with a concrete plug. These logistic studies must be done in steps over a period of 3 to 4 years as needed information is not available at present.

A demonstration project was completed in June 2010. The purpose of the demonstration project was to find out if suitable software is available and if it is a practical way to carry out this type of simulations. The results of the demonstration project have been used for internal information and a decision for continued work with logistic studies. An evaluation report is on the verge of being finalised.

The aim of the logistic studies is to be a part of the decision making process for operation and control of all activities, and also to create information needed for detailed design of systems and equipment with regard to:

- Time needed for various activates.
- Bottlenecks and sensibility for disturbance.
- Layout and design of different parts of the facility.
- Design requirements for technical systems.
- Determine the need of different machines/vehicles and required capacity.
- Form a model for control, supervise and follow up of operation and production.
- Organisation structure for the final repository and need of staffing.
- Costs.

Since the Logistics study is depending on results from, amongst others, the project *"Transport system for buffer and backfill material"* and that project is on hold, there can be very little or no progress in the Logistics study until the Transport system project is generating results.

Mission control system, MCS

Within this project, a prototype of a comprehensive automatic system for the management and control of transport and production logistics for the final repository will be developed. Preparatory work has been made during 2010 and formally the project was started in October 2010. The decision to develop a mission control system establishes a working method for the final repository that facilitates the use of automated vehicles.

The scope of the first months of 2011 will be to define system properties and programme structure. The mission control system and a related data base will be developed during 2011. Test of the system will start in 2012.

Drilling machine for deposition holes

For the drilling of the deposition holes for various projects, SKB has used a modified Tunnel Boring Machine (TBM). In total SKB has drilled 17 deposition holes at Äspö HRL. A "state of the art" investigation of available technologies was performed during 2006 and the conclusion was that the push reaming technique would be the method that could meet stringent requirement on the deposition hole and still have high production rate required for the final repository. This technology has also been tested in Finland for drilling of three deposition holes in the research tunnel at Olkiluoto. The same technology has been used for the excavation of the two KBS-3H deposition tunnels at –220 m level in Äspö HRL.

SKB are currently following Posivas work on the subject. Posiva are expected to have a new drill available for these purposes during 2011.

6 Äspö facility

6.1 General

The Äspö facility comprises the Äspö Hard Rock Laboratory and the Bentonite Laboratory, the later taken into operation in 2007. The Bentonite Laboratory complements the underground Hard Rock Laboratory and enables full-scale experiments under controlled conditions making it possible to vary experimental conditions and to simulate different environments.

Äspö Hard Rock Laboratory has over the last year entered a new interesting phase in its history, for example with the excavation of the outer section of the Prototype Repository that began as scheduled at the end of November. The operation of the already ongoing experiments in the Äspö Hard Rock Laboratory has continued and some have been completed (e.g. Temperature Buffer Test) with respect to field work. For those now remains work to analyze, evaluate and report results from the experiments.

With regard to operation, maintenance and development of the facility, it has been an intense year both under and over ground. During the last period of the year has restoration work been performed underground to prepare the tunnels TASS and TASQ for coming experiments, the work to establish a geotechnical laboratory has begun and the facilities for the chemistry laboratory are expanding to increase opportunities for researchers in Nova FoU to use the Äspö Hard Rock Laboratory.

Important tasks of the Äspö facility are the administration, operation, and maintenance of instruments as well as development of investigation methods. Äspö HRL is the residence of the unit *Repository Technology* 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 spent nuclear fuel and for low- and intermediate level waste.
- Develop the horizontal application of the KBS-3-method (KBS-3H).
- Perform experiments in the Äspö HRL commissioned by SKB's Research unit.
- Secure a safe and cost effective operation of the Äspö HRL.
- Prosecute comprehensive visitor services and information activities in co-operation with SKB's Communication department.

The *Repository Technology (TD)* unit is organised in four operative groups and one 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.
- 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.

Earlier were also Public relations and visitors group, TDI, a part of the Repository Technology unit. However the group were transferred to the reorganised Communications department within SKB in May 2010 and is now named Communication Oskarshamn. The group and its personnel are however still located at Äspö HRL and have a continuously close co-operation with the facility and the daily coordination of underground activities. Communication Oskarshamn is responsible for presenting information about SKB and its facilities. They arrange visits to the facilities all year around as well as special events.

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

6.2 Bentonite laboratory

General

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 which 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 break-through 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. Out flowing 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

A number of bedtests have been performed in the Bentonite Laboratory with the purpose of better describing characteristics of the bed which will be installed in the deposition tunnels. The tests include stacking of blocks after a given pattern on a not compressed bed of pellet materials, with and without concurrent water inflow. Bed stability during water inflow will also be tested. The results will be used to describe the prerequisites for block installation.

The final ½-scale test (Test 4) done as part of the Baclo project consisted of filling the chamber for 5.44 m of its 6 m total length. This allowed for two, fracture-isolated sections to be constructed within the same assembly (at 2.1 m and 4.2 m distance from the rear of the test chamber, with an additional 1.2 m of backfill installed beyond the location of second wetting band. This allowed for evaluation of how a series of isolated tunnel sections will interact as water influx to the tunnel

Figure 6-1. *Stacking of blocks after a given pattern on a not compressed bed of pellet materials.*

Figure 6-2. Half-scale tests in the Bentonite Laboratory.

progresses. The "fractures" in Test 4 were also supplied with water at 0.0025 l/hr, but wetting was extended to 12 days (288 hrs; 43.2 l total supplied). This ensured isolation of the two sections of tunnel before water was supplied at 0.2 L/min at the rear of the chamber (via two isolated inlet points, each supplying 0.1 L/min).

The final test showed generally similar behaviour to that seen previously where a single isolated pocket of unsaturated backfill pellets existed.

6.2.1 Impact of water inflow of backfill

Background

The backfill of deposition tunnels is proposed to consist of stacks of blocks of highly compacted smectite, surrounded by blown-in smectite pellets. Preceding tests on "half-scale" have indicated that water entering spot-wise from the rock can cause piping at critically high inflow rates but cause uniform wetting at sufficiently low flow rates. The question is what the critical inflow rate really is and how fractures with several inflow spots affect the wetting process, and whether the flow is different if the inflow takes place from a hole in a steel wall or from water-saturated rock.

Objectives

The specific goal of the project was twofold: 1) to evaluate the outcome of the continued tests with wetting and percolation of backfills of stacked blocks of compacted smectitic blocks surrounded by smectite-rich pellets, and 2) to identify the process of wetting and percolation of pellet fill adjacent to natural granitic rock slabs, simulating the walls of blasted tunnels.

Experimental concept

In one of the experiment series the earlier used test arrangement with a tunnel-like steel construction was used but now equipped with several inflow spots for simulating a water-bearing fracture. The idea was to measure the water pressure generated at the spots under constant flow rate conditions, and to record the outflow from the pellet mass with special respect to the risk of piping and erosion.

The other experiment series had the form of injecting water at stepwise increased pressure for investigating the nature of water inflow into and through the pellet fill.

Results

The experiments with inflow into the artificial tunnel showed that flow of 0.1 L/min or less along a single flow path is unlikely to cause substantial disruption to the backfill. At higher flow rate along a single pathway erosion will occur and can be disruptive. There was a tendency for inflows entering the backfill at different locations to combine, potentially forming a feature that was much more erosive that would occur in separate flows that in total were equal to the combined feature. One feature that was notably different in the tests was the deformation of the front-face of the backfilled volume and swelling-induced failure of the internal formwork used to simulate the internal sections of an actual tunnel.

The rock slab tests turned out to be of fundamental importance since they clearly showed that inflow of water from the rock into an adjacent pellet fill has the form of uniform, diffusion-like migration at pressures lower than a critical level, and piping and quick penetration of the fill at a certain critical level (Figure 6-4).

Figure 6-3. *Wetting at/near inner fracture feature showing location of restraint failure and subsequent clay swelling.*

Figure 6-4. *Appearance of water penetrating pellet filling contacting an initially water saturated rock slab.*

An important conclusion from the experiment series was that water entering from a single spot, that can be the crossing of two water-bearing fractures, does not follow the contact between rock and pellets at low and moderate water pressures, but takes place in the form of local penetration and formation of channels perpendicular to the contact surface at a sufficiently high inflow rate. This demonstrates that experiments with inflow from steel plates are not representative of the conditions in real rock.

6.3 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 2010 has been stable, with a very high degree of availability. The year began with much snow and cold which put the facility on test. Two of the facility's pumps broke down in the coldest period, resulting in high heating costs. Heating of ventilation air to the tunnel has contributed to high electricity costs. The high level of snow resulted in that the cost of road maintenance doubled.

An independent consultant is conducting an energy analysis of the plant and a proposal to energy conservation measures will be finished to the business planning for 2011.

The rock maintenance has been going on as planned and the contractor expects to keep the timetable in the maintenance plan. In an area at the –290 m section, roof and walls have been sprayed with concrete and a number of rock bolts have been installed in accordance with protocols from the large rock inspection.

Work on upgrading the elevator machine has been performed as planned. A new security computer has been installed and the unit to the electrical motor has been replaced to a more modern model. The work was well planned and was done in three days. To maintain security, the tunnel was closed while the work was going on and only emergency work was carried out.

The exchange of cable ladders, to a stainless steel model, in the elevator shaft between the levels –340 m and –220 m has been carried out during the summer. The work with restore the TASQ-tunnel and the TASS-tunnel after completed experiments has begun. In the tunnel new measuring dykes will be casted, and then the roadway bill be paved with asphalt.

During the planning of the excavation of the outer part of the Prototype Repository it was found that in order to do the necessary analyses a good geotechnical laboratory is required. After much discussion it was decided that the present goods receipts will be converted to that purpose. The goods receipt must then move to the current drilling core archive, which now needs smaller space since many cores can be stored elsewhere. The reconstruction is ongoing and will be ready to receive samples from the excavation of the outer part of the Prototype Repository. During the reconstruction a new laboratory will be completed and that can be used for various activities.

During the autumn the work with at new water- and wastewater plant began. Drains that previously were collected in a tank and transported by truck will now be pumped into a two-kilometre long pipeline to OKG's treatment plant. To become independent from the disruption from OKG`s waterworks a water reservoir will be built at the laboratory, and to meet the emergency services requirements a fire water reservoir of about 100 m^3 has been completed.

6.4 Communication Oskarshamn

SKB operates three facilities in the Oskarshamn municipality: Äspö facility, Central interim storage facility for spent nuclear fuel (Clab) and the Canister Laboratory.

Site investigations have been performed during 2002–2009 in the municipalities Oskarshamn and Östhammar. In June 2009 SKB decided to select Forsmark as the site for the final repository for Sweden's spent nuclear fuel.

The main goal for the Public Relations and Visitor Services Group is to create public acceptance for SKB, which is done in co-operation with other departments at SKB. The goal will be achieved by presenting information about SKB's facilities and RD&D work e.g. at the Äspö facility. Furthermore the team is responsible for visitor services at Clab and the Canister Laboratory.

In addition to the main goal, the information group takes care of and organises visits for an expanding amount of foreign guests every year. The visits from other countries mostly have the nature of technical visits.

The team also has the responsibility for the production of SKB's exhibitions; stationary, temporary and on tour.

The information group has a special booking team at Äspö which books and administrates all visitors. The booking team also is at Oskarshamn NPP's service according to agreement.

General

The main goal for the communication unit in Oskarshamn is to create public acceptance for SKB, which is done in co-operation with other departments at SKB. The goal will be achieved by presenting information about SKB, our facilities and the RD&D work which is carried out at for example Äspö. Furthermore, the unit is responsible for the visitor services at the central interim storage (Clab) and the Canister Laboratory and for taking care of and administrating all visitors to SKB's facilities. The unit has the responsibility for SKB's exhibitions, for school information in Oskarshamn as well as in Östhammar, the magazine Lagerbladet etcetera.

During 2010, the three facilities in Oskarshamn were visited by 11,340 persons. The visitors represented the general public, municipalities where SKB has performed site investigations, teachers, students, politicians and journalists. The information group also takes care of and organises visits for a great amount of foreign guests every year. The visits from other countries mostly have the nature of technical visits and the total number of foreign visitors 2010 was 1 512. The total number of visitors to all SKB facilities including *"Final repository information activities"* in Oskarshamn and Forsmark was 18,374. See Figure 6-5 below.

An organizational review of the department of EIA and public information has been carried out, and the public relation officers in Oskarshamn were transferred to the reorganised Communications Department within SKB in May 2010. The unit is located at Äspö HRL and have a continuously close co-operation with the facility and the daily coordination of underground activities. The visitor service is still a large and important part of the tasks carried out by the unit.

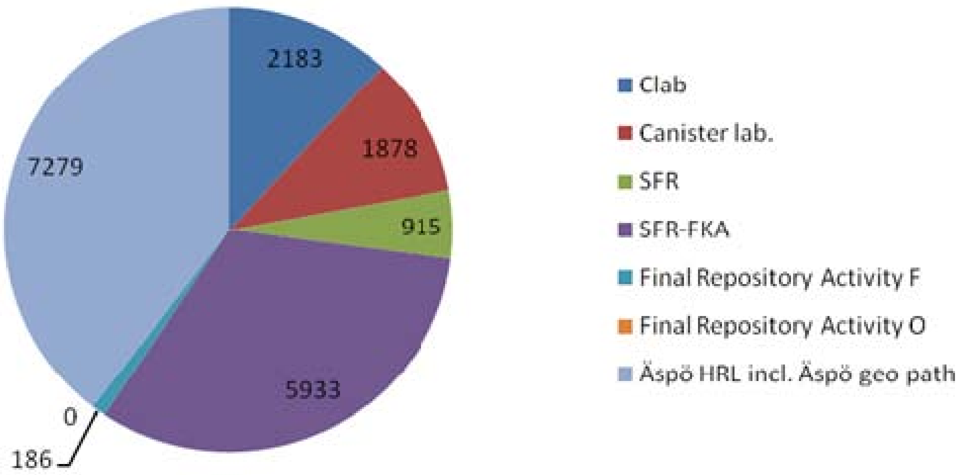


***Figure 6-5.** The total number of visitors to all SKB facilities during 2010.*

Special events and activities

In 2010 following events and activities took place:

- There have been a number of VIP-visits during the year, e.g. President Obama's Blue Ribbon Commission on nuclear waste, representatives from the French Parliament. TAEC, Japan NDA, England, Taiwan Power Company, to mention a few. We have also had visits from IF Metall, Swedish Radiation Safety Authority (SSM) with guests and researchers from different universities in Sweden.
- The special summer arrangements "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 1,500 at SFR. Tours for the general public also took place some Saturdays during the year.
- Like every year, SKB visited the harbour of Visby with the transportation ship M/S Sigyn during the traditional political week "Almedalsveckan" (July 4–10). Every party with a seat in the Swedish parliament is present. SKB had the opportunity to meet many of the politicians and organisations. Members of the group have been engaged in the tour.
- SKB was during the summertime also present at the local events "Latitud 57" and "Framtidsdagarna" in Oskarshamn.
- 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 the public were invited to a geological walk through Oskarshamn. The Geological Day was arranged for students during one day (September 10) and for the public during one day (11th of September). The events attracted about 100 participants in total.
- The 24th of September a contribution to "EU's Researchers' Night" was held at Äspö. The theme was "machines in the final repository". The event attracted about 60 persons.
- On the 27th of November the Äspö Running Competition was held in the Äspö-tunnel. 80 participants, men and women, ran all the way up to the surface from –450 metres depth. This event has been a tradition for twelve years now and is much noticed by media.
- On the 4th 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. 50 people took the chance to visit Äspö and at the same time see the show.
- The unit also went to schools within the municipally of Oskarshamn and met students in the 9th grade and students in the 3rd grade of the high school. SKB has also met students in the municipality of Östhammar. Three-four times a year, a news letter is sent out to the teachers. All students in 9th grade in Oskarshamn are offered a visit at Äspö HRL and the Canister Laboratory and all students in the 3rd grade are offered a visit to Clab.
- During 2010 the unit published three issues of the magazine Lagerbladet which is sent out to all the households in the municipality and to subscribers all over Sweden. Anyone can subscribe for free. The goal with Lagerbladet is to tell the public about SKB's work in a way that is not too technical and also to show the persons behind SKB.
- The unit has started planning of the 25 year celebration at Äspö HRL 2011.

7 Environmental research

7.1 General

Äspö Environmental Research Foundation was founded in 1996 on the initiative of local and regional interested parties. The aim was to make the underground laboratory at Äspö and its resources available for national and international environmental research. The activities have since 2003 been concentrated to the Äspö Research School. When the activities in the school was concluded as planned in 2008, the remaining and new research activities were transferred within the frame of a new co-operation, Nova Research and Development (Nova FoU).

7.2 Nova research and development (Nova FoU)

Äspö Hard Rock Laboratory is a world unique underground research laboratory which is now open for more general research. Nova FoU (www.novafou.se) is the organisation which implements this policy and facilitates external access for research and development projects to the SKB facilities in Oskarshamn (Figure 7-1).

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 following SKB facilities:

- Äspö Hard Rock Laboratory.
- Bentonite Laboratory at Äspö.
- Canister laboratory in Oskarshamn.
- Site Investigation Oskarshamn (Laxemar).

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 7-2).

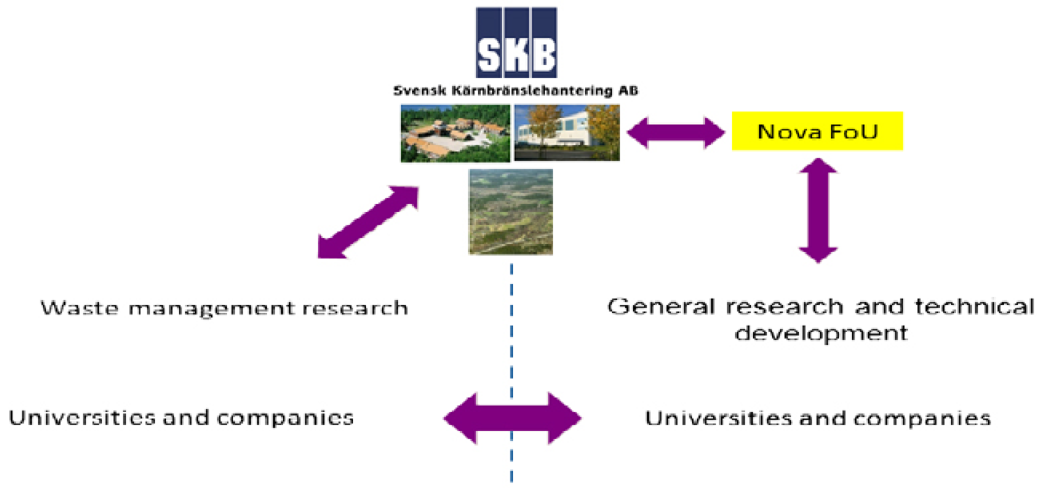


Figure 7-1. Nova FoU provides access to the SKB facilities and data for universities and companies for general research and technical development. Nuclear waste management research is handled by SKB.

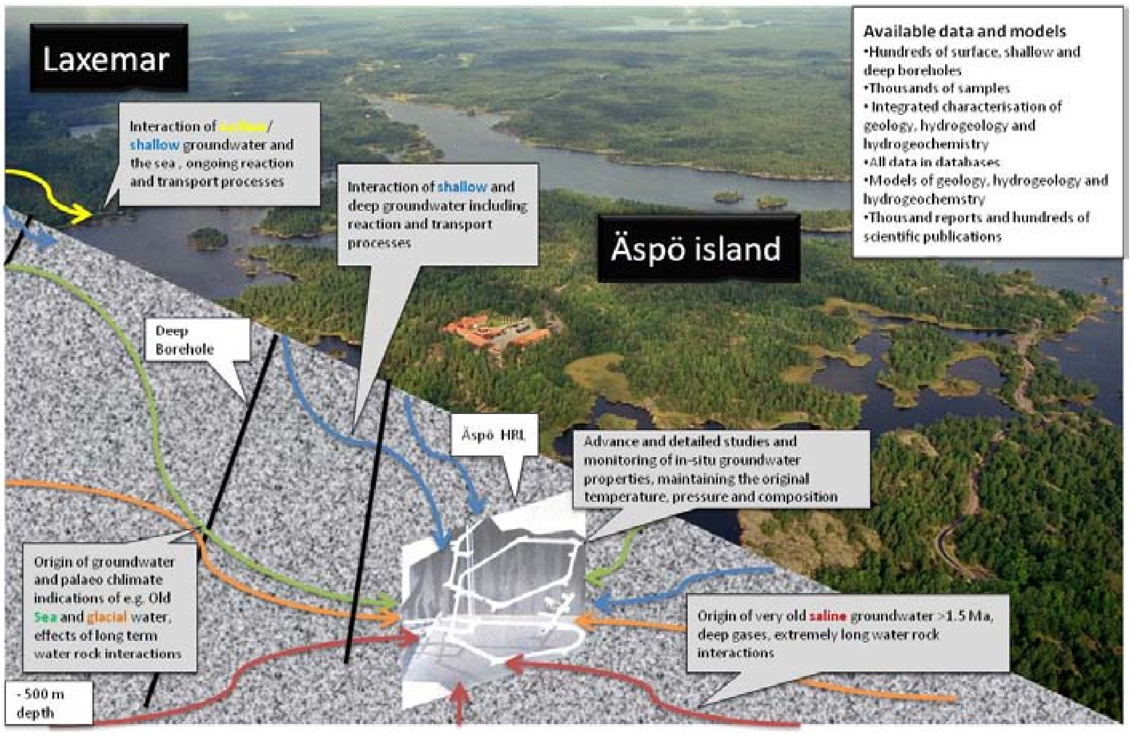


Figure 7-2. *The Äspö and Laxemar areas have been studied in terms of geology, hydrogeology, hydrogeochemistry and ecology. This information can be used for a number of purposes, for example to describe the water cycle and hydrogeochemical processes in 3D.*

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. Possible scientific and technical work at Äspö HRL is:

Scientific work:

- How life is formed in underground conditions.
- Evolution of life where sunlight and oxygen are absent.
- How the deep parts of the hydrological cycle work.
- Interaction between deep and shallow groundwater systems.
- The nature of complex hydrogeochemistry.
- The character of water totally unaffected by man (deep brine).
- Development of fracture fillings over geological time.
- Environmental changes revealed by fracture minerals and groundwater.
- Generation of fracture networks in three dimensional space.

Technical development:

- Visualisation, simulation and animation of phenomena in natural science.
- New sampling, measuring and orientation devices for underground work.
- Material and technical development in corrosive and high pressure underground environment.

7.3 Status of the Nova FoU projects

The status of the ongoing research and development projects within Nova FoU for year 2010 are described below.

7.3.1 Lanthanoids in bedrock fractures (Linnaeus University)

The aim of the project is to characterise and describe the variability in concentrations and fractionation patterns of lanthanoids in fracture minerals (primarily calcites) and ground waters in Proterozoic bedrock.

The status of the project for the reporting period is that: (1) concentrations and fractionation patterns of lanthanoids in both calcites and groundwaters have been statistically analysed and interpreted, (2) the abundance and fractionation of lanthanoids in the groundwaters have been compared with results of Multivariable Mixing and Mass balance (M3) modelling and (3) the relationship between lanthanoid concentrations and drilling-water% in groundwater samples have been studied.

The major results are as follows. There was no significant correlation between drilling-water content and lanthanoid concentrations (Figure 7-3), which is a good starting point for further statistical analyses and interpretation of the behaviour of the lanthanoids.

The calcites show overall a strong relative enrichment of the light lanthanoids, which also is to be expected from partition coefficients obtained in other previous laboratory experiments. The extent to which the light lanthanoids are enriched however varies substantially, and in some cases even the heavy lanthanoids are just as high as the light ones. It seems that a large part of the fractionation in the calcites can be explained by the fractionation of lanthanoids existing in the deep groundwaters (only current-day data exists) and partitioning into the calcites according to existing partition coefficients. This will increase the understanding of the interaction of lanthanoids (and indirectly actinides) in groundwater and fracture minerals in crystalline bedrock.

The spin-off effects from the project are so far mainly that the results can be used as a reference and starting point for other detailed lanthanoid and trace-metal investigations in other kind of deep-environmental materials such as other fracture minerals, bacteria and different types of groundwater.

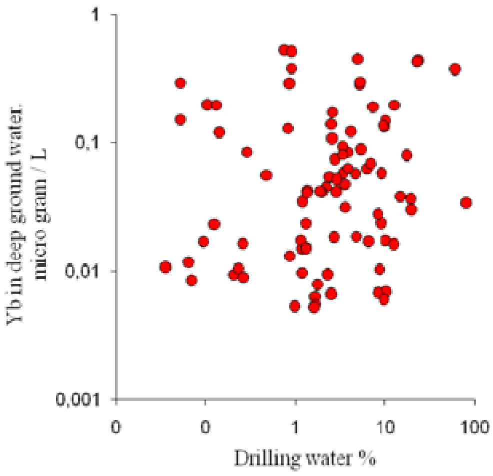


Figure 7-3. *Scatterplot of drilling-water percentage and lanthanoid concentrations in groundwater.*

7.3.2 Fluorine in surface and ground waters (Linnaeus University)

The main aim of the project is to increase the understanding of the behaviour of fluorine in waters at different levels in the ground (from the surface down to 1,000 m or more) in the boreal environment. In more detail the project aim is to: (1) describe and explain the high fluorine concentrations in the water in the lower reaches of the Kärrsviks stream (this stream was included in the Site Investigation programme for Oskarshamn, see Figure 7-4), (2) characterise and model fluorine abundance and transport in overburden and bedrock groundwaters in Laxemar, Forsmark and Äspö and (3) identify the sources of high fluorine concentrations occurring in many wells in the region (the county of Kalmar).

The status of the project for the reporting period is to submit first manuscript early 2011 and to initiate and finish a study concerning fluoride distribution and patterns in overburden groundwaters in the Laxemar area, by using Sicada data from soil tube monitoring and characterization. Fluoride in specific boreholes in Äspö tunnel will be approached using Visual MINTEQ©-modelling.

The major results are the findings and characterization of a temporal and spatial fluoride pattern within the Kärrsviks stream and its catchment, confirming the hypothesis of indirect influence from fluorine-rich bedrock (Götemar intrusion) as a source for elevated fluoride concentrations in the surface waters of the catchment. The mechanism is weathering of glacial deposits, partially consisting of Götemar granite, and greisen fractures (which are strongly connected to the intrusion and, as well, rich in fluorite).

The spin-off effects from this project will be increased information and knowledge on fluorine abundance and transport in surface and ground waters in Laxemar and Äspö and elsewhere in the county of Kalmar, which has practical implications in terms of water supplies (concerning both private wells and public water resources). Many wells, both in the overburden and bedrock, in these areas contain fluorine concentrations, which are above the threshold values for drinking water, an issue that will be thoroughly discussed and highlighted within the project. In particular, the project will lead to a greater understanding of the mechanisms causing the well-water fluorine concentrations to increase in many areas, which is valuable information for the community. The findings may also lead to spin-off effects of economical value.

Figure 7-4. *The Kärrsviks stream has significantly elevated concentrations of fluoride, caused by the weathering of fluoride-rich minerals such as in Götemar granite (top left corner).*

7.3.3 Modelling of groundwater chemistry (Linnaeus University)

The aim of the project is to increase the understanding of chemical reactions and transport in fractured Proterozoic bedrock. At the present time, a major task is to contribute to the updating of the Äspö Site Descriptive Model (Äspö SDM) by providing calculations and interpretations based on the M3 modelling. In addition the potential artefacts caused by drilling water will be studied.

The status of the work during the reporting period is to focus on the exploration of the data from the Sicada database and to perform M3 modelling for the Äspö SDM project. The aim was to investigate the mixing proportions of the different waters types present in the boreholes at Äspö (i.e. KAS, HAS and the boreholes from the tunnel) and calculate the changes of the mixtures.

The main modelling is based on the following reference waters: old saline, glacial, marine (Littorina Sea) and meteoric water. Some additional modelling is planned for the end of this period in order to investigate the potential influence of the Baltic Sea water in the marine signature in some fractures.

The main results of this ongoing project have been presented at the 13th international Water Rock Interaction symposium (http://wri13.cicese.mx/) which was held on the 20th of August.

The major results for the Äspö SDM project are:

- Meteoric and Glacial reference water dominate in the mixtures (Figure 7-5).
- Meteoric and Glacial water proportions change moderately over time in most of the sampled fractures at Äspö.
- Old saline and marine reference water proportion are stable with time in most of the Äspö fractures.
- In some specific fractures, some changes in mixing proportion with time are noticed. These changes are connected with the increase of the salinity (Figure 7-5).
- Baltic Sea water influence is clearly identified from the increased Mg content in some of the samples.
- In addition to mixing, chemical reactions have altered the water composition.

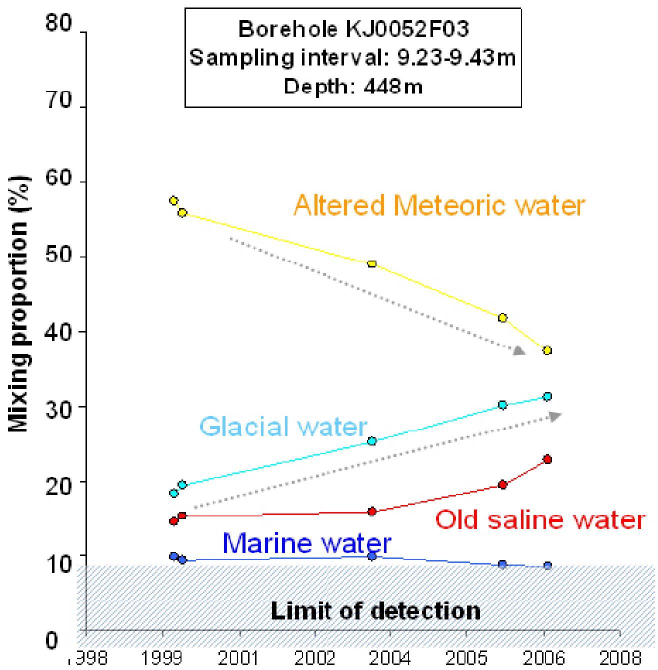


Figure 7-5. *Changes of the mixing proportions with time in the borehole KJ0052F03 in the Äspö tunnel.*

Spin-off effects from the project:

- The Äspö SDM project is a test case for methods and descriptions to be used when constructing the final repository.
- The modelling will give understanding of the groundwater evolution during and after the tunnel constructions in crystalline bedrock.

7.3.4 Geobiology of microbial mats in the Äspö tunnel (University of Göttingen)

Aim and setup:

The aim of the project is to study biomineralisation, biogeochemistry and biodiversity of chemolithotrophic microorganisms in the Äspö Tunnel.

Three sets of flow reactors, each consisting of four units, were installed in 2006 and connected to aquifers of different chemical composition and age at sites TASA1327B (Figure 7-6), NASA 2156B, TASF. These flow reactors enable a contamination-free study of the spatial and temporal development of microbial communities and associated mineral precipitates. Since the installation, the flow reactors are routinely sampled two or three times per year for monitoring physicochemical fluctuations, microbial communities, and microbial mat development. A part of the project will continue until the end of 2011. Long-term experiments are planned to continue for indefinite time.

In addition to high-resolution mineral, element and biomolecular studies of mineralizing microbial mats, corresponding studies are performed on SKB drill cores to elucidate biosignatures of fossil deep biosphere communities in fracture minerals. These studies are performed using Time-of-Flight secondary ion imaging mass spectrometry (ToF-SIMS, in cooperation with SP, Borås) and Raman spectroscopy.

Microbiological Results:

16S rDNA-DGGE analyses reveal that fluid-borne microorganisms (of aquifers down to 2156B) largely reproduce the pristine mat structures and compositions in the flow reactors compared to an open pond system. Sulphate-reducing bacteria similar to *Desulfolobus propionicus, Desulfobacterium autotrophicum* and *Desulfotalea psychrophila*, as well as the methanotrophs *Methylomonas sp*. and *Methylobacter sp*. have been shown to occur ubiquitously in all mat systems. Microbial mats dominated by the iron-oxidizers *Mariprofumdus sp.* and *Gallionella ferruginea*, are generally multilayered systems containing also bacteria similar to ammonia-oxidizers like *Nitrosomonas sp*., to the sulphur-oxidizing *Thiocapsa sp*., and the lithoheterotrophic alpha-proteobacterium *Citricella thiooxidans.* The aquifer of the deepest section (TASF) clearly differs from all other sites investigated with respect to community composition, biofilm structure and complexity.

Figure 7-6. *Flow reactor set (white boxes) installed at TASA 1327B in 2006.*

Geochemical results:

Analysis of Trace and Rare Earth Element (TREE) accumulations within iron oxidizing microbial mat communities in the dark and air-tight flow reactors at TASA 1327B (Figure 7-7) and NASA 2156B revealed a massive (up to 10^6 fold) accumulation of most of the TREE within the mineralized microbial mats after two and nine months, respectively.

Time-of-flight secondary ion mass spectrometry (ToF-SIMS) was implemented as a new method for identifying organic biomarkers and spatially resolves their distribution directly on geobiological samples. ToF-SIMS imaging was successfully applied to microscopic cryosections of mineralized microbial mats to correlate specific lipid biomarkers (e.g. glycerophospholipids, archaeal tetraether lipids) with their source organisms.

An integrated geochemical approach to microbial biosignatures preserved in fracture minerals obtained from drill core KJ 0052F01 enabled the identification of several fracture mineral generations and a putative ancient biofilm that may have existed during a late glacial period, when the fracture was reactivated and water conducting.

Potential spin-off effects from the project:

Microbial mats accumulating TREE may potentially be used for the recovery of precious trace elements, and for water remediation purposes. These microbial communities or synthetic systems with similar properties may serve as an organic filter/buffer also for capturing radionuclides. Defining biosignatures of recent and ancient deep biospheres will be helpful for palaeo-environmental reconstructions, which may also support considerations about the long-term storage of nuclear waste.

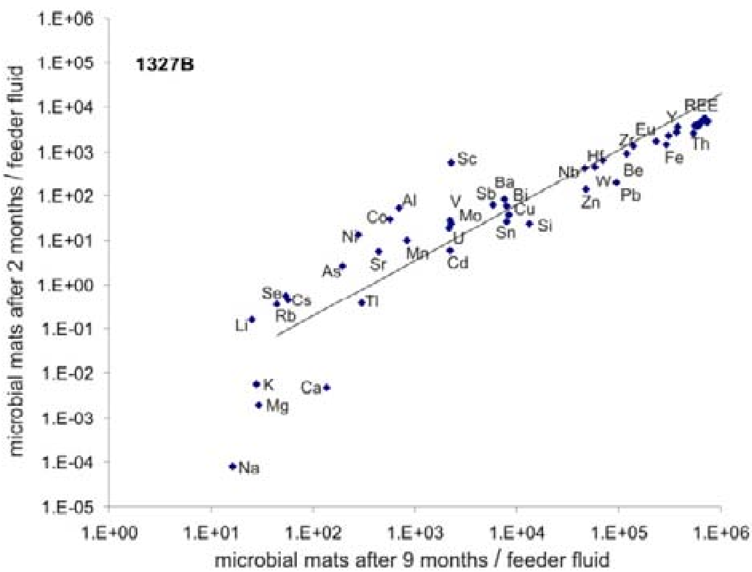


Figure 7-7. *Trace and rare earth element accumulation within iron oxidizing microbial mats in dark and air-tight flow reactor at TASA 1327B after 2 and 9 months respectively (normalized on the supplying aquifer).*

7.3.5 Coastal modelling (Royal institute of technology, KTH)

The aim of the project is to study hydrogeological pathways and coastal dynamics with integrated transport and altering processes in water from land to the Sea.

A DarcyTools flow model for Forsmark has now been completed. Compared to earlier Forsmark models, new surface elevation data and also newly developed surface hydrology features have been included. This enables to obtain more complete flow patterns from soil infiltration to the Baltic Sea, including flow through the surface waters (lakes and streams), overburden and the bedrock in greater detail than has been done in the past. All flow is assumed to be laminar and driven by pressure/gravity. In its current form, the model assumes a uniform (average) aquifer depth. Additional complexity of the spatially variable overburden/soil depth in the catchment is now added by using the developed soil model from SKB. With this feature, the model will capture all major structural complexity, from complicated sub-catchments and surface water areas, to variable overburden and conducting fracture zones of the bedrock. Testing of the flow model is currently in progress in collaboration with experienced model developers.

Once the flow testing is completed, particle tracking will be implemented for computing the water transit times within the catchment, and evaluating the flow/transport partitioning between different sub-domains (surface and subsurface). Identification of the hydrological pathways and transit times will provide key quantities for understanding the basic hydrology and for investigations of reactive transport and geochemical analysis of the existing data, or for geochemical modelling.

7.3.6 3D localisation system of persons, the Alfagate project (NeoSys AB)

The aim is to develop and apply RFID (Radio Frequency Identification) technology in tunnel environment. The technology is used to identify in 3D persons or objects in the tunnel environment. The project creates an open software structure which is not dependent of hardware and which will be integrated with other Äspö HRL systems.

The server software/driver Charon is used as the link between the hardware and the database within the Alfagate project. AlfaGate Admin is the software which handles the administrative parts of the system. The AlfaGate Tracker is the visualisation part of the system which shows the locations of the persons in the tunnel (Figure 7-8) and is used in the control room. A simpler version of the visualisation system is the AlfaGate viewer which is used in areas for the public. AlfaGate Pending is the gateway system controlling persons entering and leaving the tunnel.

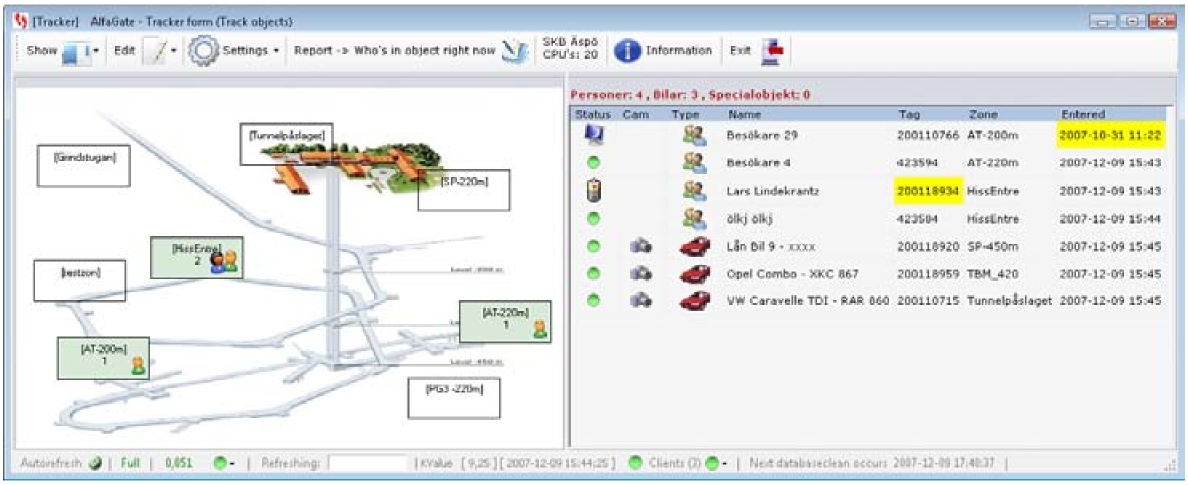


Figure 7-8. AlfaGate Tracker is the visualisation system which shows the locations of the persons in the Äspö HRL.

The status of the project is that it is in the development phase towards the commercial systems of TaggMaster, Aeroscout and Identec.

The major results are that the AlfaGate system is further developed towards the Identec's RFID HW and supports TagMasters RFID HW systems.

The spin-off effect from the project is that there is a great commercial interest for the system in Sweden and abroad. Additional local competences are needed in the company and cooperation agreements with local companies are discussed.

7.3.7 Integrated fire protection, the SAFESITE project (NeoSys AB)

SKB requires a fire security system based on the best available technology. The aim of the SAFESITE project is to integrate the detection and verification of smoke or fire together with the entrance and logistic control of people and vehicles. True integration with the RFID system and other security systems are required.

The major results are that international companies such as Siemens and Niscaya have shown great interest and are included in the testing and verification of the system to be installed.

The spin-off is great interest from companies and organisations to follow the development of the SAFESITE system.

7.3.8 Utilisation of waste energy, the EoS project (Municipality of Oskarshamn)

The EoS (Eden of Sweden) project focus on utilising the waste heat from different industrial process plants. EoS is aiming at demonstrating the latest technology for energy efficiency e.g. within housing, water cleaning, leisure facilities, green house production and as a research facility. The project is of national and international interest due to the huge amount of waste heat available globally and which can be utilized as a resource. The spin-off effect of this project is that it will create local competence in a field of potential global interest. A feasibility study is ongoing and will list about five possible research projects within the field of utilisation of low graded heat.

7.3.9 Detailed fracture mineral investigations (Linnaeus University)

The aim of the project is to characterise and gain information from fracture minerals in bedrock fractures. Investigations of fracture minerals provide a useful tool to understand palaeohydrogeological conditions. Groundwater in crystalline rocks is mainly transported along fractures and different groundwaters subsequently flowing along fractures may precipitate a sequence of minerals on the fracture walls. Examination of these mineral coatings ideally yields a palaeohydrogeological record of formation temperatures, fluid compositions and potential origin. The project will lead to publications of several scientific papers on fracture minerals and their input to the understanding of past and present redox conditions in the bedrock, groundwater-mineral interactions, biological activity in bedrock fractures, stability of groundwater systems in Proterozoic rocks etc.

7.3.10 Expert group for the harbour remediation project in Oskarshamn (Municipality of Oskarshamn)

The aim of the expert group is to support and scientifically review the harbour remediation project in Oskarshamn. An expert group under the management of Nova FoU has been formed consisting of experts from the company Land, Water and Waste Management Group AB (LWWMG) and from the institution of Natural science at the Linnaeus University.

7.3.11 Hydrochemical interaction between a tunnel and its surroundings – development of prediction models (Chalmers university of technology)

Investigations carried out show that groundwater recharge in rock increases during the building phase of underground constructions. The project aims to investigate the following related changes:

- Provide a deeper insight into and quantify chemical changes in surface water and groundwater caused by underground construction within a catchment area.
- Create an understanding of how the chemical change in the groundwater caused by underground construction can in turn affect reinforcements in the underground constructions, grouting measures and the functioning of the drainage system.
- To further develop numerical modelling tools to facilitate the use of data that can be gathered before the construction phase of an underground facility in order to assess, which hydrochemical conditions will prevail during the construction, and operational phases of the facility.

Research and development initiatives will also provide a basis for improving the content of environmental impact assessments in conjunction with underground projects. Furthermore the project aims to provide a basis for constructing safer tunnels with cost-effective maintenance.

The primary focus of the proposed project is to use acquired knowledge to create prediction models with the aim to predict hydrochemical changes in conjunction with underground construction, based on information gathered prior to the construction phase.

7.3.12 Trace elements in fracture minerals and groundwater (Linnaeus University)

The overall aim of the project is to characterise and describe the variability in concentrations of lanthanoids and other trace elements in fracture minerals and ground waters in Proterozoic bedrock. In more detail, the aims are to:

- Determine the distribution of lanthanoids and other trace elements in a variety of fracture minerals, including different generations of calcite, fluorite and pyrite.
- Determine the concentrations of lanthanoids and other trace elements in dissolved and colloidal form in the groundwater.

The solid-phase studies will focus on several generations of fracture minerals collected from bedrock cores stored in Oskarshamn (collected during the site investigation). The analyses will be carried out in the Department of Earth Sciences, University of Gothenburg. Shortly, the minerals are identified using SEM and optical microscopy, carefully picked by hand from grind material and mechanically cleaned from impurities of other mineralogical phases. Selected minerals are thereafter dissolved with appropriate acid for each mineral and the solutions subsequently analysed by ICP-MS (Agilent 7500a ICP-MS).

The groundwater studies will focus on collecting lanthanoids and other trace elements with DGT samplers (passive samplers) in 4-5 selected boreholes in the Äspö tunnel.

7.3.13 Corrosion protection of rock bolts (Swerea KIMAB AB)

Rock bolts made of carbon steel, galvanised steel, galvanised and epoxy coated carbon steel or stainless steel are rock reinforcement alternatives in tunnels. The corrosion-related lifetime for cast-in bolts is uncertain as is the corrosion protection capacity of the coatings now used, due to insufficient data. On openly exposed visible parts serious damage is frequently observed within short time whereas the state of parts in the rock is largely unknown.

The purpose is to formulate requirements for corrosion protection of rock bolts and to provide a technical and economical basis for a rational selection of materials and coatings. A further aim is to gain increased knowledge of the corrosion effects of groundwater in contact with rock bolts.

Quality control methods that are relevant for corrosion resistance of rock bolts and similar parts on real-life conditions will be developed. The efficiency of available corrosion protection will be experimentally documented.

8 International co-operation

8.1 General

Nine organisations from seven countries has in addition to SKB participated in the co-operation at Äspö HRL during 2010, see Table 8-1. Six of them; Andra, BMWi, CRIEPI, JAEA, NWMO and Posiva together with SKB form the Äspö International Joint Committee (IJC), which is responsible for the coordination of the experimental work arising from the international participation. Numo (Nuclear Waste Management Organisation of Japan) was represented as an observer at the IJC-meeting in May, 2009 and May 2010. Nagra left the central and active core of participants 2003 but are nevertheless supporting the Äspö activities and participates in specific projects.

Several of the participating organisations take part 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. Several of the participating organisations also take part in the project Alternative Buffer Materials.

SKB also takes part in work within the IAEA framework. Äspö HRL is part of the IAEA Network of Centres of Excellence for training in and demonstration of waste disposal technologies in underground research facilities.

Table 8-1 Prioritised activities for the International co-operation during 2010

Projects in the Äspö HRL during 2010	Andra	BMWi	CRIEPI	JAEA	NWMO	Posiva	Kaeri	Nagra	Rawra
Natural barriers									
Long Term Sorption Diffusion Experiment									
Colloid Transport Project					X				
Microbe Project		X							
Task Force on Modelling of Groundwater Flow and Transport of Solutes			X	X	X	X	X		
Engineered barriers									
Prototype Repository		X				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				
Task Force on Engineered Barrier Systems		X	X		X	X		X	X

Participating organisations:
Agence nationale pour la gestion des déchets radioactifs, Andra, France.
Bundesministerium für Wirtschaft und Technologie, BMWi, Germany.
Central Research Institute of the Electronic Power Industry, CRIEPI, Japan.
Japan Atomic Energy Agency, JAEA, Japan.
Nuclear Waste Management Organisation, NWMO, Canada.
Posiva Oy, Finland.
Korea Atomic Energy Research Institute, Kaeri, Korea.
Radioactive Waste Repository Authority, Rawra, Czech Republic.

8.2 Andra

Andra, the French radioactive waste management agency, carries out an extensive research and development programme at Bure (Meuse/Haute-Marne District) in order to support the conception and licensing processes of a deep geological disposal called CIGEO (Centre Industriel de stockage Geologique).

In the framework of this R&D program, the main interests of our participation in the Äspö activities are related to:

- Interaction between the materials involved – iron, glass, clay, cement – and the rock in natural conditions.
- Construction and management of the disposal cells.
- Sealing of the shafts and drifts.

In this context, Andra has been involved in 2010 in three major experiments: TBT, Lasgit and ABM. These projects are all devoted to the understanding of the THMC behaviour of Engineered Barrier Systems. Andra has, however, decided to stop its participation to the EBS Task Force.

8.2.1 Alternative buffer materials

Andra has been involved in the ABM project at different levels:

- It has provided different clay materials to be put in the different parcels: Callovo-Oxfordian claystone (COX) either as intact slices or as crushed material to be recompacted like the other bentonites and a European Georgian bentonite (Deponit).
- It has supported a large scale laboratory experiment called AMB_2 built and monitored by the CEA, to study the THMC behaviour of the recompacted claystone under conditions representative of the in situ test.
- It supports three laboratories (CEA, G2R and LEM) to conduct chemical and textural analysis of different clay materials after dismantling of the parcels.

In 2010, the ABM_2 experiment has been dismantled. The claystone and the pore water are being analysed. A tentative modelling of the experiment is being conducted. The final report of this study will be available in the following months.

Samples of different clays materials: MX80, Deponit, Febex and COX; have been analysed with different complementary techniques by the three Andra's partners: FTIR, XRD, Gl-µXRD, TEM, SEM, SEM-EDX, µRaman. The accuracy of most of these techniques was previously tested on samples coming from the LOT project.

Far from the interface with the iron heater, no evidence was found of significant chemical or textural transformations or evolutions of the initial material. Microscopic observations were made difficult by mounds developed on the clay between dismantling and analysis. Nonetheless, modifications of clays that occurred are hydrolysis, cation exchange in the interlayer space of smectites, few Fe and Mg enrichments for MX80 and Deponite, common crystallizations of Ca carbonates and Ca sulphates, possible formation of zeolites in Febex bentonite.

At the interface /Schlegel 2010/ with the iron heater, chemical transformations in three distinct faces were observed. The first type was made by a magnetite layer in contact with iron metal. Between this magnetite layer and clay, a (Fe, Si, O) layer is observed, with locally significant concentrations in S and Mg. This layer presumably corresponds to a Fe-phyllosilicate layer. Such an interface is typical of anoxic dissolution at temperature > 50°C. In contrast, the second type of interface features a layer of magnetite, usually close to the surface, but sometimes well separated from it, and laterally pseudomorphosed into (Fe, Ca) carbonates. No (Fe, Si, Mg) layer could be observed in association with this magnetite layer, but (Fe, Ca) carbonates were often present. Some of the Ca-carbonate was shown to be aragonite. Finally, the third kind of interface showed little if any corrosion. This diversity is attributed to differences in the initial state of the tube surface.

Results were presented the partners during the 2010 meeting in Stockholm.

8.2.2 Temperature buffer test

Andra is especially involved in the Temperature Buffer Test which is running since 2003 and has already produced major expected THM results. Temperature Buffer Test dismantling began late 2009 and was carried out until end of April 2010. Information on the bentonite blocks mechanical behaviour has already been collected. New data on bentonite evolution came with the samples analysis and the result mapping of final hydration state is now available. With access to the data from the dismantling operation, the THM modelling of the field test was resumed at the end of 2010. The plan is to continue with and finalise this modelling during the first half of 2011.

8.2.3 Large scale gas injection test

Lasgit is now integrated in the FORGE (Fate of repository gases) European project. Andra is active in this European project through two major experiments on gases at Bure. Therefore Andra continues to support this experiment but is not more directly active.

8.3 BMWi

In 1995 SKB and BMBF (Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie) signed the co-operation agreement being the framework and the basis for participating in the R&D 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 Bundesministerium für Wirtschaft und Technologie (BMWi) four 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), and Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig.

The general purpose of the co-operation is to complete the state of knowledge concerning potential host rocks for high-level waste repositories and, especially to extend the knowledge on the behaviour of the 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 work carried out in 2010 is described below.

8.3.1 Microbe project

Introduction

The contributions of the Forschungszentrum Dresden-Rossendorf (FZD)/Institute of Radiochemistry (IRC) to the microbe project are related to the characterization of interaction processes of selected actinides (U, Pu, Cm) with planktonic cells and biofilms generated by Äspö relevant bacteria. The work is focused on studying: (i) the generation and characterization of planktonic cells and biofilms produced by the Äspö bacterium *Pseudomonas fluorescens* under aerobic conditions, (ii) the interaction of selected actinides with planktonic cells and those fixed in a biofilm, and (iii) the spectroscopic characterization of the formed actinide species.

The activities in 2010 were concentrated on (a) the cultivation and characterization of planktonic cells of the Äspö-bacterium *P. fluorescens*, (b) studying interaction of U(VI) with planktonic cells of the Äspö-bacterium *P. fluorescens*, and (c) the generation of biofilms of the Äspö-bacterium *P. fluorescens* and studying the effect of the addition of U(VI) to these biofilms. Selected results of these topics will be reported here.

Interaction of uranium (VI) with Pseudomonas fluorescens planktonic cells

The interaction of U(VI) with *P. fluorescens* was studied in terms of the metal accumulation capability of the cells in dependence on the parameters $[U(VI)]_{initial}$, [dry biomass] and pH. Besides the quantitative determination of the uranium bound, time-resolved laser-induced fluorescence spectroscopy (TRLFS) was applied to investigate the uranium binding form at the cell surface and in the supernatants at different pH. It was also tested whether different binding forms exist when comparing "inactive" cells in a background electrolyte ($NaClO_4$) to metabolically "active" cells in minimal medium.

The investigated strain accumulates strongly pH-dependent large amounts of U(VI) with a maximum sorption at pH 6.0. It was shown that in $NaClO_4$ in the cell pellets as well as the supernatants U(VI) evidently is bound to phosphate groups, and if attached to the cell surface at pH 7.0–8.0 there presumably is additional hydroxide bound. On the contrary, in minimal medium U(VI) is precipitated on the cell surface as a uranyl phosphate mineral phase.

The strain *Pseudomonas fluorescens* CCUG32456 which has been isolated at Äspö HRL was cultivated in nutrient broth medium (DSMZ medium 1a) at pH 7.0 and 30°C. For U(VI) interaction experiments cells were harvested in the mid-exponential growth phase. The purity of the strain was analyzed with light microscopy, by plating and in situ PCR with subsequent restriction fragment length polymorphism (RFLP). RFLP typing involved the restriction enzymes *Hae*III, *Cfo*I and *Rsa*I. U(VI) accumulation experiments were carried out in 0.1 M $NaClO_4$ as background electrolyte at constant pH varying a) $[U]_{initial}$ from 0.4 to 138 mg/L and b) [dry biomass] from 0.05 to 0.6 g/L. Unless varied, [U(VI)] was set to 1·10–4 M and [dry biomass] to 0.2 g/L. Investigated pH values were 4.0, 6.0, 7.0, and 8.0 for a) and only 6.0 for b). After 48 h U(VI) contact the cells were centrifuged and supernatants were analyzed regarding [U(VI)] and [Phosphate] with ICP-MS and ion-exchange chromatography, respectively. To determine the U(VI) speciation, thereby gained supernatants and cell pellets washed in 0.1 M $NaClO_4$ were investigated using TRLFS. To compare these results to the binding of U(VI) by "active" cells, *P. fluorescens* was suspended in reduced standard succinate medium, to a final [dry biomass] of 0.2 g/L and incubated with U(VI) analogously to the experiments in 0.1 M $NaClO_4$. The washed cell pellet and the supernatant were analyzed with TRLFS. To visualize U(VI) accumulation by *P. fluorescens* TEM-EDX measurements were done.

The resulting RFLP profile for purity analysis of the cells is exemplarily shown in Figure 8-1 a. The purity analysis yielded pure cultures of *P. fluorescens* used for the U(VI) experiments.

Figure 8-1b illustrates the accumulation of U(VI) by *P. fluorescens*. Presumably U(VI) is accumulated mainly by biosorption onto the cell surface. The accumulation is strongly pH-dependent (see Figure 8-2a). A sorption maximum at pH 6.0 is traversed followed by a decrease towards higher pH. At pH 6.0 the cells accumulate 5 times as much U(VI) as at pH 4.0 at an initial [U(VI)] of ~140 mg/L.

Investigating the U(VI) accumulation in dependence on the dry biomass concentration, an asymptotic behaviour of the sorption can be observed (Figure 8-2b). The sorption levels off at about 97–98% sorbed U(VI). Hence, regardless of [dry biomass] some free uranyl will remain in solution. Consequently, this is an indication for ligands release by *P. fluorescens* leading to UO_2^{2+} mobilization. It has been validated by ion-exchange chromatography that significant phosphate liberation takes place. Using TRLFS, a UO_2^{2+} coordination with phosphate in the cell supernatants could be proven, as will be shown in the following. The U(VI) luminescence spectra of all measured supernatants (pH 4.0, 6.0, 7.0 and 8.0) as well as the cell pellets at pH 4.0 and 6.0 were very similar concerning their band positions. Thus a similar coordination must exist. All spectra of the cell pellets and supernatants are strongly red-shifted in comparison to those of the bacteria-free UO_2^{2+} reference solutions (comparison of references to an exemplary spectrum see Figure 8-3a). Mentioned spectra are characterized by emission bands at 498, 518 and 540 nm.

A comparison to the literature, in specific the emission bands of $UO_2(HPO_4)_{aq}$, $UO_2PO_4^-$ and $UO_2(H_2PO_4)^+/UO_2(HPO_4)$, suggest that a coordination of U(VI) by phosphate is very probable. An additional coordination via carboxylic groups cannot be excluded. Figure 8-3b in comparison to Figure 8-3a indicates a pH dependence of the U(VI) speciation at the cell surface. Nevertheless, the characteristic main emission band at about 518 nm is preserved at pH 7.0 and 8.0, although here a very broad UO_2^{2+} hydroxide-like spectrum is observable. Thus a ternary surface complex involving phosphate and hydroxide is conceivable, but has to be validated.

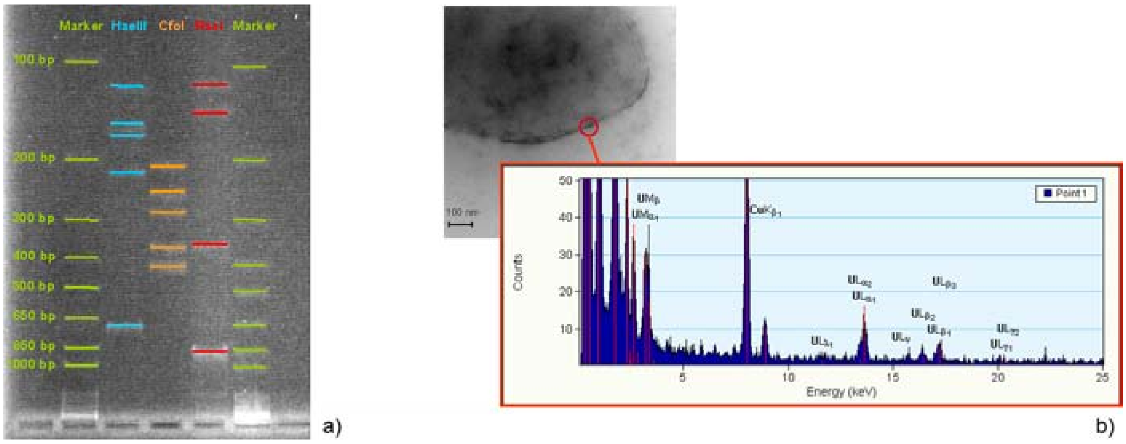


Figure 8-1. *a) Restrictions digest profiles. Marker (green), digests with HaeIII (blue), CfoI (orange) and RsaI (red). b) TEM image with corresponding EDX diagram showing biosorption of U(VI) onto the cell surface.*

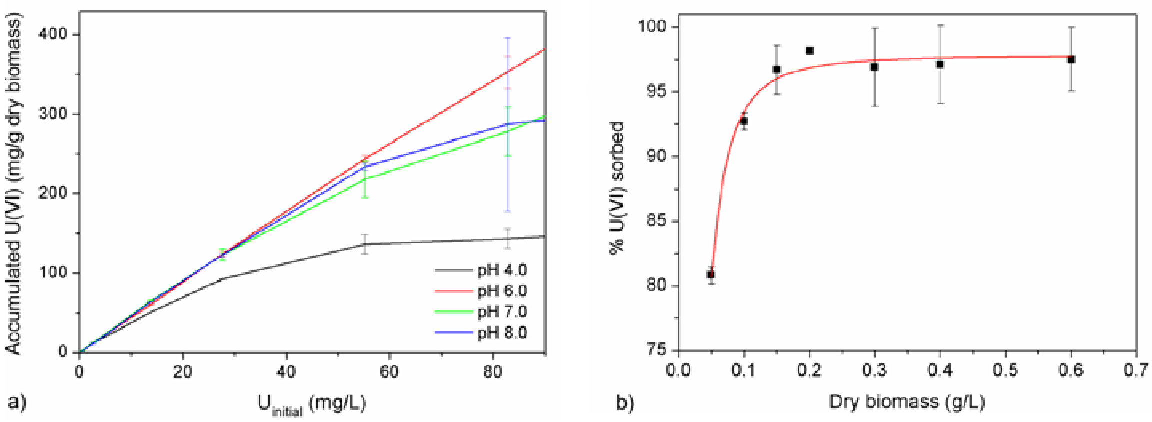


Figure 8-2. *a) U(VI) accumulation versus* $[U]_{initial}$ *in 0.1 M* $NaClO_4$*. b) U(VI) accumulation versus [dry biomass] in 0.1 M* $NaClO_4$ *at pH 6.*

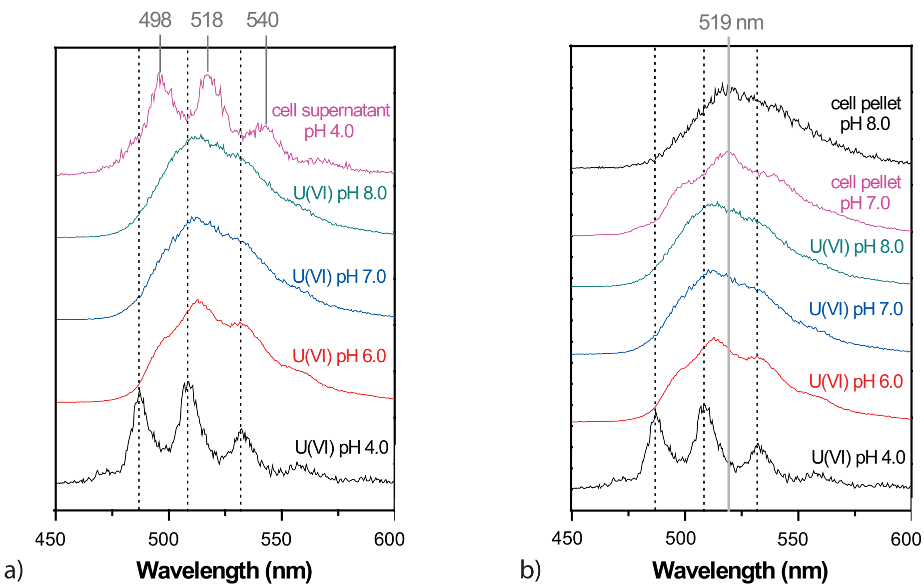


Figure 8-3. *a) U(VI) luminescence spectrum of cell supernatant at pH 4.0 in comparison to spectra of bacteria-free U(VI) solutions. b) U(VI) luminescence spectrum of cell pellets at pH 7.0 and 8.0 in comparison to spectra of bacteria-free U(VI) solutions.*

On the contrary, UO_2^{2+} with "active" cells in the tested standard succinate medium seemingly forms a uranyl phosphate mineral phase. A comparison to spectra of different minerals in the literature indicates the likelihood of meta-autunite or sodium uranyl phosphate to be present at the cell surface. The complex formed by U(VI) binding to the cell surface is characterized by main emission bands at 502, 523, 546 and 572.5 nm (Figure 8-4).

This spectrum is slightly red-shifted in comparison to the spectra of U(VI) in uninoculated medium and in the supernatant. Since latter spectra overlap almost completely. Thus in the supernatant a similar complex must be present as in the uninoculated medium. In the future EXAFS measurements will be done for precise structure determination. But already a very interesting finding could be made: in minimal medium in presence of *P. fluorescens* a uranyl precipitate is formed in contrast to the cells in 0.1 M $NaClO_4$. Whether this is an active process or not has to be investigated.

The effect of the addition of uranium to Pseudomonas fluorescens biofilms – a preliminary report of microsensor studies

The effect of uranium added in ecologically relevant concentrations ($1{\cdot}10^{-5}$ M) to *P. fluorescens* biofilms was studied by electrochemical oxygen microsensors in preliminary experiments. Microsensor measurements of the redox potential and oxygen concentration were performed in order to obtain information about the redox processes, the changes of the migration behaviour of uranium and consequently the bioremediation potential of the biofilm. For this purpose *P. fluorescens* biofilms were formed in a previously tested rotating annular biofilm reactor with a stationary outer and a rotating solid inner cylinder. On the outside of the inner cylinder eight vertically positioned glass slides with a dimension of 76×26×1 mm were placed in recessed slots on which biofilm could be formed. The Äspö strain *P. fluorescens* CCUG32456 was cultivated in a previously tested synthetic nutrient medium consisting of 0.5% (w/v) glucose, 0.25% (w/v) peptone, 0.125% (w/v) yeast extract in phosphate buffer with a pH 7 ± 0.2. In the mid-exponential growth phase the culture was harvested and the optical density was adjusted to 0.2 at 600 nm. After the addition of 9 ml of the *P. fluorescens* culture to 1 L of the synthetic nutrient medium, the medium was pumped through the biofilm reactors with a flow-rate of 15 mL/min whereas the inner cylinder rotated with 14 rpm. Since the medium was re-circulated and the experiments were performed in air atmosphere under sterile conditions, two types of biofilms developed very fast within 3 days. A thin biofilm was located on

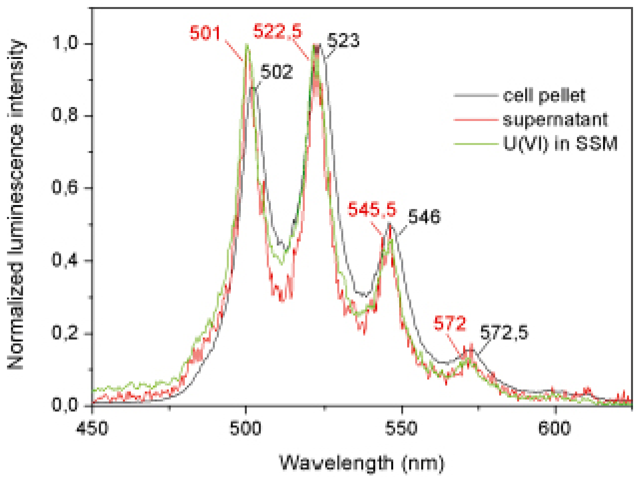


Figure 8-4. *Luminescence spectra of U(VI) with P. fluorescens cells, in the supernatant and in uninoculated standard succinate medium, pH 7.0.*

the glass slides at the glass/air/media interfaces. However, thick, mucilaginous biofilms were formed in the culture medium. These biofilms were used for preliminary microsensor experiments. The biofilm was removed from the culture medium and put inside a rectangular flow cell (Figure 8-5). During every experiment, 50 ml of the culture media was pumped through the flow cell in a closed circuit with a flow rate of 4 mL/min. Concentration profiles of oxygen were measured in the biofilms by means of electrochemical microsensors of the micro-Clark design (Unisense, Denmark) with a tip diameter of 10 µm. For redox potential measurements a miniaturized platinum electrode from Unisense with a tip diameter of 10 µm was connected via a high-impedance millivoltmeter to a reference electrode, a simple open-ended Ag/AgCl electrode with a gel stabilized electrolyte. After the measurements the obtained values were corrected using a correction factor, which is dependent on the temperature and the molar concentration of the electrolyte of the reference electrode.

The results of the microsensor measurements clearly showed a difference between the geochemical parameters of the nutrient medium in comparison to the measured values in the biofilm. The redox potential inside the biofilm showed a value of 70 ± 20 mV, which is approximately 290 mV lower than the redox potential of the surrounding medium. The low redox potential of the biofilm indicates a high respiratory activity of the microbes due to the high content of nutrients in the medium. Similarly, the oxygen concentration in the biofilm is lower compared to the medium, indicating high oxygen consumption in the biofilm, too. After the first measurements, uranium was added to the nutrient medium in ecologically relevant concentrations. For this purpose 50 µl $1\cdot10^{-2}$ M $UO_2(ClO_4)^2$ were added to 50 ml of the culture media to adjust the uranium concentration to $1\cdot10^{-5}$ mol/l U(VI). The first microprofiles in the biofilms were recorded 20 hours after the addition of uranium. The redox potential increased from 70 ± 20 mV to 259 ± 20 mV, whereas the oxygen concentration remained low. The results clearly showed an effect of the addition of uranium, indicating that the microbes of the biofilm battle the toxic effects of aqueous uranium. Furthermore, the redox potential within the biofilm indicates oxidizing conditions with the consequence that aqueous uranium of the nutrient medium is not immobilized by the biofilm. The first obtained results will be verified by further studies on *P. fluorescens* biofilm grown on the glass slides at the glass/air/media interfaces, which are more environmentally sensitive.

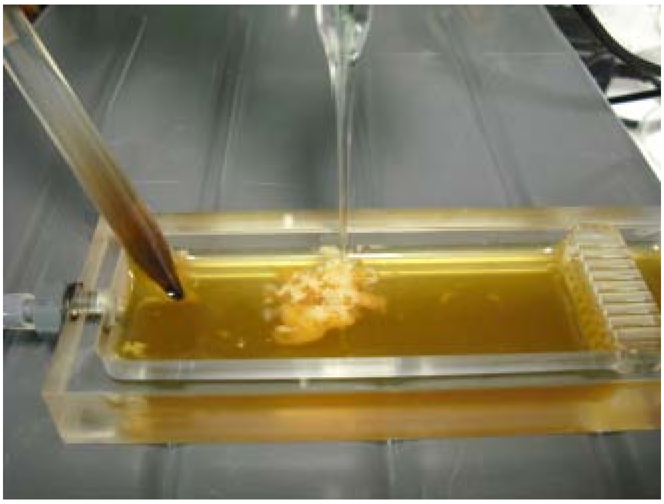


Figure 8-5. *Thick, mucilaginous biofilm, formed in the culture medium. The biofilm was exposed from the biofilm reactor into a flow cell for microsensor measurements.*

8.3.2 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 dependence of the electrical resistivity of geomaterials on their water content. In order to enable correlation of the measured resistivity with the actual water content, laboratory calibration measurements were performed in the geotechnical laboratory of GRS in Braunschweig, Germany.

The measuring programme, agreed on by SKB and GRS, includes the monitoring of two electrode arrays in the backfilled drift above the deposition boreholes 3 and 6, an electrode array in the buffer at the top of deposition hole 5, and three electrode chains in the rock between deposition holes 5 and 6, see Figure 8-6.

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 2010, the measurements have been continued. 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.

Since 2008, however, a slight increase in resistivity has been detected (see Figure 8-7). 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 %. This increased resistivity centre has stabilized in the following years. The electrodes affected by the resistivity increase are those located close to the tunnel roof – the injected current is by two orders of magnitude lower than at the other electrodes. This becomes visible when these electrodes are neglected in the evaluation (right hand side of Figure 8-7). The resulting resistivity distribution is very homogeneous with values around 2 Ωm.

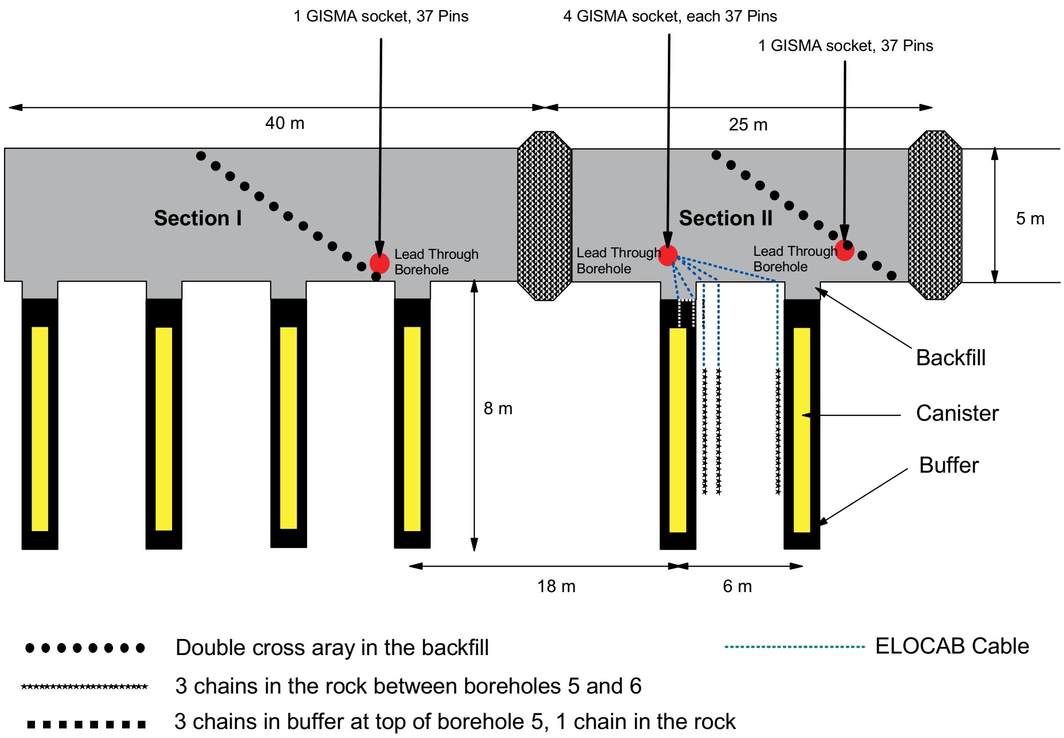


Figure 8-6. *Arrangement of electrode arrays in the Prototype Repository.*

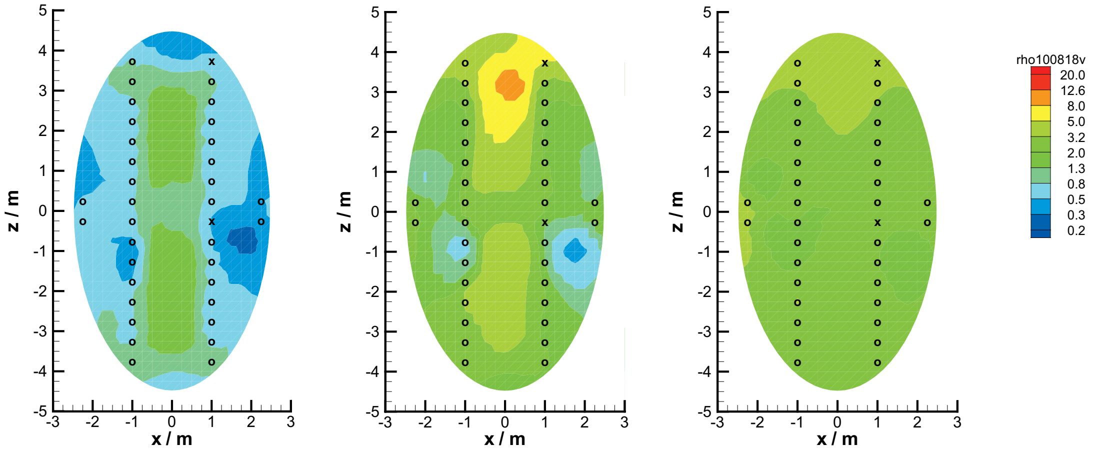


Figure 8-7. *Resistivity distributions in the backfill in Section I, November 2007 (left) and August 2010 (centre), and August 2010 when neglecting the electrodes close to the roof (right). o: Electrodes. Colour scale in Ohmmeter.*

A possible reason for the resistivity increase close to the roof may be the continuous pumping of water out of section I, which may have led to a slight desaturation or a settling of the backfill, which resulted in a degradation of the electrode coupling.

In Section II, the resistivity decreased to values around 2 Ωm in the whole cross section by the end of 2009, meaning full saturation of the backfill. In 2010, a slight resistivity increase in the tunnel centre was observed, which may also be due to pumping activities.

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 in 2011 will yield the necessary information. Additional to electrode retrieval and inspection, samples of the backfill and buffer will be taken and analysed in terms of water content and resistivity for confirmation of the in situ measurement results.

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 characterizes 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.

8.3.3 Alternative buffer materials

All results obtained on the 10 different bentonite blocks were summarized in an internal BGR progress report. Based on this report and the project meeting in April 2010 in Lund the most interesting result is the obvious redistribution of the exchangeable cations. According to the experimental setup blocks produced from rather different bentonites were in contact throughout the heating period. Apart from chemical and mineralogical differences, the bentonites had a completely different exchangeable cation population. The results proved that this exchangeable cation population changed significantly. Obviously a rather complete cation exchange process occurred in the vertical direction, e.g. from one bentonite block to the other. Such an observation was never made before.

Therefore, the 2010 research concentrated on the characterisation of this phenomenon. The interface between different bentonite blocks which stuck together after the experiment was investigated. A project internal round robin-like test was initiated called '*laboratory exchange of cation exchange capacity and exchangeable cation measurements using Cu(II)-triethylentetramine method*' which is based on 'Alternative buffer material test' reference materials. This test is conducted in order to probe the comparability of the results of exchangeable cation population from different laboratories.

8.3.4 Temperature buffer test

As an extension to the previous thermo-hydraulic modelling, the mechanical behaviour of the bentonite buffer was addressed focussing on the bentonite swelling. Coupled thermo-hydro-mechanical simulations with swelling according to Grob's Law were performed using the FLAC3D code. By means of a global sensitivity analysis the significance of the model parameters were evaluated. Based on the most significant parameters an automatic model calibration was performed using the software "optislang" which allows optimizing nonlinear tasks with many parameters. The software is able to offer a sampling-based sensitivity analysis to identify important parameters, quantify their influence and generate a so called best design in comparison to measurement results taken in situ. "Optislang" acts as controlling software that generates FLAC3D runs by itself by changing the input parameters automatically based on given ranges.

Analysis I

Using "optislang" as an optimization tool or just for parameter identification needs a careful evaluation of input parameters was performed. "Optislang" changes the parameters automatically and starts self-sufficient new calculations. To get a suitable set of input parameters as start values, the input parameter should be oriented for example to the laboratory measurement results. For each parameter a range has to be specified within which "optislang" is allowed to change the parameter during its analysis. To identify the important parameters for the transient processes and to reduce the overall calculation time, a simulation time of about 200 days was assumed to be adequate for this test of automatic model calibration. The description of the numerical model and used constitutive laws was given in the last annual report and is just referred to here /SKB 2009/.

Parameter variation

Table 8-2 shows the model parameter and the ranges of variation. For the parameter measured in the laboratory it is assumed that the values are rather confident. Therefore those parameters were varied only within a small range of 20%. All other parameters were varied within a range of 50%. The fixed heads in the sand filter were varied up to the fixed pressure applied to the lower injection points, assuming that pore pressure applied to the injection points, is spreading quite well in the permeable sand. The lower bound is chosen to be almost double of the atmospheric pressure.

Objective function

The distance between the measured (x_{obs}) and the calculated data (x_{calc}) is evaluated using an objective function, which is a sum of the equally weighted Euclidian distance calculated for selected temperature, radial and axial stress sensors:

$$d(x_{calc}, x_{obs}) = \sqrt{\sum_{i=1}^{n} \left(x_{calc,i} - x_{obs,i}\right)^2}$$

In Table 8-3 the selected sensors are listed.

Table 8-2. Model parameters, initial values and variation ranges for analysis I.

No	Parameter	Optislang-name	Initial value	Variation [%]	Range Lower bound	Upper bound
1	Density Bentonite	bento_dens	2,000	5	1,900	2,100
2	Density Granite	granit_dens	2,750		2,613	2,888
3	Density Sand	sand_dens	1,800		1,710	1,890
4	Density Sand filter	sandfil_dens	1,800		1,710	1,890
5	Young's Modulus Bentonite	bento_young	4.70E+09	50	1.00E+08	7.05E+09
6	Young's Modulus Granite	granit_young	5.50E+10		2.75E+10	8.25E+10
7	Young's Modulus Sand	sand_young	5.54E+07		2.77E+07	8.31E+07
8	Young's Modulus Sand filter	sandfil_young	5.54E+07		2.49E+07	8.31E+07
9	Fixed pore pressure boundary Sand 1	fixpp1	7.00E+05		2.00E+05	7.00E+05
10	Fixed pore pressure boundary Sand 2	fixpp2	2.00E+05		2.00E+05	7.00E+05
11	Fixed pore pressure boundary Sand 3	fixpp3	2.00E+05		2.00E+05	7.00E+05
12	Fixed pore pressure boundary Sand 4	fixpp4	2.00E+05		2.00E+05	7.00E+05
13	Fixed pore pressure boundary Sand 5	fixpp5	2.00E+05		2.00E+05	7.00E+05
14	Fixed pore pressure boundary Sand 6	fixpp6	2.00E+05		2.00E+05	7.00E+05
15	Fixed pore pressure boundary Sand 7	fixpp7	2.00E+05		2.00E+05	7.00E+05
16	Grob's Law: Maximum Swelling Deformation	MaxQuellDef	0.05	50	0.025	0.075
17	Grob's Law: Maximum Swelling Pressure	MaxQuellDruck	2.20E+07		1.10E+07	3.30E+07
18	Grob's Law: Parameter	GrobParam	–0.005		–0.0075	–0.0025
19	Intrinsic Permeability Bentonite1	bento1_int_perm	2.53E–19	20	4.83E–23	1.00E–18
20	Intrinsic Permeability Bentonite2	bento2_int_perm	3.19E–19		6.38E–23	1.00E–18
21	Intrinsic Permeability Sand	sand_int_perm	1.00E–18		2.51E–22	1.00E–18
22	Intrinsic Permeability Sand filter	sandfil_int_perm	1.00E–18		2.51E–22	1.00E–18
23	Porosity Bentonite1	bento1_poro	0.389	50	0.195	0.584
24	Porosity Bentonite2	bento2_poro	0.368		0.184	0.552
25	Porosity Sand	sand_poro	0.300		0.150	0.450
26	Porosity Sand filter	sandfil_poro	0.360		0.180	0.540
27	Specific Heat Capacity Bentonite	bento_spec_heat	1,091	20	873	1,309
28	Specific Heat Capacity Granite	granit_spec_heat	775		620	930
29	Specific Heat Capacity Sand	sand_spec_heat	900		720	1,080
30	Specific Heat Capacity Sand filter	sandfil_spec_heat	900		720	1,080
31	Thermal Expansion Coefficient Bentonite	bento_thexp	3.00E–05	20	2.40E–05	3.60E–05
32	Thermal Expansion Coefficient Granite	granit_thexp	7.00E–06		5.60E–06	8.40E–06
33	Thermal Expansion Coefficient Sand	sand_thexp	1.20E–05		9.60E–06	1.44E–05
34	Thermal Expansion Coefficient Sand filter	sandfil_thexp	1.20E–05		9.60E–06	1.44E–05
35	Heat Conductivity Bentonite	bento_wleitf	1.30	20	1.04	1.56
36	Heat Conductivity Granite	granit_wleitf	2.60		2.08	3.12
37	Heat Conductivity Sand	sand_wleitf	1.70		1.36	2.04
38	Heat Conductivity Sand filter	sandfil_wleitf	1.70		1.36	2.04

Table 8-3. Sensors considered in the objective function.

Temperature	Axial stress	Radial stress
TB208	PB201	PB202
TB230	PB208	PB204
TB247	PB214	PB213
TB261	PB218	PB215
TB283	PB227	PB217
		PB226
		PB228

Coefficients of importance

The coefficients of importance (CoI) are a prediction value to explain the influence of a single input parameter (like density, thermal conductivity, etc) on a chosen output parameter (like the measured stress at a single sensor). Depending on the regression model the CoI is defined by:

$$R^2_{-colc,obs} = R^2_{calc} - \frac{\sum_{k=1}^{N} (\gamma^{(k)}(x_{calc}) - x\mu_{obs})^2}{\sum_{k=1}^{N} (x^{(k)}(x_{calc}) - x\mu_{obs})^2}$$

Results

Figure 8-8 shows the most influential parameters on the overall objective function.

Different parameters are relevant for the single Euclidian distances of the individual temperatures and the stresses:

Stress:	**Temperature:**
(1) Maximum swelling pressure	(1) Thermal conductivity host rock
(2) Intrinsic permeability bentonite 1	(2) Thermal conductivity bentonite
(3) Porosity bentonite 1	(3) Intrinsic permeability bentonite 1
(4) Young modulus bentonite	(4) Porosity bentonite 1
(5) Maximum swelling deformation	(5) Specific heat capacity host rock
(6) Specific heat capacity host rock	(6) Parameter C of Grob (for swelling law)
(7) Young modulus sand filter	
(8) EYoung modulus sand	

The axial stresses at the sensors PB217 and PB226 are governed by a different ranking of the relevant parameters. Both sensors are influenced by a too small saturation, which changed only after beginning of water injection at the upper tubes of the sand filter. This results in a particular stress build up which differs from the stress evolution at the other sensors. The fitting of the measured and the calculated curves is not sufficient, as shown in Figures 8-9 and 8-10. Especially the calculated stresses do not lie within the range of the measured stresses. The correlation of the measured and the calculated curves is quite poor as well.

Analysis II

In view of the unsatisfactory fitting of calculated and measured curves in the first analysis; a second analysis was performed using different parameter ranges and a slightly different modelling of the swelling process. It was supposed that one reason for the very high calculated stresses could be an insufficient simulation of the swelling process. Therefore the range of the Grob's model parameter "Maximum Swelling Pressure" was changed and an additional parameter was introduced which represents a threshold for the swelling (swell_sat), ensuring that swelling does only take place when the saturation exceeds the initial saturation of the bentonite. The density of the materials was assumed to be known and was therefore not varied during the analysis. Different ranges and corrected initial values for the thermal conductivity were used. The changed parameter set is given in Table 8-4.

Some of the installed stress sensors showed signal characteristics dedicated to physical effects which cannot be reflected by the current model. The measured values were out of range of the results of the calculation or the signal sequence doesn't fit to the results of the numerical model. For this reason the sensors PB201, PB214, PB218, PB217, PB226 and PB228 weren't considered any longer (Example is given in Figure 8-11). The current sensors are shown in Table 8-5. For the evaluation the same objective function was used as before. 41 calculations were carried out with the new approach.

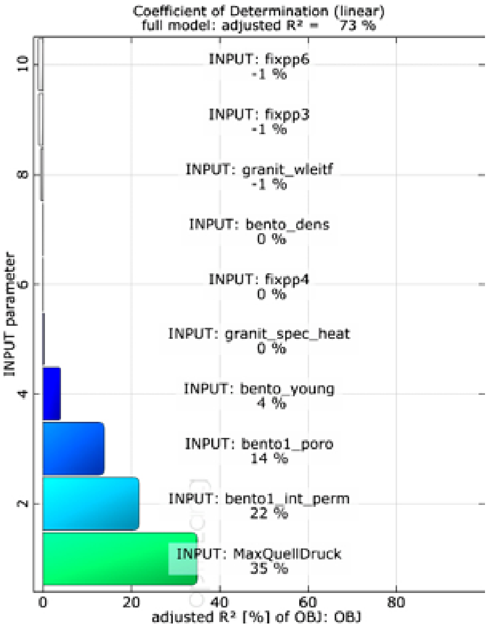


Figure 8-8. *Most influential parameters of the first sensitivity analysis.*

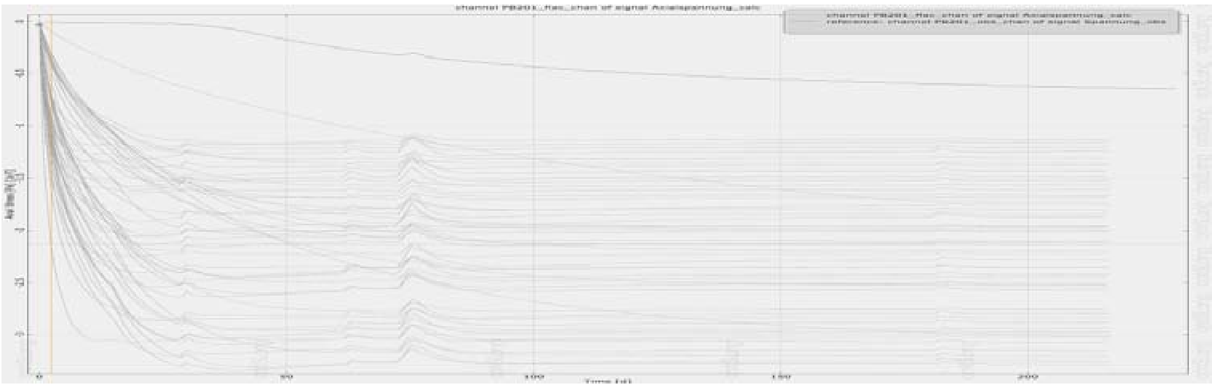


Figure 8-9. *Axial stress PB201.*

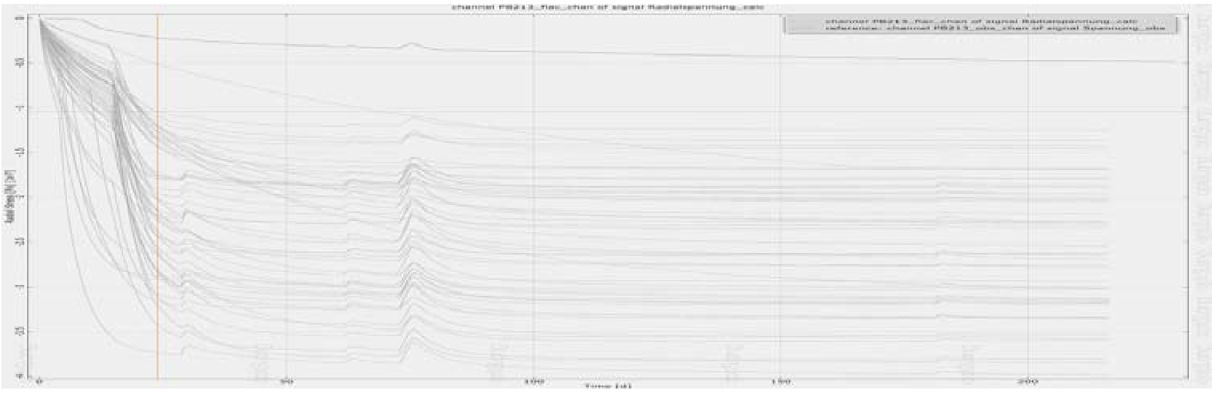


Figure 8-10. *Radial stress PB217.*

Table 8-4. Model parameter Sensitivity 2, highlighted in red are changes to the first analysis.

No	Parameter	Optislang-name	Initial value	Variation [%]	Range Lower bound	Range Upper bound
1	Young's modulus Bentonite	bento_young	4.70E+09	50	1.00E+08	7.05E+09
2	Young's modulus Granite	granit_young	5.50E+10		2.75E+10	8.25E+10
3	Young's modulus Sand	sand_young	5.54E+07		2.77E+07	8.31E+07
4	Young's modulus Sand filter	sandfil_young	5.54E+07		2.49E+07	8.31E+07
5	Fixed pore pressure boundary Sand 1	fixpp1	7.00E+05		2.00E+05	7.00E+05
6	Fixed pore pressure boundary Sand 2	fixpp2	2.00E+05		2.00E+05	7.00E+05
7	Fixed pore pressure boundary Sand 3	fixpp3	2.00E+05		2.00E+05	7.00E+05
8	Fixed pore pressure boundary Sand 4	fixpp4	2.00E+05		2.00E+05	7.00E+05
9	Fixed pore pressure boundary Sand 5	fixpp5	2.00E+05		2.00E+05	7.00E+05
10	Fixed pore pressure boundary Sand 6	fixpp6	2.00E+05		2.00E+05	7.00E+05
11	Fixed pore pressure boundary Sand 7	fixpp7	2.00E+05		2.00E+05	7.00E+05
12	Grob's Law: Maximum Swelling Deformation	MaxQuellDef	0.05	50	0.025	0.075
13	Grob's Law: Maximum Swelling Pressure	MaxQuellDruck	1.00E+06		5.00E+05	1.5E+06
14	Grob's Law: Parameter	GrobParam	–0.005		–0.0075	–0.0025
15	Intrinsic Permeability Bentonite1	bento1_int_perm	2.53E–19	20	4.83E–23	1.00E–18
16	Intrinsic Permeability Bentonite2	bento2_int_perm	3.19E–19		6.38E–23	1.00E–18
17	Intrinsic Permeability Sand	sand_int_perm	1.00E–18		2.51E–22	1.00E–18
18	Intrinsic Permeability Sand filter	sandfil_int_perm	1.00E–18		2.51E–22	1.00E–18
19	Porosity Bentonite1	bento1_poro	0.389	50	0.195	0.584
20	Porosity Bentonite2	bento2_poro	0.368		0.184	0.552
21	Porosity Sand	sand_poro	0.300		0.150	0.450
22	Porosity Sand filter	sandfil_poro	0.360		0.180	0.540
23	Specific Heat Capacity Bentonite	bento_spec_heat	1,091	20	873	1,309
24	Specific Heat Capacity Granite	granit_spec_heat	775		620	930
25	Specific Heat Capacity Sand	sand_spec_heat	900		720	1,080
26	Specific Heat Capacity Sand filter	sandfil_spec_heat	900		720	1,080
27	Thermal Expansion Coefficient Bentonite	bento_thexp	3.00E–05	20	2.40E–05	3.60E–05
28	Thermal Expansion Coefficient Granite	granit_thexp	7.00E–06		5.60E–06	8.40E–06
29	Thermal Expansion Coefficient Sand	sand_thexp	1.20E–05		9.60E–06	1.44E–05
30	Thermal Expansion Coefficient Sand filter	sandfil_thexp	1.20E–05		9.60E–06	1.44E–05
31	Heat Conductivity Bentonite	bento_wleitf	0.80	20	0.24	1.56
32	Heat Conductivity Granite	granit_wleitf	2.60		2.08	3.12
33	Heat Conductivity Sand	sand_wleitf	1.15		0.48	2.04
34	Heat Conductivity Sand filter	sandfil_wleitf	1.15		0.48	2.04
35	Saturation threshold for swelling	swell_sat	0.81		0.799	0.820

Table 8-5. Sensors considered in the objective function.

Temperature	Axial stress	Radial stress
TB208	PB208	PB202
TB230	PB227	PB204
TB247		PB213
TB261		PB215
TB283		

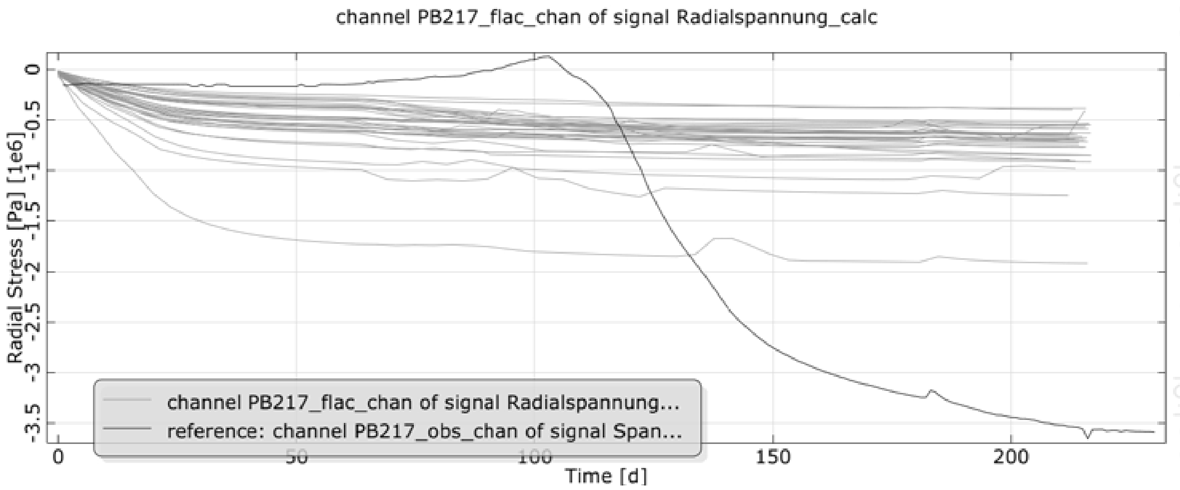


Figure 8-11. *Radial stress PB217.*

Results

After the new simulation of the swelling process the calculated values of the stresses became substantially better. The measured values are within the range of the results of the calculation. Figure 8-12 shows the result of sensor PB213 before and after the change in swelling pressure simulation.

As can be seen in the first view of the calculated values (gray) the measured value (black) for sensor PB213 is completely out of range of the variance of values. The differences are up to 35 MPa. The second view shows the same measured value with the new swelling process. The shape of the measured curve shows a good consistency with the shape of the calculated curve. Even slight fluctuations of the stress are represented in the numerical model as can be seen for example around day 30 or 75. The variance of the input parameters results in an upper bound of the calculated stress at –25 MPa and a lower bound at –2.0 MPa (at 200 days). The other regarded sensors have similar characteristics so that they could be used for the second analysis as well.

Figure 8-13 shows the most influential parameters on the overall objective function of the second sensitivity analysis.

The ability to forecast the model reaction is quite low. Only 47% of the variation of the signals can be explained by correlation to the variation of the input parameters. There is no controlling parameter identified. The most important parameter is the young modulus of the sand. Looking at the influence of the sand young modulus (Figure 8-14) not all sensors were influenced. This means that there are other effects that can't be explained by the current numerical model. This statement is confirmed when looking at selected sensors. At some sensors the most important parameter is not the young's sand modulus.

One example is given below (Figure 8-15). The graphic on the right shows the measured axial stress for the sensor PB208 and the results of the calculation. The chart on the left shows the coefficient of importance for this sensor. As can be see not the young modulus of the sand is the decisive parameter but instead for this sensor the fixed pore pressure in the sand is the essential parameter. The Coefficients of Importance for the young's modulus of the sand for sensor PB208 is equal to zero.

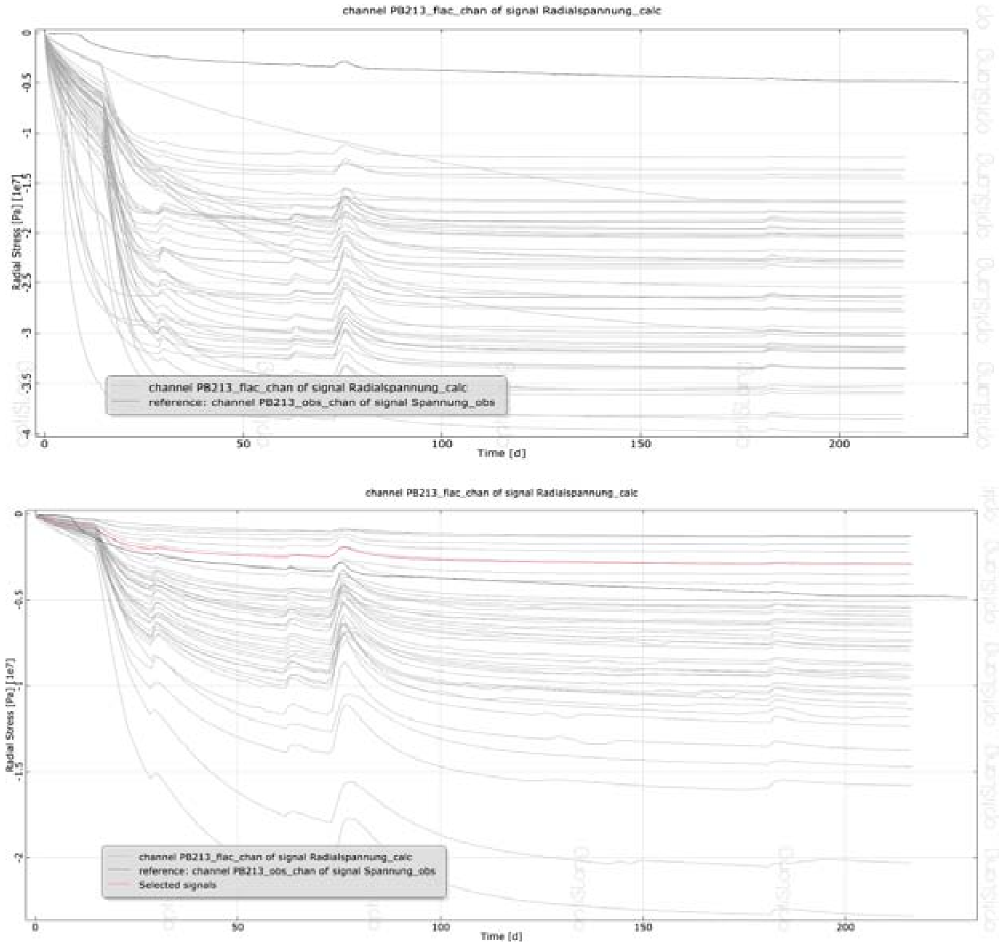


Figure 8-12. Radial stress PB213 before and after the change of swelling simulation.

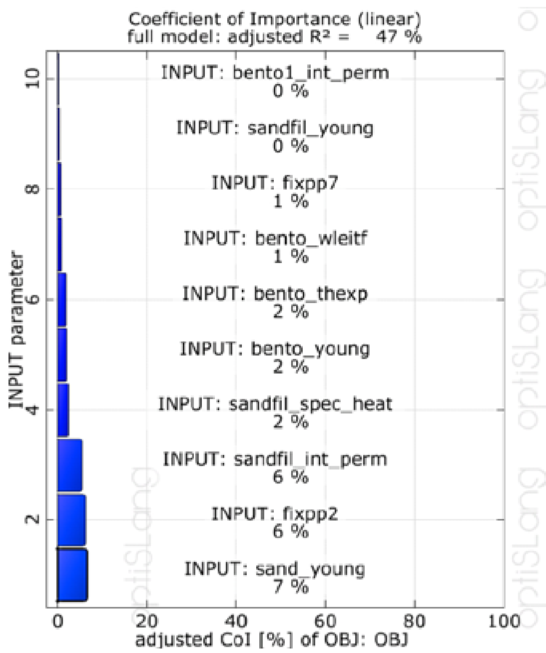


Figure 8-13. Most influential parameters of the second analysis.

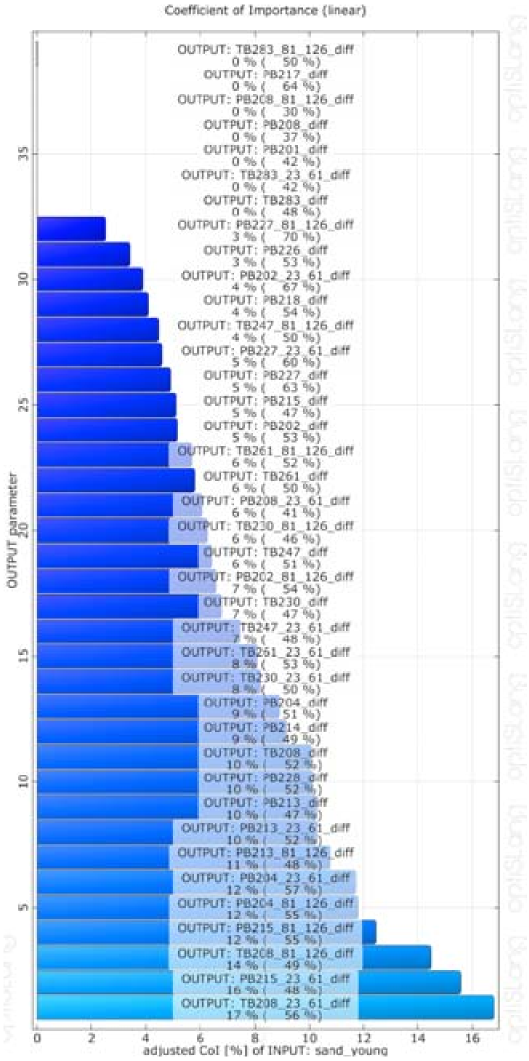


Figure 8-14. *Influence of the sand young modulus to the output functions.*

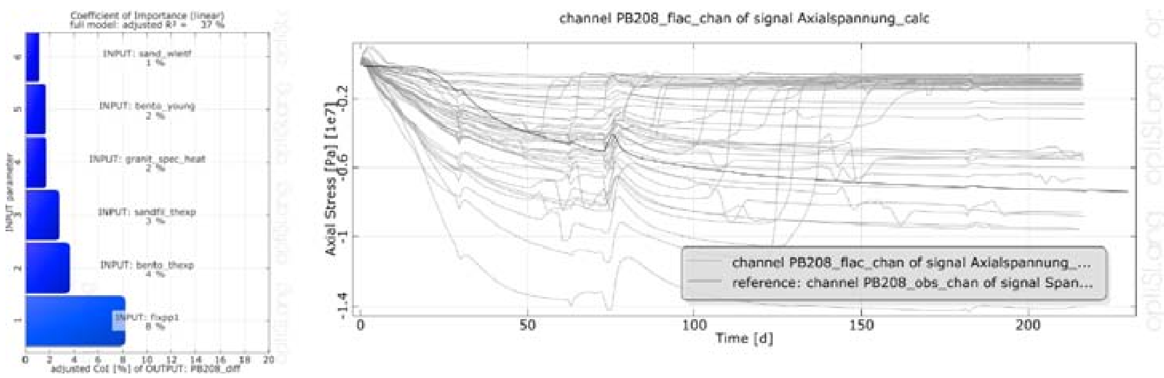


Figure 8-15. *Axial stress PB208 – fixpp1.*

For all considered sensors and especially for the stress sensors different decisive parameters have been identified. Table 8-6 shows this parameter for the considered sensors.

It can be see that only for the temperature sensors (TBs) the Young's modulus of the sand can be clearly identified as a sensitive parameter. For the stress sensors no clear assignment of a sensitive parameter is possible. This confirms the hypothesis that not all of the physical effects can be explained by the current numerical model.

Best Design

Finally there is a best design as one result of the analysis (Figure 8-16). The simulation of the stress has improved with the use of the new way of modelling the swelling process. Through the exclusion of sensors showing effects that could not be represented by the model all measured values lay centrically within the variation of the calculation results. The identified parameters of the best design are within the predefined lower and upper boundaries of the parameter range. Some parameters are situated in the upper and lower 10% limits of the variation but they are still not set to the maximum or minimum value.

This confirms the assumed range of the parameters as suitable. The qualitative representation of the radial stress over time by the model is quite good. The model values of the radial stress represent the failures of the heater shown in the measured values (Figure 8-17). In case of a failure the stress decreased. This effect is represented in a sufficient way by the model. The stress development up to 200 days is underestimated by the model. An exception is sensor PB204 where the stress is calculated as too high. The deviation between measured and calculated values is in a range from 1.25 MPa (sensor PB204) to 2.85 MPa (sensor PB213).

The analysis of the two remaining sensors for the measurement of the axial stress is still problematic. Figure 8-18 shows the comparison of sensor PB208 and PB227.

The failure of the heater around day 73 causes a decrease of the stress in the measured values of sensor PB208. This effect is not well represented in the calculation. The calculated stress at the time of 200 days is underestimated by about 5 MPa. Contrary to expectations sensor PB227 shows a high increase of stress from day 60 to day 73. The model reacts only with a very small decrease of the stress starting from day 73.

Table 8-6. CoI of the considered sensors (most important parameters).

Sensor	optislang-name	Parameter	Coefficient of Importance [–]	Ability to forecast mR^2[%]
TB208	sand_young	Young's modulus sand	10	52
TB230	sand_young	Young's modulus sand	7	47
TB247	sand_young	Young's modulus sand	6	51
TB261	sand_young	Young's modulus sand	6	50
TB283	sand_young	Young's modulus sand	8	48
PB208	fixpp1	Fixed pore pressure boundary Sand 1	8	37
PB227	bento_thexp	Thermal Exp. Coeff. Bentonite	15	47
PB202	granit_wleitf	Heat Conductivity Granite	7	53
PB204	bento_thexp	Thermal Exp. Coeff. Bentonite	9	51
PB213	sand_young	Young's modulus sand	10	47
PB215	bento_thexp	Thermal Exp. Coeff. Bentonite	8	47

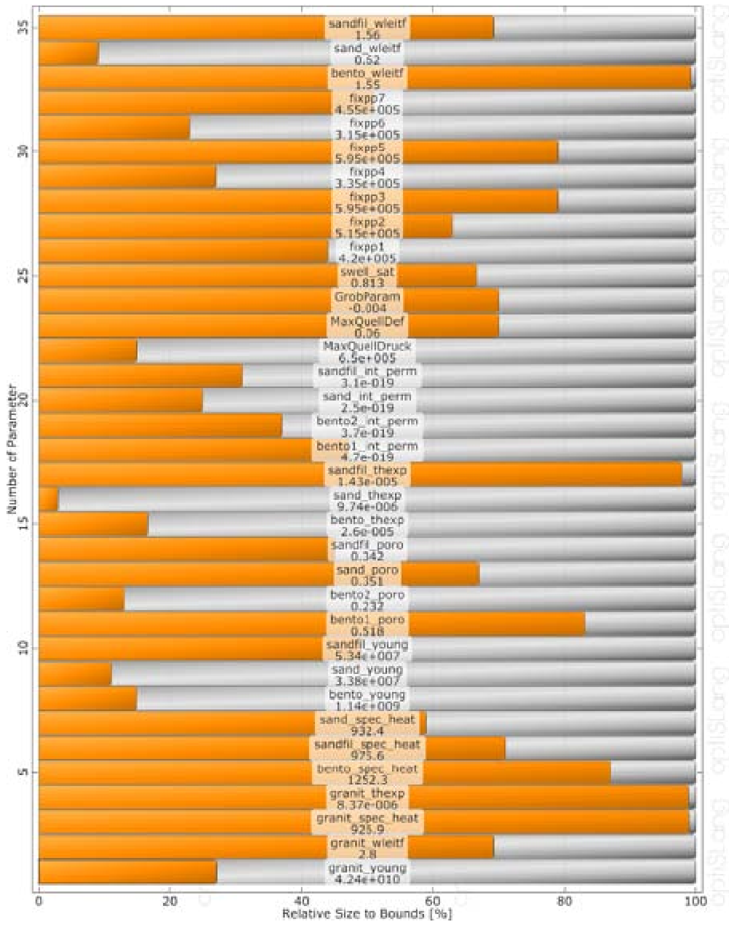


Figure 8-16. *Best design parameters.*

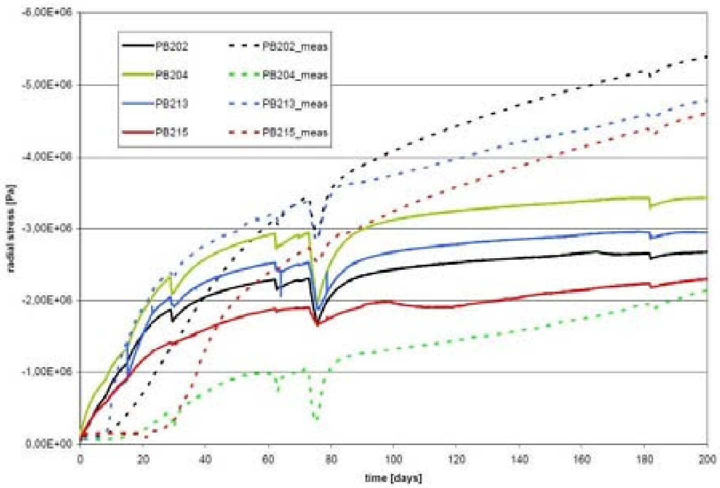


Figure 8-17. *Regarded radial stress sensors – measurement vs. Calculation.*

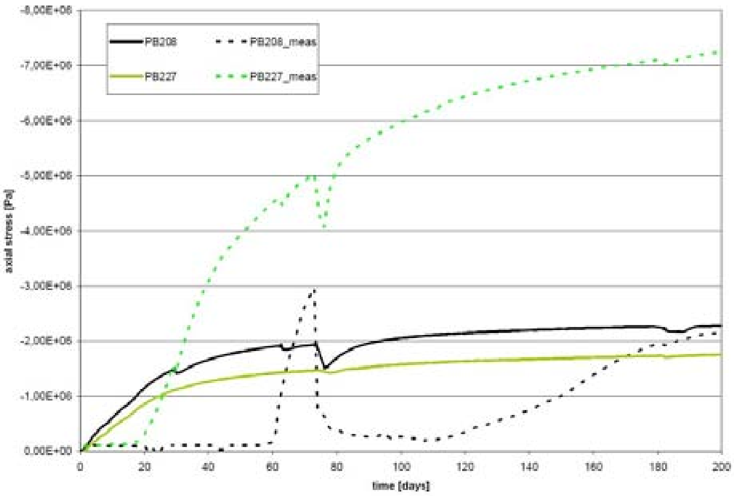


Figure 8-18. *Regarded axial stress sensors – measurement vs. Calculation.*

Summary

As an extension to the previous thermo-hydraulic modelling, the mechanical behaviour of the bentonite buffer was addressed with special focus on the bentonite swelling. Coupled thermo-hydro-mechanical simulations with swelling according to Grob's Law were performed. Based on the most significant parameters an automatic model calibration was performed by using the software "optislang" that allows optimizing nonlinear tasks with many parameters. During the analyses some sensors have been excluded that show effects that could not be represented by the model. Going through two analyses a best design for a parameter set could be defined. With this design the Euclidian distance between the measured and calculated values became minimal. For the current best design parameter set the radial stresses are within a realistic range and can be regarded as a good assessment of the stress within the experiment. The axial stresses still show contradictions. The measurement uncertainty and the effects (especially temperature effects) from the adjoining Canister Retrieval Test were not taken into account. No unequivocal sensitive parameters for the total model could have been defined yet. Reasons could be an insufficient number of parameter sets or an incomplete consideration of all physical effects in the numerical model.

8.3.5 Large scale gas injection test

BGR's activities within the Lasgit project focus on the investigation of processes and interactions that occur in the experiment, particularly with regard to the behaviour of the engineered barrier system and the influence of the excavation damaged zone (EDZ). Test evaluation and modelling exercises are executed using the finite-element code OpenGeoSys (THMC-code). In 2010, the code development was driven further to integrate the modelling of gas transport processes in clay-like materials. Recent developments include a coupled multiphase flow and elasto-plastic model to simulate dilatancy controlled gas migration. Measured data from a series of laboratory gas injection experiments were used to validate the numerical model. The work on the simulation of the Lasgit experiment was continued in 2010. The goal is to simulate the hydration stages and the gas injection tests in a three-dimensional model, taking into account the coupled hydraulic and mechanical processes in the buffer.

8.3.6 Task force on engineered barrier systems

BGR's work on benchmark 2.2 (Canister Retrieval Test) was concluded in the beginning of 2010. THM-coupled calculations of a large scale 3D-model, which included not only the Canister Retrieval Test but also the Temperature Buffer Test, were conducted and evaluated.

Within the new phase of the Task Force on Engineered Barrier Systems, which has started in 2010, BGR will focus on the Sensitivity Analysis. The objective of this upcoming task is to study the effects of value uncertainties on the results of THM-coupled calculations of engineered barrier systems. In 2010, BGR has been working on the task definition for the Sensitivity Analysis.

First model calculations (code Viper) performed in 2008 by GRS in Benchmark 2.2 (Canister Retrieval Test) – matched the measurements only partly. It was assumed, that a missing water transport process was the reason and the work was suspended.

The Benchmark 2.1 (Buffer/Container Experiment and Isothermal Test), however, proved to be successful when the process of interlayer water diffusion was considered in the model. By assuming that this process was the relevant one the work on Benchmark 2.2 was resumed in 2010. However, the extension to non-isothermal diffusion was rather complex and time consuming. Additionally, it became apparent that highly saturated water vapour was flowing from heated to comparatively cool regions in the model. Usually this leads to condensation, but in case of expansive clays it just leads to hydration and swelling. However, if swelling is not any longer possible, condensation would occur in the remaining pore space. Therefore, this effect was also implemented into the model. In the end, it was possible to describe the humidity measurements to a satisfying degree.

Figure 8-19 shows the transient development of relative humidity at three different locations in the middle plane of the canister retrieval test.

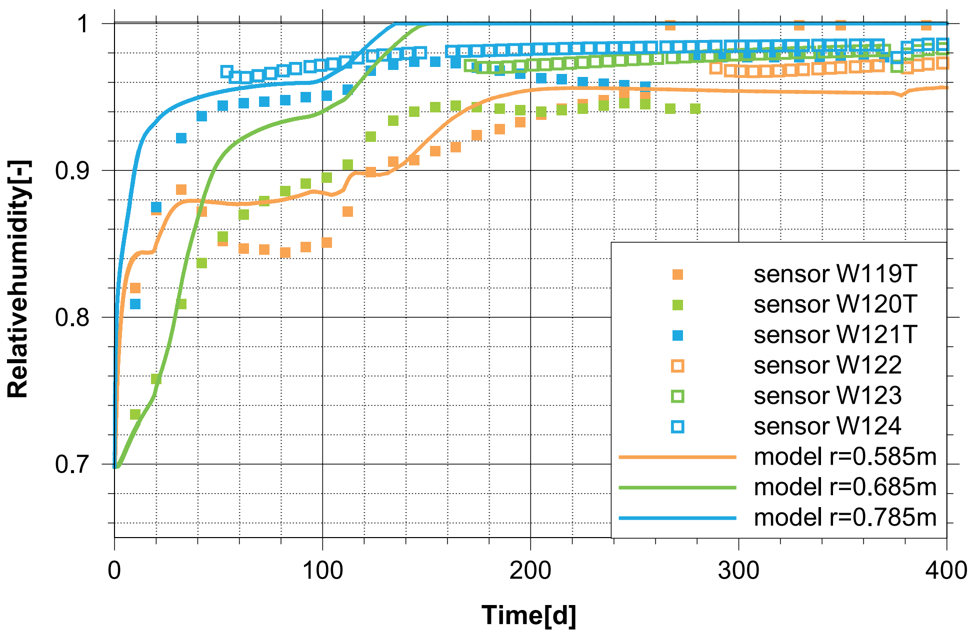


Figure 8-19. *Results from in situ measurements of the CRT (symbols) and from model calculations (lines) including non-isothermal interlayer diffusion.*

8.4 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.

8.4.1 Task force on modelling groundwater flow and transport of solutes

CRIEPI has started the modelling work for sub-task 7C, Posiva Flow Logging (PFL) characterisation and analysis of low permeable fractures and assessment of flow distribution pattern at shaft wall sections at Onkalo, Olkiluoto, Finland. Rock volumes around the target low permeable fractures, FR1-KU2 and FR1-KU3 were modelled, respectively. The dimensions of each model are 40 metres in height and a 30 metres lateral extension. Figure 8-20 shows the finite element mesh used for the numerical simulations around FR1-KU3. The FR1-KU3 is modelled explicitly by using two-dimensional finite elements. On the other hand, the surrounding rock mass with background fractures and observation boreholes are expressed by three-dimensional finite elements. The values of transmissivity were generated in the central part of FR1-KU3 with conditioning of realisations to the values at the boreholes. Figure 8-21shows an example of spatial distribution of the generated transmissivities.

In 2010, a preliminary analysis was conducted by two-dimensional modelling considering only the target fractures and their intersections with the observation boreholes. First single-hole tests and cross-hole tests were simulated. In a single-hole test, a borehole was open and the groundwater inflow to the borehole was measured by PFL, while the other boreholes were closed. On the other hand, in a cross-hole test, all the boreholes were open and the groundwater inflow to each borehole was measured. Figure 8-22 shows the boundary conditions in the numerical simulations for two single-hole tests, s-PP125 and s-PP127 and a cross-hole test, c-PP129 performed in FR1-KU3. In the numerical simulations, the groundwater inflows to the boreholes were calculated and the values of transmissivity of FR1-KU3 at the boreholes were identified to reproduce the measured inflows. Figure 8-23 shows the comparison between the measured inflows and the ones calculated by using 10 realizations of transmissivity field of FR1-KU3 with conditioning to the identified transmissivity values at the boreholes. PFL has been proved to be useful to estimate the transmissivity in low permeable fractures also. Next the spatial distribution of the groundwater inflow to a shaft, KU2 through the other target fracture, FR1-KU2 was simulated by changing the value of correlation length of transmissivity in FR1-KU2. Figure 8-24 shows examples of calculated inflow. The number of the peaks of inflow decreases as the correlation length becomes longer.

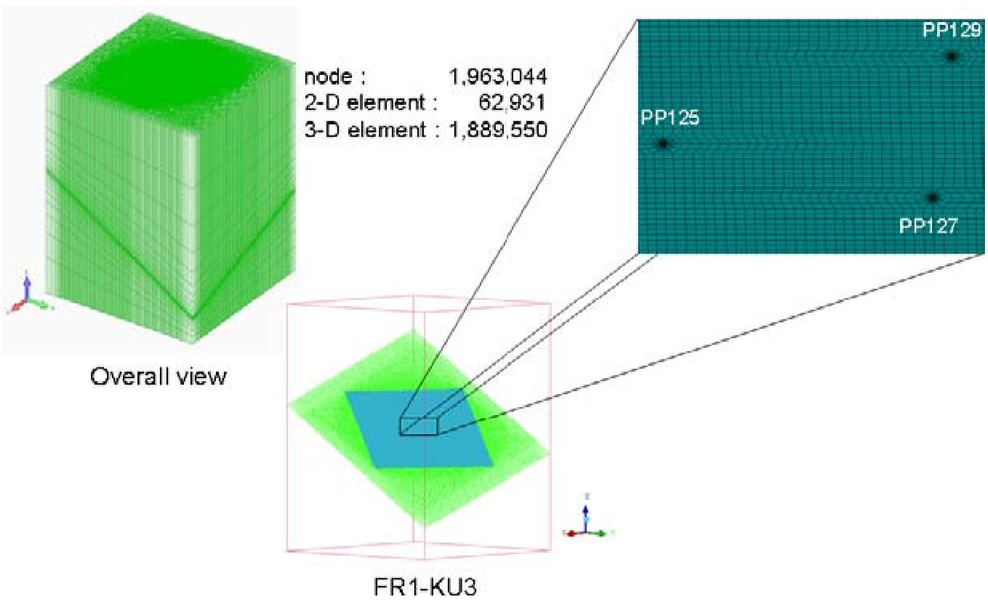


Figure 8-20. Finite element mesh used for numerical simulations for fracture FR1-KU3 in Task 7C.

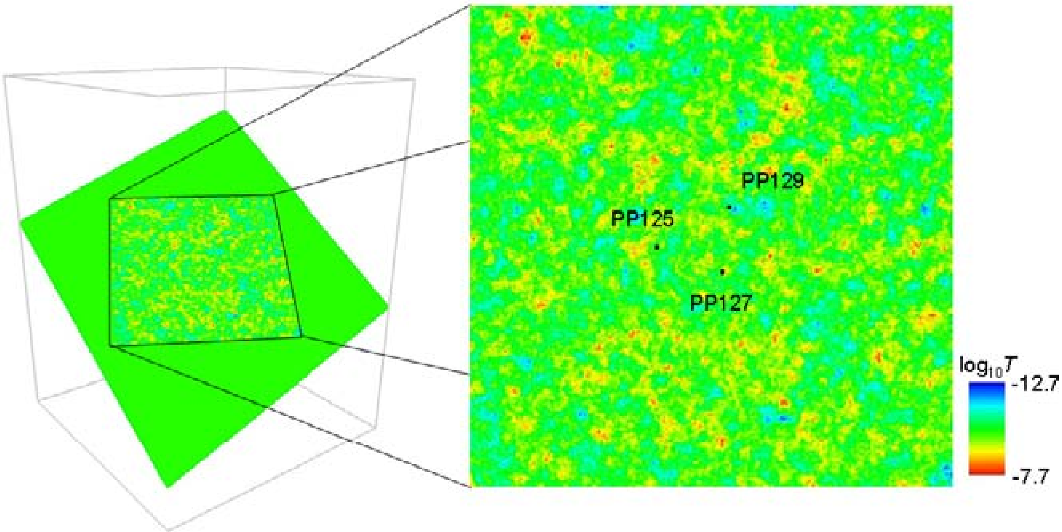


Figure 8-21. *An example of generated transmissivity field for fracture FR1-KU3 in sub-task 7C.*
(a) s-PP125
(b) s-PP127
(c) c-PP129

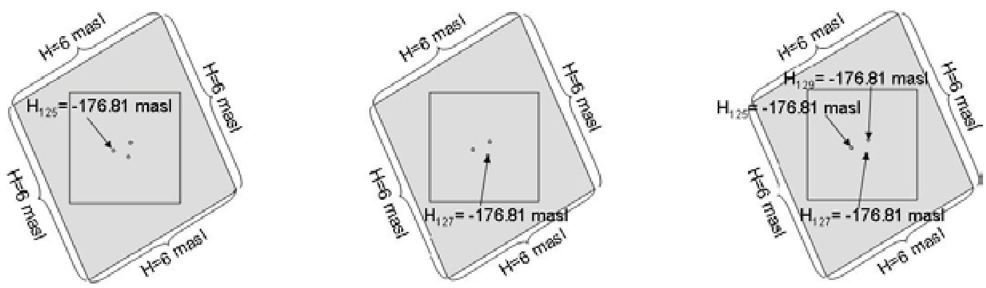


Figure 8-22. *Head boundary conditions in numerical simulations for fracture FR1-KU3 in sub-task 7C.*

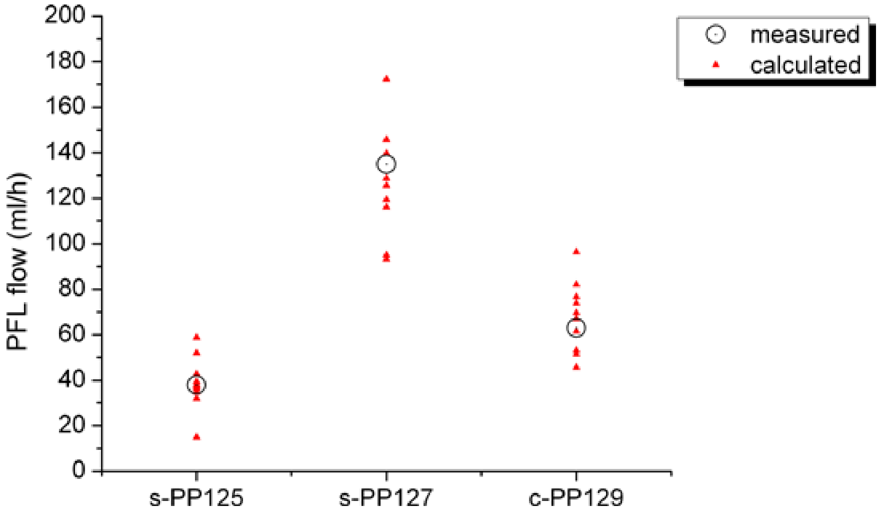


Figure 8-23. *Comparison between measured and calculated inflows to boreholes through fracture FR1-KU3 in sub-task 7C.*
(a) correlation length : 0.15 m
(b) correlation length : 0.3 m
(c) correlation length : 0.6 m

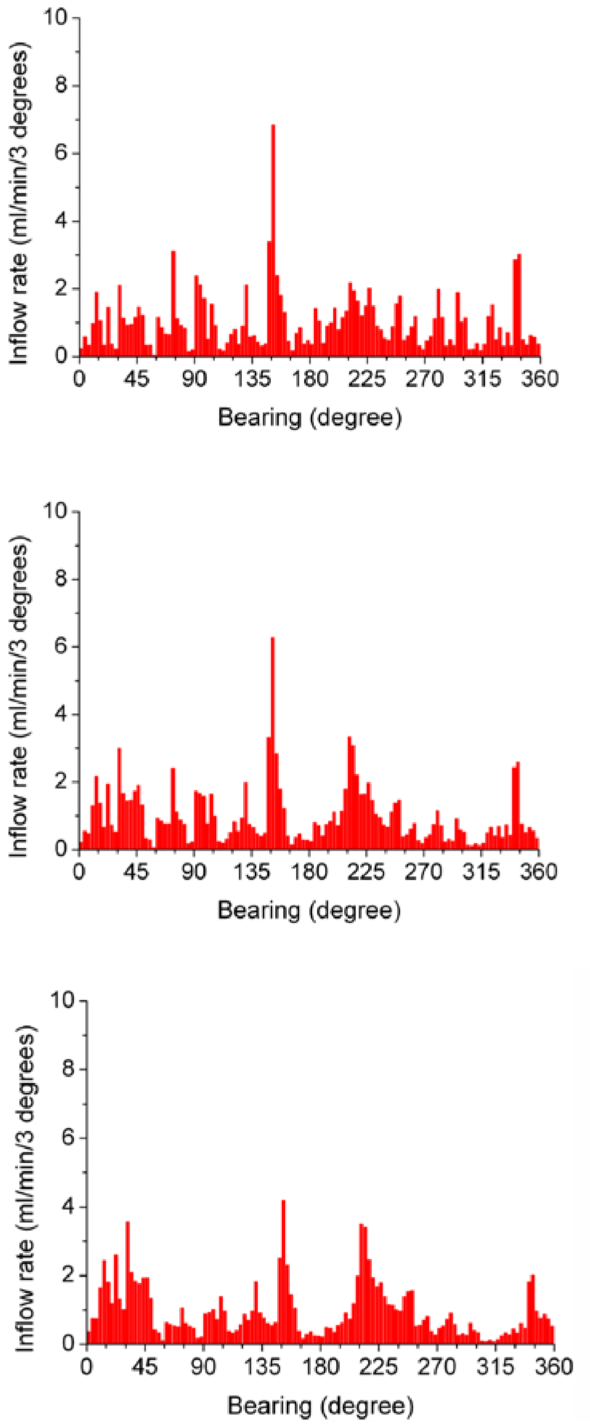


Figure 8-24. *Examples of spatial distribution of calculated inflow to a shaft KU2 through the target fracture FR1-KU2 in sub-task 7C.*

Task 8 started in 2009 with initial scoping calculation. In 2010, CRIEPI continued to conduct the initial scoping calculation.

The geometry and finite element mesh of the initial scoping calculation is shown in Figure 8-25. 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 pore pressure distribution was obtained 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 was modelled through adding elements of bentonite and decreasing the pore pressure in the bentonite down to –100 MPa. Hydraulic properties are shown in Table 8-7.

Contour plots of pore pressure are shown in Figure 8-26 (case 1) and Figure 8-27 (case 2). Contour plots focusing on bentonite are shown at right-bottom of each figure. 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.

Table 8-7. Hydraulic properties of each material.

	Hydraulic conductivity (m/s)	Porosity	P_0 (MPa)	λ
Intact rock	$1.0 \cdot 10^{-12}$	$1.0 \cdot 10^{-5}$	1.74	0.6
Fracture	$5.0 \cdot 10^{-9}$	$1.0 \cdot 10^{-3}$	1.74	0.6
Bentonite	$2.4 \cdot 10^{-13}$	0.44	9.23	0.3

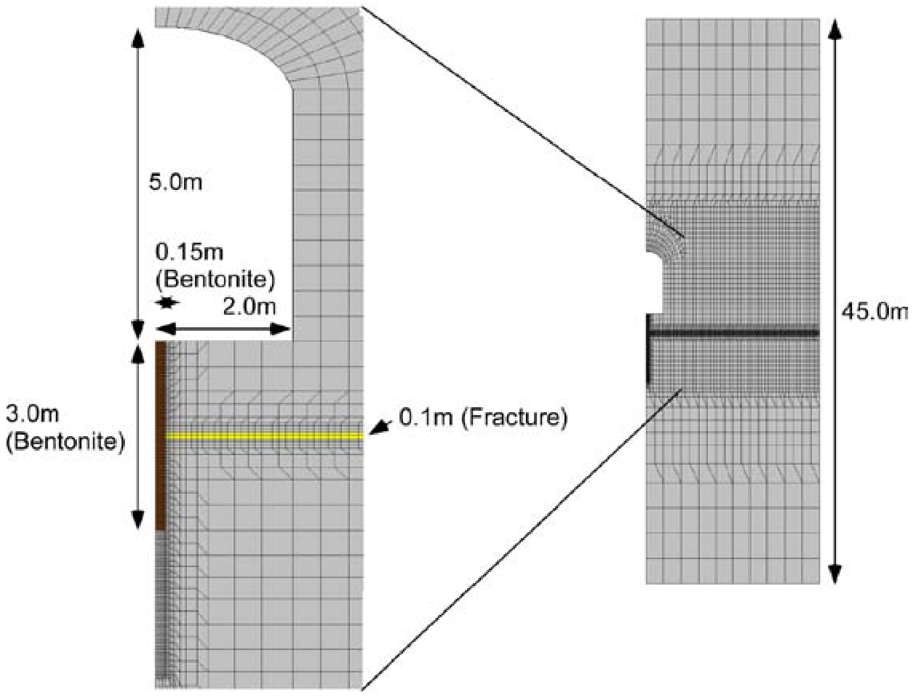


__Figure 8-25.__ Geometry and finite element mesh for the initial scoping calculation of Task 8.

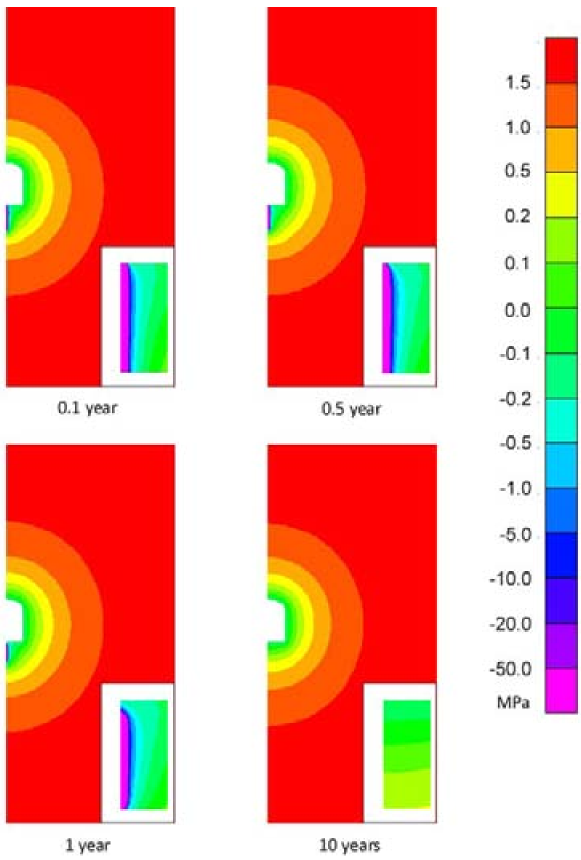


Figure 8-26. *Contour plots of pore pressure in bentonite and rock (case 1) in Task 8.*

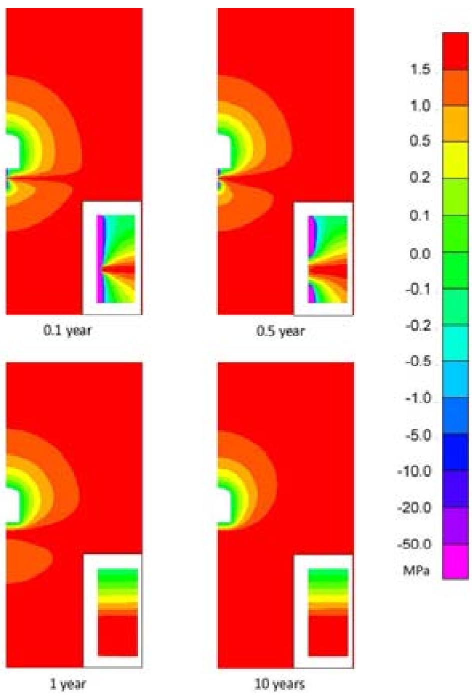


Figure 8-27. *Contour plots of pore pressure in bentonite and rock (case 2) in Task 8.*

Since it was strange that water infiltrated from the tunnel floor to the bentonite in early stage, we analysed the effect of the hydraulic boundary condition on the tunnel floor. Zero flux condition is applied to the tunnel floor in case 2' (see Figure 8-28). In Figure 8-29, the results of pore pressure distribution from case 2 and 2' are compared. In case 2', water infiltration from the tunnel floor did not appear.

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

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

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

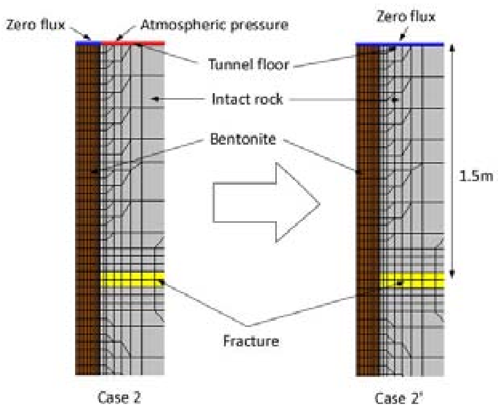


Figure 8-28. *Comparison of hydraulic boundary condition on the tunnel floor in Task 8.*

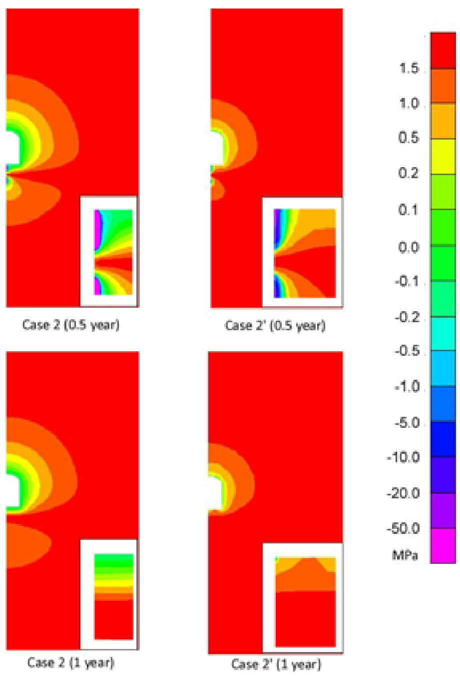


Figure 8-29. *Comparison of the pore pressure distribution in case 2 and 2' in Task 8.*

8.4.2 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 2010, THM benchmark 2.2 of Task Force on Engineered Barrier System was carried out, and LOSTUF was applied to the Canister Retrieval Test (CRT), which was carried out by SKB at its Äspö Hard Rock Laboratory in Sweden.

The CRT 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 carefully record the THM process 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 cylinders and bentonite rings in a 8.55-m-deep by 1.76-m-diameter in-floor borehole. A concrete plug and 9 rock anchors overlaid the bentonite to provide a vertical restraint against swelling.

There are three suggested tasks in benchmark 2.2. The first task is a pure thermal problem on 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 8-30. This model includes four types of compacted bentonites, which are bentonite cylinders, rings, bricks and pellets, whose initial dry densities are quite different. An empty slot between canister and bentonite is 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 homogenization process by swelling is simulated.

Results of the third task are shown here. Figure 8-31 shows the bentonite blocks which were selected for output. Figure 8-32 shows the temperature evolution. Line plots and dotted plots show the results of simulation and the measured data, respectively. In the legend, "R5", "R10" and "C3" are block names, and numbers following the hyphens show the distance from the center axis of the emplacement borehole in the unit of mm. Simulation could reproduce the temperatures very well. Figure 8-33 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 because of drying process appeared in numerical results after around 100 days.

The numerical results about water infiltration in this benchmark were so sensitive to the hydraulic properties of bentonite that the prediction of relative humidity evolution was difficult. Figure 8-34 shows the vertical total pressure evolution. Total pressure increases with swelling of bentonite. Simulated total pressures looked larger than measured ones, but measured total pressures are considered smaller than the actual ones because dry density of bentonite close to the sensor was smaller than that of surrounding bentonite. The actual total pressure is around 7–8 MPa, which were estimated from the final dry density and degree of saturation obtained after the experiment. Final total pressures obtained from the calculation are in good agreement with the estimated value. Figure 8-35 shows the dry density profile in R6, R10 and C3 bentonite blocks. Simulation could reproduce the tendency of homogenization process with swelling of bentonite. In this way, the code LOSTUF could broadly reproduce THM behaviours observed in CRT. CRIEPI summarized these results of benchmark 2.2 and submitted the final report.

In 2010, phase 2 of the Task Force on Engineered Barrier Systems started. CRIEPI started the modelling work for Prototype Repository.

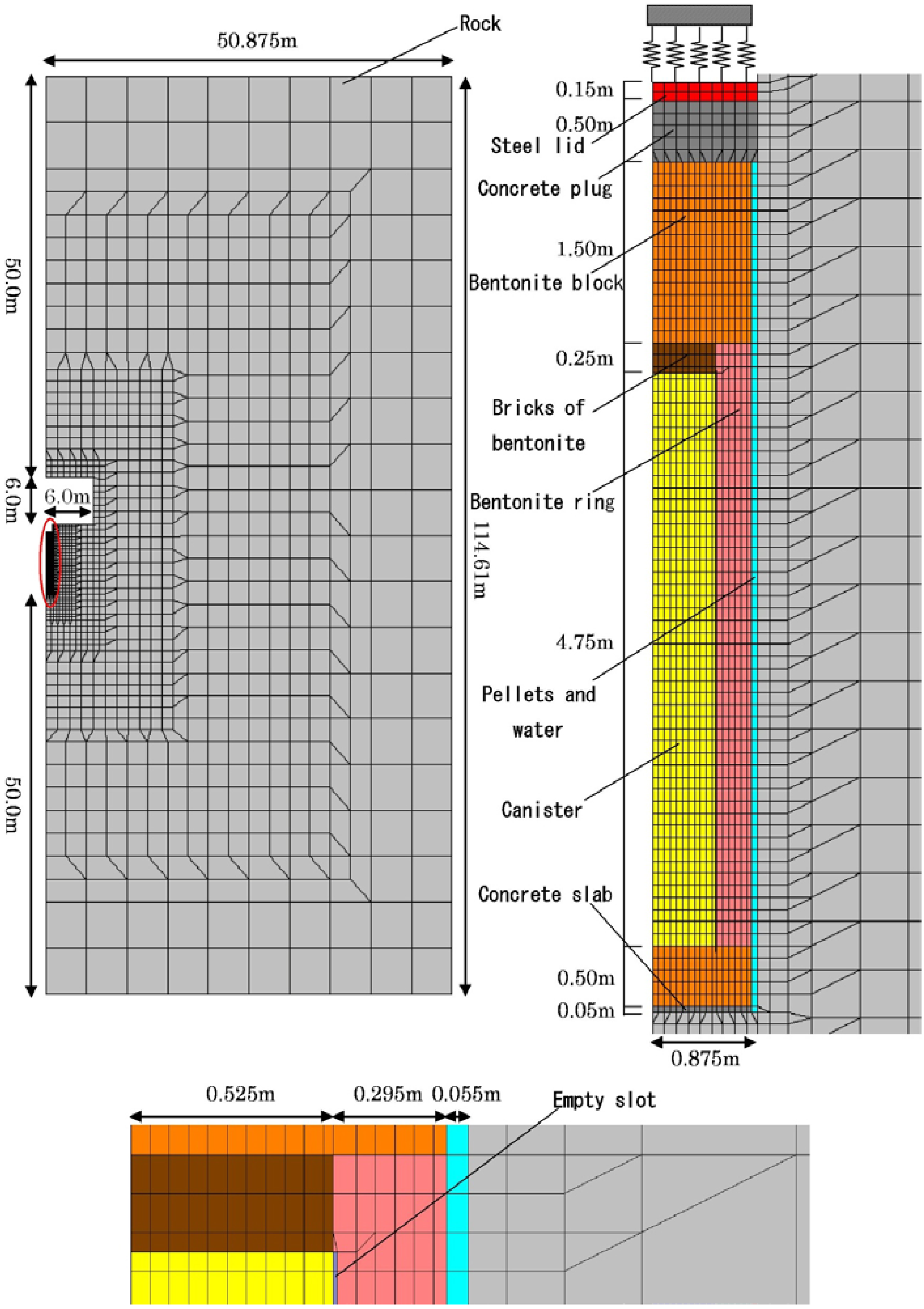


Figure 8-30. Finite element mesh for the entire CRT experiment.

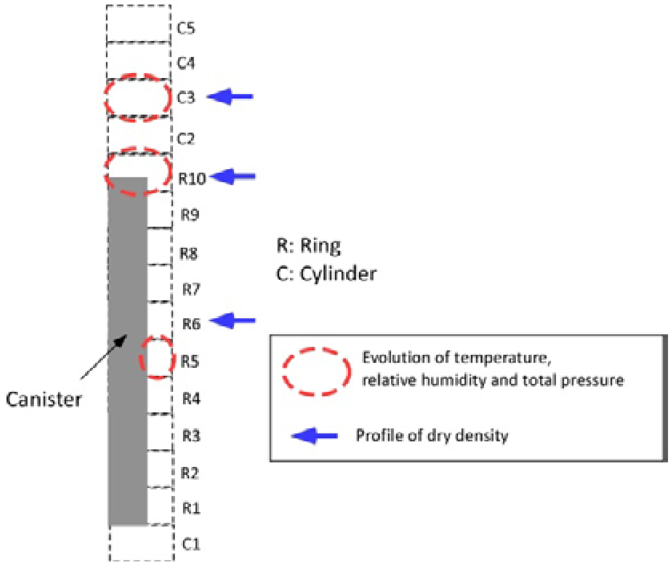


Figure 8-31. Bentonite blocks for output.

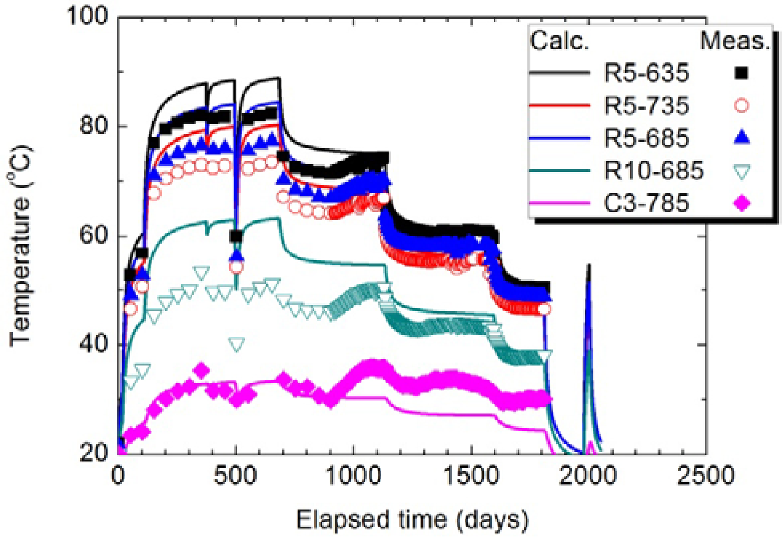


Figure 8-32. Temperature evolution in the bentonite.

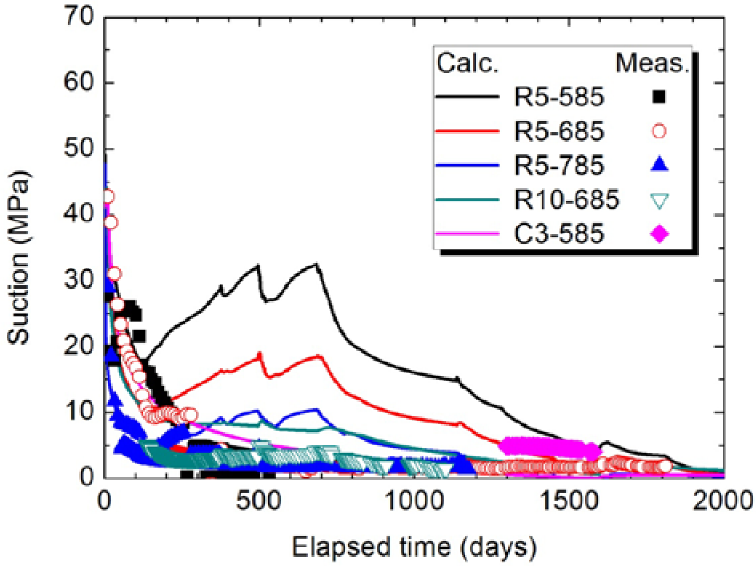


Figure 8-33. Suction evolution in the bentonite.

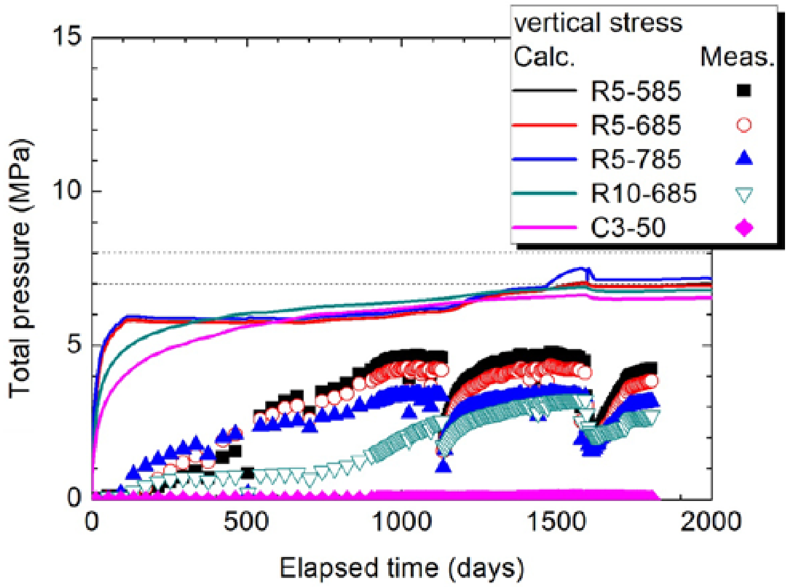


Figure 8-34. Total pressure evolution in the bentonite.
(a) R5
(b) R10
(c) C3

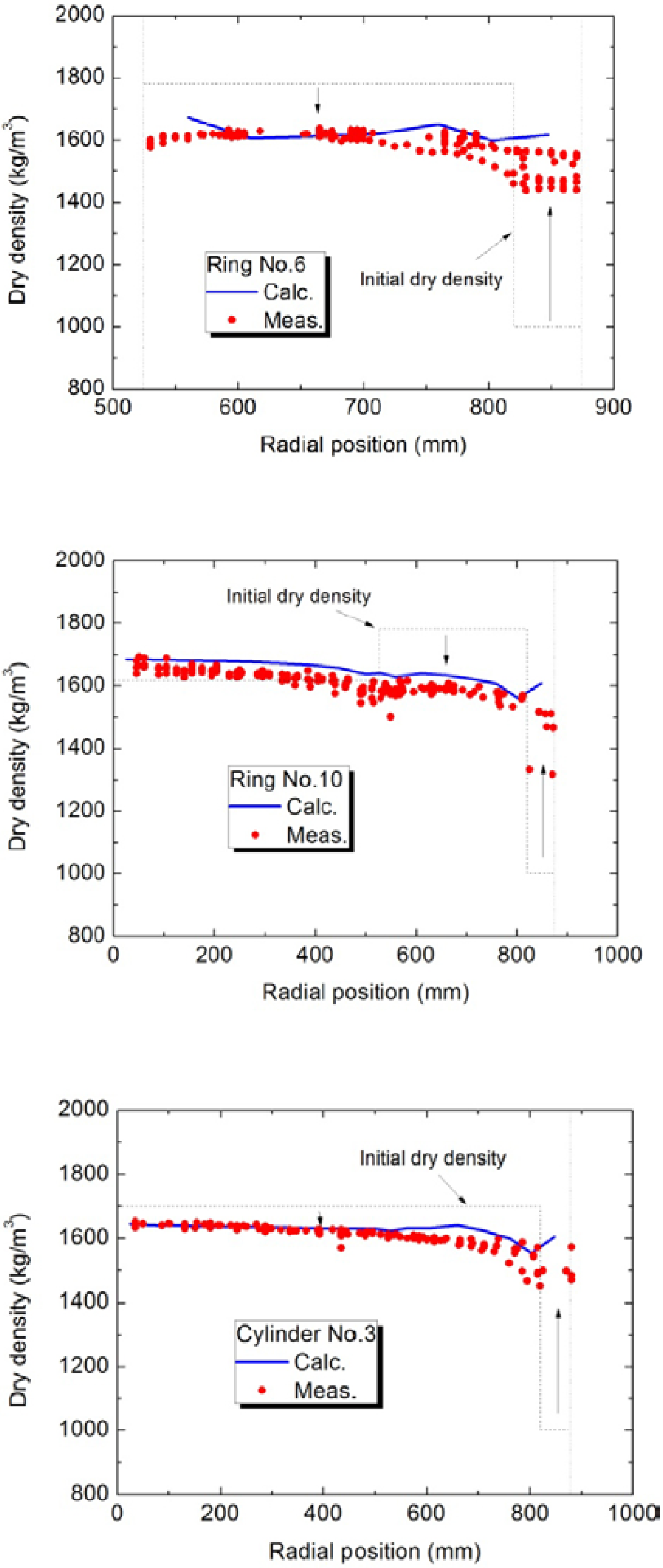


Figure 8-35. *Profiles of dry density in R6, R10 and C3 blocks.*

8.5 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 2010 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.

8.5.1 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 2010 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 hydrogeologic model uncertainty by pressure response and flow response data measured by Posiva flow log during pumping tests, and assessment of uncertainty of performance measures relevant to safety assessment derived from hydrogeologic models, i.e. to contribute to both site assessment and safety analysis methodologies in Japan.

During 2010, JAEA continued the development of hydrogeologic models for sub-task 7B, presenting a deterministic major fault zone model which focuses on the rock block scale, within the Island-scale framework characterized in the sub-task 7A. JAEA also initiated modelling for sub-task 7C, which focuses on flow and transport at the single fracture scale, including consideration of a heterogeneous distribution of fracture aperture, transmissivity and transport properties in single fractures at the 10–30 meter scale.

During 2010, JAEA participated in a workshop meeting in Vuojoki, Finland, January 12–14, 2010 to present the modelling strategies and preliminary modelling results from a simplified fault zone model for sub-task 7C and Task 8. The discrete fracture network model for modelling background fractures was added to the simplified fault zone model presented previously. Results of the analyses performed and initial conceptual modelling for sub-task 7C were presented at Task Force Meeting #26, Barcelona, Spain, May 3–5, 2010.

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

During 2010, JAEA carried out a series of detailed simulation to improve procedures for calibration of fractured rock models, and to evaluate the effect of background fractures on rock mass connectivity at the 500 m rock block scale for the Task 7B focus boreholes KR14–18 (Figure 8-36). Calibration procedure developed included the following:

1. Changing transmissivity in background fractures, including depth dependence of rock transmissivity, to calibrate average hydraulic behaviour.
2. Removing background fractures below HZ20A, to reduce hydraulic connectivity from KR14 and KR15 at deeper zone.
3. Disconnecting between KR14 and HZ002, HZ19C, to be consistent with major fault zone model derived by the derivative analysis based on cross hole interference test.
4. Making disconnection at the fracture intersection of randomly selected background fractures and fault zones, to anneal the well-interconnected fracture network.

Connectivity is one of key issues for modelling the heterogeneous flow path as measured by Posiva Flow Logs (PFL). Based on fracture sizes and intensities derived from site characterization data, the DFN derived by JAEA in 2008 and 2009 includes background fractures that are both frequent and well connected. Standard DFN models assume that every fracture is hydraulically connected each other. Moreover, the hydraulic compartmentalization as shown in Kamaishi in situ experimental site, north-east, Japan /Sawada et al. 2000/ and TRUE-Block Scale site /Andersson et al. 2002/ both showed that such DFN models overpredict the connectivity of the rock mass.

JAEA has developed an approved approach to analyse and model this fracture connectivity issue, by reducing fracture connectivity at the fracture intersections (Figure 8-37). Figure 8-38 shows the model plausibility measured by the residual sum of squared errors for both pressure response and flow response cases, with varying percentage of fracture network disconnection. Decreasing the connectivity of the background fracture network strongly affects on the model conductivity, causes less reproductivity of pressure response. The model plausibility estimated from flow response cases shows moderate correlation to the fracture connectivity. Whereas, some cases such as realization number 02 and 04 shows minimum residual sum value at 25% of fracture network disconnection.

Important lessons from JAEA's 2010 efforts on Sub-task 7B include the following:

1. Development of an accurate and defensible hydrostructural model of major structures should be a high priority. Derivative plot analysis of pressure interference tests is a useful tool to conceptualize the major features. The major structures taking account in the hydrostructural model are the most important aspect to understand the reproduction of pressure and flow responses from hydraulic interference tests.
2. It is important to define the properties of the background fractures except for major structures from a data set.
3. There is a need to develop improved measures for comparing complex, heterogeneously connected fractured rock mass models, for reproducing PFL flow response data. JAEA has proposed the use of residual sum of squares for evaluating model plausibility. But, it provides only an average difference between models and measurements, and is not sufficient to fully understand heterogeneously connected flow paths among the boreholes.
4. The heterogeneous connectivity of the background fractured rock and/or in-plane heterogeneity of major structures need to be modelled with greater accuracy to match the flow responses by PFL. JAEA has proposed to model this fracture connectivity issue, by making hydraulic disconnection at the fracture intersection of randomly selected background fractures and fault zones, although it is very challenging to calibrate both of the bulk hydraulic behaviour and local flow connectivity among the boreholes.

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

During 2010, JAEA evaluated the effect of fracture roughness or aperture variation on the pattern of inflow to the Task 7C raised bore shaft KU2 from the identified single fracture FR-1 at the ONKALO facility at Olkiluoto, Finland.

JAEA developed and parameterised a microstructural model for FR-1 based on data set provided by Posiva and on generic information. The measured data for the task includes limited aperture mapping in drift and in "PP" series boreholes, but does not include any quantitative data on the spatial pattern of aperture which is key to the task. However, Posiva did provide measurements of the fracture roughness measurement Jr, which JAEA converted to roughness measurement JRC to estimate the spatial distribution of fracture surface and aperture, using an assumed correlation between JRC and fractal dimension of aperture /Wakabayashi and Fukushige 1995, Murata 2001/. This relationship is based on generic observations of the similarity of fractal dimension between aperture and roughness (Figure 8-39).

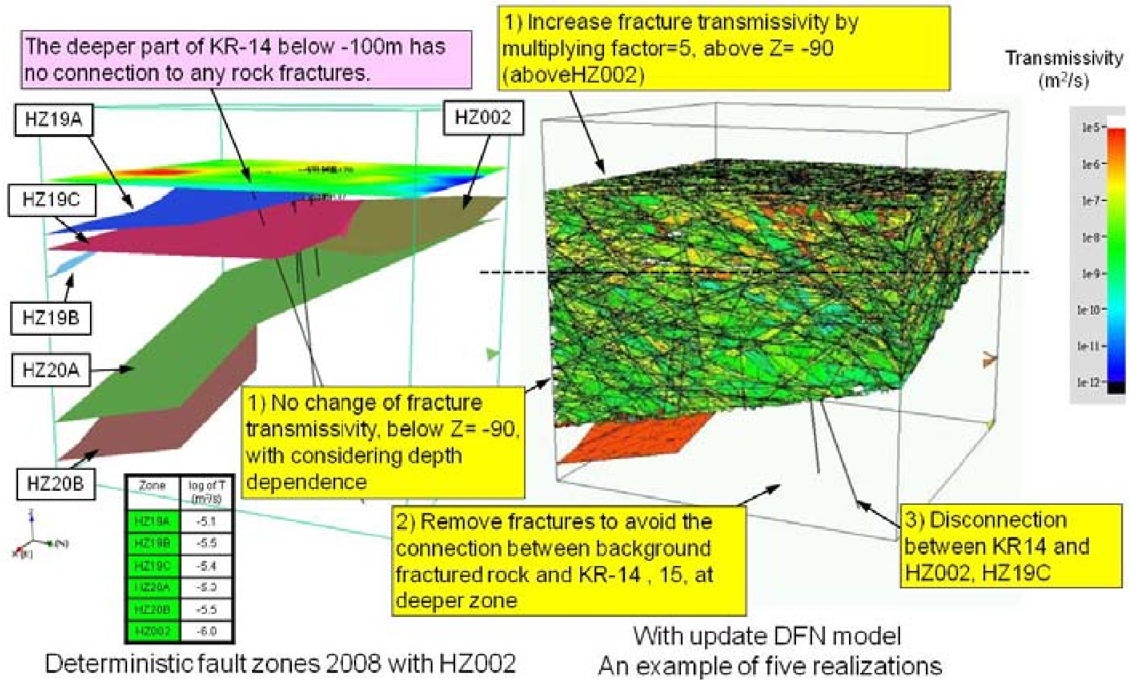


Figure 8-36. *Calibration of task 7B conceptual model during 2010.*

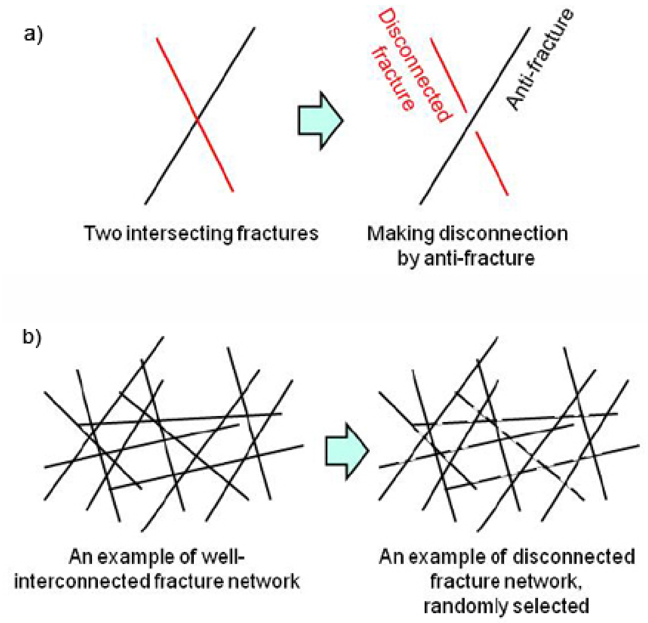


Figure 8-37. *(a) Conceptual illustration of hydraulically disconnection by an anti-fracture. (b) Intersecting background fractures without hydraulic connection.*

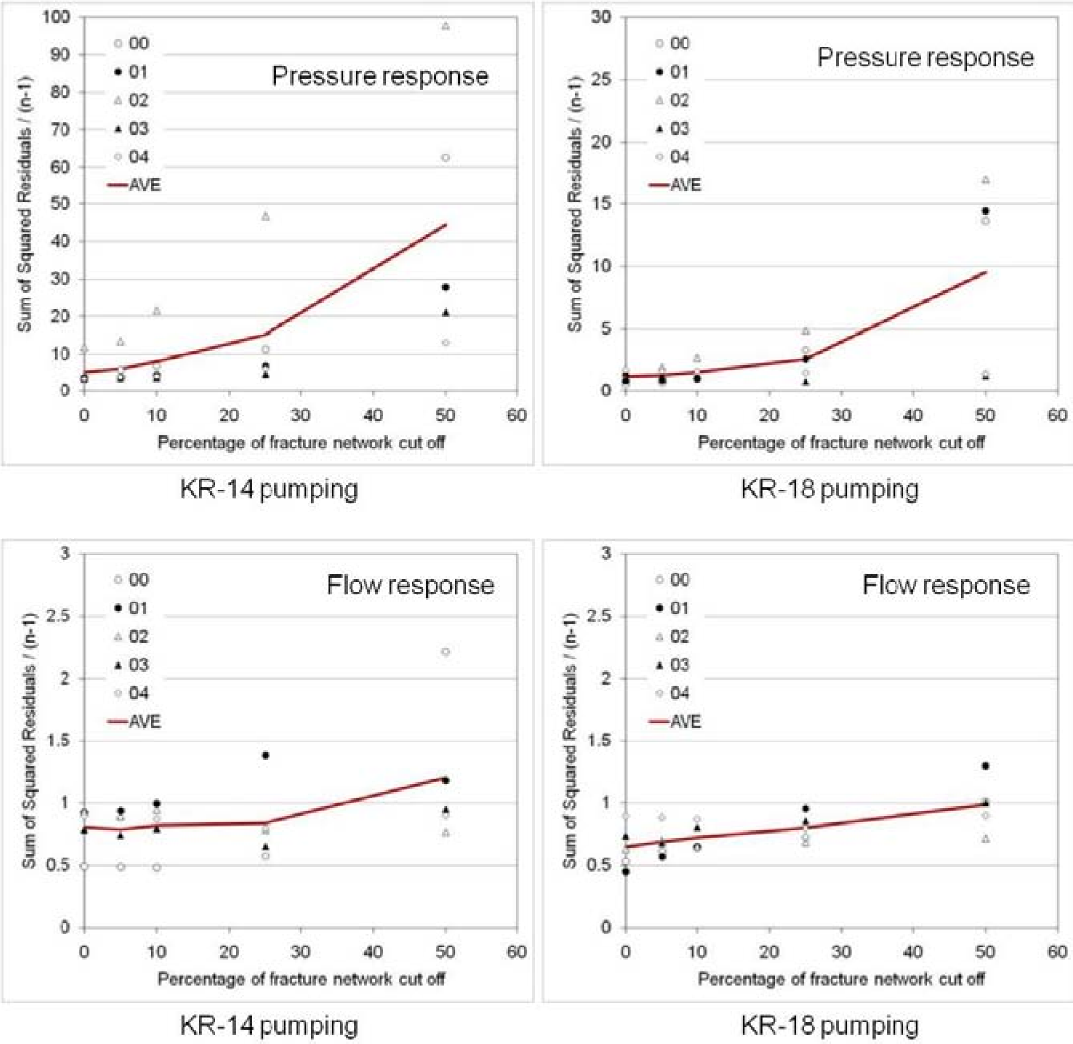


Figure 8-38. *Model plausibility measured by the residual sum of squared errors versus percentage of fracture network disconnection, for both pressure response and flow response cases.*

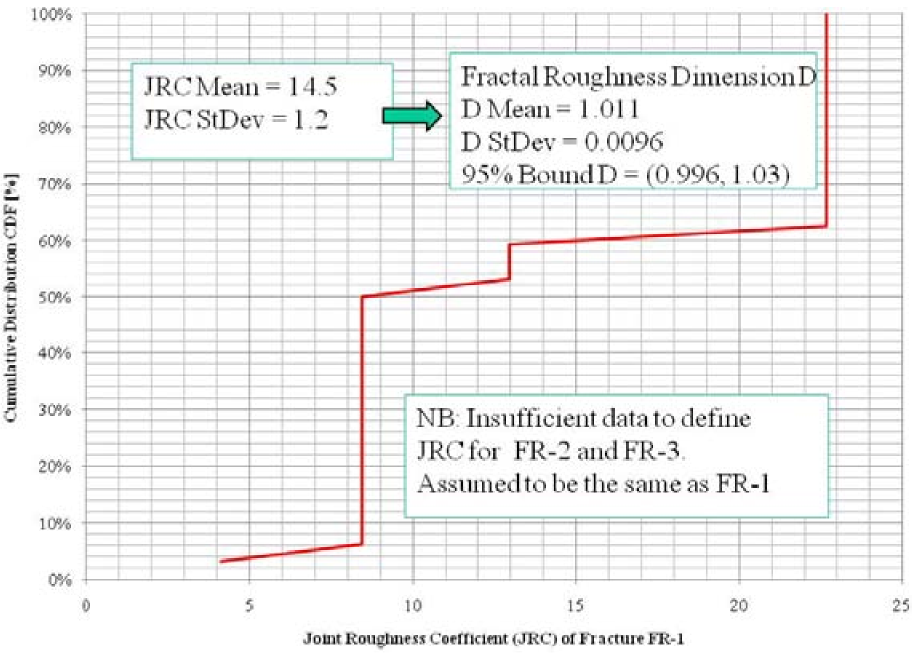


Figure 8-39. *Estimated JRC distribution and translated fractal dimension of fracture roughness.*

Figure 8-40 shows an example of fracture aperture distribution measured by 1×1 mm spatial resolution of 50×50 cm natural fracture excavated from Kamaishi in situ experimental site, north-east, Japan /Tetsu and Sawada 2010/. The aperture spatial distribution is strongly affected by two different scale geological structures, striation parallel to the shear displacement (several centimetre scale of wavelength) and slicken step perpendicular to the shear displacement (several tens centimetre scale of wavelength). Proper representation of this multi-scale aperture spatial structure is very important for flow and particularly for transport pathway evaluation. For this purpose, the site characterization should optimize to obtain the multi-scale geological structures.

Based the data available from Posiva, and the observations from Japan, a series of spatial patterns of local apertures were generated by the sequential Gaussian simulation (SGeMS software[1]) /Remy et al. 2009/. Based on the distribution of JRC values shown in Figure 8-39, the mean fractal dimension, D value for the fractal variogram is 1.01, and the 5% and 95% bounds are 0.995 and 1.03, respectively.

Another important issue is the variogram range to be used in simulation. Since fractal variograms are scale independent, so correlation length is defined. However, at every scale of simulation, there is an effective correlations length. Simulation cases were defined, and three sequential simulations of aperture were generated for each case:

- Series A: Dimension D=1.01, range 50 mm
- Series B: Dimension D=0.995, range 100 mm
- Series C: Dimension D=1.03, range 200 mm

These patterns are illustrated in Figure 8-41. The patterns do not show as strong channelling as is indicated by the detailed aperture measurement of 50 cm scale of natural fracture, as shown in Figure 8-40. However, they do provide an initial conceptual model which can be used in simulation of flow experiments and solute transport pathway analysis. The model is a purely forward model, based on the 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.

This rough fracture model was also successfully adapted to match observed inflows to the KU-2 shaft from the FR-1 fracture, as measured in the "Nappy" experiment (Figure 8-42).

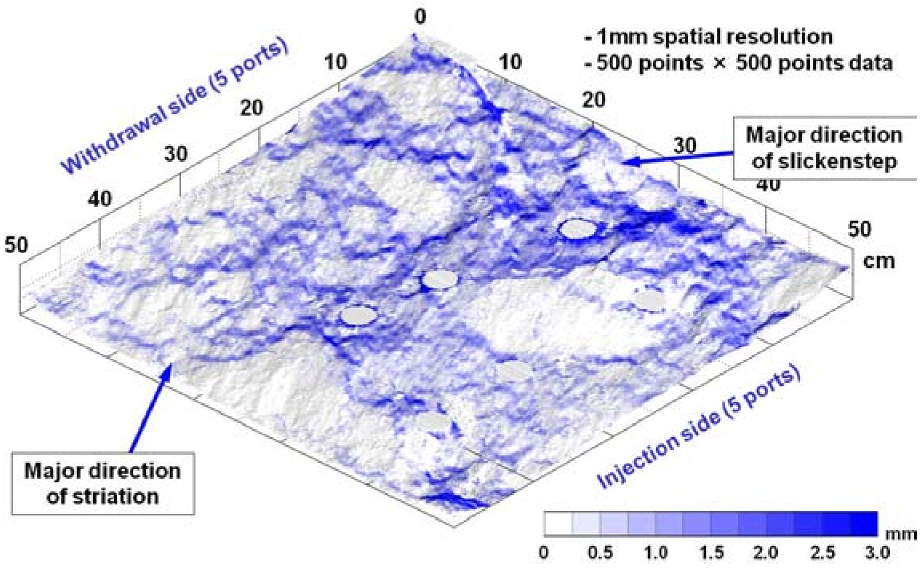


Figure 8-40. *Fracture aperture distribution measured by 1×1 mm spatial resolution of 50×50 cm natural fracture excavated from Kamaishi in situ experimental site /Tetsu and Sawada 2010/.*

[1] The Stanford Geostatistical Modeling Software (SGeMS) is an open-source computer package for solving problems involving spatially related variables. It provides geostatistics practitioners with a user-friendly interface, an interactive 3-D visualization, and a wide selection of algorithms.

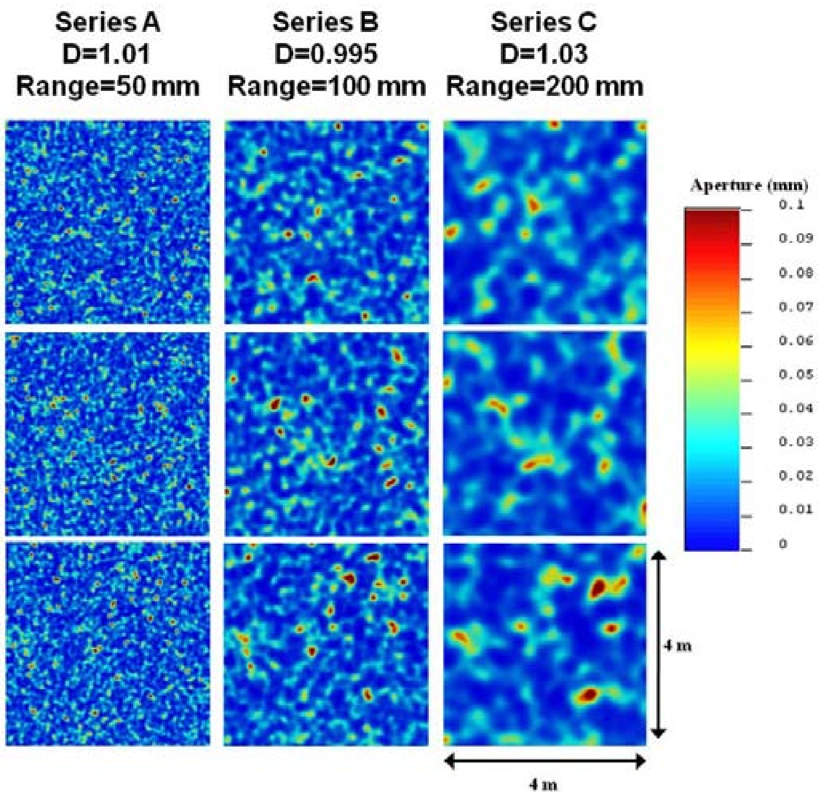


Figure 8-41. *Generated aperture distributions constrained to variogram fractal, three realizations for each model, lognormal aperture distribution with mean of 0.0160 mm.*

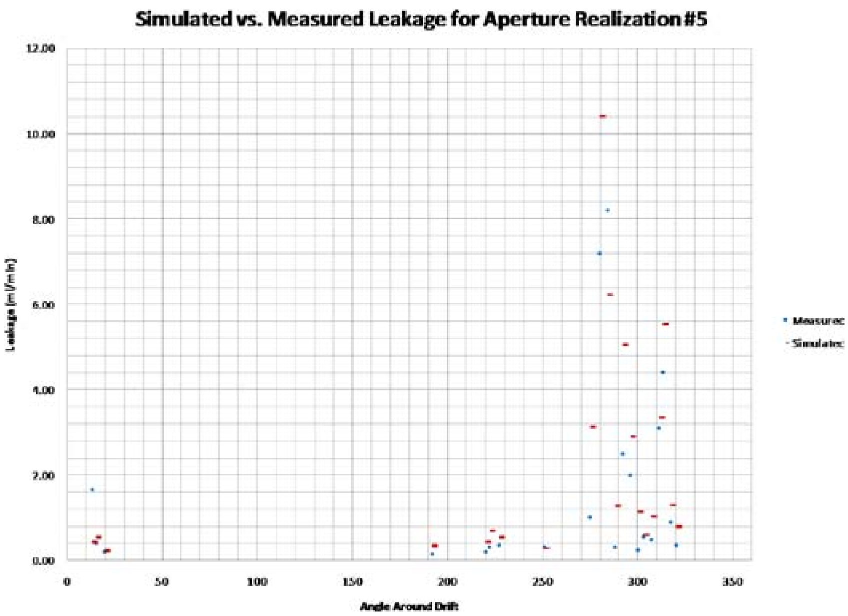


Figure 8-42. *Example matching to measured inflow patterns for fracture FR-1 in shaft KU-2, using the JAEA rough fracture models.*

Task 8 – Modelling the interaction between engineered and natural barriers

JAEA initiated participation in Task 8 of the Äspö modelling task force during 2010. Initial contributions focused on improving the understanding of the interaction of the proposed Task 8 modelling task and "BRIE (Bentonite Rock Interaction Experiment)". JAEA utilized fracture statistics from the "TRUE Block Scale" experiment /Andersson et al. 2002/ for initial model conceptualisation. During 2010, JAEA also carried out preliminary stress analysis simulations to address the effect of local stress patterns on the fractures to be intersecting the BRIE simulated canister emplacement holes. Although preliminary, these simulations demonstrated the importance of stress and fracture geometry to the BRIE experiment.

8.5.2 Alternative buffer materials

For the Alternative Buffer Materials (ABM) project, several analyses (e.g. X-ray diffraction, CEC analysis, MB measurement, ESEM observation/EDS analysis) for the parcel 1 (one year test) were conducted to identify mineralogical changes in the Japanese bentonite (one of eleven clay materials used in the ABM-test parcels). As the results of these analyses, there was no clear evidence of mineralogical change such as montmorillonite transformation to a non-swelling mineral. Increase of iron content in the clay particle was qualitatively estimated by EDS analysis, however. It may suggest the formation of Fe-montmorillonite by ion exchange reaction.

8.6 NWMO

In 2010, the Nuclear Waste Management Organization (NWMO) support to projects under the Äspö Project Agreement was conducted with specialist support from consultants which included Atomic Energy of Canada Limited (AECL), Université Laval and Intera Engineering. The results of this work are briefly described below.

8.6.1 Colloid

In 2010, the NWMO work programme on colloids was directed towards the preparation of a summary report, in collaboration with SKB, on the work performed to improve the understanding of the role of colloids on the performance of a deep geological repository. The report includes a summary of the results from SKB's Colloid Dipole and Colloid Transport projects (2005–2010), which were focused on quantifying natural colloid concentrations as a function of ionic strength, improving the understanding of colloid stability, transport, and generation from bentonite, and colloid facilitated transport of actinides. This report will appear as two separate publications, one by NWMO and the other by SKB.

The report begins with a basic introduction of colloids and their potential role in facilitating radionuclide transport. Colloid formation, compositions and concentrations are discussed for a repository setting, including natural colloids and colloids generated from the waste form and engineered barriers. A general discussion of colloid stability is followed by a chapter on colloid filtration, transport theory, and modelling approaches to understand transport. A chapter focusing specifically on bentonite stability is used to set the stage for a following discussion of montmorillonite colloid generation from bentonite including both static and dynamic experiments. Experiments on colloid attachment to rock surfaces are summarized. The next chapter summarizes laboratory and field-scale transport experiments in porous and fractured media. Radionuclide transport facilitated by colloids is discussed in light of transport experiments, radionuclide sorption by colloids, and modelling efforts to understand colloid-facilitated transport. The report is concluded with a discussion of recommendations for performance assessments.

The current understanding of colloids indicates that natural colloid concentrations are too low to have a significant impact on radionuclide transport. Radionuclide-enriched colloids generated from the waste form are likely to be trapped by the engineered barrier. Montmorillonite colloids will be released in amounts that are too small to compromise the integrity of the buffer, but could be radionuclides-enriched. However, in most groundwater, montmorillonite colloids are not stable and are likely to agglomerate and be filtered over short transport distances. Even in dilute waters the likelihood of stable colloids to be transported over significant distance is very small due to low natural water velocities, and the ability of the geosphere to trap colloids (even with the same surface charge as most minerals). In the case of fracture pathways, surface irregularities, heterogeneity in surface charge distribution and fracture aperture variability, contribute to colloid retention.

8.6.2 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 Island in Finland. A large data set is available associated with investigations for Posiva's ONKALO underground rock characterisation facility.

The model scale for Task 7 decreased from the large scale of Subtask 7A (about 15 km^3), to the rock-block scale of Subtask 7B (0.032 km^3), and finally to the single-fracture scale of Subtask 7C (36,000 m^3). Subtask 7C is the third and final subtask of Task 7,which focuses on simulating fluid flow in low-transmissivity fractures identified during the drilling of ONKPP boreholes and the subsequent construction of the three ONKALO shafts KU1, KU2, and KU3 (Figure 8-43a). The specific goals of 7C are to: 1) advance the understanding of the role of fracture micro-structural models in performance assessment; 2) use Posiva Flow Log (PFL) results to characterize in-plane fracture heterogeneities; 3) improve the ability to predict inflow to canister deposition holes; and 4) assess how data from pilot boreholes can be used to predict flow into canister deposition holes.

The region of interest for 7C covers an area of 30×30 m around each shaft and extends vertically for 40 m. Based on the borehole core analysis, it was assumed that a low-transmissivity fracture crosses the entire model domain (fracture1 in Figure 8-43b). PFL measurements conducted in the ONKPP boreholes were used to calibrate the flow model. The top of these boreholes is at a depth of about 180 m.b.s.l. within rock caverns along the main tunnel at Onkalo. The length of the boreholes is about 100 m and their diameter is 6 cm. They were drilled before the excavation of the shafts that had diameters equal to 3.5 m, as shown in Figure 8-43a. The boreholes, if left open, would naturally flow into the rock caverns. One of the activities of this subtask was to develop a near-field single fracture scale model using the PFL measurements collected during single-hole and cross-hole hydraulic tests conducted in ONKPP boreholes. Measurements of water leakage rates from fracture1 into shaft KU2 were used to test the model.

PFL flow measurements were taken at fracture-borehole intersections. The distance between boreholes was a few metres or less (Figure 8-43a). Because of the variability in the magnitude of the measured flow rates at this small scale, the aperture distribution of fracture1 was assumed to be heterogeneous. The aperture was thus modelled with the random field generator FGEN /Robin et al. 1993/, which can be linked with the numerical simulator HydroGeoSphere /Therrien et al. 2009/. Local aperture values were calculated from nine available PFL flow measurements, using the cubic law. The aperture mean and variance were then calculated and used as input for the generation of the aperture field for HydroGeoSphere flow and transport simulations. One of the main challenges was to evaluate the aperture correlation length value. Because available data are limited, the correlation length was estimated from literature values. A resulting aperture field is shown in Figure 8-44, where velocity vectors show the inflow distribution to the shaft.

Simulation results show that the uncertainty associated with the PFL flow rate measurements, which sum is usually smaller than the actual natural outflow from a specific borehole, needs to be accounted for during model calibration of single-hole and cross-hole hydraulic tests. Moreover, it is shown that the variation of correlation length may cause inversion of flow directions at fracture-borehole intersections, which is a relevant aspect for the analysis of cross-hole hydraulic interference tests. Finally, field observations and modelling results indicate that, for a given shaft, the total flow rate into the shaft is smaller than the PFL flow rates measured at the intersection between fracture1 and the pilot boreholes prior to drilling the shaft. This difference needs to be further investigated and understand as it has implications on the approach to evaluating inflow into canister deposition holes.

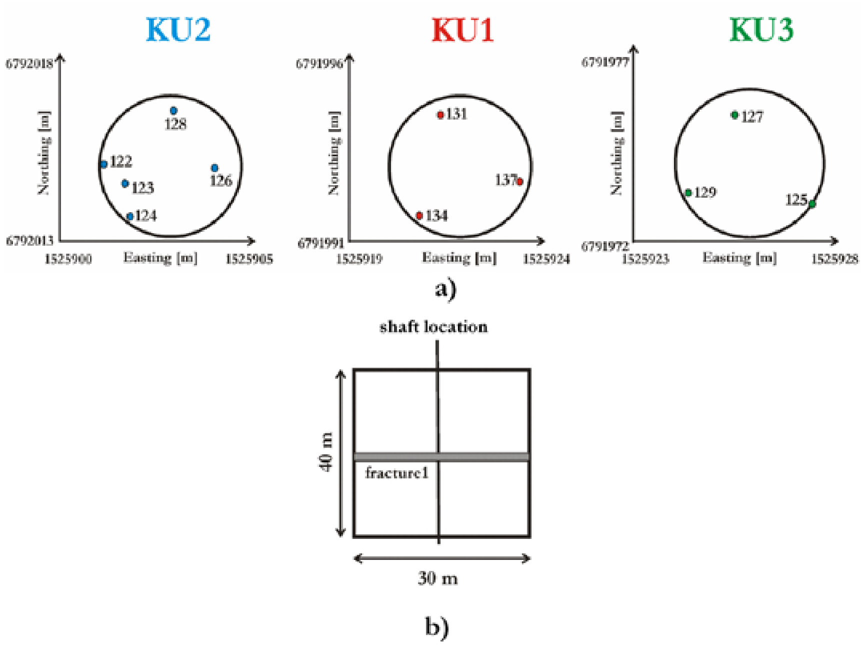


Figure 8-43. *a) Location of ONKPP boreholes inside the shaft diameters and b) cross-section through the model domain.*

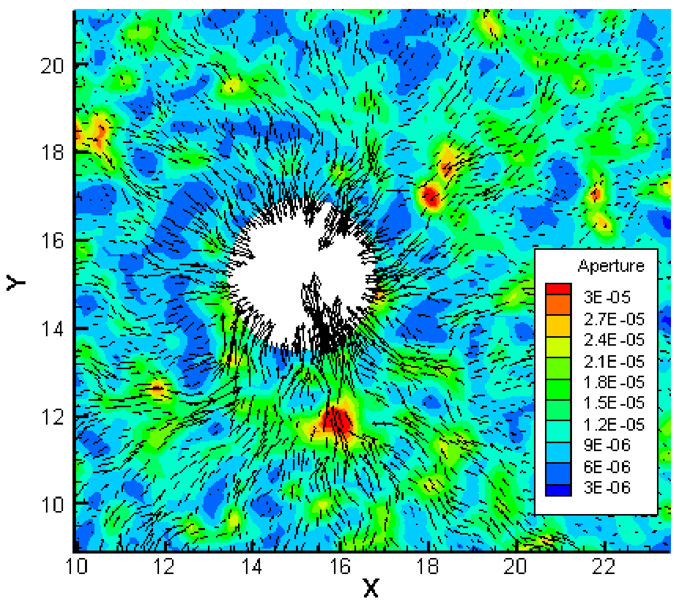


Figure 8-44. *Close-up of fracture1 showing the inflow into the shaft: the vector length is proportional to the velocity magnitude and the aperture scale is in metres.*

8.6.3 Large scale gas injection test

NWMO is providing modelling support for the Large Scale Gas Injection Test (LASGIT) using the TOUGH2 code modified with pressure-dependent permeability and capillary pressure to simulate microfracturing. The full data set for the 2009 gas injection test was received at the end of September 2010. The very complex and hydromechanical nature of the experimental results is evident. Work on modelling this set of experimental data has commenced. Ongoing work includes experimenting with different parameter distributions, more extreme pressure dependent permeability and capillary pressure functions, and testing of the applicability of the Open GeoSys code to modelling the processes in the LASGIT experiment. Open GeoSys is a finite element code capable of simulating hydromechanical coupling in a multiphase flow system.

8.6.4 Task force on engineered barrier systems

In 2010, NWMO completed its contribution to the Task Force on Engineered Barrier Systems (EBS-TF) for the THM modelling of the Canister Retrieval Test undertaken by NWMO's modelling team from AECL. A final report on the results of modelling using CODE_BRIGHT was submitted to the Task Force Secretariat in early 2010 /Guo 2009/.

8.7 Posiva

Posiva's co-operation with SKB continues with the co-operation agreement signed in the autumn of 2006. The focus of the co-work has been organized in different areas like canister line, clay line, underground openings line including RSC studies and safety related research.

Posiva also contributes to several of the research projects within Natural barriers. The implementation and construction of the underground rock characterization facility Onkalo at Olkiluoto in Finland give possibilities to co-operate within the research and development of underground construction technology. Posiva's co-operation is divided between Äspö HRL activities and more generic work that can lead to demonstrations in Äspö HRL. The work was performed during 2010 is described below.

8.7.1 Task force on modelling of groundwater flow and transport of solutes

Task 7

Task7 is a task in the Äspö Task Force on Groundwater Flow and Transport of Solutes. It was started at the end of the year 2000 and progresses through modelling exercises as well as laboratory experiments. Task 7, initiated in 2008, seeks to uncover the potential of Posiva Flow Log (PFL) measurements in the reduction of uncertainties when determining the retention properties for the Performance Assessment through site, block and near-field scales (Task7A, 7B and 7C, respectively).

In Task7B, with the appropriate numerical tools developed in 2009 the calculation and assessment of flows was the primary goal especially in comparison with the field measurements. Task7C targeted the identification of a justifiable microstructural (conceptual) model of a single fracture (Task7C1), stochastic simulation of the thus resulting head and flow fields, as well as the retention properties (Task7C2), the numerical reproduction and assessment of the "nappy experiment" (Task7C3) and determining the uncertainties of the results with respect to the assumptions, conceptual models, boundary conditions etc.

The sensitivity of calculated head and flow results was assessed with respect to the various elements that defined the Discrete Fracture Network (DFN) models. These elements include the orientation and size distribution of the fractures, the distribution of the transmissivity field and its correlation to the size of the fractures, the presence of the large, deterministic zones and the boundary conditions. Contrary to earlier findings on head, the calculated flow showed considerable variability and thus proved a usable indicator for the adequate parameterization of the DFN model. Model parameter identification was primarily based on manual calibration, but the potential of the Ensemble Kalman

Filter (EnKF) method already used in Task7A was also demonstrated. The EnKF approach was further improved and incorporated into and the FEFTRA program package used in the simulations. With the accepted model input the derived quantities like the retention properties were determined.

A considerable part of the Task7C deliverables was produced. Having tried two different approaches, the conceptual model (microstructure) of the transmissivity field was eventually based on a multivariate normal distribution considering its efficiency and usability in other Posiva projects. Numerical tools for path line calculations had to be and were improved.

Posiva's team delivered scoping flow calculations for the Task Force Workshop held in Vuojoki (February, 2010), presented a large number of simulation cases with their interpretation in the Task Force Meeting in Barcelona (May, 2010), as well as initial results for the Task7C modelling exercise in Lund (December 2010). Documentation of this work is underway in the form of an article to be published in the Hydrogeology Journal of the International Association of Hydrogeologists (IAH).

Task 8

In 2010, Posiva participated on Task 8 with VTT as their subcontractor. In the meeting in Barcelona early in 2010, Posiva's modelling team presented some initial scoping calculations for Task 8a which were for the BRIE (Bentonite Rock Interaction Experiment). These axisymmetric 2D model results were done using COMSOL Multiphysics 3.5a and TOUGH2 v.2.0. The models included wetting of bentonite with and without a fracture in the bedrock. The model geometry was axisymmetric cylinder of bedrock (height 45 m, radius 20 m) with tunnel section (height 5 m, radius 2 m) and bentonite buffer (height 3 m, radius 15 cm) inside. The modelling results were in good agreement with other modelers but differences in TOUGH and COMSOL saturation time were observed due to some differences in model definition. After the first meeting, the COMSOL model was transferred to version 4.0a and the model was re-defined. The new results agree with the TOUGH results and the results of others. The results included contour plots of the deposition hole near-field pressures and degree of saturation in bentonite as well as the bedrock in different time steps. The bentonite seemed to saturate approximately in one year in the fractured case and within five years in the case without fracture.

After the meeting in Barcelona, Task 8b was introduced. The objective of this task was to improve the knowledge of the bedrock bentonite interface with regard to groundwater flow. Posiva's effort for this task is 3D modelling of the problem in the task definition with COMSOL Multiphysics v.4.0a. For now, the model includes the evolution of saturation (or pressure) in 3D geometry with three deposition holes and tunnels in 40×40×40 m block of bedrock with simple boundary and initial conditions for pressure. One of the holes is filled with bentonite and a 10 cm horizontal fracture cuts all the deposition holes. The results are going to be presented in Task Force Workshop on December. Next, the initial pressure will be defined according the given data. In addition, the realistic fractures in the given CAD file remain to be implemented to the model as well as some chemistry.

8.7.2 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 four ½-scale tests simulating the inflow conditions in bedrock and their influence to the backfill has been reported during 2010.

8.7.3 Long term test of buffer material

Posiva`s task in this project is to study the chemical conditions developing in the bentonite. Posiva participated the project meeting arranged in Lund April 2010. No new test parcels were retrieved during the year and no research activities were realized.

8.7.4 Alternative buffer materials

During the year 2010 Posiva continued 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), 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.

8.7.5 KBS-3 Method with horizontal emplacement

SKB and Posiva are engaged in an R&D with the overall aim to investigate whether the KBS-3H concept can be regarded as a viable alternative to the KBS-3V concept. The project is jointly executed by SKB and Posiva and has a common steering group. During 2008–2010 it was executed complementary studies of horizontal emplacement KBS3H phase. The target was to solve a number of pre-designed issues and conduct component tests in the field and select the most appropriate design. Also it was planned full-scale system tests in a representative environment. Also under planning was next project phase *"KBS-3H Description update and performance of full scale tests, 2011–2014"*.

8.7.6 Large scale gas injection test

The third gas injection stage was started in September following third hydration stage. This will be reported in the forthcoming summary report of the year 2010 activities. The related issues have been pursued further within an EU project, FORGE.

8.7.7 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. During the first half of the year 2010 the reporting of the ongoing selected test cases was finalised and the content of the next phase were planned. Benchmark cases for THM and C were prepared

8.8 Rawra

The activities have been assured by Nuclear Research Institute, plc, responsible for research of buffer materials and technical University Liberec, testing their computer codes in the frame of Task Force on EBS.

8.8.1 Alternative buffer materials

Bentonite pore water has been studied using experimental results in combination with geochemical modelling. A similar approach with support of PHREEQC2 has been use in studies of bentonite Rokle. Experimental data were gained from water leachate as well as from high pressure compressing. Preliminary results of bentonite pore water composition are then available. The basic model of bentonite erosion is focused on bentonite saturation with water brought by fracture in the granite host structure. Mechanical and chemical erosion are supposed to be leading processes in the phase of saturation. Experimental device and the results of bentonite swelling to fractures are shown in the following pictures. In the introductory experiments, there was used just slightly compacted bentonite Rokle. Fracture diameter was 165–177 µm. Water flow was regulated by a peristaltic pump, the concentration of colloids in the solution is measured none directly through the aluminum concentration, using ICP-MS.

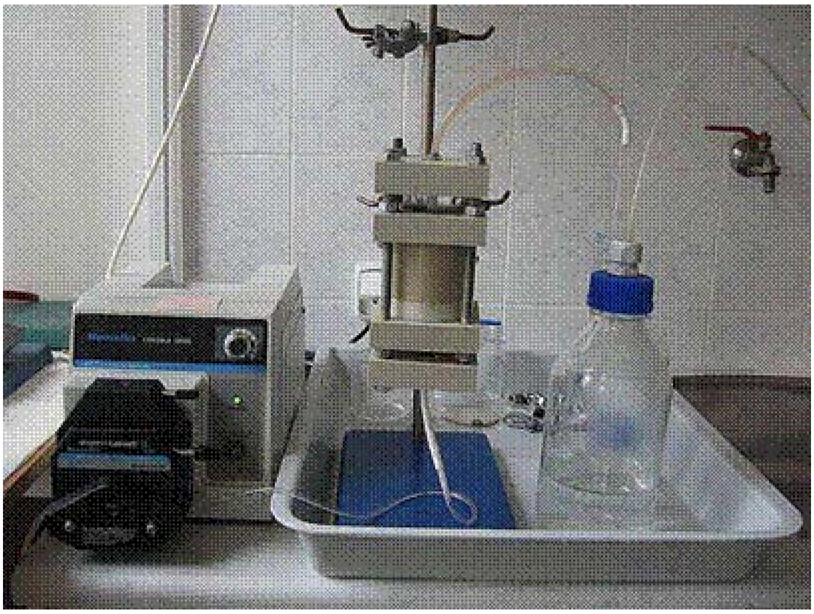


Figure 8-45. Experimental devices.

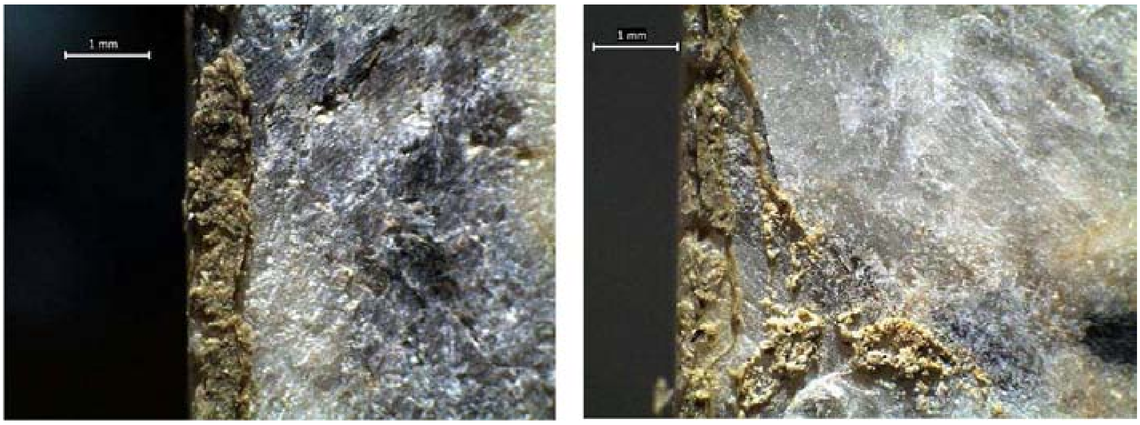


Figure 8-46. Penetration of bentonite to a fracture in granite.

8.8.2 Task force on engineered barrier systems

The experiments and model tasks within the Task Force, BRIE, Prototype Repository, erosion and homogenization has been defined and characterized. The proposal for the way of using and developing software solutions has been defined as well. Simulation software concerned were ANSYS, COMSOL, and special individual codes FLOW123Dand ISERIT. Transport of liquid phase has been implemented to ISERIT code. In the ANSYS code, the material model of bentonite was generalized and the plasticity module was added. There was also covered a simple option of homogenization module through simplification of transport equations. Saturation of bentonite was calculated with respect to a point and/or linear sources.

8.9 KAERI

Since 2007 KAERI has joined to the Äspö Task Force that is a forum of the international organizations for modelling of groundwater flow and solute transport in fractured rocks. At 2010, KAERI conducted the Task 7B as a member of the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes. Task 7 consists of subtask 7A, 7B and 7C, and they are defined following their domain scales for concern. Task 7B concerns the block scale modelling of interference tests at KR14–18 with 500×500×500 m domain to understand how to integrate the background fractures into the groundwater flow model using PFL and HTU (double packer system of Posiva) data, and how to use the major fractures zones as boundary conditions in the block scale groundwater flow modelling. Task 7C is related to simulation of groundwater flow in a single fracture.

8.9.1 Task force on modelling of groundwater flow and transport of solutes

For the Task 7B, the block-scale groundwater flow at the Olkiluoto site of Finland was simulated to evaluate the effect of the background fractures on the groundwater flow modelling in the fractured rocks. The deterministic discrete fracture network was constructed from the relatively large fracture zones identified by the hydrogeological surveys. The hydraulic conductivity field calculated from the fracture network was assigned the finite element domain under an equivalent porous method. The groundwater flow simulations for natural condition and two pumping tests using the modelling domain showed relatively good agreement with the measurements of hydraulic heads and drawdown, but brought exaggerated values and did not local features in flow rates in the boreholes. To resolve this problem, the background fractures were included in constructing the fracture network. Stochastic approach was used to generate the realizations of the background fracture network and the modified hydraulic conductivity fields were prepared from the networks. From the evaluation on the results of groundwater flow simulations using the probabilistic background fractures data, the overestimated flow rates were alleviated and the local flows were appeared. It revealed that considering the background fractures for simulating groundwater flow in fractured media was effective in describing the measurements of flow rates, which could directly affect on the transport of solutes, as well as hydraulic heads. In addition, a series of simulations also showed that the hydraulic responses such as drawdown from the pumping tests were available in characterizing the hydraulic properties when the hydraulic conditions including boundary conditions were uncertain, and the simulation for a packed-off borehole condition was required to estimate the uncertainty of a groundwater flow in a fractured media.

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