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Äspö Hard Rock Laboratory

Annual Report 2011

Svensk Kärnbränslehantering AB

Mars 2012

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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 2011 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 TASS tunnel, (2) Hydrogeology – monitoring and storage of data in the computerised Hydro Monitoring System and (3) Geochemistry – sampling of groundwater in the yearly campaign and for specific experiments.

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 2011, work has been performed in the projects: *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) and *BS TASS – Follow up of TRUE Block scale structures* in the TASS tunnel has also been initiated.

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 2011 a new phase with a new PhD-student started.

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 2011 the reports from the experimental work been printed.

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 2011 some of the Matrix Fluid Continuation data has been published.

Radionuclide Retention Experiments are carried out with the aim to confirm results of laboratory studies in situ. 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. Some of the analysis and evaluations from the experiments 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. All field tests were finalized during 2010, so 2011 was used for analysis, evaluation and reporting.

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 2011 focus has been on developing methods to observe radionuclide sorption onto granitic material using autoradiographic methods as well as adapting batch sorption methods to the needs within the project.

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 2011, for Task7 work has mainly been performed within 7C (deposition hole scale). The Task 8 work mainly contained updated scoping calculations coupled to *The Bentonite Rock Interaction Experiment (BRIE).* The BRIE project is ongoing, and has couplings to Task 8 in terms of data deliveries but also predictive modelling within the task may provide support to the experiment.

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 2011 the excavation of the backfill in Section II started.

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. The activity in the Lot project has during the year been limited to managing the three ongoing test parcels.

The objective of the project *Alternative Buffer Materials* is to study clay materials that in laboratory tests have shown to be conceivable buffer materials. Three test parcels with different combinations of clay materials are installed in boreholes at Äspö HRL. The parcels are heated carefully to increase the temperature in the buffer materials to 130°C. The heaters in two parcels were activated initially and in the third parcel heaters were activated when the buffer was fully saturated. The status of the work with analyses of reference material and material from test package 1 has been described in a report that was published 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. The activities for 2011 have been kept at a very low level, with continued data collection, maintenance of equipment, supervision of the test and reporting of measured water pressure, water inflow and total pressure.

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 2011 the reporting of the buffer analyses has progressed.

The *Temperature Buffer Test* aims at improving our current understanding of the thermo-hydromechanical behaviour of buffers with a temperature around and above 100°C during the water saturation transient. The experiment has generated data since the start in 2003 and the temperature in the buffer around the lower heater had, in the end of 2008, reached a value of 150°C. The dismantling of the experiment started during 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. During 2011 a number of reports have been prepared during the final phase of the project.

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 2011 the MPT was initiated, including detailed planning and start-up of some time-critical activities. Detailed planning for the excavation and preparation of a KBS-3H drift has also been initiated during 2011.

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. During 2011 the test programme of Lasgit concentrated on gas injection.

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 2011 the project has written their final reports.

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. The removal of experiment 3 was successfully performed during august 2011.

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 2011 the goals set by SKB have been reached as demonstrated by agreement between the project decision and project plan and by overall success of the work as manifested by delivering of four reports.

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 concrete 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 2011 the experiments of this project has been prepared and deposited in niche NASA2861A.

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 2011 has mainly focused on following up on and reporting activities from 2009 with the rock bolts and rock support and has mainly been focused on the work done at Äspö HRL but also to develop an international agreed procedure for measuring the pH value in low pH concrete products.

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. The first phase of the Task Force was concluded in 2011 and the second phase started in 2010. Two Task Force meetings have been held during 2011; one in Barcelona, Spain in the end of May and one in Toronto, Canada in the end of November.

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 200 different objects, known today, are needed. Several projects within mechanical- and system engineering are ongoing.

Full-scale tests with fully automatic operation of the *Deposition Machine* have during 2011 been in progress.

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 2011 adjustment on the crane has been made.

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) was ordered in the end of 2010 and delivered in August 2011.

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. The required software was purchased in 2011 and during the year planning and discussions between stakeholders have continued. The process has resulted in a well planned and established project which will be implemented in close cooperation between stakeholders.

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. Definition of properties and program structure was finished during the first months of 2011. The mission control system and a related data base were developed during 2011.

In the project *Transport system for buffer and backfill material* work in the project has during 2011 been focused on increasing the level of detail from the feasibility study and to work out a requirement specifications for the included equipment.

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 during 2011 been continuously ongoing with the extension of the tunnel. During the year the pre-investigation in order to identify a suitable location for the extension has been made. The operation of the already ongoing experiments has continued and some have been completed with respect to field work. In the beginning of 2011 work was initiated in the new geotechnical laboratory and one of the first tasks was connected to the Prototype Repository project. During the later part of 2011 plans have been made to reorganize the Repository Technology (TD) unit and from the 1^{st} of January 2012 extend the unit with two further operative groups.

To support the research and development commissioned by SKB´s two programmes additional spaces are needed underground. A new experimental site is also required for the ongoing development of the KBS-3H-method and above this SKB International AB also requires new experimental sites to further develop Äspö HRL as an international research platform. In the *Pre-Investigation for tunnel expansion* the aim is to create new and extended opportunities for the continued technology development in full scale and in realistic environments and to strengthen the role of Äspö HRL as an open national and international facility for research and technology development in the nuclear industry as well as in other research areas/industries.

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 2011 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.

In *Impact of Water Inflow of Backfill* the specific goal has been 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 to identify the process of wetting and percolation of pellet fill adjacent to natural granitic rock slabs, simulating the walls of blasted tunnels.

The operation of the facility during 2011 has been stable, with a very high degree of availability. An independent consultant has done an energy audit at the facility and the object monitoring and personnel tracking system has been upgraded during the year. In the end of 2011 a road has been constructed at which the borehole deviation testing facility is planned to be placed.

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 2011 the three facilities in Oskarshamn were visited by 9,471 persons. Among the events and activities that took place during the year was "Urberg 500" arranged during six summer weeks, there has been school information, "The Geological Day" was arranged and Äspö HRL celebrated 25 years.

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 2011, twenty-one projects were ongoing within the Nova FoU framework.

International co-operation

In addition to SKB, nine organisations from seven countries participated in the international co-operation at Äspö HRL during 2011. 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 2011.

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 TASS-tunneln, (2) Hydrogeologi – övervakning och lagring av data i det datoriserade hydromoniteringssystemet och (3) Geokemi – den årliga provtagningen av grundvatten samt provtagning för specifika experiment.

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 2010 har arbete skett inom delprojekten: *TRUE-1 Completion* (analys av material, fokus på målsprickan, från överborrningen av två borrhål vid TRUE-1 som genomfördes under 2007) och *BS TASS – Uppföljning av TRUE Block Scale Structure i TASS-tunneln*.

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 2011 har en ny fas av projektet inletts.

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 2011 har rapporter som summerar experimentarbetet tryckts.

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 2011 har en del av experimentdata från Matrix Fluid Continuation blivit publicerat.

Radionuklidfördröjningsexperimenten genomförs in situ för att befästa de resultat som erhållits i laboratoriestudier. 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 Resistance 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. En del av analyserna och utvärderingarna från experimenten är summerade 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. Alla fältarbeten blev färdiga under 2010. 2011 har ägnats åt analyser, utvärderingar och rapportering.

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 2011 har fokus legat på att utveckla metoder för att observera radionuklid sorption på granitiskt material med hjälp av autoradiografiska metoder samt att anpassa behoven av metoder för sorption inom projektet.

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 2011, har arbetet i Task 7 främst utförts inom Task 7C. I Task 8 har arbete främst utförts i form av uppgifter av dataleveranser, men arbete med progronosmodeller har under året genomförts som ger stöd till experimentet men också ger en möjlighet att jämföra modellresultaten för experimentet.

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 2011 startade uttaget av återfyllnaden i Sektion II.

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. Aktiviteterna i Lot-försöket har under året varit begränsat 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 testpaket 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 har beskrivits i en rapport som publicerades i början av 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. Aktiviteterna för 2011 har hållits på en mycket låg nivå med fortsatt datainsamling, underhåll av utrustning, övervakning av försöket och rapportering av uppmätt vattentryck, vatteninflöde och totaltryck.

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 2011 har rapporteringen av buffertanalyserna fortsatt.

Syftet med *TBT-försöket* är att förbättra förståelsen av buffertens termiska och hydromekaniska utveckling under vattenmättnadsfasen 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. Under 2011 och den avslutande fasen av projektet har en mängd rapporter förberetts.

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 2011 inleddes arbetet med MPT, inklusive detaljerad planering och start av vissa tidskritiska aktiviteter. Detaljerad planering för brytning och beredning av KBS-3H-driften har också inletts under året.

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 2011 var testprogrammet för Lasgit koncentretat kring gasinjektioner.

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 2011 har projektet skrivit sina slutrapporter.

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 2011 monterades experiment 3 framgångsrikt ned.

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 2011 har de mål som SKB satt för projektet, och som framgår i avtal mellan projektbeslut och projektplan, uppnåtts och fyra rapporter har levererats.

I *"Betong- och lerprojektet"* är syftet att öka förståelsen för processer i samband med nedbrytning av låg- och medelaktivt avfall i en betongmatris, nedbrytning av cementen självt genom reaktioner med grundvattnet och växelverkan mellan cement, mark och angränsande material som bentonit och den omgivande berggrunden. Under 2011 har experimenten i detta projekt förberetts och deponerats i NASA2861A.

Syftet med "Lågt pH-programmet" är att utveckla betongprodukter med låg pH som kan användas i slutförvaret för använt kärnbränsle. Dessa produkter ska användas för tätning av sprickor, 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 2011 har främst fokuserat på uppföljning av verksamheten från 2009 med bergbultar och bergförstärkning, och har främst varit fokuserat på arbete som utförts på Äspölaboratoriet, men även på att utveckla ett internationellt överenskommet förfaringssätt för mätning av pH-värdet 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 2011 har den första fasen av arbetsgruppen för "Engineered Systems Barrier" (EBS) avslutats och den andra fasen av arbetsgruppen startades under 2010. Två "Task Force"-möten har hållits under 2011, en i slutet av maj i Barcelona, Spanien och en i slutet av november i Toronto, Kanada.

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 200 olika objekt kommer att behövas. Flera projekt inom mekanik- och systemkonstruktion pågår.

Fullskaliga tester med helautomatisk drift av*"Deponeringsmaskinen*" har under 2011 pågått.

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 2011 har justeringar på kranen gjorts.

SKB har ett kontinuerligt behov av att utföra transporter med tung last i Äspötunnelns ramp. För att utföra dessa transporter beställdes ett fordon kallat *Multi Purpose Vehicle (MPV)* under slutet av 2010. Fordonet levererades i augusti 2011.

Huvudsyftet med *Logistikstudierna* för slutförvaret för använt kärnbränsle är att kunna simulera all verksamhet i förvaret under driftfasen. Den programvara som behövdes köptes in under 2011 och under året har planering och diskussioner mellan intressenterna fortsatt. Processen har resulterat i en väl planerad och etablerat projekt som kommer att genomföras i nära samarbete mellan berörda parter.

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. Definition av egendom och programstruktur avslutades under de första månaderna av 2011. Kontroll-systemet och en relaterad databas har utvecklats under året.

I projektet *Transportsystem för buffert och återfyllningsmaterial* har arbetet under 2011 varit inriktat på att öka detaljnivån från förstudien och arbeta med kravspecifikationer för utrustningen.

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. Under 2011 har arbetet med utbyggnad av Äspölaboratoriets underjordsanläggning varit ständigt pågående och under året har undersökningar för att identifiera en lämplig plats för utbyggnaden gjorts. Driften av de redan pågående experimenten har fortsatt och en del fältarbeten har avslutats. I början av 2011 stod det nya geotekniska laboratoriet klart för att ta emot de första provkropparna från Prototypförvarsprojektet. Under senare delen av 2011 upprättades planer för att omorganisera enheten Slutförvarsteknik för att från och med den första januari 2012 utöka enheten med ytterligare två grupper.

För att stödja forskning och utveckling på uppdrag av SKB:s två program behövs ytterligare utrymme under jord. En ny experimentplats behövs också för den pågående utvecklingen av KBS-3H-metoden och utöver detta behöver också SKB International AB nya experimentområden för att utveckla Äspölaboratoriet som en internationell forskningsplattform. *Förstudien inför utbyggnad av Äspölaboratoriets underjordsanläggning* syftar till att skapa nya och utökade möjligheter för den fortsatta fullskaliga teknikutvecklingen i realistiska miljöer samt att stärka Äspölaboratoriet i rollen som en öppen nationell och internationell anläggning för forskning och teknisk utveckling inom kärnkraftsindustrin samt inom andra forskningsområden/branscher.

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 2011 har ett antal bäddtester utförts med syfte att bättre beskriva egenskaper av bädden som kommer att installeras i deponeringstunneln.

Det specifika målet i *Inverkan av vatteninflöde i återfyllning* har varit att utvärdera resultatet av de fortsatta testerna med vätning och filtrering av återfyllnad med staplade block gjorda av komprimerad smektitrik lera omgivna av pellets samt för att identifiera processen av vätning och filtrering av pellets i anslutning till råa granitiska bergytor för att simulera väggarna i tunnlar som brytits genom sprängning.

Driften av anläggningen under 2011 har varit stabil med en mycket hög tillgänglighet. En oberoende konsult har gjort en energikartläggning över anläggningen och övervaknings- och spårsystemet har uppgraderats. I slutet av 2011 byggdes en väg där en anläggning för kalibrering av sonder för krökmätningar av borrhål ska anläggas.

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 2011 besöktes de tre anläggningarna i Oskarshamn av 9 471 personer. Band de evenemang och aktiviteter som ägde rum under året arrangerades exempelvis "Urberg 500" under sex sommarveckor, det har även hållits skolinformation, "Geologins dag" har arrangerats och Äspölaboratoriet firade 25 år.

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 användningen 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 2011 pågick 21 projekt inom Nova FoU:s ramverk.

Internationellt samarbete

Förutom SKB har nio 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.

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, geotechnical and rock-mechanical conditions to be observed during excavation of the laboratory. This phase also included planning for the construction and operational phases.

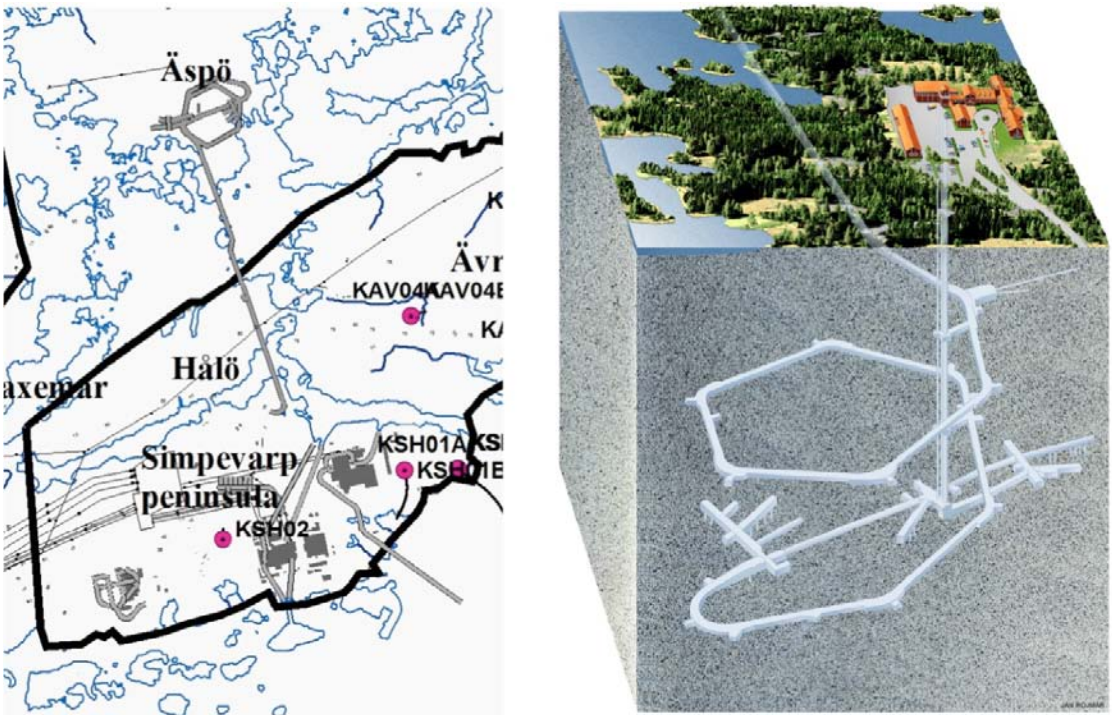


Figure 1-1. Overview of the Äspö HRL facilities and the Simpevarp peninsula.

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 2011–2016 is described in SKB´s RD&D-Programme 2010 (SKB 2010).

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 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 task in stage goals 1 and 2 were after completion at Äspö HRL transferred to the Site Investigations Department of SKB. The investigation methodology has hereafter been developed in the site investigations performed at Simpevarp/Laxemar in the municipality of Oskarshamn and at Forsmark in the municipality of Östhammar. Since the Site Investigations Programme has been finalized, the work has continued within the technology department. 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 assessment 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) aswell 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.

During the last year the development of the KBS-3-method has been a priority, as well as the continued development efforts in the KBS-3-project, which forms the main part of the development activities.

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.
- Development the horizontal applications 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 has the past years been 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 was also Communication Oskarshamn, KO, a part of the Repository Technology unit. However the group were transferred to the reorganised Communication department within SKB in May 2010. 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.

During the later part of 2011 plans have been made to reorganize the Repository Technology (TD) unit and from the 1st of January 2012 extend the unit with two further operative groups – Rock Characterization and Construction Technology (TDU) and Chemistry Laboratory (TDK). The reorganization also means that a research coordinator for the national and international work will be placed in the unit (see Section 6).

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 2011, eight organisations from seven countries have in addition to SKB participated in the co-operation at Äspö HRL or in Äspö HRL-related activities. For each partner the co-operation is based on a separate agreement between SKB and the organisation in question.

The participating organisations are:

- Agence Nationale pour la Gestion des Déchets Radioactifs (Andra), France.
- Bundesminesterium für Wirtschaft und Technologie (BMWi), Germany.
- Central Research Institue of Electric Power Industry (CRIEPI), Japan.
- Japan Atomic Energy Agency (JAEA), Japan.
- Korea Atomic Energy Research Institute (Kaeri), Korea.
- Nuclear Waste Management Organisation (NWMO), Canada.
- Posiva Oy, Finland.
- Radioactive Waste Repository Authority (Rawra), Czech Republic.

Andra, BMWi, CRIEPI, JAEA, NWMO and Posiva together with SKB form the Äspö International Joint Committee (IJC), which is responsible for the co-ordination of the experimental work arising from the international participation. Nagra left the central and active core of participants 2003 but are nevertheless supporting the Äspö activities and participants in specific projects. 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.

The vision for the newly formed Äspö Advisory Group is to increase the international experimental activities at Äspö HRL and thereby develop Äspö as a Centre of Excellence. Focus for the Äspö Advisory Group has during the initial year been the planning and construction of new experimental sites at Äspö HRL, organisation of the IJC-meetings and international reporting of experiments at Äspö.

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.

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 2011–2016 are presented in SKB´s RD&D-Programme 2010 (SKB 2010).The information given in the RD&D Programme related to Äspö HRL is detailed in the Äspö HRL Planning Report (SKB 2011b) 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 2011.

Joint international work at Äspö HRL, as well as data and evaluations for specific experiments and tasks have previously been reported in Äspö International Progress Report series. This report series was in the beginning of 2011 discontinued and the Status and Planning Reports will be replaced by a web portal. International participants will have access to the new web portal that complements and replaces Planning and Status Reports. Other project information, previously reported as internal reports, can in the future be presented either as internal project documents or as a public report (R, TR or P-reports).

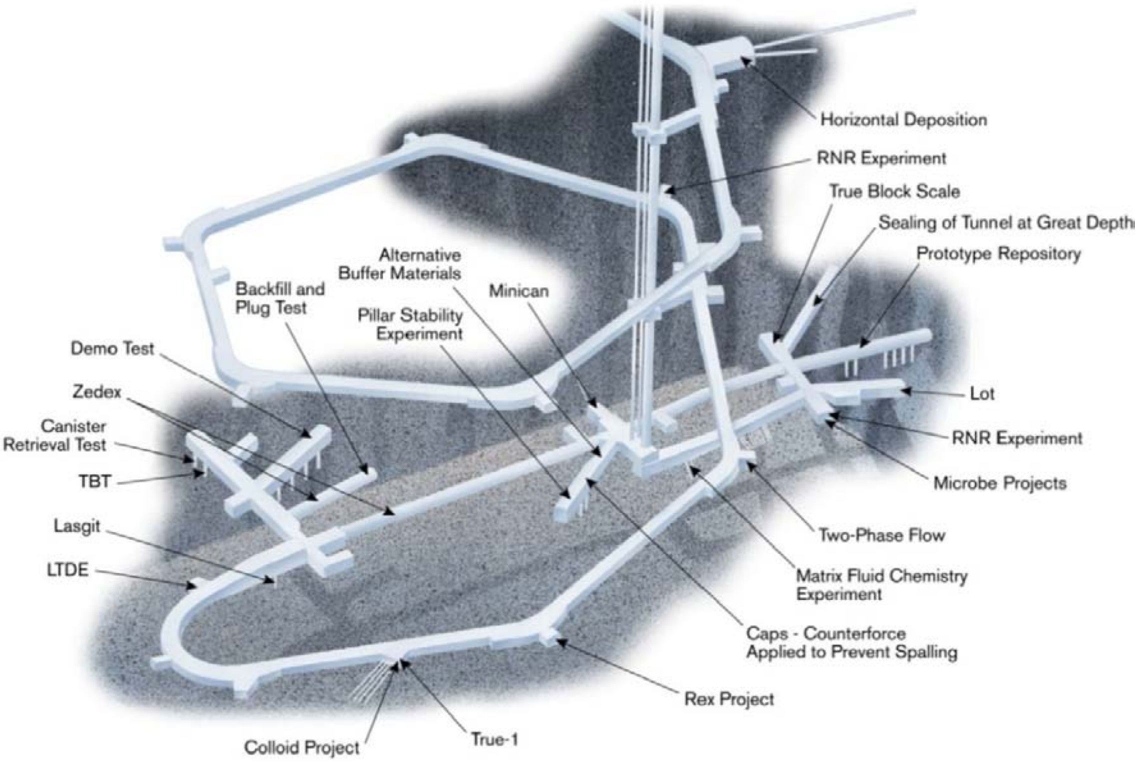


Figure 1-2. *Allocation of experiment sites from –220 m to –460 m level.*

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 (STDT-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 continuously 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 2011 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.
- Open research and technical development platform, Nova FoU.
- International co-operation.

2 Geoscience

2.1 General

Geoscientific research is a part of the activities at Äspö Hard Rock Laboratory as a complement and an extension of the stage goals 3 and 4, see Section 1.2. Studies are performed in both laboratory and field experiments, as well as by modelling work.

The objectives 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.

Experts in the fields of geology, hydrogeology and geochemistry are stationed on site at Äspö HRL, however, there is a vacancy in rock mechanics. The responsibility of the experts in respectively geoscientific field involves maintaining and developing the knowledge and methods of the scientific field as well as geoscientific support to various projects conducted at Äspö HRL.

The main task within the geoscientific field is the development of an Äspö Site Descriptive Model (SDM), see Section 2.2. The activities further aim to provide basic geoscientific data to the experiments and to ensure high quality of experiments and measurements related to geosciences.

2.2 Äspö site descriptive model

Background

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 2-1. The present 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).

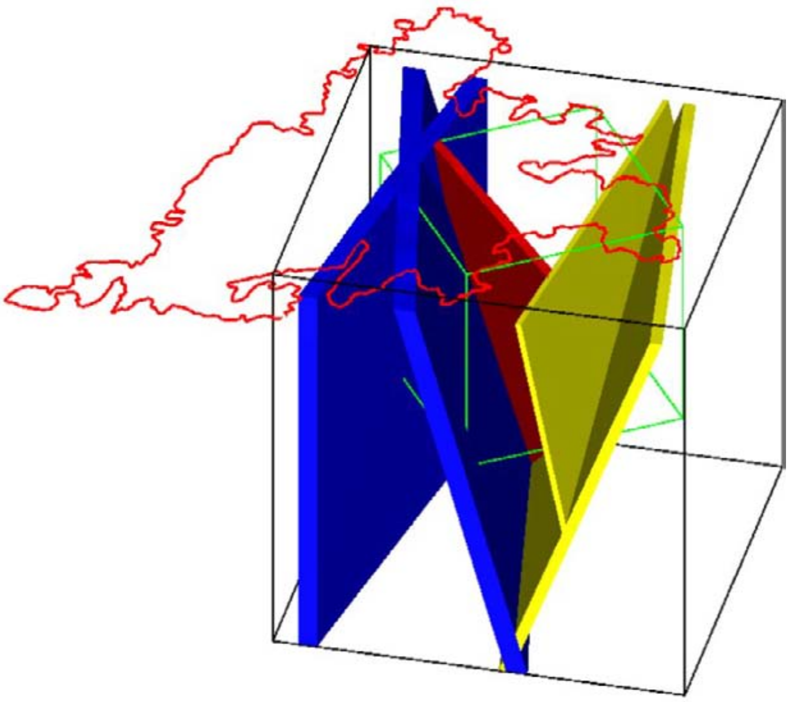


Figure 2-1. *Modelling work to help understand the geological, hydrogeological and geochemical conditions of the Äspö site.*

The SDM facilitates the understanding of the geological, hydrogeological and geochemical conditions at the site and the evolution of the conditions during operation of Äspö HRL. 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.

Objectives

The objectives for the Äspö Site Descriptive Model are:

- Describe the geoscientific conditions in Äspö HRL with the SDM methodology used for the Site Investigations (geology, hydrogeology, hydrogeochemistry, rock mechanics, 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.

Experimental concept

The experimental concepts for the project are:

- 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 methology 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 printed (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 (Mattsson 2011), Figure 2-2. 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. M3 modelling has been used to determine end members and what reactions that needs to be modelled with the chemical transport model PhreeqC.

2.3 Geology

The geological work at Äspö HRL is covering several fields. Major responsibilities 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.

In addition, the development of new methods in the field of geology is a major responsibility. As a part of the latter, the continuation of the Rock Characterisation System (RoCS) project is being conducted, see Section 2.3.2.

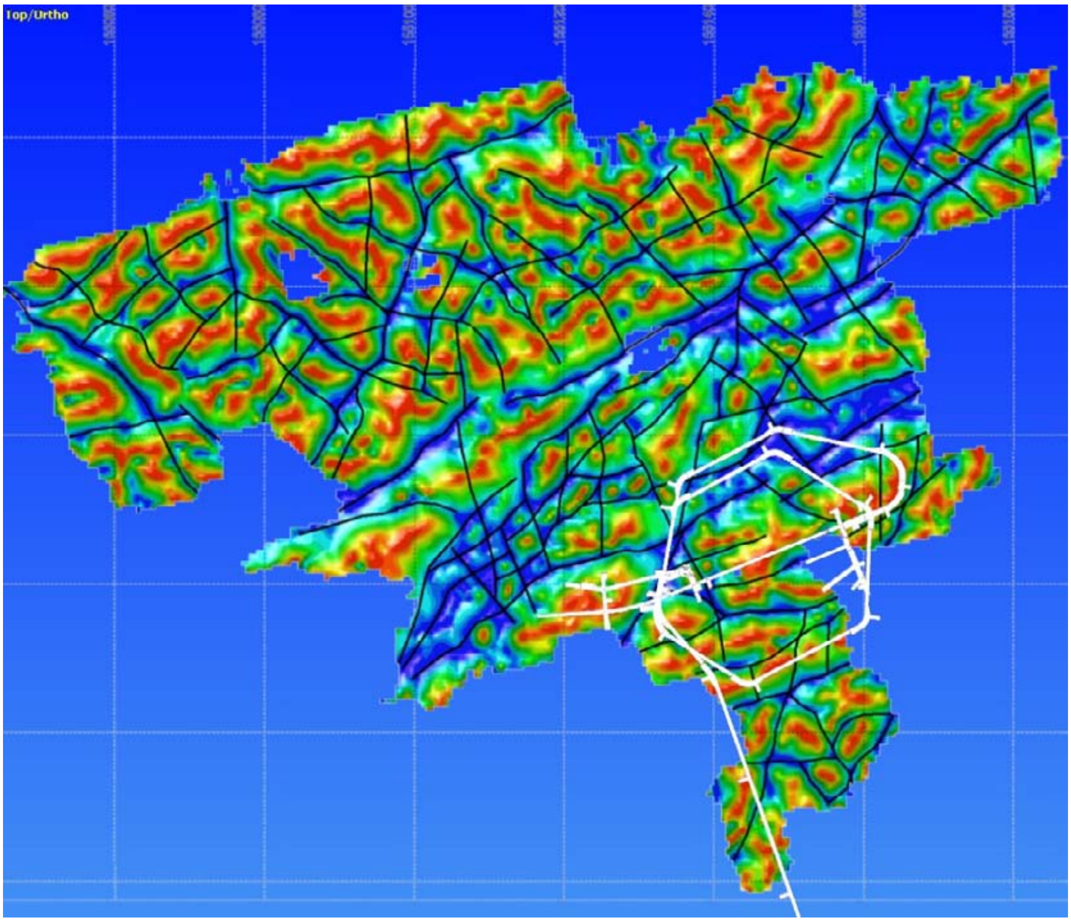


Figure 2-2. Lineament interpretation of ground surface magnetic measurements performed in 1988 (Nisca and Triumf 1989, Mattsson 2011).

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 second proof of the report concerning the geological mapping of the TASS-tunnel has been received at the end of the year. The report concerning modelling of water bearing fractures at the –450 m level is now printed (Markström et al. 2010). 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 Tunnel Mapping System (TMS) has almost been completed.

The expansion plans of Äspö HRL have continued and preliminary sites for two new tunnels and one extended plus a number of niches have been decided. Core logging and photographing of the drill cores from the boreholes KA2051A01, KA3007A01 KA3011A01 and KA3065A01 for the planned new tunnels and niches has been performed. Only overview core logging has been performed so far of the drill core from KA3065A01, the other ones have been logged with the Boremap system. The latter two holes have been drilled along the planned tunnels TASU and TASP respectively.

The concrete ceiling of the TASL-tunnel (the main rescue chamber on the –420 m level of the Äspö HRL) was during an inspection found to have a number of fractures. These fractures have been marked with spray paint (Figure 2-3) and documented with a total station as well photographed in order to perform photogrammetry and create a 3D-model.

As a part of the BRIE-project (Buffer-rock interaction experiment) mapping of the inner part of the TASO-tunnel floor took place early this year and a number of short drill cores have been logged with the Boremap-system and photographed. Four, about 10 m long holes were drilled in the walls and fourteen, about 3 m long in the floor. The logged drill cores are from the boreholes KO0011A01 and B01, KO0013G01, KO0014G02-04, KO0016G01, KO0017G02-04, KO0018A01 and B01, KO0018G02 and 03, KO0019G01, KO0020G02-04. The cores from boreholes KO0017G01 and KO0018G01 have so far only been overview logged and photographed.

The Concrete and Clay project have drilled two 4 m long boreholes KA2862G01 and 02 in the niche NASA2861A. The cores from both boreholes have been overview logged and photographed. A suitable site for the Alternative Reference Design for Buffer and Backfill, the KBP1008-project (Nuclear Fuel Programme, project 1008) has been inspected and photographed in the TASM-tunnel.

2.3.2 RoCS – II – 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.

Figure 2-3. *TASL-tunnel. Irregular fractures marked with yellow paint in the ceiling and on the walls.*

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 Austrian company 3G Software & Measurement (3GSM) delivered in 2010 the hardware and software for the photogrammetry part of RoCS. After that a number of tests have been performed by SKB in tunnel environment in order to get acquainted with the equipment as well as with the photogrammetry.

The development of the core logging software Boremap has continued including the mapping module in RoCS (Figure 2-4). A program version of the mapping software that is almost ready to be used for tunnel mapping is now available. Two FATs (Factory Acceptance Tests) have been conducted during the fall 2011 and some adjustments in the software are still needed.

2.4 Hydrogeology

Background

The understanding of the hydrogeology at Äspö HRL has developed over time with a first descriptive model produced 1997 and a second one in 2002. The objective now is to upgrade the existing hydrogeology model by including data collected during 2002–2008. The main features are the inclusion of data collected from various experiments and the adoption of the modelling procedures developed during the Site Investigations in 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.

Figure 2-4. *TASS-tunnel. A first test of the RoCS mapping system (a prototype) in tunnel environment. The mapping is taken place directly on the laptop screen.*

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.
- Provide 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 overall hydrogeological characterisation and analysis methodology. Further the experimental concept also includes support of experiments and projects with hydrogeological expertise.

Results

During the year the site descriptive modelling was scaled back in favour for other projects. Hydrogeological input was delivered to several experiments and projects. Results are presented in the framework of each project.

The main project was the Äspö Tunnel Extension project for which the following were produced:

- Site recommendation.
- Site characterization programme and subsequent site characterization.
- Hydrostructural model (interim).
- Tunnel inflow forecasts (interim).
- Control monitoring programme for the tunnel excavation phase.

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 and meteorological 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

The experimental concepts are long term measurements of various hydrogeological variables to provide support for the understanding of the hydraulic connectivity of the site and its geoscientific processes.

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 at large.

The monitoring is reported every four month period through quality control documents and on an annual basis, describing the measurement system and basic results.

2.5 Geochemistry

Background and objectives

The major aims within the geochemical work are to:

- Establish and develop the understanding of the hydro geochemical properties of the Äspö HRL rock volume.
- Maintain and develop the knowledge of applicable measuring and analytical methods.
- Ensure that experimental sampling programs are performed with high quality and meet overall goals within the field area.

Results

During the year has core drilling and investigations been performed for the location of the main tunnel for the project Äspö Extension. From the hydro-geochemical point of view water sampling has been performed during drilling and in connection with the hydrological tests in four core boreholes. There are significant hydrogeochemical differences between some of the waters sampled. As an example, in the drill hole SA3007A01 the hydrogeochemical data reveal two different waters. Those were related to the different flow patterns observed in the hydrology. One water sample was characterized by an in-mixing of Meteoric and Baltic Sea water from shallower depth. This observation was also consistent with the fracture zone described by the geologists.

2.5.1 Hydrogeochemical monitoring program

Background

The hydrogeochemical program includes a range of sampling points in Äspö HRL, surface waters, near surface waters, and in core- and percussion boreholes. After the site investigation was completed has a reduced monitoring program compiled for geochemistry in the area around Äspö. The selection of monitoring objects has been primarily to meet the needs of SKB’s geochemical information in connection with Äspö SDM and other projects, as well as Nova FoU.

Objectives

The monitoring program 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. Its aim is to create time series and opportunity to detect/exclude the influence of the surface waters chemical composition caused by SKB’s own activity.

Results

During 2011 the programme for Äspö HRL has been modified to better serve the on-going activities, especially in connection to the planned expansion of the HRL. Groundwater fluctuations due activities such as drilling and blasting during construction of a new tunnel may cause indirect changes in groundwater pressure and flow, and thus also in groundwater chemistry. Three campaigns have been done during the year. Two regular where 13 boreholes sections was sampled in May and 14 in November. In addition to this, a further campaign in October where performed for the boreholes that will be filled or other way is influenced by the expansion of the tunnel. All analytical results are expected to be reported during 2012.

During the year sampling of surface water, soil tubes and precipitation has been performed at regular intervals. The soil tube SSM000240 broke down and was decommissioned.

Further on, the installations of the new sampling equipment in five percussion boreholes resulted in sampling campaigns in April and September was performed in HLX01, HLX08, HMJ01, HAV14 and HLX27. This will better support the sampling of the shallow water at Laxemar and Ävrö for the project Äspö SDM. Also a campaign of core boreholes in April was performed during the year. All analytical results are expected to be reported during 2012.

3 Natural barriers

3.1 General

Experiments at Äspö HRL are performed at similar conditions that are expected to prevail in the bedrock of the future repository for spent nuclear fuel in Forsmark. Even though the hydraulic and geologic properties at Forsmark are different from those at Äspö, the on-going physical and chemical processes are the same. The goal of all experiments is to obtain data and knowledge that is relevant for the understanding of processes which are of major importance for the long-term performance of the repository.

Models for groundwater flow, radionuclide migration and chemical/biological processes are developed and tested. The aim is to evaluate the usefulness of the models.

The ongoing experiments and projects within the Natural barriers are:

- Tracer Retention Understanding Experiments.
- Colloid Transport Project.
- Matrix Fluid Chemistry Continuation.
- Transport Resistance at the Buffer-Rock Interface.
- Padamot.
- Fe-oxides in Fractures.
- Sulphide in repository conditions.
- Swiw-tests with Synthetic Groundwater.
- Äspö Model for Radionuclide Sorption.
- Task Force on Modelling of Groundwater Flow and Transport of Solutes.
- BRIE – Bentonite Rock Interaction Experiment.

3.2 Tracer retention understanding experiments

Background

The Tracer Retention Understanding Experiment (TRUE) project was initiated in the mid 1990s with the aim of improving the understanding of solute transport and radionuclide retention in fractured rock. The project is in its inherent nature multidisciplinary including basic site characterisation, laboratory investigations leading up to carrying out of solute experiments at different spatial and temporal scales addressing various processes, including advection sorption and diffusion. The experiments have included a strong element of evolving conceptual modelling of the fractures and networks of conductive fractures and structures involved. The project has benefitted a lot from the interaction with the Äspö Task Force on groundwater flow and solute transport, cf. Section 3.11, which has included blind predictions and subsequent evaluation. The project, which is now coming to its conclusion, has over its duration produced a large number of technical reports in the SKB report series as well as in peer-reviewed scientific journals. The project has in its final phase included elements of post mortem analyses involving epoxy resin injection and subsequent over-coring and analysis, cf. Section 3.2.1, and revisitation of the heterogeneity of structures involved in tracer experiments, subsequently being exposed by tunnel excavation, cf. Section 3.2.2.

Objectives

The overall objective of the TRUE 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 and heterogeneity of select TRUE Block Scale structures as observed 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 (Gustafson et al. 2009).

Results

During the year the final report of the Fault Rock Zones Characterisation project has been finalised (Winberg 2010). This work presents application and test of various technologies used for qualitative and quantitative description of the wall rock and fracture filling pore spaces of conductive fractures. This work has paved the way for subsequent application to Feature A and the TRUE-1 site within TRUE-1 Completion, cf. Section 3.2.1. Furthermore, a study quantifying the sorption properties of the wall rock rim zone and fault gouge infillings has been finalised (Byegård and Tullborg 2011). The results of work related to TRUE-1 Completion and follow up of TRUE Block Scale structures in the TASS tunnel are presented in Sections 3.2.1 and 3.2.2, respectively. The initiation of the project reviewing bedrock porosity concepts originally planned to be started during 2011 has been postponed till 2012 by SKB.

3.2.1 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.

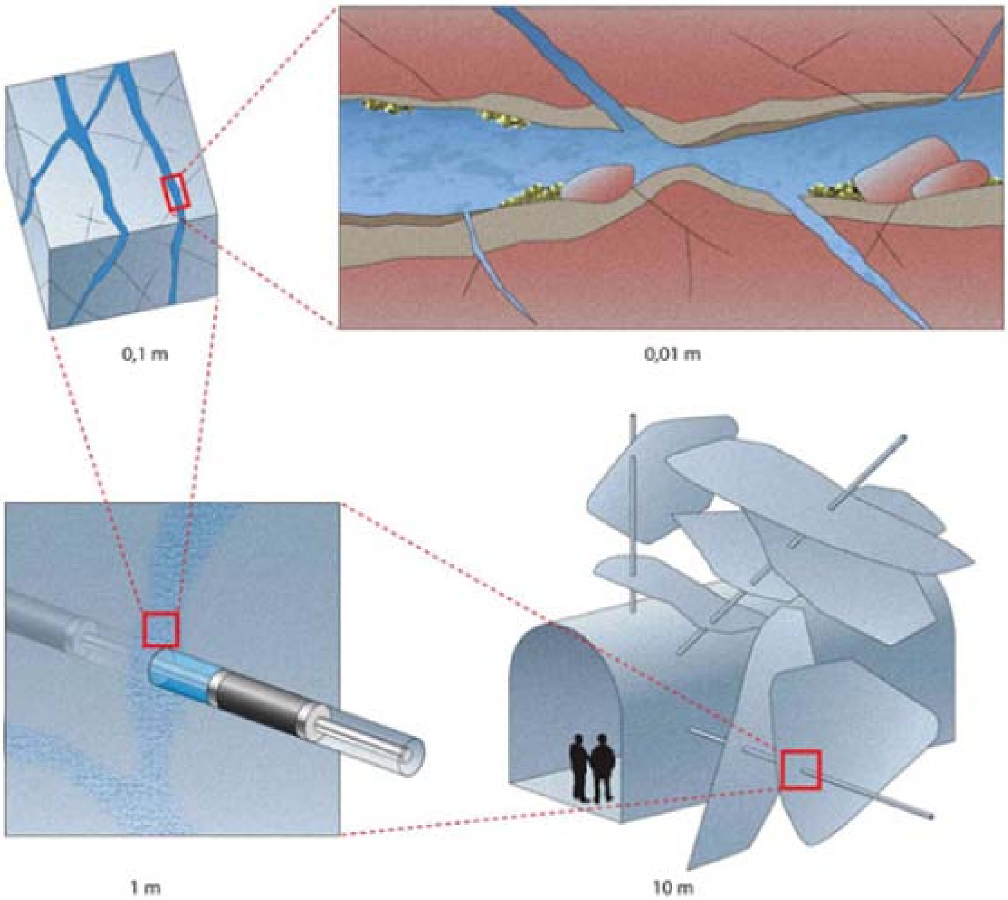


Figure 3-1. *Schematic representation of transport scales addressed in the TRUE programme.*

Objectives

The general objectives of TRUE-1 Completion are to:

- Improve the knowledge of the inner structure of Feature A through epoxy injection and subsequent analyses, including improvement of the identification and description of the immobile zone(s) that are involved in observed retention effects.
- Perform complementary tests useful to the SKB Site Investigations, including in situ K_d and Single well injection withdrawal tests (SWIW tests).
- Improve the description of zones of immobile water that contributes to observed retention effects. The approach was identification and mineralogical-chemical characterisation of the sorption sites where Cs was found.
- Update the conceptual microstructure and sorption 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 activities at the TRUE-1 site did not interfere with the projects in general 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

During 2011, the three primary reports covering tracer tests (Nordqvist et al. 2011), epoxy injection with overcoring (Sigurdsson and Hjerne 2011) and analyses of core material (Hakami et al. 2011), have been completed and thereafter reviewed. For these reports remains correction after review before printing. The final report for TRUE-1 Completion was initiated, however not completed, during 2011. This report will include a summary of the primary reports, conclusions and updated conceptual models for Feature A at the TRUE-1 site. The plan is to finalize all four reports during the first quarter of 2012, after which the project will be finished.

3.2.2 Follow-up of TRUE Block Scale structures in the TASS-tunnel

Background

The current study involves a detailed follow-up of a conductive structure comprehensively investigated in the TRUE Block Scale rock volume, using information from pilot boreholes for the TASS tunnel, and from exposure in the TASS tunnel itself.

The TRUE Block Scale experiment 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 boreholes, performing, evaluating and modelling a series of comprehensive tracer experiments using radioactive tracers. The Tunnel Sealing Project involved construction of an 80 m long tunnel (the TASS tunnel) at the Äspö HRL with the principal aim of demonstrating the ability to seal a tunnel to prevent significant water inflows 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 and Laxemar respectively 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 possibility to investigate further relevant TRUE Block Scale structures in the TASS tunnel, the representatively of information from associated pilot boreholes, provide an opportunity to assess the heterogeneity in structure properties over a larger extent of the structure and also allows assessment of heterogeneity at different scales of observation. The study bears relevance to the detailed site characterisation to be carried out in conjunction with construction of a repository at Forsmark.

Objectives

The objective of the current work is to describe in detail the geological and hydrogeologic heterogeneity of Structure #20, as seen in its intercept inside the TASS tunnel and in the various boreholes which intersect the structure. This is achieved through geometrical, geological and hydrogeological analysis of available data. The hydrogeological analysis include assessment of pressure responses recorded in the instrumented borehole array during drilling of the TASS pilot boreholes and grouting and an assessment of the variability in hydraulic material properties obtained from hydraulic tests in boreholes. The performed analysis formed the base for an updated conceptual description (geometry, geology, structural geology, mineralogy, geochemistry, hydraulic material properties, and hydraulic connectivity) of the structure between the TRUE Block Scale and the TASS sites.

Experimental concept

Geological, structural-geological, mineralogical, geochemical characterisation of intercepts of Structure #20 as obtained from samples from TRUE Block Scale boreholes, TASS pilot boreholes and the TASS tunnel. Photographic documentation of cores and tunnel intercepts. High-resolution photography of tunnel intercepts. Compilation and analysis of available hydrogeological records, including pressure responses during drilling of the TASS pilot boreholes and hydraulic tests performed in the TASS pilot and TRUE Block Scale boreholes. Assessment is made of heterogeneity of the structure with respect to analysed characteristics, including assessment of representatively of information from pilot boreholes.

Results

Geological Data analyses

The analyses performed has included reinterpretation of BIPS images, production of fracture statistics (SICADA), production of cumulative Fracture Intensity (CFI) plots (by borehole) and stereonets. Structure #20 has been mapped using observations of drill core and BIPS imagery and as exposed in the TASS tunnel, the latter complemented by mapping of Structure #20 in tunnel photographs (including outlining of boundaries and digitising of fractures). Notable is that the geological/structural geological and mineralogical analyses has been made using a unified photographic platform.

Fracture mineralogy

Fracture mineralogical analysis have been made using existing and new information collected core mapping and tunnel mapping, including production of thin sections (SEM and microscopy), stable isotopes, assessment of fracture surfaces (SEM) and whole rock geochemistry.

Samples from the TASS tunnel, pilot boreholes and TRUE Block Scale boreholes show:

Overall similar characteristics with regards to mineralogy and characteristics of ductile and brittle deformation and wall rock alteration. Minor differences are related to the heterogeneity of Structure #20 in general. This pertains in particular to mylonite thickness variation, brittle fracture intensity, thickness of fracture fillings, mineralogy of mylonite, cataclasite and brittle fractures variation of larger distances, mylonite grain-size and amount of wall rock fragments, and variation in kinematic shear sense indicators (both strike slip and normal and reverse dip slip is indicated).

Hydrogeological analyses

The structure geometry and intercept in the tunnel of Structure #20 projected purely on geometrical grounds (extrapolation of structures in RVS) has been found to comply well with the intercepts (and geometry) established through analyses of pressure responses in the TRUE Block Scale boreholes during drilling of the TASS pilot boreholes.

Attribution of hydraulic properties to the analysed Structure #20 has been made by grouping of data according to test type and subsequent univariate statistical analysis. Comparison of "global" (all established borehole intercepts) and "local variability" (TASS pilot boreholes only) in hydraulic properties was established.

It was found that the variance and geometric mean transmissivity of Structure #20 based on the TASS pilot boreholes differ within 45% of the "global mean" established based on all available data on the structure. This finding suggests that the statistical sample for Structure #20 as obtained from the TASS pilot boreholes may be regarded as representative of the "global statistical properties" of the structure (as interpreted jointly from data from the TRUE Block Scale boreholes and the TASS pilot holes).

Integrated modelling

The combined use of geological, structural-geological and mineralogical mapping and analyses has enabled identification of core, transition zone and total thickness of structure in the drill cores and in the tunnel. Overall the picture is one of geological and mineralogical consistency between intercepts of Structure# 20 as seen in the drill cores, and in its exposure in the tunnel, although there are differences in the thickness (of core, mylonite and transition zones) and amounts of the mineral constituents. The geological and mineralogical consistency is matched by a corresponding hydraulic consistency in terms of average transmissivity and its variability. This indicates that the TASS pilot boreholes represent well Structure #20 in a "global sense".

3.3 Colloid transport project

Background

In contact with dilute groundwater bentonite buffer has the potential to release montmorillonite colloids that can be transported out from the buffer. A significant release can give high mass loss from the bentonite that may endanger the buffer functionality. In a scenario with a leaking canister, the montmorillonite colloids may enhance the transport of sorbing radionuclides out towards the geosphere, in particular strongly sorbing radionuclides.

Objectives

The Colloid Transport Project is part of the Colloid Formation and Migration (CFM) project steered from Switzerland. The main aim in the CFM is to investigate the ability of the bentonite barrier to release montmorillonite colloids in contact with dilute groundwater.

A large bentonite erosion test will be performed at Grimsel test site with a proposed start 2012. The release of montmorillonite colloids form the buffer will be followed, as well as the transport pattern of radionuclides that will initially be spiked to the bentonite. The groundwater in Grimsel can be seen as representative for glacial melt water possibly intruding to repository depth. The partners in the project contribute with experimental data from laboratory for support of the design and evaluation of the large scaled in situ test.

Other aims of the CFM project are to

- Study transport and retention mechanisms of montmorillonite colloids in water bearing fractures.
- Develop methods for measuring colloid release from the bentonite barrier in situ.
- Study sorption of radionuclides to montmorillonite colloids with focus on sorption/desorption kinetics.
- Develop predictive models for colloid transport in water bearing fracture.

Experimental concept

There are different parts of the Colloid Transport project that supports the CFM. One part is the part directly supporting the in situ experiments at Grimsel. Tracer experiments as well as colloid transport experiments are performed at Grimsel and samples are sent out to the partners laboratories, where KTH is analyzing samples for colloid concentration, colloid size distributions and metal content by PCCS, SPC and ICP-OES.

There are also experimental parts providing data that are needed to model the upcoming in situ experiments. Sorption/desorption kinetics for radionuclides to montmorillonite colloids are needed for modelling the radionuclide transport in the system. There is also of a need to better understand the radionuclide sorption to colloids as such compared to the sorption of radionuclides to bentonite. Since smaller colloids presumably are more easily transported than their larger counterparts, and they have significantly larger specific surface areas, it is important to quantify the sorption on these small colloids. When using Kd-values the sorption is normalized to mass, and is representing a large size distribution. It is important to see how big a difference there is in sorption capacity per gram, for the larger and the smaller colloids. It may also be so that the smallest colloids from the montmorillonite colloids have other surface characteristics than the larger ones. At the Royal Institute KTH a PhD-student is studying the sorption to colloids and the sorption and desorption kinetics. For the sorption /desorption nuclear magnetic resonance (NMR) is introduced to be able to get sorption data as sharp as possible. For the colloid size experiments, filter studies as well as centrifugation studies are performed. Flow field fractionation will also be tested during an exchange with INE-FZK where the PhD student will spend around four month.

Results

The Colloid Transport project started a new phase with a new PhD-student starting August 2011. Sorption experiments with model colloids (latex) of different sizes with Co and Cs just ended and are in the evaluation phase. Start up kinetic studies with NMR with humid colloids and Co and tested are now evaluated, to soon be expanded to a system with montmorillonite colloids and radionuclides. From earlier parts of the project irradiation studies of bentonite are now finished and published.

3.4 Long term sorption diffusion experiment

Background

Transport of radionuclides in water-conducting rock fractures over 5–50 m distances has been studied within the Tracer Retention and Understanding Experiments (TRUE) experimental programme, see Section 3.2, since the late 90's (Winberg et al. 2000, Andersson et al. 2002). Advection, dispersion, sorption and diffusive mass transfer are relevant processes of which dispersion and diffusive mass transfer can be difficult to distinguish by modelling alone of concentration-time curves.

Because the evaluation of the results of the TRUE experiment (Winberg et al. 2002) identified diffusion processes as an important retention mechanism, a demand for extended knowledge of diffusion and sorption processes over longer time scales in a controlled rock volume was identified. A sorption-diffusion experiment without advection and dispersion effects was consequently set up.

Objectives

The Long term sorption diffusion experiment (LTDE-SD) aims at increasing knowledge of sorption and diffusion under *in situ* conditions and to provide data for performance and safety assessment calculations, i.e.

- To obtain data on sorption properties and processes of individual radionuclides on natural fracture surfaces and inner surfaces in the rock matrix.
- To investigate the magnitude and extent of diffusion into matrix rock from a natural fracture *in situ* under natural rock stress and hydraulic pressure and groundwater chemical conditions.
- To compare laboratory derived diffusion constants and sorption coefficients for the investigated rock with the sorption behaviour observed *in situ* at natural conditions, and to evaluate if laboratory scale sorption results are representative also for *in situ* conditions.

Experimental concept

The experiment is focussed on both matrix rock and a typical conductive fracture in medium grained Ävrö granodiorite, 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, 5 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, 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 radiation detection technology is also used for a continuously follow up of the γ-emitting tracers. The temperature, pH and Eh are monitored continuously with a flow through electrochemical cell. After completion of tracer circulation, the rock surrounding the core stub and the test section in the matrix rock is retrieved by large diameter (300 mm) over-coring. Sample cores (24 mm diameter) are extracted from the fracture surface on the core stub and from the matrix rock surrounding the test section in the small diameter extension borehole. The sample cores are sectioned into thin slices (3 of 1 mm, 3 of 3 mm, 3 of 5 mm, and so on) and analysed for radionuclide tracer content.

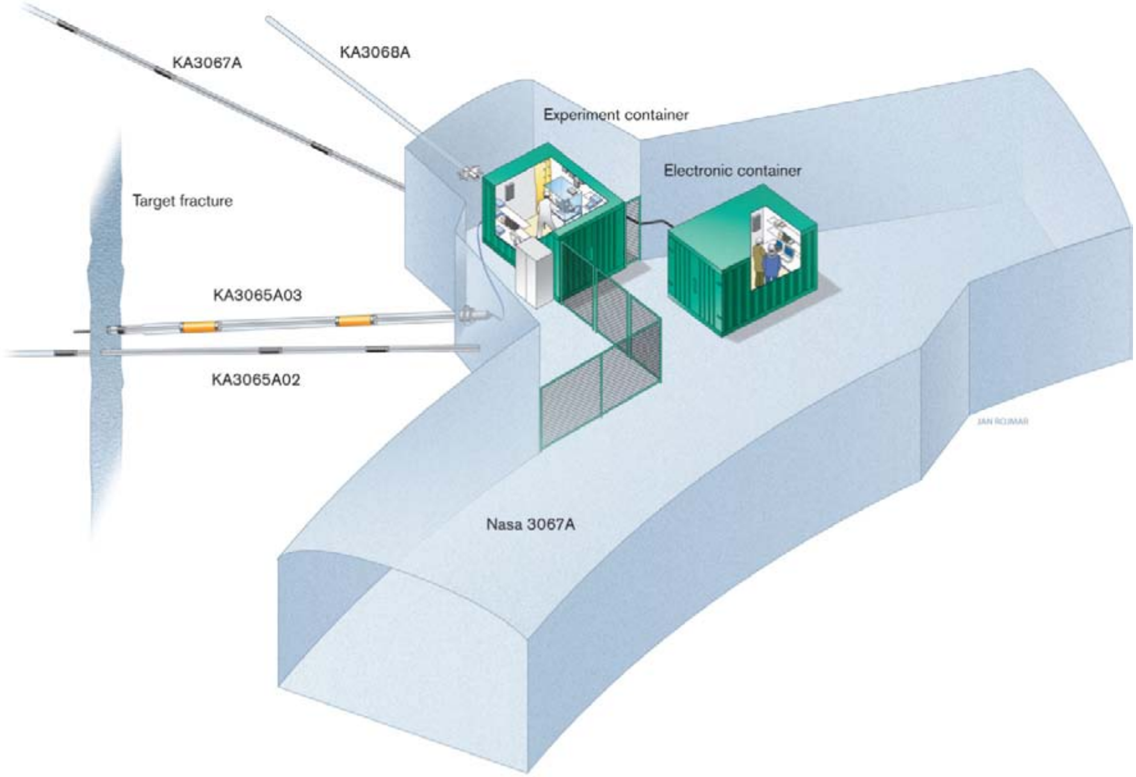


__Figure 3-2.__ The LTDE-SD experiment layout at niche NASA 3067A in Äspö HRL, at a depth of about –410 meter level. The experimental borehole KA3065A03 ends at the target fracture leaving a short core stub (177 mm diameter) with a natural fracture surface in the bottom of the borehole. A small diameter extension I drilled further into the unaltered rock beyond the fracture surface.

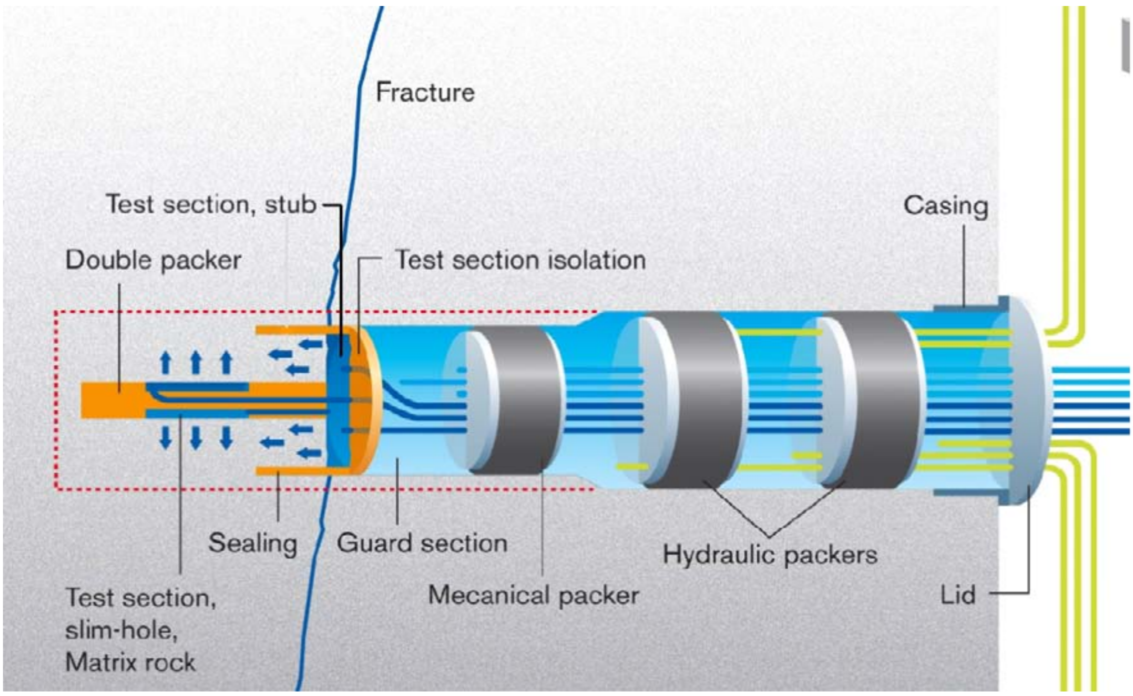


__Figure 3-3.__ Schematic of borehole instrumentation and test section design in KA3065A03 showing the ~3 mm wide and 177 mm diameter stub section in front of the natural fracture and the 300 mm long and 36 mm diameter slim hole section in matrix rock. The rock volume enclosed by the red dotted line was extracted by over-core drilling at termination of the experiment.

The project also involves laboratory experiments using the core material from the exploration borehole KA3065A02, the core of the 36 mm extension borehole and fracture material from the opposite side of the stub surface in KA3065A03. Both batch sorption and through diffusion experiments are included.

Results

The experimental tasks of the project were completed in 2010. Reports summing up the experimental work, including basic evaluation and first modelling attempt, were printed in mid 2011 (Nilsson et al. 2010, Widestrand et al. 2010a, b). Tentative future activities include extended evaluation and modelling.

Out of 22 tracers injected, it was possible to follow 21 in the aques phase and 11 tracers; ^{22}Na, ^{36}Cl, ^{57}Co, ^{63}Ni, ^{109}Cd, $^{110\,m}$Ag, ^{133}Ba, ^{137}Cs, ^{157}Gd, ^{226}Ra, ^{237}Np were possible to follow in the rock fabric. Non sorbing ^{36}Cl and weakly sorbing ^{22}Na has penetrated typically up to 30 mm during the 200 days of in situ experiment. The moderately sorbing tracers (^{137}Cs, ^{63}Ni, ^{133}Ba) is present in quite high concentrations in the first slices but have decreased to a level 3–4 order of magnitude at 3–6 mm depth. Species mainly sorbed by surface complexation (e.g. ^{153}Gd, $^{110\,m}$Ag) is found in the first few millimetres.

Autoradiograph analyses of the sliced rock samples indicate that the radionuclides diffuse in a heterogeneous pattern. The migration paths can visually be associated with microfractures and with the biotite part of the rock. The general shapes of the penetration profiles (and forward tailing) indicates significant influence of heterogeneous distribution of porosity in micro scale creating migration paths were fast diffusion can take place, Figure 3-4.

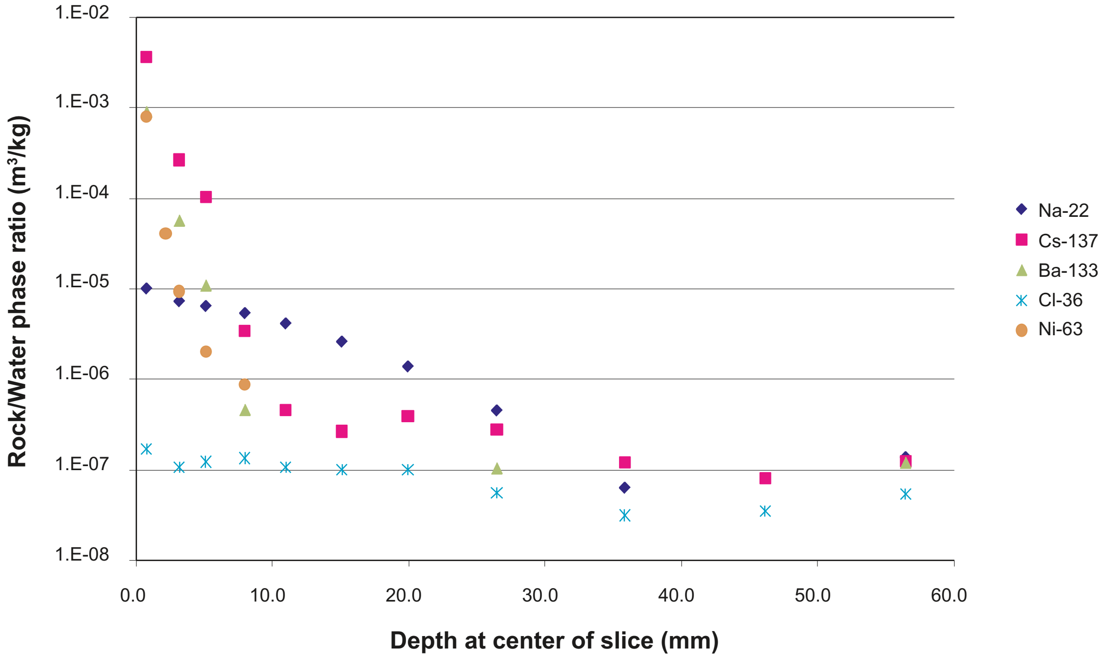


Figure 3-4. *Example of diffusion profiles in matrix rock (medium grained Ävrö granodiorite) surrounding the slim-hole test section. Sample core D13 with relatively deep penetration of tracers. The Y-axis refers to the measured tracer concentration in the rock sample (Bq/kg) divided by the tracer concentration in the water phase (Bq/m³). Values where the tracer concentrations in the rock samples were below detection limit have been omitted in the figure.*

Radionuclide sorption and diffusion

The modelling using a single-rate matrix-diffusion model to fit the penetration profile results has yielded the following results:

Using a diffusivity determined in an independent through diffusion experiment on samples from the LTDE-SD site (Widestrand et al. 2010a), a sorption coefficient, K_d was varied in order to fit the experimentally obtained penetration profile. The K_d obtained in this process is typically 1–2 orders of magnitude lower than the corresponding K_d determined by batch sorption experiments on LTDE-SD site specific samples. For the opposite approach (i.e., using the batch sorption determined K_d as a fixed parameter and varying the diffusivity to fit the *in situ* experimental data), diffusivity values (i.e., illustrated by the formation factor) need to be increased 1–2 orders of magnitudes compared to laboratory-derived parameters to fit the *in situ* experimental data.

Using an approach in which both the diffusivity and the sorption coefficients are allowed to vary in order to fit the *in situ* experimental data (i.e., no address of any independently measured laboratory data) indicates that a somewhat lower K_d in combination with a somewhat higher diffusivity, both in comparison with laboratory measurements, is needed to fit the *in situ* experimental data. It should be noted that modelling of penetration profile data can give unique values of K_d and diffusivity. This is contrary to the technique using only the time dependence of the loss in the aqueous phase which only is sensitive to the combined product of the diffusivity and the K_d (Widestrand et al. 2010b). However, it is worth noting that the present technique involves variation of two parameters to a very low number of data points which introduces considerable conceptual uncertainty to this modelling approach.

An illustration of the three modelling concepts is given in Figure 3-5 which shows the results of modelling using the ^{137}Cs tracer in comparison to the experimentally obtained results from A16 core sample, representing penetration into a natural fracture surface.

A conclusive summary of the modelling is that the interaction observed in this experiment (occurring mainly in the rock material less than 5 mm from the water-rock interface) seems to be influenced by a somewhat decreased K_d compared to batch sorption experiments and with an increased diffusivity compared to the results obtained by through diffusion experiments.

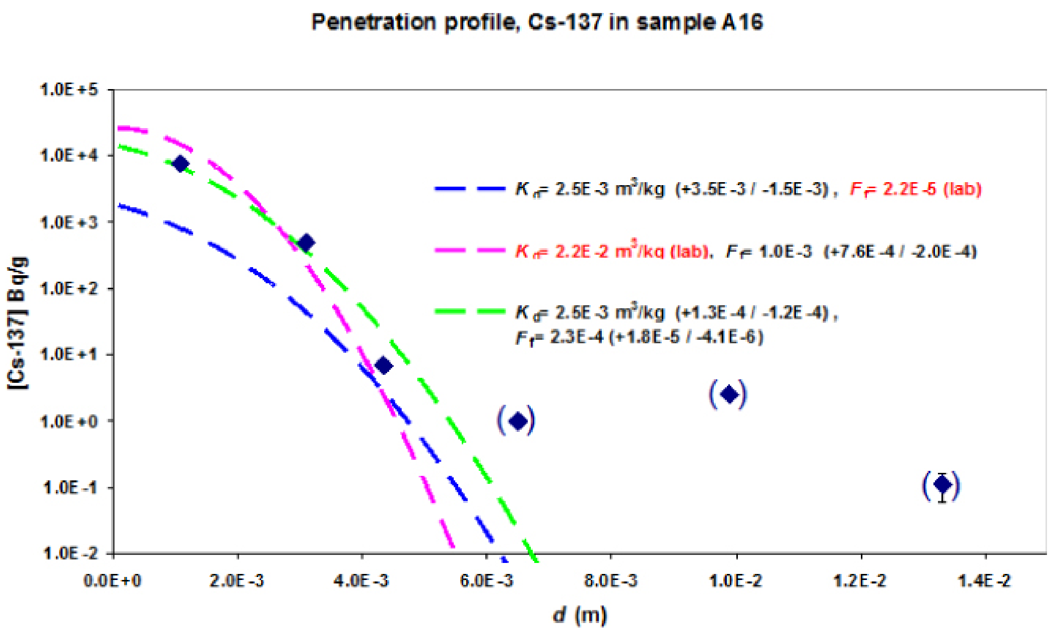


Figure 3-5. *Exemplification of how successively progressed fitting of the single-rate diffusion model to the in situ experimental results can be obtained by the different cases: Case 2 – fixed diffusivity, K_d varied (blue line), Case 3 – fixed K_d, diffusivity varied (red line), Case 4 – both K_d and diffusivity varied (green line). As mentioned in the text the modelling has been focused on the slow penetration profile process (which constitutes >99% of the sorbed tracer, therefore the datapoints representing the very minor but fast penetration process have been excluded.*

A forward tailing can be seen for all the tracers that have been subject to modelling (i.e., ^{36}Cl, ^{22}Na, ^{133}Ba, ^{63}Ni and ^{137}Cs). This result is proposed to be caused by porosity heterogeneity, e.g., fracture associated migration paths where comparatively fast diffusion could take place. However, the possibility of a contamination had taken place during the sampling cannot fully be excluded; likewise an impact of other transport mechanisms must probably be further explored. The data points considered as associated to this tailing have not been included in the modelling which has to be taken into consideration regarding the modelling values obtained from curve fitting. This exclusion has been justified by the fact that the tailing part of the penetration curve only constitutes a very minor part of the total amount of the tracer added, but one must be aware that the modelling interpretation is made under the conditions of not addressing the very minor but fast migration process.

In addition to the tailing observed for the penetration profiles, the general shape of the curves deviates significantly from the shape yielded by the homogeneous diffusion-sorption model. Given the observation in the ^{14}C-PMMA studies of a heterogeneously distributed porosity (Widestrand et al. 2010a), the difficulty to fit a single-rate based diffusion model to the measured results does not come as a surprise.

The amount of ^{36}Cl (anionic species) in the rock is approximately one order of magnitude lower than what should be expected from the porosity data (Widestrand et al. 2010a). A modelling attempt has indicated that an anion exclusion effect corresponding to an effective decrease of the diffusivity by a factor of 3 to 7 may provide good conceptual agreement with the anion exclusion theory, for the combination of the ^{36}Cl and the ^{22}Na results. However, it should be noted that this concept demands a decrease of the porosity with approximately a factor of 10 compared to the porosity measured using water saturation technique.

As a complement to the modelling, K_d values have been calculated by simply applying the ratio of the aqueous concentration of the tracer at the end of the circulation phase of the *in situ* experiment and the tracer concentration in the rock closest to the water-rock interface boundary. This technique produces K_d values higher than the ones obtained by the modelling of the penetration profiles but lower than what are obtained from corresponding modelling using only the results of the tracer loss in the aqueous phase.

3.5 Matrix fluid chemistry continuation

Background

The first phase of the project, the Matrix Fluid Chemistry Experiment (1998–2003), was to understand the origin and age of fluids/groundwater in the rock matrix pore space and in micro fractures, and their possible influence on the chemistry of the groundwater from the surrounding, more highly permeable bedrock. To accomplish this, matrix fluids were sampled from a borehole drilled into the rock matrix at 420 m level in Tunnel 'F'. Fluid inclusions in core samples and water/rock interactions have also been studied to determine their contribution, if any, to the composition of the matrix fluids/groundwater.

This phase was finalised and reported in Smellie et al. (2003). One general conclusion is that porewaters can be sampled successfully from the rock matrix and no major differences are apparent in the porewater chemistry compared to groundwaters from more highly conductive fracture zones in the near-vicinity of the experimental borehole. The main conclusions are:

- Groundwater movement within the bedrock hosting the experimental borehole site has been enhanced by increased hydraulic gradients generated by the presence of the tunnel, and to a much lesser extent by the borehole itself.
- Over experimental timescales (~ 4 years) solute transport through the rock matrix is mainly by small-scale advection via an interconnected micro fissure network and by diffusion.
- Over repository timescales diffusion of pore fluid/water from the rock matrix to the adjacent microfracture groundwaters, or *vice-versa*, will become more important depending on the nature of the existing chemical gradients.

- At Äspö, permeable bedrock at all scales has facilitated the continuous removal and replacement of the interconnected pore space waters over relatively short periods of geological time, probably hundreds to a few thousands of years.
- Fluid inclusions have made no obvious contribution to the sampled matrix waters.
- Although stringent measures were taken to minimise microbial activity, microbial mediated SO_4 reduction has been identified as a major perturbing effects on: a) the SO_4 and Fetot contents, b) the behaviour of pH and total alkalinity, c) the decrease in $\delta^{13}C$ and increase in ^{14}C, and d) the component ratios in the free gas above the water.

Objectives

The continuation phase of the project, Matrix Fluid Chemistry Continuation, commenced in 2004 focussing on areas of uncertainty which remained to be addressed.

These involved studies to:

- Determine more accurately the transmissivity and hydraulic conductivity of the rock matrix within and surrounding all test sections used for sampling porewater and groundwater.
- Characterise hydrochemical the nature and extent of the microfracture groundwaters which penetrate the rock matrix and the influence of these groundwaters on the chemistry of the porewaters.
- Extend studies on rock core specimens to confirm or otherwise the rock porosity values previously measured in the earlier study.

Experimental concept

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

Special downhole equipment, see Figure 3-6, was constructed to ensure: 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) the collection of pore waters (and gases) under pressure, and f) convenient sample holder to facilitate rapid transport to the laboratory for analysis.

This experimental equipment, with some modifications, has been used also in the Matrix Fluid Chemistry Continuation phase from 2005-11-28 through to 2006-08-11 to conclude sampling groundwaters from the micro fractures and to concentrate on measuring the hydraulic parameters of the micro fractures and the rock matrix.

Results

Some of the Matrix Fluid Continuation data have been published in the open literature (Tullborg and Larson 2006, Waber and Smellie 2008), but due to other SKB priorities the final publication of the Matrix Fluid Continuation phase and its integration with the Matrix Fluid Chemistry Experiment phase has not been possible from 2007 to the present day.

From a general hydraulic viewpoint, the matrix borehole KF0051A01 is dry with no water inflow recorded during drilling and no evidence of water-bearing fractures. Based on knowledge from other `dry´ locations at the Äspö HRL, the hydraulic conductivity of the rock surrounding the matrix borehole was expected to be in the range of 1.0E-14 to 1.0E-11 m/s. The results from the matrix borehole measurements indicate that the hydraulic conductivity is in accordance to what was expected, although in the lower region ranging from 7.4E-16–5.8E-13 m/s. This compares with 1.0E-14–5.8E-13 m/s in the rock surrounding the matrix borehole, indicating there is no large difference between the test sections containing visible micro fractures or not. However, there is evidence

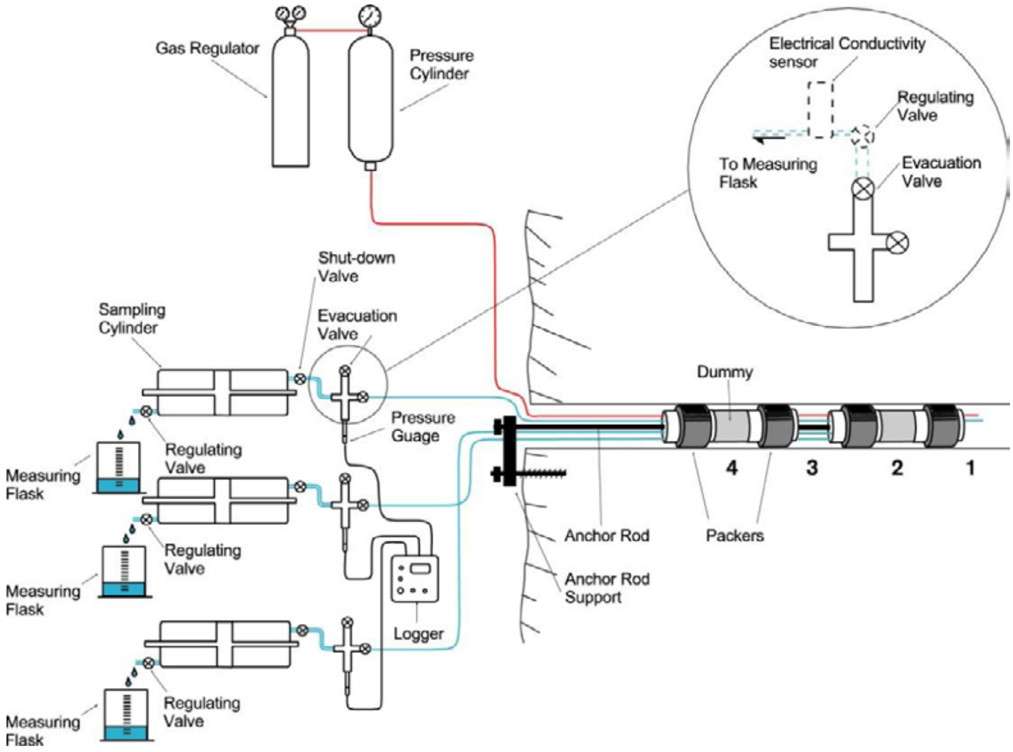


Figure 3-6. *Matrix Fluid Chemistry experimental set-up. Borehole Sections 2 and 4 were selected to collect matrix fluid, Sections 1–4 were continuously monitored for pressure.*

in some cases that micro fractures close to the test section sampled for matrix fluid can explain a somewhat higher conductivity than expected from the sampled section. Overall, these variations in conductivity in otherwise pure matrix rocks may be explained by heterogeneous conductivity in the micro fractures and that preferential hydraulic micro conductors may exist close to visible micro fractures.

These small heterogeneities in hydraulic conductivity close to the sampled borehole sections reflect, in some instances, differences in matrix water chemistry. However, these compositional differences are very small compared to nearby fracture groundwaters indicating that the collected waters (sampled periodically over a period of 7.5 years) originated from the low-permeability rock mass without mutual influence via more conductive micro fractures within the metre scale.

They are interpreted as representing pore water in a transient state of diffusive interaction with different types of old palaeowaters which have periodically characterised the fracture network at the Äspö HRL over geological timescales (thousands to possibly hundreds of thousands of years).

Porosity measurements to supplement data from the Matrix Fluid Chemistry Experiment were carried out by Tullborg and Larson (2006). Measurements were conducted on samples from a drillcore representing the porphyritic Äspö quartz monzodiorite. Water saturation measured on eleven 60 mm long core pieces was used to calculate the connected porosity which ranges between 0.32 and 0.44 vol. %. Some of the 60 mm length samples were subsequently cut into 35 slices of various thicknesses (3 mm, 6 mm, 10 mm and 20 mm), and water saturation was measured. On average, higher connected porosity values were measured in the thin slices compared with the 60 mm thick samples. This is mainly because the thinner samples have a higher relative portion of pores created by mechanical failure than the thicker samples; this is also due to a higher portion of micro fractures which have lengths exceeding the thicknesses of the samples.

The total porosity in the samples studied from the Äspö quartz monzodiorite ranges from 0.89 to 1.51 vol.% (~70% of the measurements are within the range of 1.10±0.13 vol.%), and connected porosity (by water saturation) of 60 mm long drillcore pieces ranges between 0.32 and 0.44 vol.%.

3.6 Transport resistance at the buffer-rock interface

Background and objectives

At the Department of Chemical Engineering and Technology Royal Institute of Technology in Stockholm a simple analytical model for mass transfer between water flowing in fractures and the buffer surrounding the copper canister has previously been developed. It has been used in SKB safety analysis to assess the rate of in transport of corrosive agents, release of radionuclides and release of colloids by chemical erosion. The original model is based on the assumption that the fracture can be modelled as a slit between plane surfaces. Other groups have verified the model by comparison with numerical models. We have also extended the model to variable aperture fractures by numerical studies and been able to devise simple approximate formula suitable to be used in safety analysis codes. The long-term aim is to experimentally verify the Qeq concept for variable aperture fractures.

Experimental concept

Recently some simple scoping experiments in a variable aperture slit where a dye was allowed to diffuse into stagnant water were made. The results partially validate the Qeq concept as the predicted expansion of the dye front into the water in the slit agrees with what is expected using the Qeq model concept.

During 2011, based on the previous experience, the equipment has been modified and some new equipment has been built. Some additional experiments were also made. In one experiment a more rapidly diffusing species was tested. In another experiment the new equipment was used. This is a 15×15 cm large slit where the dye injection chamber was modified to facilitate injection of the concentrated dye.

Figure 3-7 shows this equipment and the dye diffusion after two months. On the left the variable aperture slit is seen. To the right a tapered slit with 0.00 mm at the bottom and 1.00 mm aperture 100 mm above the bottom filled with dye of a known concentration is shown. The latter is used to calibrate the dye concentration in left picture. The aperture distribution in the variable aperture slit has previously been determined by filling it with a known concentration of dye.

Some problems were encountered. After a little more than a month a gas bubble started to grow in the upper part of the slit. After two months it had intruded several centimetres down from the top. The gas bubble can be vaguely discerned in the picture. New tighter valves will now be installed to hinder this.

Results

A set of computer programs were developed to facilitate and automate the analysis of the hundreds of pictures taken from the experiment shown in the figure above. The experimental setup has been further improved to avoid gas bubbles. New experiments have been performed with Carmin dye, which has been used so far. Carmin was troublesome because it sometimes degraded slowly over the long experimental times, up to four months Uranin a very strong organic dye and copper, an inorganic coloured ion was tested to see if they can be used. The advantage expected with copper is that it has a much larger diffusion coefficient and potentially could speed up the experiments by a factor of two or more. This was found to have to low a light absorption to be useful. In the Uranin experiments the diffusion front evolution as erratic at early times stabilising later.

A model was made to simulate the propagation of the diffusing dye in the variable aperture fracture to in detail simulate/predict the propagation of the dye in the fracture in the experiment(s). The experiment with Uranin gave a good agreement with model predictions. The predicted diffusion distance agreed within a factor of 2 with the predicted distance.

Granite cores, 14 cm in diameter, with a fracture along the axis were obtained from Äspö. The cores were forced apart along the fracture and cast of both sides were made using a transparent acrylic resin (Figure 3-8). These replicas of real fractures will be used in future diffusion experiments.

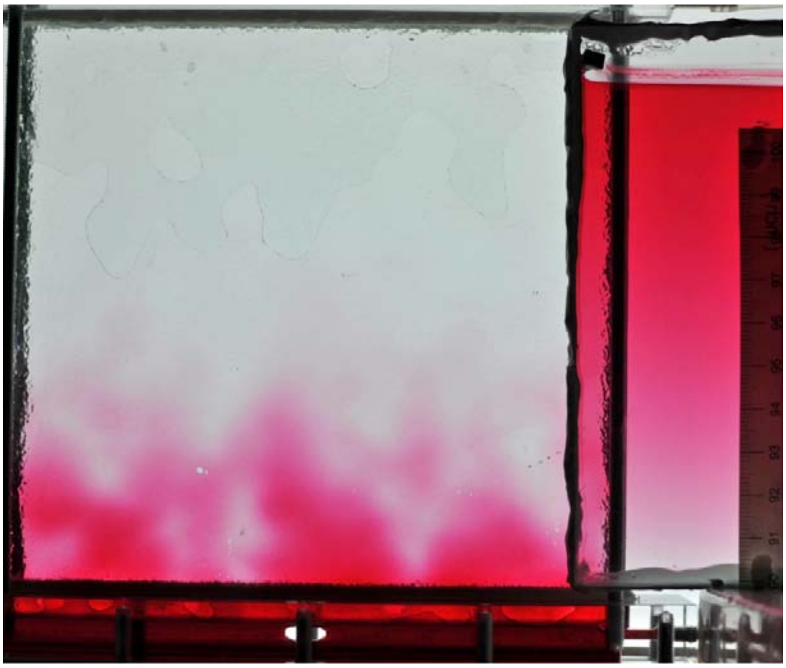


Figure 3-7. Dye diffusion after two months.

Figure 3-8. Picture of Rock fracture from Äspö left and the two cast sides fitted together with red dye between them.

A first test experiment with water flowing horizontally to sweep away the dye diffusion from below has been made. It was clearly seen that the dye was swept by the flowing water and that the effluent contained dye. This experiment has not yet been evaluated. Based on the experience from this setup a modified setup is planned.

3.7 Padamot

Background

Palaeohydrogeology is a term used as a common name for information from fracture minerals that are 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 (Bath et al. 2000) and subsequently Padamot (Palaeohydrogeological Data Analysis and Model Testing) 2002–2005 (Milodowski et al. 2005). A continuation of the Swedish part of the project at Äspö has thereafter been agreed by SKB. This has been called Padamot Continuation and is focused on the use of uranium series analyses in order to give time and space constraints on redox processes in the bedrock aquifer. One of the most important criteria to ensure the long-term stability of a deep geological radioactive waste disposal system is maintenance of reducing hydrochemical conditions over the lifespan of the repository and the behaviour of redox sensitive elements (e.g. Fe, U, Ce) under present and past bedrock conditions is therefore of great interest in this context. Of particular relevance is the potential for deep penetration of oxidising, sub-glacial water during periods of glaciation. Uranium, being a redox-sensitive element which occurs naturally in the bedrock and groundwaters can therefore be used, in conjunction with its decay series descendants, to indicate groundwater redox conditions. Not only can contemporary conditions be characterised, but evidence of past changes (e.g. during the last glaciation) can be preserved in minerals which coat the fracture walls along groundwater pathways.

Objectives

The 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.

Results

The experimental concept used for the uranium series analyses as well as the results of these analyses have been described in earlier HRL annual reports and will not be repeated here. A full account of the different analytical approaches and the results will be included in the final reporting of the PADAMOT Continuation project. The second part of the final report will include the revisitation of the methodology used for fracture mineralogical studies during the SKB Site Investigations in Forsmark and Laxemar during 2002 to 2008 (Sandström et al. 2008, Drake and Tullborg 2009) and will give an updating of this based on experiences from the site investigation and other studies on fracture mineralogy carried out during the last decade. Several experiences will be highlighted of which only a few are mentioned here.

It is obvious that during the last ten years the possibilities of analysing very small samples with good precision have increased and it is also, as a result of ongoing debates in the scientific society, evident that during a period of ten years certain issues became more in focus than others. For example, during the site investigations the representatively of measured sulphide values in the groundwater has been discussed and as a result the possibilities to confirm biogenic sulphide reduction in the past via studies of sulphide minerals has become increasingly important. If the drillcore quality permits even very small euhedral crystals of the latest calcite and pyrites can be studied, not only for stable isotope composition but also for zonation (e.g. Drake et al. 2012) providing palaeohydrogeological information.

The very detailed studies of Fe-oxides described in Section 3.8 have contributed methods to solve questions about the origin of Fe-oxyhydroxides that may be found at the fracture surfaces.

he methodology for studies of the near-surface redox front used for example at Laxemar has also been tested on drillcores from Greenland, as part of the Greenland Analogue Project (GAP) managed by SKB, Posiva and NWMO. The challenge, in addition to the relatively poor drillcore quality, was the very small amount of U available for the U-series analyses. Nevertheless the combined use of Alpha spectrometry and multicollector ICP-MS analyses made it possible to get comparable analyses.

3.8 Fe-Oxides in fractures

Background

The Fe-oxide studies described in this section were carried out by the members of the Nano Science Group at the Geological Institute, University of Copenhagen in close cooperation with SKB. Some aspects of the studies contributed to two Master's Theses (Lindbæk Skovbjerg 2005, Christiansen 2004) whilst other aspects contributed to post doctoral studies (Dideriksen and Stipp 2005, Dideriksen et al. 2007, 2010).

The combined general interests of SKB and the University of Copenhagen relevant for radioactive waste disposal in fractured granite included the following topics:

- 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?
- Does the suite of trace components and isotopes measured in minerals from fracture linings provide information about conditions of the water that passed through them in the past?
- Iron itself can be an indicator of redox state. Fe-isotope fractionation, a very new topic of research, might give clues about redox conditions during Fe-mineral formation or as a result of its inclusion in other secondary fracture minerals.

For a more direct application to problems for Swedish waste disposal, these topics were extended and rephrased more specifically 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 us anything about solution conditions during genesis?
- What is the uptake and retention capacity of green rust under solution conditions relevant for Äspö?
- Is it possible to find evidence to support or 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?

Studies related to these topics commenced with an Initial Phase, a three year project entitled 'Fe-oxides in fractures: Genesis and trace component uptake', which was conducted from 2003–2006. This involved studies of Fe(III) oxides and oxyhydroxides in natural fractures with emphasis on their structure and geochemistry, formation conditions and their ability to take up trace elements (Dideriksen et al. 2007). Groundwater flowing into fractures from the surface would be expected to decrease temperature and increase oxidation potential, facilitating precipitation of Fe-oxides with a different chemical signature than those produced from hydrothermal solutions. In parallel with this Initial Phase, on-going studies at the University of Copenhagen focussing on 'Green Rust' were nearing completion (Lindbæk Skovbjerg 2005, Christiansen 2004).

Furthermore, as part of these Initial Phase studies a Feasibility Study was carried out in 2006 to develop a method for differentiating between Fe-oxides precipitated: a) from hydrothermal solutions, b) from natural, low temperature groundwaters, and c) as an artefact of drilling activity (Dideriksen and Stipp 2005). The method used Fe(III)/Fe(II) ratios, Fe-isotope fractionation and rare earth element distribution and has been successful on very small quantities of sample. With this method, it was possible to define a boundary plane marking the limit of evidence for oxidising water penetration from Fe-oxides gathered from fractures in drill cores.

Based on the results from the Initial and Feasibility studies, a Continuation Phase was carried out during 2006–2008 on a larger sample suite (28 samples) taken from the upper approximately 110 m of drillcore material from the Laxemar site. These were used to establish the penetration depth of oxidising waters below ground surface at different sites.

The Fe-oxide fracture linings were used 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.

Objectives

The most important objective of the Initial Phase study (including the Feasibility Study) was to investigate the possibilities for establishing a redox indicator or geothermometer for the iron oxides.

This entailed characterising minerals in the red- and brown-stained fractures in granite using core samples from the Oskarshamn borehole KOV01, the Äspö borehole KAS06 and directly from the Äspö tunnel. Additional material from borehole KFM02A in Forsmark was collected to address suspected contamination by anthropogenic-derived fine metallic material from drill wear, suggesting that Fe from the drilling could contaminate the fracture linings.

The objectives of the final Continuation Phase study were:

- To complement data from the Äspö HRL and Oskarshamn.
- To integrate samples from site characterisation studies in the Laxemar subarea.
- To sample a well-defined fracture network to demarcate the spatial depth of potentially penetrating oxidising waters.
- To use these data to better interpret the Äspö data already obtained from the Initial Phase and Feasibility Phase Studies.

Experimental concept

A glove box set-up, where Atomic Force Microscopy is possible *in situ*, was used to investigate green rust (precursor to later amorphous and more crystalline varieties of low temperature Fe-oxides) 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

Background laboratory studies

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 presence could be important in the remediation of, for example, Cr(VI) by its reduction to the non-toxic Cr(III). The uptake capacity during formation and transition to Fe(III)-oxides is essentially unknown at present and this was addressed by studying the uptake of Cr(VI) preferentially on green rust sulphate (Lindbæk Skovbjerg 2005). This resulted in Cr(III)-substituted ferrihydrite being initially produced together with Cr(III) substituted goethite and, when left in solution, the ferrihydrite dissolves and reprecipitates as Cr(III)-substituted goethite. Goethite has a low solubility and the incorporation of Cr(III) into the crystal structure decreases the solubility even more, so therefore goethite is an effective sink for trivalent chromium. These Fe(II)-oxyhydroxides minerals could be an important sink for radioactive species (e.g. released during canister corrosion) where Fe is abundant in the natural fractures or in materials brought into the repository.

Work carried out by Christiansen (2004) concentrated on the transformation of $Fe(OH)_2$ to green rust sulphate (GR_{SO_4}) and further to goethite during oxidation. A GR_{CO3} type compound from Fe(II)-rich groundwaters located in Sweden and Bornholm was successfully identified. However, the study showed that more work is required to determine the thermodynamic properties, structural models and natural occurrence of green rust compounds.

Field site studies

The Swedish field site studies of Fe-oxide identification and composition, combined with the development of a method using Fe isotope measurements to trace low temperature oxidising conditions, form the basis of the investigations conducted.

From the various sites studied within the Initial Phase, the Feasibility Study Phase and the Continuation Phase, three types of natural Fe-oxides have been identified:

- **Type I:** Hematite with a large particle size and little variation in Fe isotope composition, occurring at depths ranging from the surface to 800 m; this is of considerable age and hydrothermal in origin.

- **Type II:** Crystalline Fe-oxides (goethite, magnetite, hematite with smaller particle sizes) occurring at depths down to 110 m below surface; well formed crystals of low temperature origin representing earlier oxidation effects compared to Type III.
- **Type III:** X-ray identified amorphous, nanometre-sized Fe-oxides occurring at depths down to 50 m below surface; these are considered amorphous and low temperature in origin indicating formation during recent iron cycling.

Thus, in general, the studies indicate that the fractures of the upper 50 m are currently experiencing episodes of oxidation (i.e. meteoric recharge), whereas earlier events of low temperature oxidation have occurred down to depths of 110 m below surface for brief periods (i.e. meteoric recharge and/or glacial melt waters).

A goethite-bearing sample from about 90 m depth and adjacent silicates was analysed for oxygen isotopes to test a possible relationship to glacial waters. Although the analysis was complicated by the presence of silicates in the goethite-bearing material, the calculated isotope composition of the goethite formation water was $\delta^{18}O$ = –6.0‰ to –4.9‰ V-SMOW. These values indicate that the goethite formed from meteoric water or from older seawater suggesting that oxidising waters may penetrate to depths of about 90 m without glacial influence.

In the samples studied, no evidence has been found of natural, low-temperature formation of Fe-oxides below 110 m depth. However, considering the relatively small sample set, the possibility that low-temperature Fe(III)-oxides might also exist in deeper fractures that were not sampled cannot be excluded. Nevertheless, the identification of nanometre scale Fe-oxides indicates oxidising conditions in the recent past in the upper 50 metres. Most likely, Fe-oxides at these shallow depths are continuously forming and dissolving as a consequence of fluctuating redox boundaries. The crystalline nature of the deeper, low-temperature Fe-oxides indicates that they are older. The absence of extensive alteration, of the type seen in the upper 20 m of the bedrock, for the deeper fracture material, suggests formation during a fairly brief event where oxygenated water reached depths of ~110 m (Dideriksen et al. 2010). The explanation and consequences to this observation are still under debate.

3.9 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 (Hallbeck 2009, Tullborg et al. 2010, Rosdahl et al. 2010). 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 softeners in plastics and rubber.

Objectives

The aim of this project is to study the processes behind microbial sulphide production in deep groundwater and drilled boreholes as well as the regulating factors for dissolved sulphide.

Experimental concept

An experimental activity in Äspö HRL is planned for February 2012 that will focus on the possible effects from the borehole instrumentation on the microbial sulphide production in groundwater and boreholes.

Borehole instrumentations from two boreholes drilled in the 1990´s will be dismantled and investigated. The boreholes have different sulphide concentrations and an important objective will be to compare the conditions in the boreholes and determine any differences that could be related to the extent of microbial sulphide production.

Borehole instrumentation consists of pipe strings, packers and tubing. In addition tape is used for holding the tubing and pipe string together during the installation procedure. Pipe strings are made of Aluminium or stainless steel, packers of stainless steel and rubber, tubing of polyamide plastics (Tecalan) and tape of PVC plastics (poly vinyl chloride).

The investigation will include the following:

- Assessment of corrosion of metal.
- Assessment of leaching of softeners from plastics.
- Microbiological analyses.
- Analyses of stable isotopes.

Total number of cells and numbers of sulphate reducing bacteria (SRB) will be determined on the various materials of the borehole instrumentation. The results may indicate if the sulphide reducing processes are related to a certain material (metal corrosion or surfactants in plastics). Samples will also be collected for DNA extraction and determination of species of bacteria if enough material can be collected. Analyses of stable isotopes as ^{13}C in precipitated calcite can give information of what carbon source that is likely to be utilised by the bacteria. Observations and analyses of corrosion on metal parts and plastics give information of presence, degree and cause.

Results

Some results concerning sulphide from previous experiments in this project and from investigations during the monitoring programme in Forsmark can be summarised as follows:

- The concentration of sulphide and sulphate reducing bacteria increase with time in a packed-off section during periods without pumping. The sulphate reducing bacteria and concentration of sulphide decrease after discharge of water from the section and as the fraction of water from fractures increase.
- The location of water-bearing fractures in a drilled borehole and the transmissivities of the fractures influence the obtained sulphide concentration from a borehole section.
- In surface boreholes the design of the instrumentation, such as the water stand pipe has an influence on the sulphide concentration in packed-off sections.

Figure 3-9. *Parts of the instrumentation in a core drilled borehole. Pipe string and tubing attached with black tape. The instrumentation in core drilled boreholes is used for pressure measurements and chemical monitoring.*

3.10 Swiw-test 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 and potassium replaced by nitrate, lithium, magnesium. Besides, in order to compare to a normal Swiw test, Uranine, rubidium and caesium normally used as tracers within the site investigations were also added. This synthetic groundwater is injected in the fracture. In the withdrawal phase of the test the content of the "natural" tracers 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

All field tests were finalized during 2010, so 2011 was used for analysis, evaluation and reporting. However, due to several complications during the chemical analysis, the final report of the project could not be finalized during 2011 as previously planned. Analysis, evaluation and modelling are completed, but conclusions and reporting are underway. The report will be completed during early 2012.

The results presented here should be considered as preliminary. However, it is clear that the tests were successful from an experimental point of view, resulting in large data sets of good quality, probably useful for extended evaluations beyond the scope of this project. Two main tests were carried out with different experimental time, resulting in clear differences between the two tests regarding tracer breakthrough. It is also indicated that diffusive mass transfer plays an important role for the experimental results. Interpretation is underway, but there are indications of slow diffusion (i.e. rock matrix) and possibly also that multiple-rate diffusion is occurring.

3.11 Äspö model for radionuclide sorption

Background

Today, geochemical retention of radionuclides in the granitic environment is commonly assessed using sorption coefficient, 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 the 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

During 2011, the overall objective of this project has been revised, with focus being redirected to provide experimental evidence for the formulation for process quantifying models for geochemical retention of radionuclides, in granitic environments, using a laboratory approach. Particularly, operational objectives are to experimentally:

a) 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,
b) 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.

Experimental concept

The project is divided into three research activities:

1. Preparatory studies.
2. Surface area dependency of sorption.
3. Localisation of sorption.

The project works with pure mineral samples and also a drill core, similar to the rock material used in the LTDE experiment (see Section 3.4). 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. Previously, mineral specimen have been crushed and characterised and their specific surface area has been determined (e.g., Dubois 2011, Dubois et al. 2011). During 2011, focus has been on developing methods to observe radionuclide sorption onto granitic material using autoradiographic methods as well as adapting batch sorption methods to the needs within the project. Furthermore, previously started porosimetry determinations have been continued, through testing of the employed experimental method and investigation of additional mineral samples and particle sizes. In addition, numerous replicates of previous porosity measurements have been conducted, in order to increase the quality of the results, in many cases giving values close to the detection limit of the employed method.

Results

Porosity of mineral samples

Figure 3-10 shows the porosity of chlorite as a function of the reciprocal of the characteristic particle size. As expected, the specific volume increases as the particle size decreases. The insert to Figure 3-10 shows a chunk of the chlorite and a SEM image of one of the crushed samples. The SEM picture indicates possible contributions to the porosity, showing highly damaged particles. Figure 3-11 displays the apparently linear relation between specific pore volume and specific surface area obtained for all investigated mineral samples. Presently, the dependence between specific pore volume, specific surface area and particle size is under interpretation, tentatively using a conceptual model of a particle with a mechanically disturbed zone at the surface of the particle surrounding a core of pristine material (insert to Figure 3-11).

Autoradiography

The localization of sorption of caesium, strontium, europium and nickel on granitic drill cores was investigated with help of autoradiography. While results for nickel were inconclusive, since the activity used was too low to allow detection of the radionuclide, results for caesium, strontium and europium were promising in the preliminary experiments. Figure 3-12 exemplifies the obtained results, indicating that caesium and strontium sorbs strongly on dark minerals (like magnetite and biotite, in black in the photographs) but not on e.g., K-feldspars (in pink in the photographs.

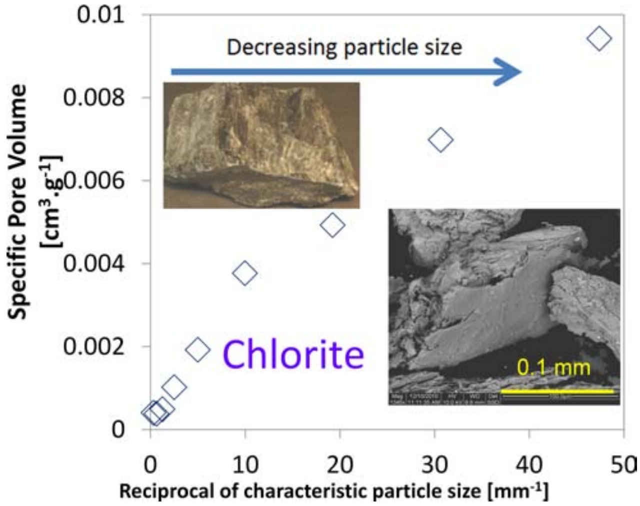


Figure 3-10. *Specific pore volume of chlorite as a function of the reciprocal of the characteristic particle size.* ***Inserts:*** *Photo of chlorite specimen (chunk) and SEM of crushed material.* ***N.B.*** *Preliminary results.*

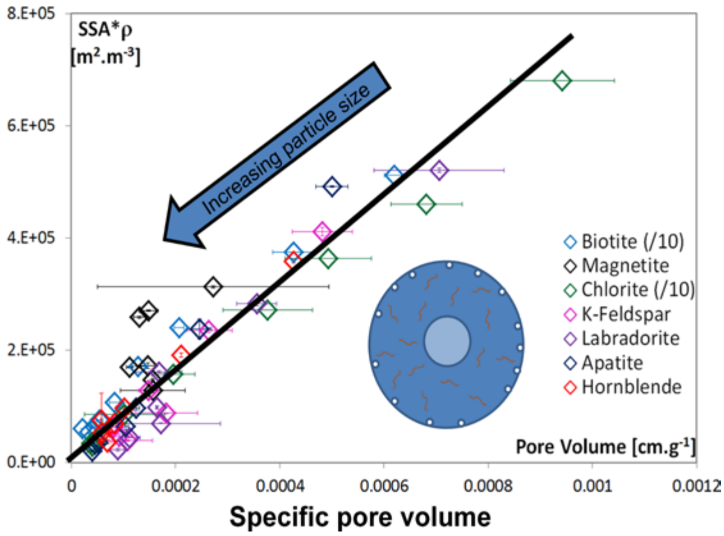


Figure 3-11. *Specific surface area [m^2 m^{-3}] as function of specific pore volume [cm^3 g^{-1}] of various particle size fractions of biotite, magnetite, chlorite, K-feldspar, labradorite, apatite and hornblende.* ***Insert:*** *Schematic cross-section with a disturbed zone with artificial porosity at the surface of a particle.* ***N.B.*** *Preliminary results. Values for chlorite and biotite have been divided by a factor of 10.*

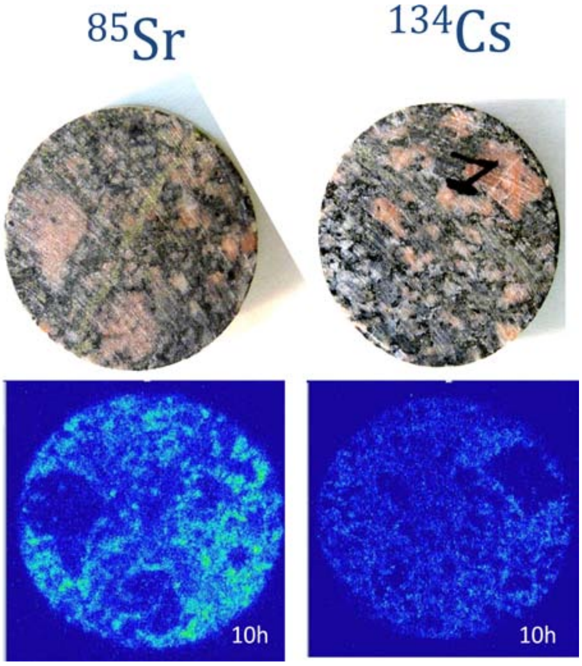


Figure 3-12. *Sorption of strontium (left) and caesium (right) onto drill cores of granitic material. The photographs (upper) indicate the location of dark minerals, such as biotite and magnetite, in black areas and, for example, K-feldspar by the pale, pink areas. The lighter parts in the autoradiographs (lower) indicated the location of activity, and thereby the sorption, after 10 h of exposure to test solution containing the radionuclide.*

3.12 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, 1^{st} 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 solute transport in order to demonstrate their use for performance and safety assessments.

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".

Task 8 is a joint effort with the Task Force on Engineered Barriers, and will be addressing the processes at the interface between the rock and the bentonite in deposition holes. Task 8 has continued in terms of planning and scoping calculations. The BRIE (Bentonite Rock Interaction Experiment) project, which is coupled to Task 8, is ongoing, see Section 3.13.

Results

During 2011, for Task 7 work has mainly been performed within 7C (deposition hole scale). The Task 8 work mainly contained updated scoping calculations coupled to BRIE. The BRIE project is on-going, and has couplings to Task 8 in terms of data deliveries but also predictive modelling within the task may provide support to the experiment. It will also provide a possibility to compare the modelling results to the experiment.

The 27th international Task Force meeting was held at Äspö HRL in March. 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. The minutes of this venue have been distributed to the Task Force members.

A workshop for Task 7 and 8 was held in October where modelling approaches and plans for the future modelling were presented and discussed. The venue took place in Gothenburg, Sweden. The description and the status of the specific modelling sub-tasks within Task 7 and 8 are given in Table 3-1.

Table 3-1. 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 in internal documents).
7B	Sub-task 7B is addressing the same as sub-task 7A but in a smaller scale, i.e. rock block scale. Sub-task 7B is using sub-task 7A as boundary condition. (Updated final results presented at Task 7 and 8 Workshop in October).
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 October).
8	Interaction between engineered and natural barriers
8A	Initial scoping calculation (reported as presentation files).
8B	Scoping calculation (Updated results presented at Task 7 and 8 Workshop in October).
8C	Initial predictions (Preliminary results presented at Task 7 and 8 Workshop in October).

3.13 Bentonite rock interaction experiment

Background

Bentonite Rock Interaction Experiment (BRIE) has its focus on the common boundary at the thin interface between the bentonite clay and near-field host rock. BRIE is linked to Task 8 that is intended to be a joint effort of the taskforce on groundwater flow and transport (GWFT) and the Task Force on engineered barrier systems (EBS).

Objectives

BRIE and Task 8 together are intended to lead to:

- 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 deposition holes.

Experimental concept

The experiment is subdivided into two main parts. Part I describing the selection and characterization of a test site and two central boreholes, see Figure 3-13, and Part II handling the installation and extraction of the bentonite buffer. The characterization will result in a deterministic description of the fracture network at a small scale (≈10 m). This will include all identified fractures and the water-bearing part of the fractures.

Results

A decision that the site was suitable for the experiment was taken in early 2011 and additional boreholes were therefore drilled for characterization of the site. Investigations include e.g. monitoring of pressure, hydraulic tests and core mapping. Late in 2011 two central boreholes were drilled and bentonite will be installed in 2012. Three main geometrical features are so far identified in the TASO tunnel: a deformation zone perpendicular to the tunnel; an excavation damaged zone (EDZ) and a number of interesting conductive fractures. Focus will be on investigating wetting of the bentonite in contact with the rock matrix and a few conductive fractures located below 2 m depth.

Figure 3-13. *One of two central boreholes (300 mm) in TASO-tunnel for installation of bentonite.*

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 real repository.

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

During 2011 following experiments and projects within the Engineered Barriers were conducted:

- 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.
- 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. The retrieval of the outer section, which started in 2011, is made in cooperation with Posiva. Furthermore, the following organisations are participating and financing the work with the dismantling; NWMO (Canada), ANDRA (France), BMWi (Germany), NDA (United Kingdom), NAGRA (Switzerland) and NUMO (Japan).

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.

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.

The outer test section was decommissioned during 2011 after approximately eight years of water uptake of the buffer and backfill.

Results

The installation of the inner section (Section I with deposition holes #1, #2, #3, #4) 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 the outer section (Section II with deposition holes #5 and #6) 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 in the beginning of January 2004. At that date the heating in canister 2 failed. It was then decided to turn off the power to all of the six canisters. Four days later, also damages on canister 6 were observed. The drainage of the tunnel was then opened again. During the next week further investigations on the canisters were done. The measurements showed that the heaters in canister 2 were so damaged that no power could be applied to this canister. The power to the rest of the canisters was

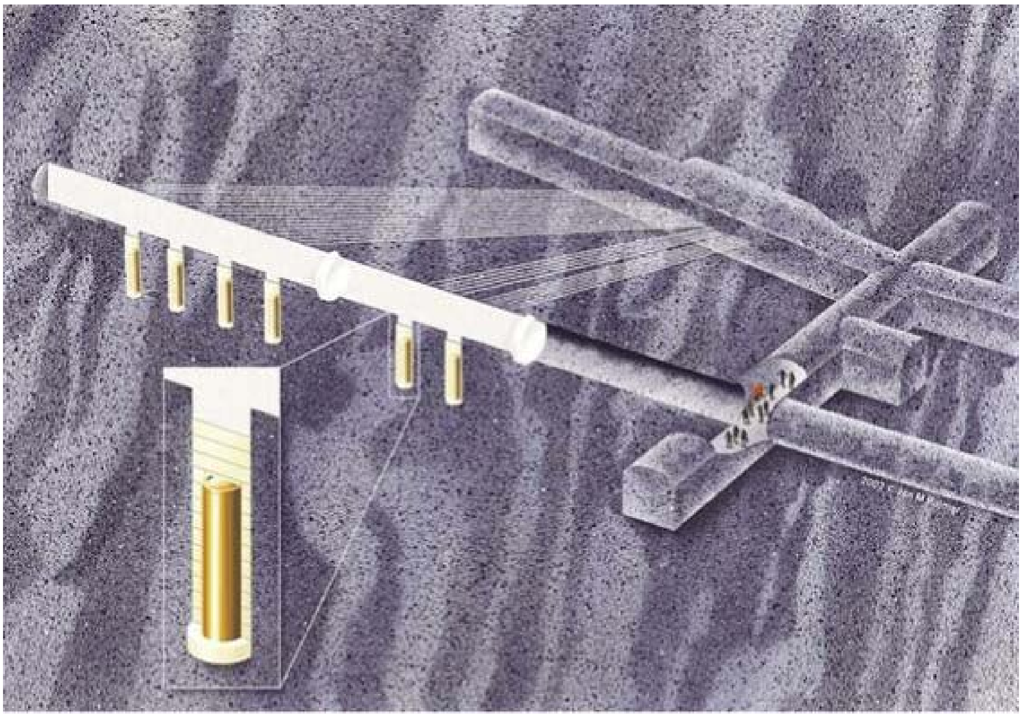


Figure 4-1. Schematic view of the layout of the Prototype Repository (not to scale).

applied in the middle of November 2004 again. The drainage of the tunnel was kept open. At the beginning of August 2005 another failure of canister 6 was observed. The power to this canister was switched off until beginning of October 2005 when the power was switched on again. During 2008 new problems were observed with the heaters in canister 6, resulting in that the power was reduced to 1,160W.

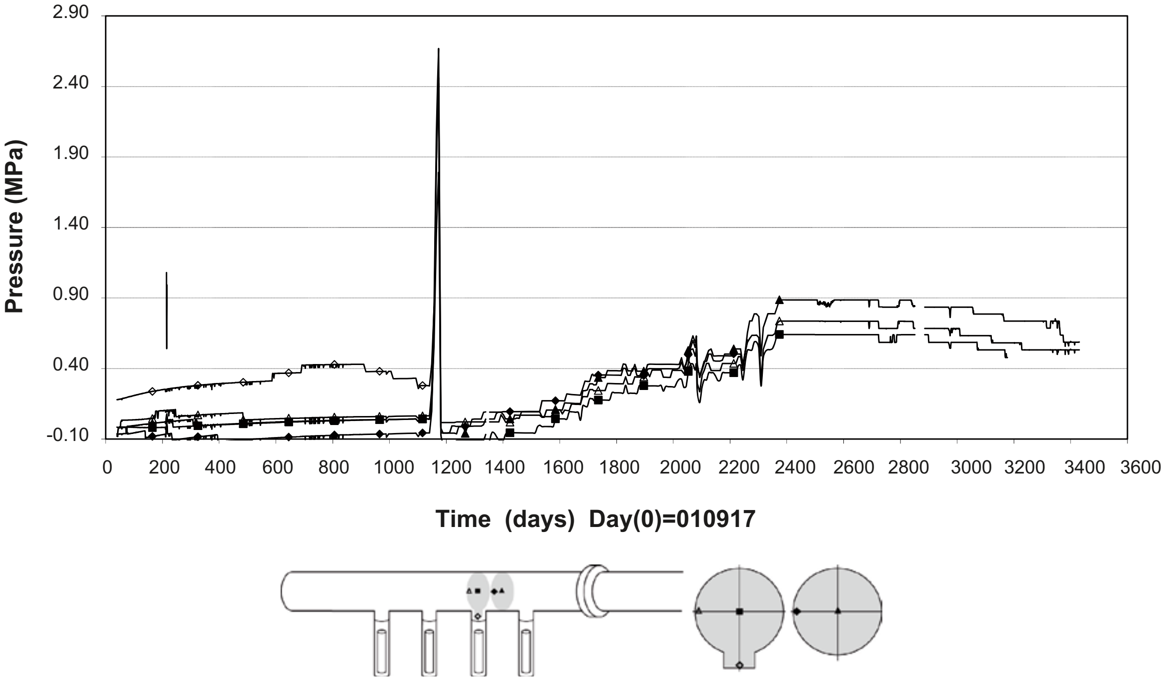


***Figure 4-2.** Examples of measured total pressure in the backfill around deposition hole 3 (17th September 2001 to 1st January 2011).*

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 (Barcena and Garcia-Sineriz 2001). In addition resistivity measurements are made in the buffer and the backfill (Rothfuchs et al. 2003). The outcome from these measurements is profiles of the resistivity which can be interpreted to water ratios of the backfill and the buffer.

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 (Harrström and Andersson 2010).

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 (Duckworth et al. 2009).

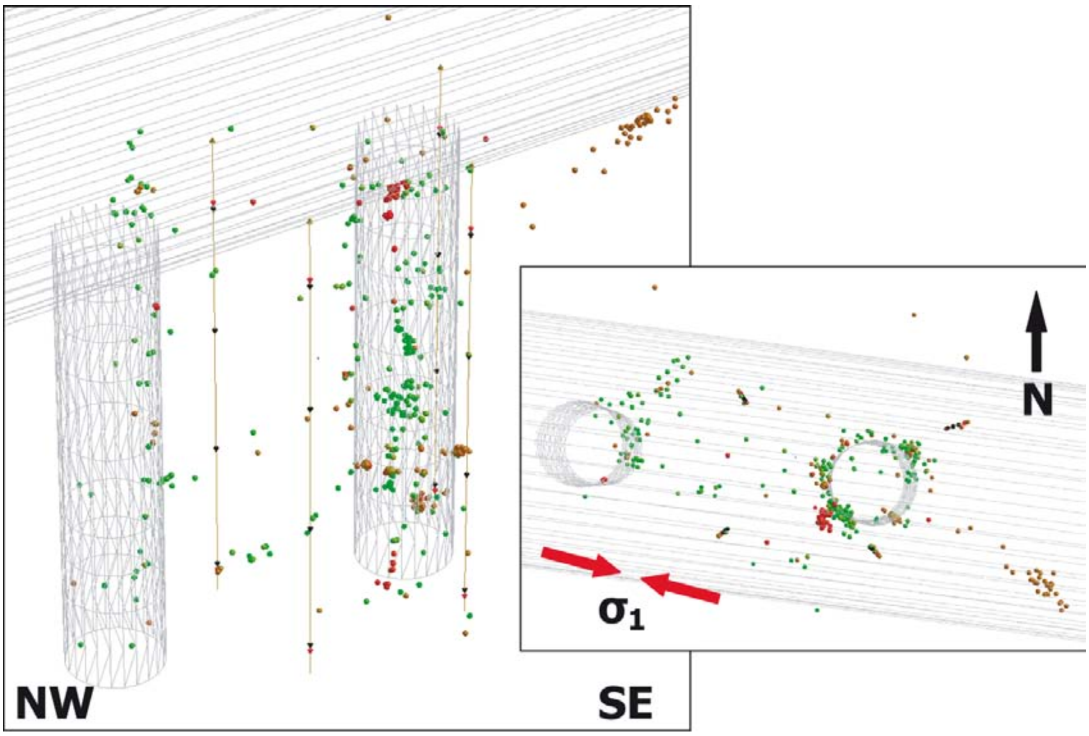


Figure 4-3. Projections of all AEs located during the heating phase (20th March 2003 to 30th September 2008). In total there have been 848 events over the last six years of monitoring (events are scaled by time).

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 published (Lydmark 2010, 2011).

The saturation of the buffer in the deposition holes No 1 and 3

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.

Hydration of the backfill in Section I

Sensors for measuring total pressure, pore pressure and relative humidity have been installed in the backfill. Data from these measurements is indicating that the backfill is saturated in Section I.

Opening and retrieval of Section II

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 has 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 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.

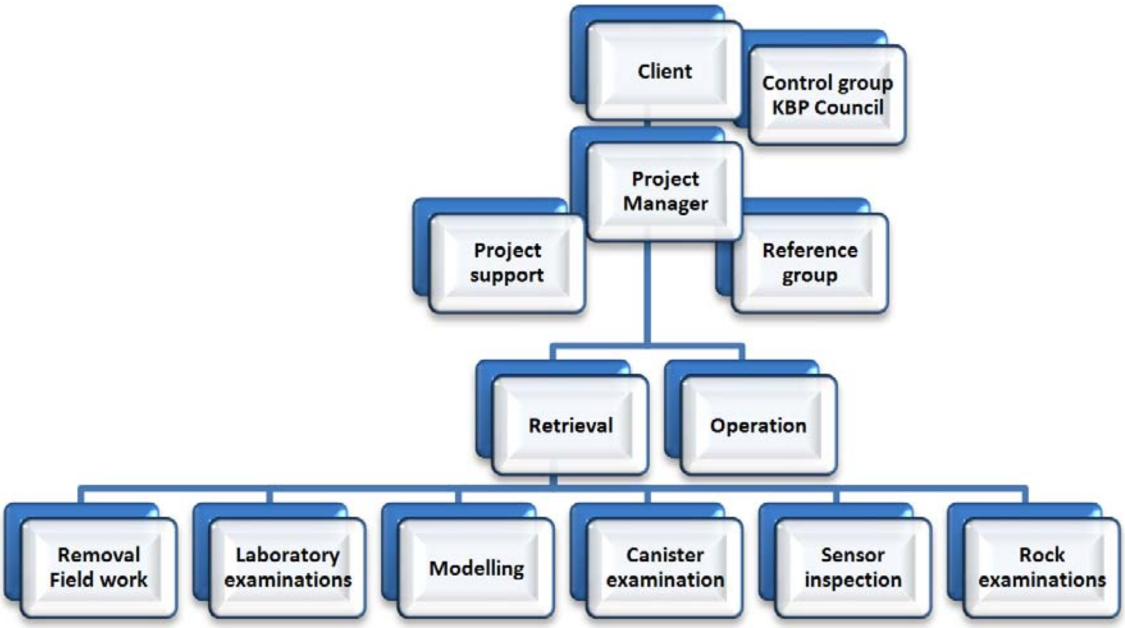


Figure 4-4. *Organisation chart for the project.*

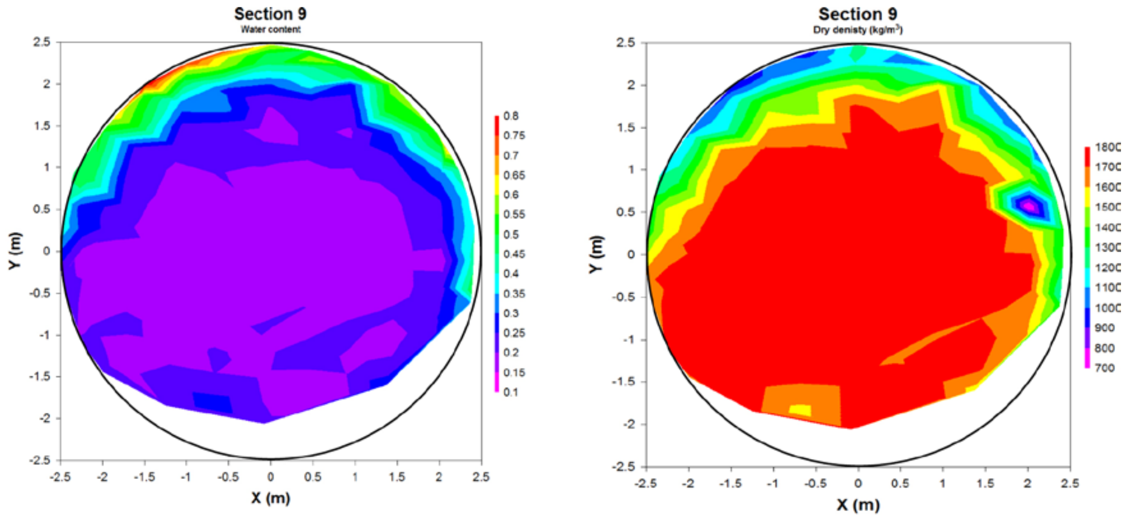
The breaching of the outer plug started in December 2010. The plug was removed mechanically by core drilling and hydraulic demolition, see Figure 4-5. This work was preceded by four core-boreholes where the contact surface between concrete and rock can be studied. Before breaching the plug, a number 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.

Figure 4-5. *Breaching of the outer plug in December 2010 with the core drilled holes before hydraulic splitting.*

The excavation of the backfill in Section II started in February 2011. The backfill was dug away by machine-type tractor excavators in layers of two metres. Samples were taken in these layers with the object of determining density and water content and about 1100 determinations were made in 11 layers. An example of preliminary results from this work is shown in Figure 4-6. During the excavation no evidence of piping or erosion of the backfill material were observed. Furthermore the contact between the backfill material and the rocks surface of the tunnel seems to be good and the preliminary analyses of the results from the determination of the density and water content of the backfill material is showing that it was fully saturated. Totally about 900 tonne of backfill material was removed and transported away from the tunnel.

After the excavation of the backfill had passed the deposition holes the excavation of the buffer started. The buffer was excavated by core drilling from the upper surface of the buffer, see Figure 4-7. After the core drilling of each buffer block, larger parts were mechanically removed from the buffer in the deposition holes. Samples were taken among others form the cores, with the objective of determining density and water content immediately after removing the buffer.



a) *b)*

Figure 4-6. *Preliminary results from the determination of a) the water content b) the dry density of the backfill material in sample-section 9.*

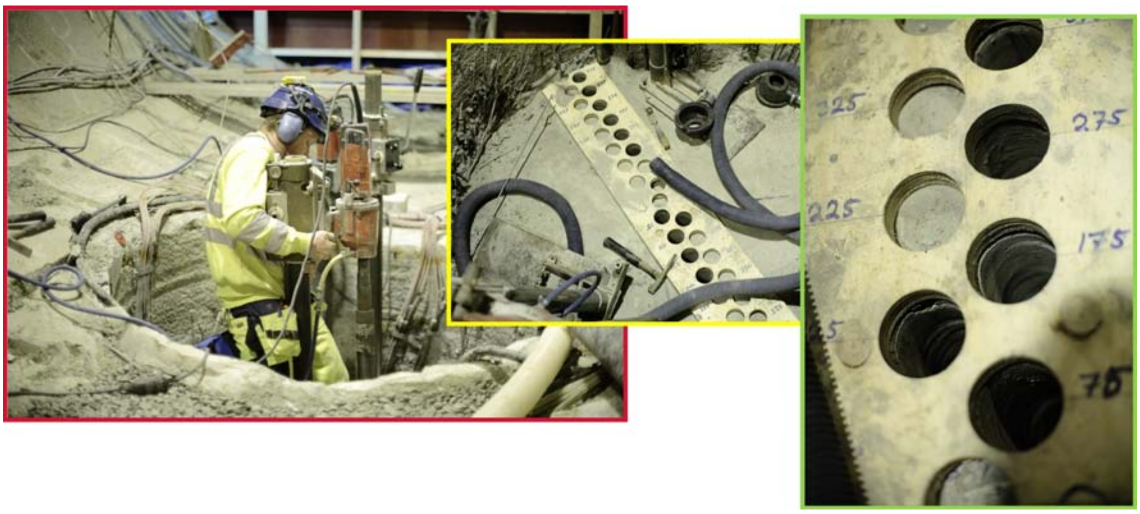


Figure 4-7. *Core drilling of the buffer. A template was used to get the right position of the cores.*

Altogether more than 3,500 determinations of water content and density were made at the Äspö Geolaboratory for each of the deposition holes. Preliminary data from these tests on one block surrounding the canister in deposition hole 5 are shown in Figure 4-8. Samples were also taken for analysis of possible biological, chemical and mechanical changes in the buffer. These analyses started during 2011 and will be finalised during 2012. About 40 tons of buffer was removed and transported away from the two deposition holes.

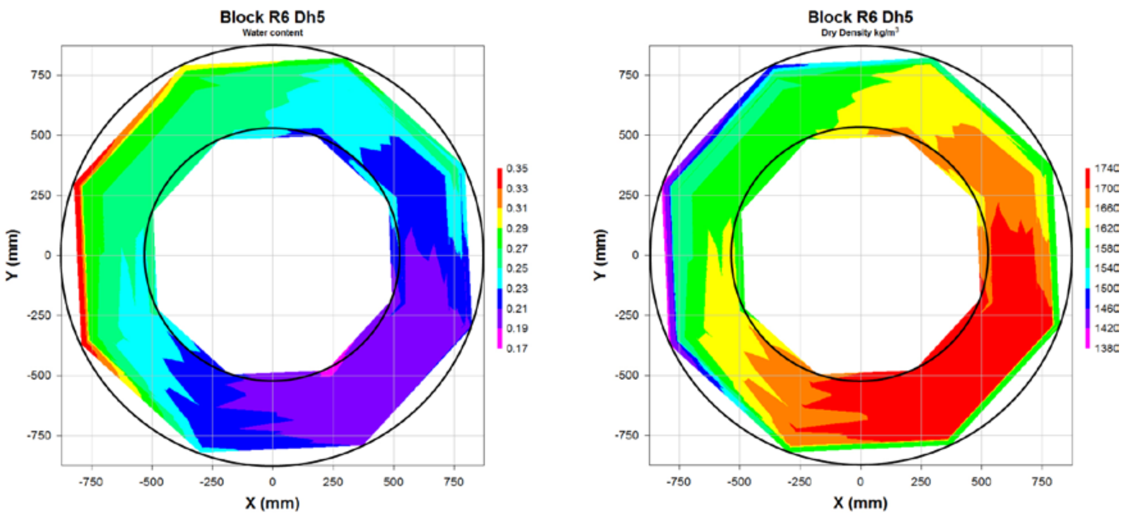
The modelling activities, planned to be incorporated in the project, were completed during 2011. However, the THM-modelling of the Prototype Repository continues within EBS Task Force. One report concerning THM modelling of the bentonite buffer was published during 2011 (Kristensson and Hökmark 2010).

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 reported in technical reports, scientific articles, and models 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.

In a HLW repository, there will be a temperature increase and a thermal gradient over the bentonite buffer as a result of the decaying spent fuel. Original water in the bentonite will thereby be redistributed parallel to an uptake of water from the surrounding rock. The Long Term Test of Buffer Material (LOT) project aims at studying possible alteration of the bentonite as a result of the hydro-thermal evolution, both with respect to mineralogy and to sealing properties.



a) *b)*

Figure 4-8. *Preliminary results from the determination of a) the water content B) the dry density of the buffer in deposition hole 5, block R6.*

Objectives

The general objectives in the LOT test series may be summarized in the following items:

- Collect data for validation of models concerning buffer performance under quasi-steady state conditions after water saturation, e.g. swelling pressure, hydraulic conductivity and rheological properties.
- Check of existing models concerning buffer degrading processes, e.g. mineral redistribution and montmorillonite alteration.
- Check of existing models concerning cation diffusion in bentonite.
- Collect information concerning survival, activity and migration of bacteria in bentonite under repository-like conditions.
- Check of calculated data concerning copper corrosion, and collect information regarding the character of possible corrosion products.
- Collect information, which may facilitate the realization of the full-scale test series, e.g. the Prototype project, with respect to preparation, instrumentation, retrieval, subsequent analyses, evaluation and data handling.

Experimental concept

The LOT test series includes seven test parcels, which all contain a heater, central tube, clay buffer, instruments and parameter controlling equipment. The test parcels have been placed in boreholes with a diameter of 300 mm and a depth of around 4 m. The test concerns realistic repository conditions except for the scale and the controlled adverse conditions in four parcels. Temperature, total pressure, water pressure and water content, are measured during the heating period. At termination of the tests, the parcels are extracted by overlapping core-drilling outside the original borehole. The water distribution in the clay is determined and subsequent well-defined mineralogical analyses and physical tests of the buffer material are made, see Table 4-1.

Table 4-1. Test program for the LOT project.

Type	No.	max T (°C)	Controlled parameter	Time (years)	Remark
A	1	130	T, [K^+], pH, am	1	Reported, TR-00-22
A	0	120–150	T, [K^+], pH, am	1	Reported, TR-09-31
A	2	120–150	T, [K^+], pH, am	6	Reported, TR-09-29
A	3	120–150	T	>10	Ongoing
S	1	90	T	1	Reported, TR-00-22
S	2	90	T	9	Ongoing
S	3	90	T	>10	Ongoing

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

Results

The activity in the Lot project was limited to managing the three ongoing test parcels, finalizing the A0 report, and publishing the major results from the A2 test in the Nantes conference proceedings.

The three remaining heating tests have now been running for almost twelve years. The power has been 500 W in the two standard tests resulting in the predefined maximum temperature of 90°C, and 750 W in the adverse condition test, leading to maximum temperature of 130°C. Figure 4-9 shows the temperature evolution during the 12 years of operation in the warmest section in test parcel A3. No significant problems are reported for any one of the three ongoing parcel and a majority of the installed sensors are still well functioning.

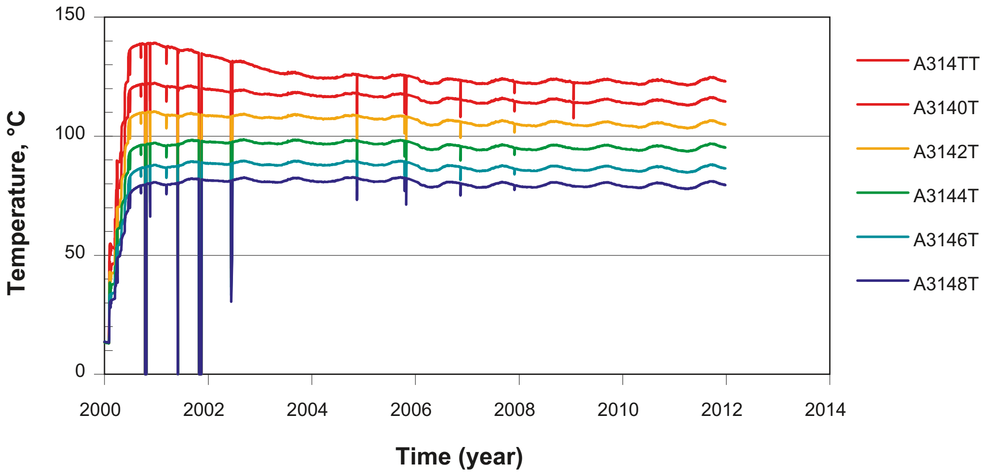


Figure 4-9. *Temperature evolution in the warmest section in test parcel A3 during the twelve years of operation. A314TT (uppermost curve) indicate the temperature at canister surface, and the following curves indicate the temperatures in the bentonite close to the canister and successively closer to the rock (A3148T).*

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 ongoing.

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 (see Section 4.3). Three test parcels containing heater, central tube, pre-compacted clay buffer blocks, instruments and parameter controlling equipment have been emplaced in vertical boreholes with a diameter of 300 mm and a depth of 3 m, see Figure 4-10. 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 in the beginning of 2013. The retrieval of parcel 3 is preliminary scheduled to 2015.

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 facilitates 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.

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, 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

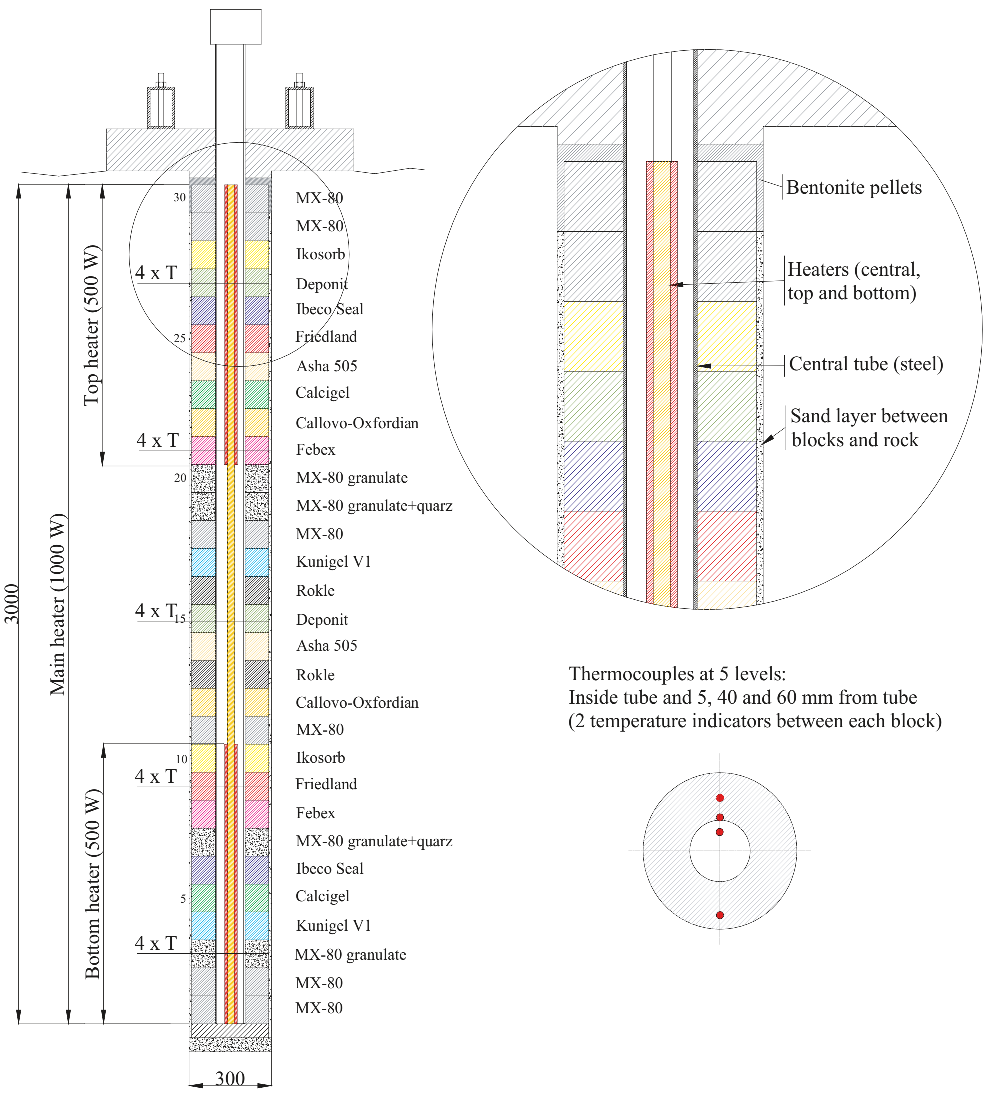


Figure 4-10. Cross section showing the experimental set-up in the ABM test. The figure also shows the block configuration in test parcel 1.

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 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 both on reference material but also in material taken from test package 1. A slightly decrease in swelling pressure could be determined, especially for the Asha 505 material.
- The saturation with a Na-Ca type groundwater has resulted in replacement of some sodium by calcium in bentonites that were initially Na-dominated. The cation distribution indicates a significant compositional difference between the upper and lower parts of the package. Whereas lateral gradients within the blocks are insignificant a vertical gradient in the relative cation distribution has developed during the field experiment.
- 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 technical report describing the status of the work performed by SKB with analyses of reference material and material from test parcel 1 has been written and is out for internal review (Svensson et al. 2011). In addition, a number of non-SKB financed technical reports and articles have been published by the other participating organisations.

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 TASS tunnel. 3D visualisation of the experimental set-up is shown in Figure 4-11. 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.

The inner test part is filled with a mixture of bentonite (30%) and crushed rock (70%). 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.

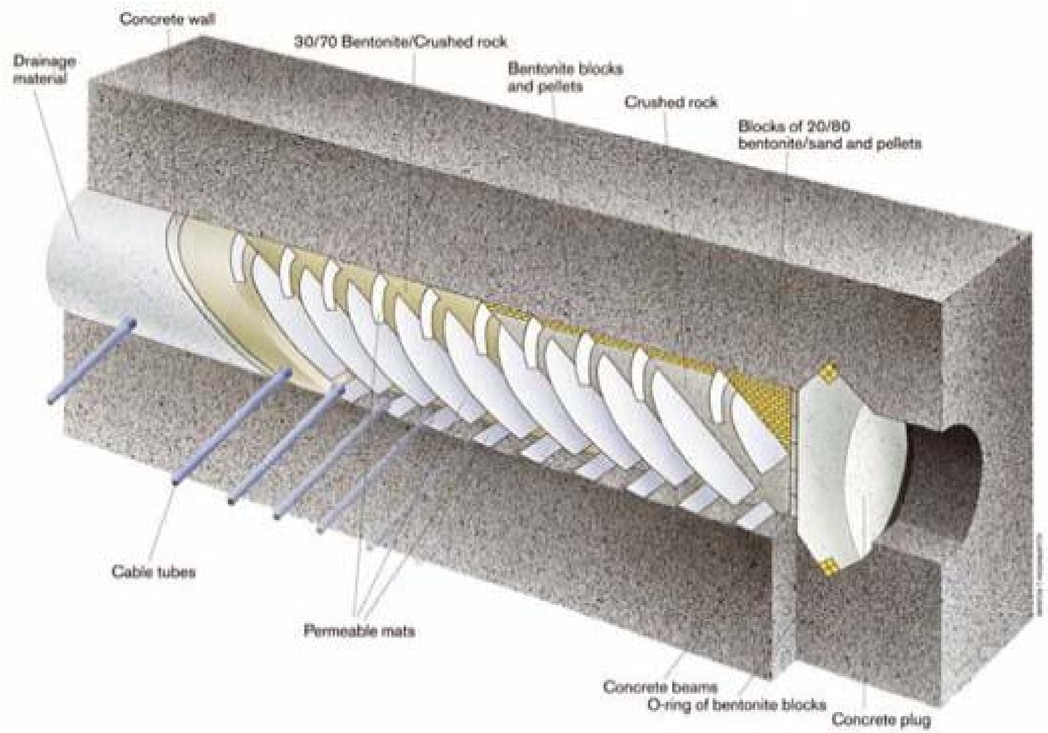


Figure 4-11. *Illustration of the experimental set-up of the Backfill and Plug Test.*

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 activities for 2011 have been 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. This is in agreement with what was planned.

4.6 Canister retrieval test

Background

According to the Swedish KBS-3 method, the spent fuel is encapsulated in tight copper canisters disposed in crystalline rock at a depth of 400–700 m and surrounded by buffer that prevents flow of waters. When water saturated, the confined buffer generate a considerable pressure due to the swelling ability of the bentonite clay and the material becomes tight. This swelling ability is an important 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 (CRT) is to demonstrate the retrieval technique for deposit canisters of KBS-3 design when a bentonite 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 were 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, see Figure 4-12. The hole was sealed using a plug, the heaters were turned on and an artificial water supply controlled the water inflow at the deposition hole wall. The plug was designed to allow for some vertical displacement, using a mobile lid connected to nine rock anchors, to simulate the mechanical reaction from a filled tunnel when the buffer become saturated and swell.

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 2011. An article, "*Hydro-mechanical and chemical-mineralogical analyses of the bentonite buffer from a full-scale field experiment simulating a high level waste repository*", has been accepted for publication in Clays and Clay Minerals, and a detailed SKB-report manuscript, "*Report on hydro-mechanical and chemical-mineralogical analyses* *of the bentonite buffer*", has been finalized and submitted. The work described in the article and report aimed at investigating if there had been any changes in the material characteristics by comparing properties of samples retrieved from the CRT buffer with the properties of reference material.

The manuscript "*Homogenization of engineered barriers, simulations verified against Canister Retrieval Test data*", based on the material presented at "Clays in Natural & Engineered Barriers for Radioactive Waste Confinement" (Nantes, 29th March–1st April, 2010), has been published in Physics and Chemistry of the Earth.

In the EBS Task Force framework, manuscripts describing the modelling of CRT, using Abaqus and CODE_BRIGHT, have been submitted for publication as SKB-reports. The format and titles are to be decided.

The full scale modelling of CRT in EBS Task Force, using CODE_BRIGHT, has not been performed during 2011 according to what was planed beforehand. The predictive modelling of the Prototype Repository has been prioritized and it was more time consuming than expected.

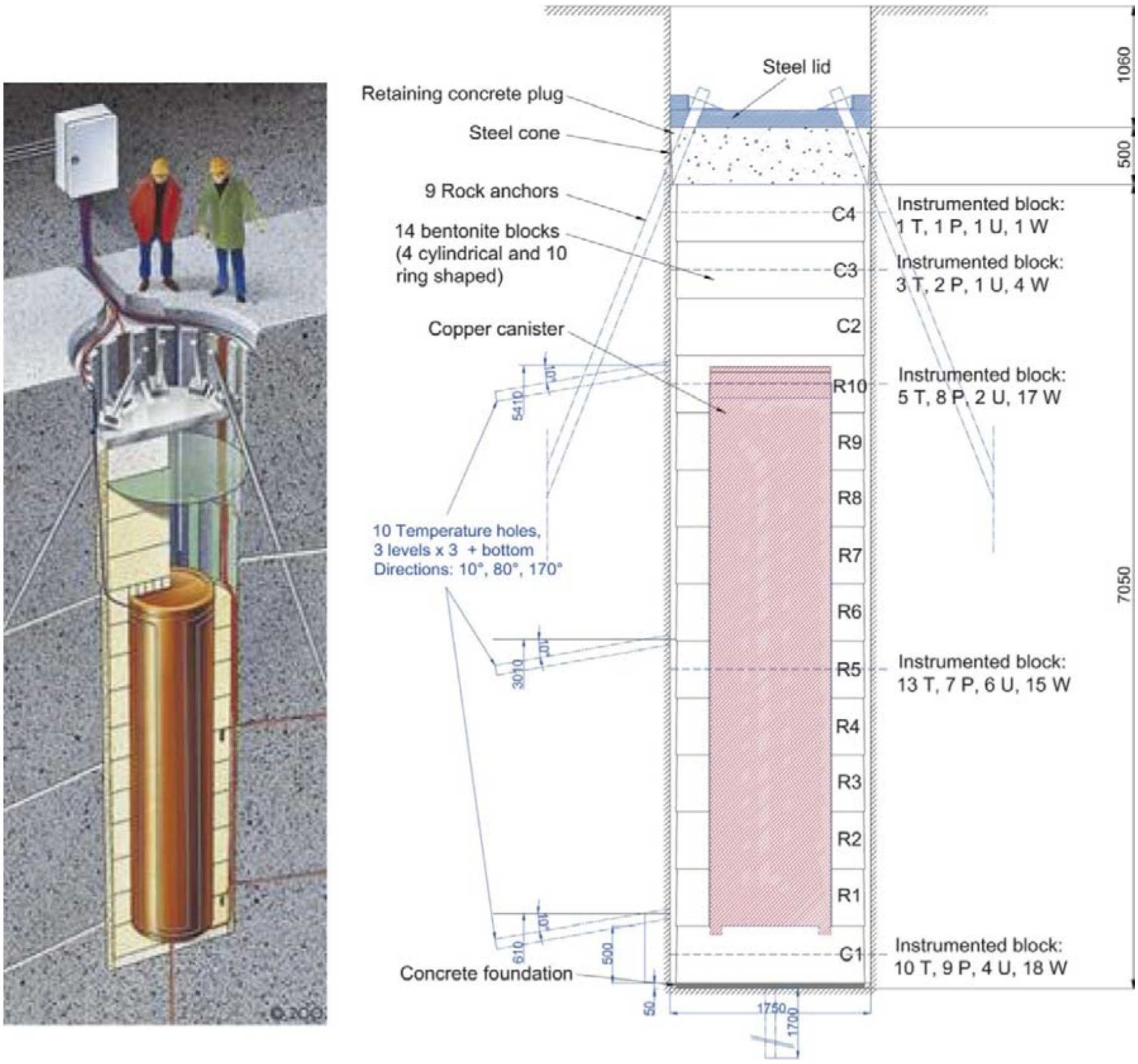


***Figure 4-12.** The Canister Retrieval Test is aiming at demonstrating the readiness for recovering of emplaced canisters also after the time when the bentonite is fully sutured.*

4.7 Temperature buffer test

Background and objectives

The Temperature Buffer Test (TBT) is a joint project between SKB and ANDRA which was previously supported also 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 meters 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 4-13). 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.

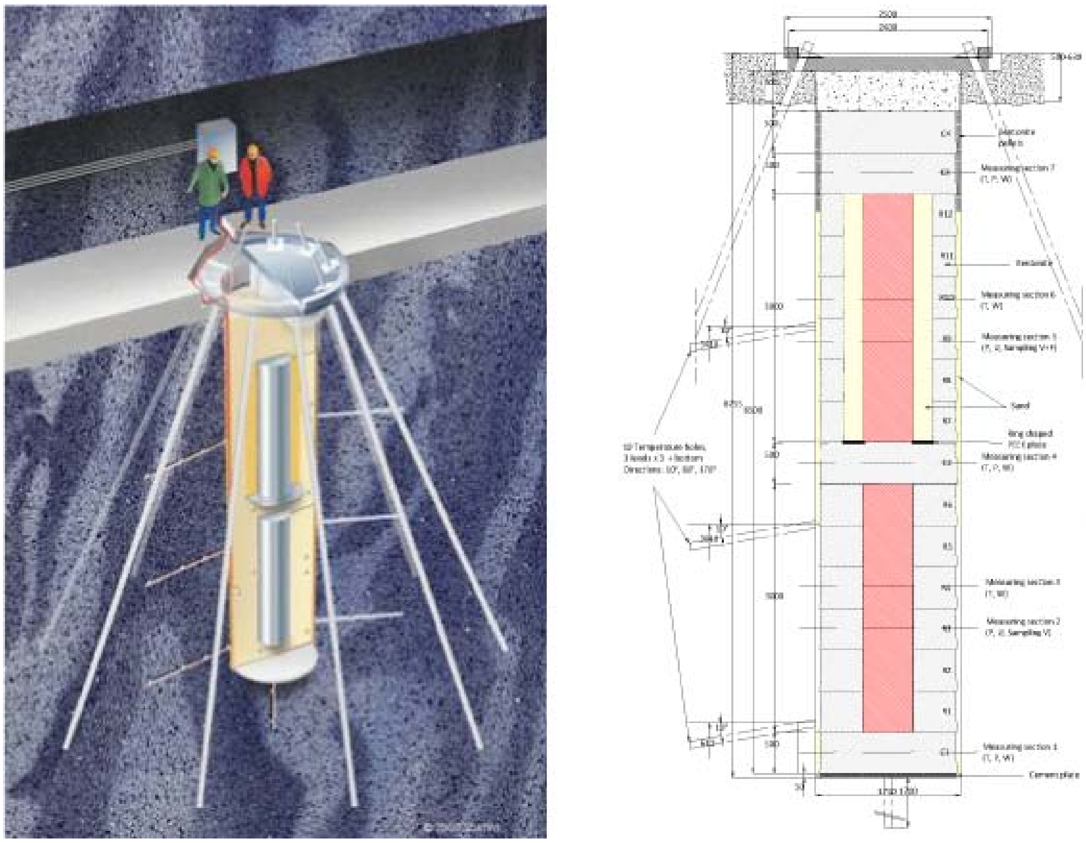


***Figure 4-13.** Principle design and experimental set-up of the Temperature Buffer Test.*

The canisters were heated with 1,500 W power from day 15 to day 1,171, when the power was raised to 1,600 W. This was a compensation for the termination of the neighbouring Canister Retrieval Test (CRT). Around day 1,700 the power was raised by steps to 2,000 W in the lower heater and reduced to 1,000 W in the upper heater. The heating was terminated on day 2,347 in August 2009. The temperature distribution prior to this event is shown in Figure 4-14. At this time the temperature on the mid-section of the lower heater was above 150°C.

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

THM modelling

Earlier evaluations of THM processes have 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).

The final THM modelling began after the dismantling operation in 2010. The main part of this work has been numerical modelling of the field test. Three different modelling teams have presented several model cases for different geometries and different combinations of processes solved. Two different numerical codes, Code_Bright and Abaqus, have been used. The work has also included different evaluations of experimental results with the aim to validate a number of data sets, and to assess the conditions in the tests prior to the dismantling operation. Finally, the validity of the material models has been assessed. This has been an evaluation of different constitutive equations and parameter values, especially for the bentonite, for their ability to reproduce the experimental results. The final THM modelling was completed during 2011.

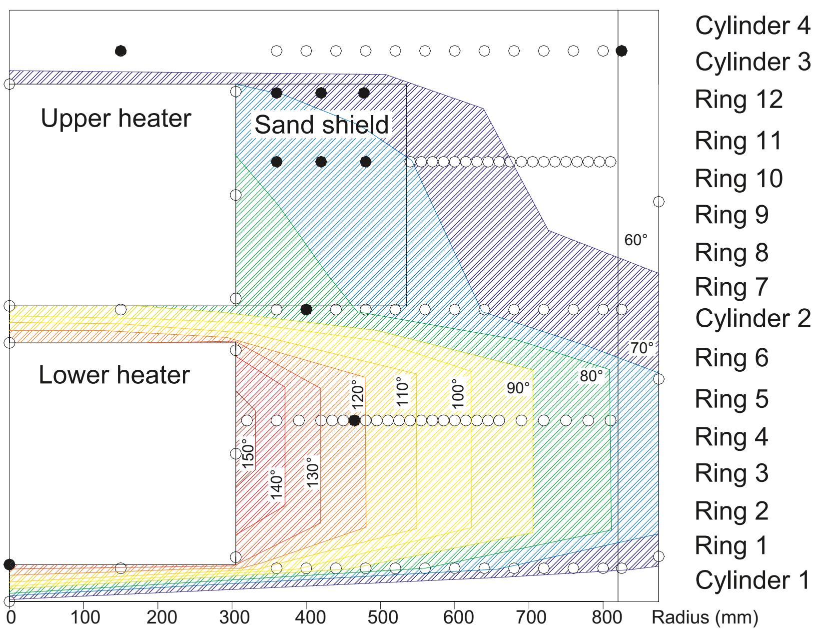


Figure 4-14. *Temperature distribution on August 16 2009. Rings indicate sensor positions. Filled rings indicate sensors out of order.*

Hydro-mechanical and chemical/mineralogical characterization program

This program was launched subsequent to the dismantling operation. Exposed material from the experiment (primarily samples taken at 100 mm radial distance in Ring 4) and reference material has been tested and analyzed. The following physical properties have been 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 properties (jar method). The following mineralogical properties (methods within brackets) were 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 NH4, ICP-AES), mineralogical composition in bulk and clay (XRD), mineralogical composition in bulk and clay (FTIR), element distribution and microstructure (SEM and TEM), iron oxidation state (Mössbauer spectroscopy). The main goal has been to investigate if any significant differences could be observed between exposed material and the reference material. This work was completed during 2011.

Reporting

A number of reports have been prepared during the final phase of the project: i) the report from the dismantling operation; ii) the report from the base characterization program (water content and density); iii) the installation report; iv) the last sensors data report (including the reporting of the sensor function control); v) the report from the hydro-mechanical and chemical/mineralogical characterization program; and vi) the report from the final THM-modelling. The reviewing process and the report series for these reports have been defined during 2011.

4.8 KBS-3 method with horizontal emplacement

Background

The KBS-3 method is based on the multi-barrier principle and constitutes the basis for planning the final disposal of spent nuclear fuel in Sweden. The possibility to modify the reference design, which involves vertical emplacement of singular canisters in separate deposition holes (KBS-3V), to consider serial disposal of several canisters in long horizontal drifts (KBS-3H) has been considered since the early 1990s. The deposition process for KBS-3H requires pre-assembly of each copper canister and its associated buffer material in prefabricated, so-called Supercontainers.

Most of the positive effects of horizontal emplacement compared with vertical emplacement are related to a reduced volume of excavated rock, and hence less backfill material. Examples of positive effects are:

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

Technical challenges involve excavation of the deposition drifts (up to 300 m long) with strict geometrical constraints, optimised positioning and deposition of the supercontainers and filling blocks, cf. Figure 4-15 and Figure 4-16, and a controlled and efficient saturation process.

In 2001 SKB published a RD&D programme for the KBS-3H alternative. The RD&D programme (SKB 2001) was divided into four stages: Feasibility study, Basic design (2001–2003), Demonstration of the concept at Äspö HRL and subsequent Evaluation (2004–2007). This was followed by Complementary studies of horizontal emplacement (2008–2010), the latter which is detailed in subsequent sections. These development steps have all been made in close cooperation between SKB and Posiva.

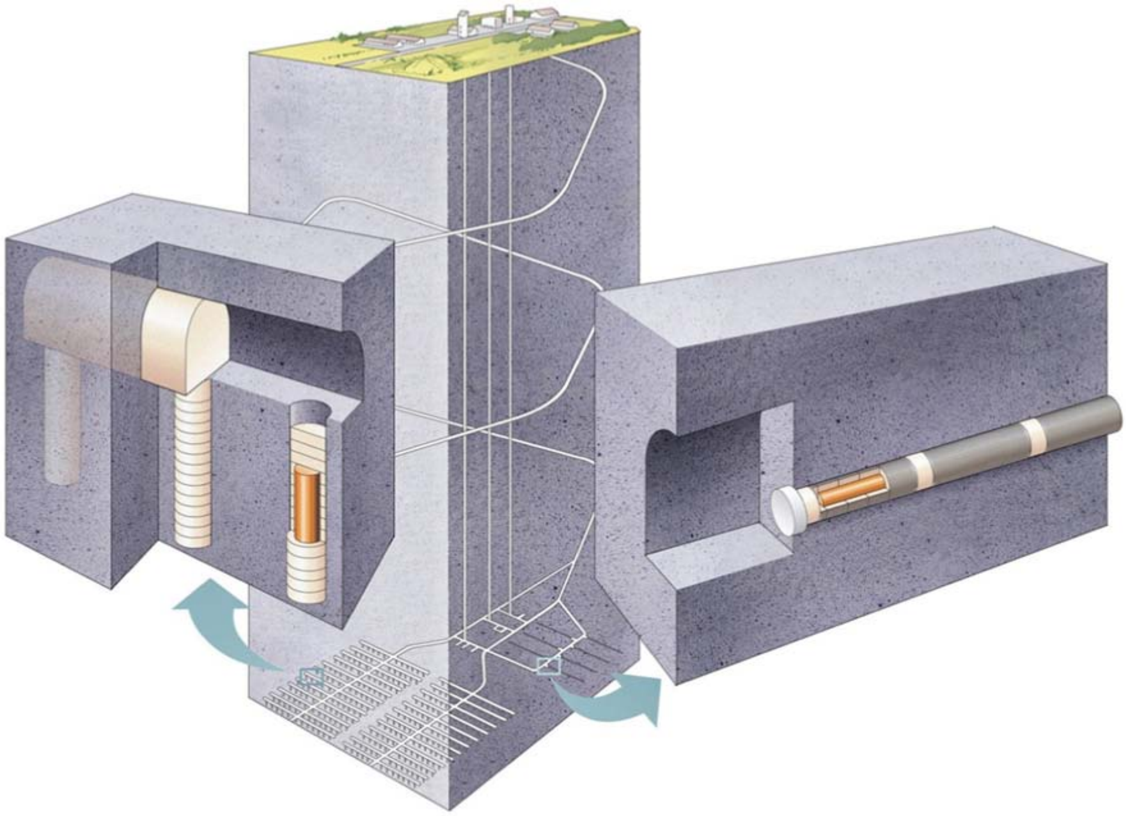


Figure 4-15. Schematic drawing of the KBS-3V reference design (left) and KBS-3H (right).

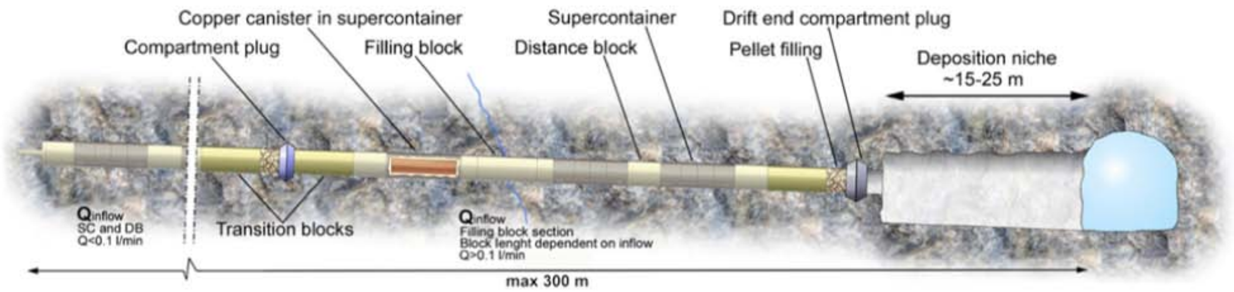


***Figure 4-16.** Updated KBS-3H drifts design. Updated features are the recently designed filling blocks with new inflow criteria, the drift end compartment plug (DECP) and the possible removal of double compartment plugs to separate fractures of higher inflow from the rest of the drift, tentative calculations indicate that these inflows can be handled with filling blocks.*

Complementary studies of horizontal emplacement, 2008–2010

The Complementary studies project phase aimed at reducing the knowledge gap between the KBS-3V reference design and the alternative horizontal emplacement to a level where a decision to go ahead with safety assessments and full-scale sub-system tests for KBS-3H could be made.

It is hence closely coupled with the subsequent KBS-3H System Design phase and the purpose of these two phases was to facilitate a detailed comparison and a possible change of reference design from KBS-3V to KBS-3H.

One of the prioritised objectives of this project phase was the establishment of a robust drift design, i.e. a design that will yield a well-defined and consistent initial state and ensures long-term safety. Toachieve this several uncertainties related to design and buffer that had been identified during earlier project phases were handled.

These were divided into four principal areas:

- Drift components.
- Thermal spalling.
- Buffer issues.
- Wetting technique.

One of the main objectives of this project phase was the selection of a KBS-3H reference design. This milestone was reached when DAWE (Drainage, Artificial Watering and air Evacuation) was selected, thereby providing a well-defined way forward for the KBS-3H project. The DAWE design will be used as a basis for further technical development, planning, safety analysis, radiation protection and work on environmental impact. Selection of a reference design required evidence on the long-term performance of the buffer including its interaction with other materials. Bases for material selections have been established and titanium is recommended for the Supercontainer, compartment plugs and other supporting structures. The buffer and filling components have all been brought to a conceptual level of design. Although not all buffer issues have been solved they have been further constrained during the recent project phase.

A structure for a KBS-3H specific production line reports has been developed. The full production line reports will be written in the upcoming project phase and will provide descriptions of how to manufacture, handle and inspect the engineered barriers and underground openings within the facilities of the KBS-3H system.

The overall goal of the KBS-3H project 2008–2010 was to develop the KBS-3H solution to such a state that a decision to go ahead with full-scale testing and demonstration could be made. No critical issues have been identified and a good basis for continuation has been established. A new project phase has also been approved by the SKB and Posiva boards with the ultimate goal of enabling a detailed comparison, and a possible change of reference design from KBS-3V to KBS-3H. Such a step would include KBS-3H specific safety assessments for Forsmark and Olkiluoto, an update of the KBS-3H description and performance of full-scale sub-system tests.

In the following the objectives and current status of the ongoing KBS-3H System Design phase, 2011-2015 are outlined, with specific focus on Äspö-related activities.

Objectives

The ultimate goal of the KBS-3H System Design phase is to bring KBS-3H design and system understanding to such a level that a PSAR can be prepared and that a comparison between KBS-3V and KBS-3H is made possible. For components and sub-systems this will be achieved by assessing the design bases and requirements, and based on this, reaching the system design level in accordance with SKB's model of delivery. This is expected to be achieved by the end of 2014.

Experimental concept

Demonstrations at Äspö HRL

One of the main steps in the system design phase is the verification of the selected reference design. This includes verification that:

a) the design solution meets the requirement specification.

b) the product can be manufactured such that the requirement specification is fulfilled (control program).

These steps are carried out mainly at the Äspö HRL as part of the Sub-system Demonstration sub-project the focus of which is to **verify the functionality of equipment, methods and components developed within the KBS-3H project**. The sub-project consists of two main activities that were initiated during 2011, the Multi Purpose Test (MPT) which is part of the EU-project LucoeX and the excavation and preparation of a new KBS-3H drift at the 420 m level.

The Multi Purpose Test (MPT)

The MPT is basically a down-scaled (spatial and temporal) non-heated installation of the reference design, DAWE, and includes the main KBS-3H components, see Figure 4-16. The drainage, artificial watering and air evacuation procedures included in DAWE will be followed, after which the test conditions will be monitored for approximately 400 days followed by dismantling and sampling.

The test will be carried out in a 20 m section of the full face drift DA1619A02 (d=1.85 m), c.f. Figure 4-17, at the –220 m level which implies that the hydraulic boundary conditions will differ from those foreseen at typical repository depth.

The MPT has two main objectives:

- To test the system components in full scale and in combination with each other to verify the design.
- To test the ability to manufacture full scale components, carry out installation (according to DAWE) and monitor the initial system behaviour.

Verification is the overarching objective and the test is expected to provide important experiences from working at full-scale at ambient *in situ* conditions, although not fully representative of typical repository depth, enabling the recognition of potential implementation issues related to the DAWE design.

Excavation and preparation of a KBS-3H drift

A new KBS-3H test site is planned to be established at the 410 m level of the Äspö HRL, being more representative of typical repository depth.

The excavation and preparation of a KBS-3H drift have three main objectives:

- Demonstration, comparison and verification of performance of pilot borehole drilling techniques over a 300 m length scale, including fulfilment of defined geometrical requirements. This includes:
  – test and verification of deviation measurement equipment in the deviation facility currently being constructed at the Äspö HRL,
  – assessment of transferability of results and experiences between sites.
- Reaming of pilot borehole for KBS-3H experimental drift to full-size drift diameter (1,850 m diameter) over a 100 m length scale.
- Application and performance at a repository depth of KBS-3H groundwater control techniques:
  – Prediction of the hydraulic conditions in a drift based on measurements in the pilot borehole.
  – Comparison of relative information value of boreholes of different diameter and associated characterisation methods, 76 mm cored boreholes used as standard by both SKB and Posiva. No customised equipment is available for boreholes of larger diameter.
  – Post-grouting using Mega-Packer.

Results

Results of the previous project phase, Complementary studies of horizontal emplacement, are reported in (SKB 2012). On the basis of the outcome of this phase SKB and Posiva jointly decided to continue with the new System Design Phase.

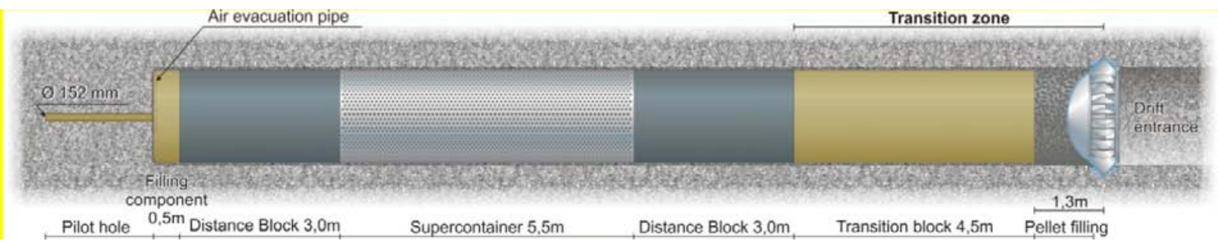


***Figure 4-17.** Schematic illustration of the MPT layout.*

The MPT was initiated during 2011, including detailed planning and start-up of some time-critical activities. This included development of a detailed test design including sensor positions, soft- and hardware updates of the deposition machine and the purchase of a buffer mould for the blocks. Complementary geologic and hydraulic characterisation of the drift section was performed, indicating inflows in the order of 0.025 l/min to the 17.8 m long MPT section.

Detailed planning for the excavation and preparation of a KBS-3H drift has also been initiated during 2011. This has included review of drilling and measurement techniques and involvement in the planning of the planned borehole deviation test facility, and in the ongoing development of new underground experimental facilities at the 410 m level, c.f. Section 6.2.

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 Hard Rock Laboratory (HRL).

The multiple barrier concept is the cornerstone of all proposed schemes for the underground disposal of radioactive wastes. Based on the principle that uncertainties in performance can be minimised by conservatism in design, the concept invokes a series of barriers, both engineered and natural, between the waste and the surface environment. Each successive barrier represents an additional impediment to the movement of radionuclides. In the KBS-3 concept, the bentonite buffer serves as a diffusion barrier between the canister and the groundwater in the rock. An important performance requirement of the buffer material is that it should not cause any harm to the other barrier components. Gas build-up from, 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 1,110). A further year of artificial hydration occurred (Stage 3, day 1,110 to 1,385), followed by a more complex programme of gas injection testing in filter FL903 (Stage 4, day 1,430–2,064). In late 2010 attention moved from the lower array filter (FL903) to the upper array. Stage 5 started on day 2,073 and is still on-going.

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 4-18). 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.

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.

Figure 4-18. *The Large scale gas injection test at the –420 m level in Äspö HRL.*

Results

During 2011 (day 2,160–day 2,524) the test programme of Lasgit concentrated on gas injection. During two previous gas injection campaigns, testing had occurred at the lower-plane of the canister in filter FL903. The focus of experimentation moved to the upper canister array of filters. 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.

Initially filter FU912 was selected as this small filter has the most difference in dimension compared with FL903; however this was seen to be strongly coupled with filter FU909. Testing was therefore switched to filter FU910. A hydraulic constant head test was successfully conducted in filter FU910 and was completed during December 2010. The hydraulic data shows that filter FU910 has a lower hydraulic conductivity and lower specific storage compared with filter FL903. Following hydraulic testing a period of shut-in occurred to allow the pressure in the upper array to equilibrate.

Gas injection was initiated on day 2,256 (8th April) using neon as the permeant. The test plan was to follow similar gas pressurisation steps as gas test 2 in filter FL903 with four pressure ramps and three periods of constant pressure. Stage one saw gas pressure in filter FU910 raised from an initial 1,047 kPa to 2,250 kPa over an 18 day period. Gas pressure was then held constant for a period of 32 days. Stage 2 began on day 2,306 and saw gas pressure increased from 2,250 kPa to 3,500 kPa over 18 days, followed by a period of constant pressure for 36 days. Stage 3 began on day 2,360 and saw gas pressure increase from 3,500 kPa to 4,750 kPa over a period of 17 days.

Following gas Stage 3 pressure was held constant for a considerable period so that the gas injection system was re-filled with neon and so that gas flow at a pressure close to break-through could be investigated. The final gas entry stage was initiated on day 2,477 (14th November), with gas pressure raised from 4,750 kPa to a pressure sufficient to initiate gas break-through.

As can be seen in Figure 4-19, gas breakthrough occurred on day 2,490.3 13 days into the gas injection stage. Break through occurred at a pressure of 5,187 kPa, which is similar to the stress recorded at axial stress sensor PC903 on the canister (5,230 kPa). Sensor PC903 and filter FU910 are separated by approximately 1 m.

Gas entry pressure in filter FU910 (5,190 kPa) was lower than that observed in filter FL903 in the two previous tests (5,660 and 5,870 kPa). Break-through occurred at a stress lower than expected as stresses in the system continue to increase with time.

The characteristics of gas entry are also dissimilar for FU910 compared with FL903. In filter FL903 following breakthrough the gas pressure decayed and reached a quasi-steady-state in a similar manner to laboratory test results. As shown in Figure 2, in filter FU910 a pressure drop is observed following breakthrough. However, gas pressure then began to rise again and reached nearly 5,300 kPa, before slowly decaying. This is different from the behaviour previously seen. It suggests that a small pulse of gas entered the system, possibly along the interface between the buffer and canister. This sink was small and soon filled and pressure continued to rise, until at 5,300 kPa the gas was able to propagate further.

The response of stress and pore water sensors on the deposition hole wall were similar to those seen previously. Therefore, whilst the evolution of gas pressure is dissimilar, the underlying physics driving gas propagation is consistent.

Figure 4-20 shows the pressure response of other upper-array filters. On day 2,495 pressure in FU909 began to rise in a series of steps. This behaviour shows that gas migration was occurring through a series of pulses to this sink. Over a period of 30 days the pressure in FU909 increased, eventually reaching a pressure similar to that in FU910. On day 2,508 a single pulse of pressure reached filter FU911, increasing pressure by approximately 1 MPa. No further increases are observed and pressure decayed steadily due to diffusion. On day 2,519 the axial stress reading on the canister (sensor PC903) increased, indicating that gas had migrated to this point.

The observations show that gas continues to migrate within the deposition hole, reaching a number of sink points. The difference in behaviour in filter FU909 and FU911 shows that certain locations are more favourable for continued gas flow, whilst other locations (FU911) become isolated sinks. The behaviour is highly dynamic and complicated.

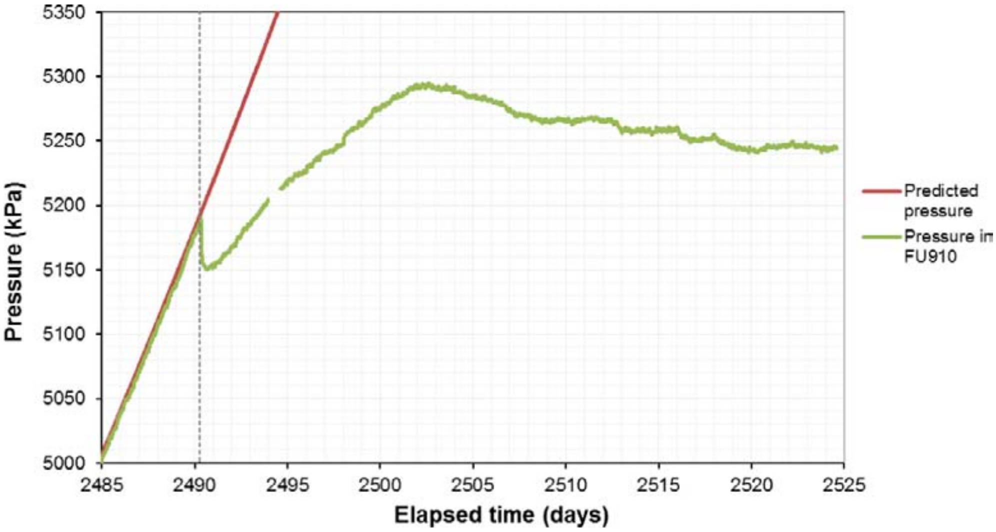


Figure 4-19. Pressure response of filter FU910, showing gas breakthrough at day 2,490. Similar to previous tests a sharp drop in pressure is seen at breakthrough. However, in contrast to previous tests, gas pressure in FU910 increased and reached a second peak before decaying.

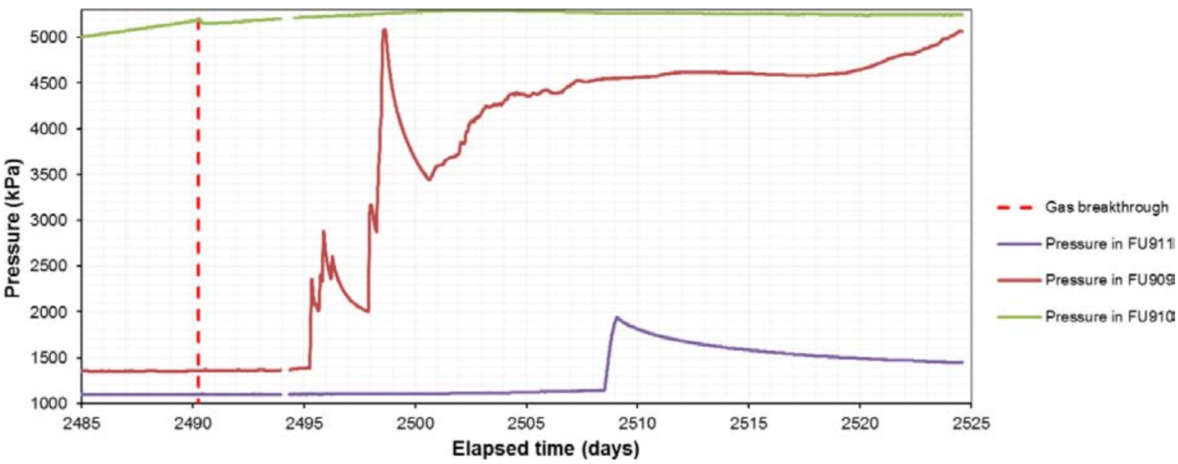


Figure 4-20. Pressure response of all upper-array filters. Approximately five days after gas break-through the pressure in filter FU909 began to increase in a series of events. By the end of 2011 the pressure in FU909 was similar to that in gas injection filter FU910, suggesting very good connection between the two filters. On day 2,508 pressure in filter FU911 increased in a single pulse, followed by a slow decay caused by diffusion.

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 inflow of 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 nano-sized particles of silica in water, has shown to be a promising grout. When a salt is added to the solute, 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 project was a development/research project and the basic principle was that almost data and observations was to be documented in order to answer the specific goals set up for the project but also for use in further development of technique and methodology. The overall objective has been to demonstrate a grouting procedure based on SilicaSol and the prioritised goals has been:

1. Confirmation of that silica sol can be used at a water pressure that is current in deposition tunnels in a final repository.
2. Confirmation that at repository level it is possible to achieve a sealing effect corresponding to a maximum inleakage to a tunnel of 1 l/min per 60 m tunnel with grouting agents applicable for a repository.

The projects were given the following milestones related to the goals above:

1. Confirm models for penetration length and sealing effect.
2. Show that a sealing can be achieved with grouting fans outside the tunnel contour.
3. Show that a sealing can be achieved with grouting fans inside the tunnel contour.
4. Show that a post-grouting can give a sealing effect of the rock mass.
5. Show that drips can be sealed by means of post-grouting.
6. Identify limits when silica sol is applicable with respect to hydraulic aperture at a groundwater pressure that is current in deposition tunnels in a final repository.
7. Identify special demands on implementation and equipment when silica sol is used for grouting.
8. Achieve other experiences regarding controlled and efficient implementation.

Experimental concept

The project excavated a tunnel, TASS at 450 m depth in Äspö HRL. The pre-study, in 2006, comprised besides extensive surveys of rock cores and hydraulic tests also a study where a suitable location was chosen with respect of likelihood of meeting the prioritised goals. The most difficult goal to meet was be sure that the ground water pressure was high enough. The tunnel direction was chosen to be perpendicular to larger fracture zones on order to “hit” water early in along the tunnel.

The experiment started in spring 2007, with drilling boreholes in special pattern to confirm that a penetration length of the grout could be observed. Both cementitious grout and silica sol was tested. Special care was taken to an eventual erosion of grout where studies of both how to mix cement and the technique was adapted to avoid risk for erosion of grout. One short fan outside the tunnel contour started the excavation of the TASS tunnel.

The total experiment comprised two fans outside the tunnel contour, 20 m long and three fans inside the contour with excavations of the tunnel in between. When the full length of the TASS tunnel was reached post-grouting campaign was initiated. The location was where the inleakage was higher than the targeted, where the first fan inside the contour was located. An extensive systematic post-grouting with full fans in roof, walls and floor was done, spring 2009. See Figure 4-21.

***Figure 4-21.** Although the repository facility will be located in rock mass of good quality with most relatively low fracturing, sealing by means of rock grouting will be necessary.*

Results

The project has written their final reports, see Table 4-1 below.

Table 4-1. Final reports from the project Sealing of Tunnel at Great Depth.

IPR-08-18, The TASS-tunnel project "Sealing of tunnel at great depth", Geology and hydrogeology – Results from the preinvestigations based on boreholes KI0010B01, KI0010B01 and KI0010B01 (Hardenby et al. 2008)
R-08-122, Berguttag i TASS-tunneln, Delresultat t o m september 2008 (Malmtorp et al. 2009)
R-08-123, Injekteringen av TASS-tunneln. Delresultat t o m september 2008 (Funehag 2008)
R-10-31, Slutrapport från drivningen av TASS-tunneln (Karlzén and Johansson 2010)
R-10-35, Äspö HRL, The TASS-tunnel, Geological mapping (Hardenby and Sigurdsson 2011)
R-10-39, Injekteringen av TASS-tunneln. Design, genomförande och resultat från förinjekteringen (Funehag and Emmelin 2011)
R-11-09, Efterinjektering av TASS-tunneln. *In print*

Present status

The tunnel reached its final length, 80 m, in spring 2009. The field test had a flexible planning in order to adapt to the encountered rock conditions, results and experience gained. The outcome was six grouting fans.

The inflow is measured in three weirs and the project target max 1 l/min and 60 m tunnel is distributed proportionally to the length of the section measured. For section 10–34 m (fans outside the contour) the inflow, measured in weir is 0,3 l/min which corresponds to, or is smaller than, the target set for the section, max 0,4 l/min.

For section 34–48 m (fans inside the contour and postgrouted) the inflow target was not met. The inflow is stable. The reason for increasing inflow is now being analysed.

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 reference 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 4-22), 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 miniature canister does not have 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.

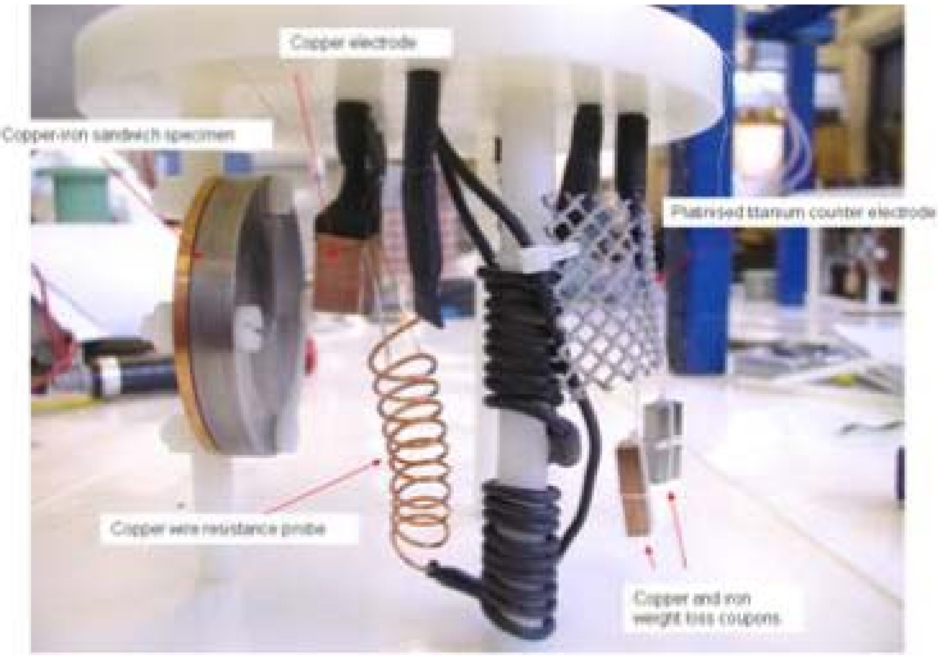


Figure 4-22. Test electrodes inside support cage around model canister experiments.

Figure 4-23. Model canister being lowered into support cage containing bentonite pellets in annulus.

The experiments are located where there are many fractures around the boreholes, leading to a plentiful supply of natural reducing groundwater to the canisters.

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.

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. Further details on experimental concept are presented in Smart and Rance (2009).

Results

The removal of experiment 3, located in borehole KA3386A04, was successfully performed during august 2011. The canister in its steel cage was removed from the borehole and placed into a transfer tank filled with Äspö water. Whilst still under the surface the steel cage was put into at transfer flask custom made for the purpose, and transported to Serco facilities in the UK for evaluation. The project managed to keep the oxygen level in the water at an anoxic level during the whole process. Sensors and samples located outside the support cage in the borehole were also successfully retrieved in the process.

During the retrieval of the canister, sampling of the water in the transfer tank was performed. Immediately after retrieval of the steel cage, samples were taken from the surface of the steel cage.

In the U.K. the canister were put in an inert environment before opening the transfer flask. Directly after opening the transfer flask, samples for analyses were taken from the bentonite in the annulus of the steel cage. Immediately after the canister was removed from the steel cage microbial analyses of the canisters surface were performed. The canister was thereafter sectioned for further analyses.

Results from all analyses will be presented during the first half of 2012. The purpose of the analyses is to confirm the extent of corrosion of both copper and cast iron.

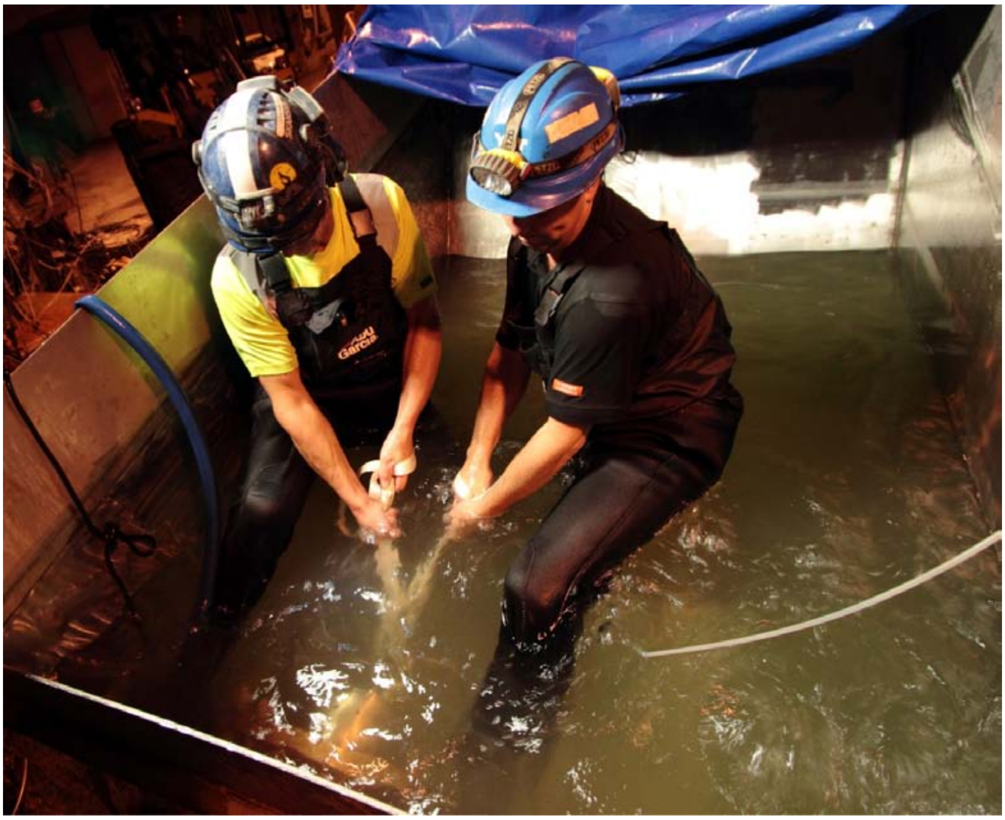


Figure 4-24. *Stefan Grandin Svärdh and Jonas Hallberg pulling out the steel cage from the KA3386A04 bore hole.*

Figure 4-25. Equipment for sampling of the steel cage surface.

4.12 Cleaning and sealing of investigation boreholes

Background and objectives

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

Results

The major conclusions from the work are: 1) identifications of suitable positions for placing borehole seals can be made on the basis of available borehole data, 2) assessment of the hydraulic function of borehole seals can be made by use of numerical groundwater flow modelling, 3) boreholes of large-diameter can be sealed in a practical way by suitable combination of concrete and clay materials, 4) chemical interaction of clay and concrete can cause degradation of both, requiring further investigations, 5) more knowledge is required for preparing boreholes before sealing can start.

The goals set by SKB have been reached as demonstrated by the agreement between the project decision and project plan and by the overall success of the work as manifested by delivering of four reports.

4.13 Concrete and clay

Background

Concrete and other cement based materials are important components in repositories for Low and Intermediate Level Waste (LILW). 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 different types of waste. Cement based materials are also known for high retention capabilities of many of the radio nuclides present in a LILW repository.

In the repository the cement will be 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. 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 the understanding of the processes related to the degradation of low- and intermediate level waste in a cement matrix, the degradation of the concrete itself through reactions with the ground water and the interactions between the cement and adjacent materials such as bentonite and the surrounding host rock.

Experimental concept

During the time period 2010–2012 a total of about 15 experiments will be prepared and deposited at different locations in the Äspö HRL. 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.
- Interactions between the cement and the surrounding materials such as the bedrock and the bentonite.
- Studies of the evolution of a high-pH plume in the bedrock surrounding the deposition hole.

The specimens are cast into cylinders with a diameter of 300 mm and a length of one meter in the bentonite laboratory. The cylinders are then transported to the experimental site where they are deposited in a Ø 350 mm hole in the tunnel floor as shown in Figure 4-26. 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 or grout and finally the deposition hole is sealed to avoid contact between the specimens and surface water, Figure 4-27.

Figure 4-26. *Deposition of the cylinders NASA2861A.*

Figure 4-27. *The sealed experimenting.*

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 about 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 2011 the experiments of this project has been prepared and deposited in niche NASA2861A. 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 concrete matrix.

4.14 Low pH-programme

Background

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 construction of plugs for the deposition tunnels. The low pH concrete developed within the programme will be used for construction of a full size plug for sealing of a deposition tunnel during 2012.

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. A full size low-pH concrete plug will be constructed during 2012.

SKB has for many years had a close co-operation with Posiva, Finland, and NUMO, Japan, in this field. For the establishment of an agreed procedure for measuring of pH values in low-pH concrete also ENRESA in Spain, NAGRA in Switzerland, JAEA in Japan have participated in a joint project called "The pH-project".

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 preliminary 1, 2, 5 and 10 years for evaluation of the behaviour of the low-pH grout but also corrosion of the rock bolts.

During 2009 field tests also started on corrosion behaviour of steel in low-pH concrete. 24 samples was prepared and placed in an open container in a niche at Äspö HRL.

Each specimen contained three steel bars, Figure 4-28 and Figure 4-29. Each steel bar, with a diameter of 20 mm and a length of 200 mm, was carefully cleaned and weighed with an accuracy of a thousandth gram.

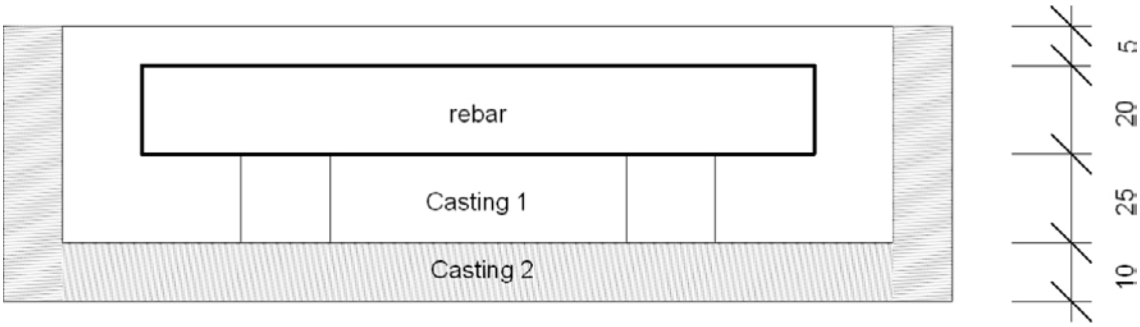


Figure 4-28. *Specimen dimensions.*

Figure 4-29. *Mould and steel bars on supports before casting.*

Figure 4-30. *Container in Äspö HRL with samples corrosion tests.*

The specimens were then placed for field exposure in an open container in niche NASA2715 at the Äspö HRL, Figure 4-30.

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 2011 has mainly been focused on following up the activities from 2009 with the rock bolts and rock support and corrosion field tests. 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 final preparation of an official report of the work performed during 2009. The results are now published in a SKB report, R-11-08 with the heading *"Low-pH cementitious material, Development of rock bolt grout and shotcrete for rock support and corrosion of steel in low-pH cementitious materials"*

During the reporting period the preparation for over coring of the first set of rock bolts has been ongoing but the actual field work has been postponed to 2012. The first result of the corrosion experiments with carbon steel in low-pH concrete is however reported in R-11-08.

The final project meeting within the pH-programme was held in Madrid Spain, March 2011. The preparation of the project report including the agreed proceeding has been ongoing during the reporting period. The results from the pH-project will be reported in a SKB report R-12-02 with the heading *"Development of an accurate pH measurement methodology for the pore fluids of low-pH cementitious materials".* This report is expected to be ready mid 2012 and that will also be the end of "The pH-project".

SKB has for many years had a close co-operation with Posiva, Finland and Numo, Japan, in this field. The work during 2011 has mainly focused on reporting of the work done at Äspö HRL but also to develop an international agreed procedure for measuring the pH value in low pH concrete products. The work with pH measuring procedures has been in cooperation with six waste management organisations and pH measurements have actually been performed in nine different national laboratories.

4.15 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 Canister 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.

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

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 4-3. 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)

Experimental concept

THM

Phase 1

All defined tasks of phase 1 are given in Table 4-4. Participating organisations besides SKB were: Andra (France), BMWi (Germany), CRIEPI (Japan), Nagra (Switzerland), Posiva (Finland), NWMO (Canada) and RAWRA (Czech Republic). All together 12–14 modelling teams were participating in the work. Phase 1 was finished in 2011.

Table 4-4. 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

Phase 2

The second phase includes 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), RAWRA (Czech Republic) and NDA (England). All together 10–15 modelling teams are foreseen to participate in phase 2.

Geochemistry

SKB (Clay Technology, Amphos21), Nagra (University of Bern, Madrid), Posiva (VTT), and RAWRA (NRI) participate in the modelling work in the chemistry part of the Task Force. Several experimental data sets have been made available for modelling (Benchmarks 1–4), listed in Table 4-5. 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 4-5. 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 2011; one in Barcelona, Spain on May 30–June 1and one in Toronto Canada on November 22–24. 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 in 2011and the second phase started in 2010.

THM

Phase 1

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. Final reports have been delivered.

Task 2, that concerns modelling of the Canister Retrieval Test at Äspö HRL, was the main modelling object during 2009 and 2009. Altogether 8 modelling teams were working with this Benchmark. The task was divided into two parts where the first part was to model the thermo-hydro-mechanical behaviour of a central section of the test hole with given boundary conditions. The second part was to model the whole test. All reports about this task have been delivered (two in 2011). A summary report with conclusions will be delivered during 2012 and was presented in the Toronto meeting.

Phase 2

Sensitivity analyses
This task 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 has been delivered and the work has started.

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 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 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 started 2010 and has been ongoing 2011. The project is described in more detail in Chapter 3. Five modelling teams have started working with this task and presented the status of the work.

Homogenisation

This is a task related to erosion and loss of buffer and backfill and subsequent homogenisation afterwards 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 parts. In the first part a number of simple laboratory tests that have been made will be modelled and used for checking/calibrating the mechanical model. In the next part one or two laboratory tests that simulate bentonite lost in a deposition hole will be performed and preceded by predictive modelling.

The task description has been delivered and includes laboratory results for the first part. Modelling has started and modelling results from two groups have been presented during the meetings. Figure 4-31 shows example of results and comparison with measurements.

Prototype Repository

This task is to model one of the two outer deposition holes in the Prototype Repository in Äspö HRL. 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 "subassignment" which might be interesting to study on its own. The three steps 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 subassignment).
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.

Five modelling teams have started to work with this task. Most of them have finished step 1 and are working with the following steps. The original plans were to have predictions ready before the excavation of the outer section was finished but the large models have yielded calculation problems so no actual prediction has been delivered. Since the excavation was finished at the end of 2011, the coming results cannot be considered true predictions.

Geochemistry

During the year, the University of Bern (Nagra), Universidad Autonoma de Madrid (Nagra), the Paul Scherrer Institute (Nagra), Clay Technology (SKB), Amphos21 (SKB), B+Tech (Posiva), Gruner (Posiva), Czech Nuclear, Research Institute (Rawra), and GRS have contributed to the C-part activity. During the year representatives from the Serco Assurance (NDA) and NWMO organizations have participated in the C group meetings.

The following issues have been dealt with during 2011.

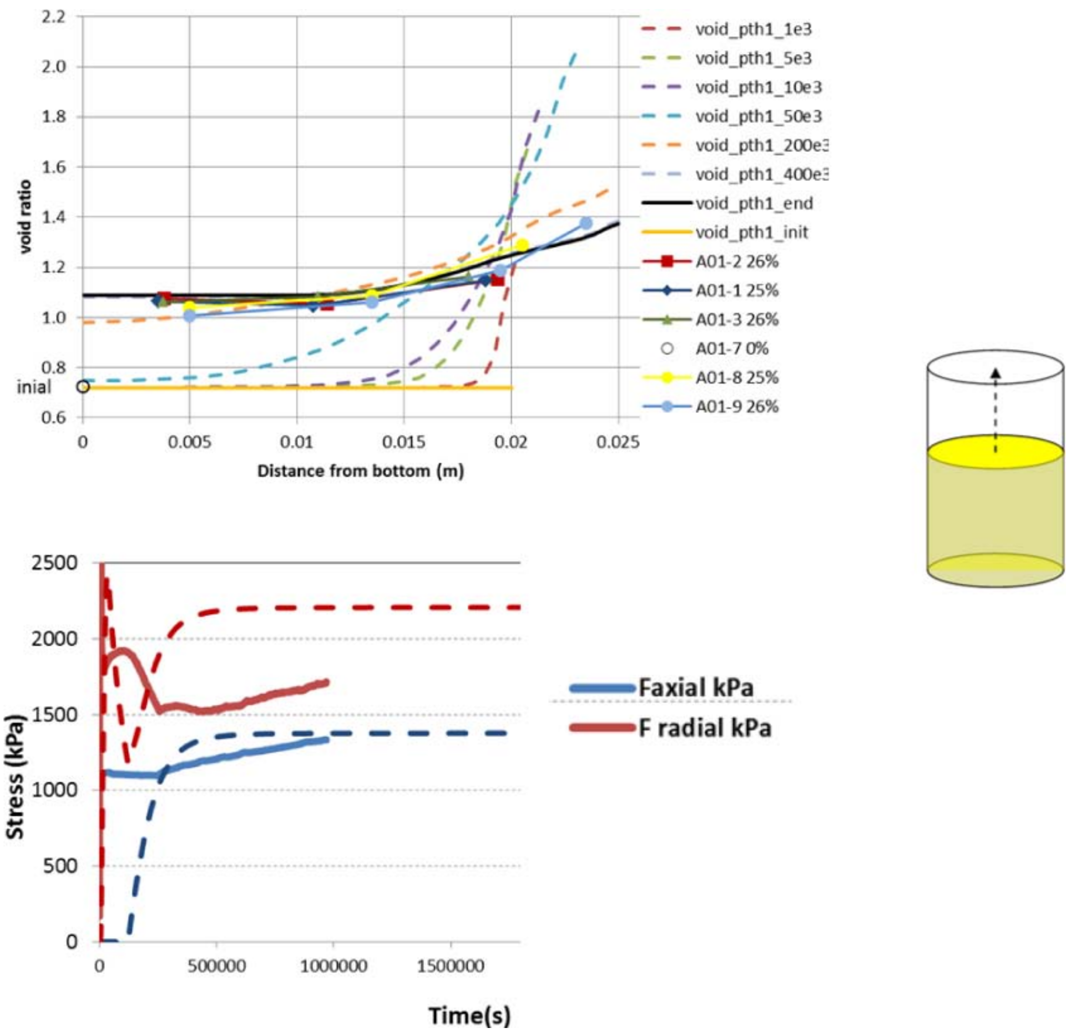


***Figure 4-31.** Example of results from a homogenisation task (25% axial swelling). **Upper:** Void ratio distribution as function of distance from bottom. Modelled with Abaqus at different times and measured after termination (lines with symbols). **Lower:** Measured and modelled radial and axial stresses. Measured: solid lines; Modelled: dashed lines.*

Modelling work

Four experimental data sets on bentonite systems have so far been presented for use as benchmark calculations: (1) NaCl diffusion in Na-montmorillonite and $CaCl_2$ diffusion in Ca-montmorillonite, (2) gypsum dissolution and sulphate diffusion in Na- and Ca-montmorillonite, (3) calcium/sodium exchange in compacted montmorillonite, and 4) core infiltration of Äspö ground-water through bentonite from the LOT test.

During the year, Amphos21 presented modelling of benchmark 1, and THC modelling of the POSIVA near-field evolution.

Universidad Autonoma de Madrid and the University of Bern have performed additional modelling of benchmark 4.

Gruner presented modelling of reference bentonite porewaters for the Olkiluoto site.

GRS presented geochemical calculations of sealing materials for HLW Repositories in Salt Rock Formations.

The Paul Scherrer Institute performed experiments concerning “uphill diffusion of $^{22}Na^{+}$ in montmorillonite”. The experiment was proposed by Clay Technology, which also presented modelling of the experiment.

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

Clay Technology has presented continued modelling concerning all four benchmark data sets. The extension of the ion equilibrium approach to pressure and water flow responses due to externally applied water pressure gradients were presented. 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. Further, the role of hyperfiltration of solutes was illustrated by modelling the core infiltration experiment.

Code development

The in-house code developed by Clay Technology to handle ion-equilibrium has been improved to model diffusion of more than one type of ions.

Presentations of additional theoretical and experimental work

The approximations Donnan equilibrium and the Poisson-Bolzmann equation has been theoretically evaluated by use of Molecular Dynamic simulations.

The coupling between porewater, porosity and swelling pressure in bentonite has been discussed.

Electro-migration and electro-osmosis study of water-saturated compacted sodium montmorillonite using tracers Seichi Sato, Hokkaido University.

Bentonite erosion into granite fracture: preliminary results, R. Cervinka, NRI.

An introduction to the NDA RWMD plans, team and tools, was presented by Serco Assurance.

The extent of hyperfiltration will be evaluated in the Äspö field "BRIE" project, which thereby combines the THM and C project.

5 Mechanical- and system engineering

5.1 General

At Äspö HRL and the Canister Laboratory in Oskarshamn, techniques for the final disposal of spent nuclear fuel are under development. Both well established existing technologies and new technologies will be used. As far as possible standard equipment, modified and adapted to the activity, will be used. Where no standard equipment is available new objects must be developed.

5.2 Technical Development at Äspö HRL

The technical systems, machines and vehicles that need to be developed for the future final repository are being identified in an inventory project.

A total of over 200 different products and components known today are to be developed. Preliminary plans were made on when the production of machines must begin and when they should be completed. In addition, assessment could be made whether production of prototypes are necessary. The number of objects and affiliated information is due to change since the specifications are working documents.

The development of a model for costs has been included in the work. Several projects within mechanical- and system engineering are ongoing and the activities in some of the different projects are described in the text below.

5.2.1 Deposition Machine

Background

The equipment that performs the deposition of the canister containing the used fuel into the vertical deposition hole of the KBS3V-system, needs to lift, turn and handle 25 to 27 tonnes with an accuracy of ± 5 mm in all directions and at all times, and do it 6,000 times. There must not be any kind of damage done to the canister when deposited, and it has to be kept in a radiation shield tube until the deposition is completed. The project that would result in the current prototype, Magne, was started in 2003. The machine was built in Germany and delivered at Äspö HLR in 2010 (see Figure 5-1).

Objectives

The objectives of the current phase are to perform long term tests with the machine, and to develop the systems for navigation and positioning.

Experimental concept

The tests are performed in a tunnel at Äspö HLR, to collect data and to evaluate the reliability and availability of the objects. Also the service requirements during continuous operation are tested. The tests are performed and evaluated in cycles of 40 depositions.

Results

Full scale tests with fully automatic operation are in progress. Recorded test runs were started at the end of 2010, continued during 2011 and will continue during 2012 until several full test cycles of 40 depositions have been performed without any kind of interruption or error. This may be until about 1,000 depositions have been performed. Up till now 191 recorded depositions have been made within the long term test period.

Fine adjustment of the software continues and detected errors are corrected. A remote connection is established, and Navitec Systems are using the remote connection for maintenance and fine adjustment of the software. A test report will be completed during 2012.

Figure 5-1. Magne was built in Germany and delivered at Äspö HLR in 2010.

5.2.2 Equipment for backfilling

Background
After deposition of canisters in the future final repository, the tunnels will be filled with backfill material in order to seal the deposition tunnel. In order to perform this and meet the requirements a concept with a mobile platform with a robot has been developed (see Figure 5-2). Robot handling has the advantages of good capacity and excellent precision which is basic conditions to achieve excellent quality of the backfill in the final deep repository.

Objectives

The goal of the project is to manufacture and install a prototype of the backfilling equipment at Äspö HRL in order to test the basic concept.

Experimental concept

The equipment will also be used to verify performance and identify if any parts of the process needs further development or redesign.

Results

During 2011 the following activities has taken place:

- Computer simulations of the robot.
- Practical tests with scanning equipment.
- An industrial robot was ordered and delivered.
- The mobile platform and handling equipment has been engineered and manufactured.

Installing of all components will take place during early 2012 and tests are scheduled to begin in second quarter 2012.

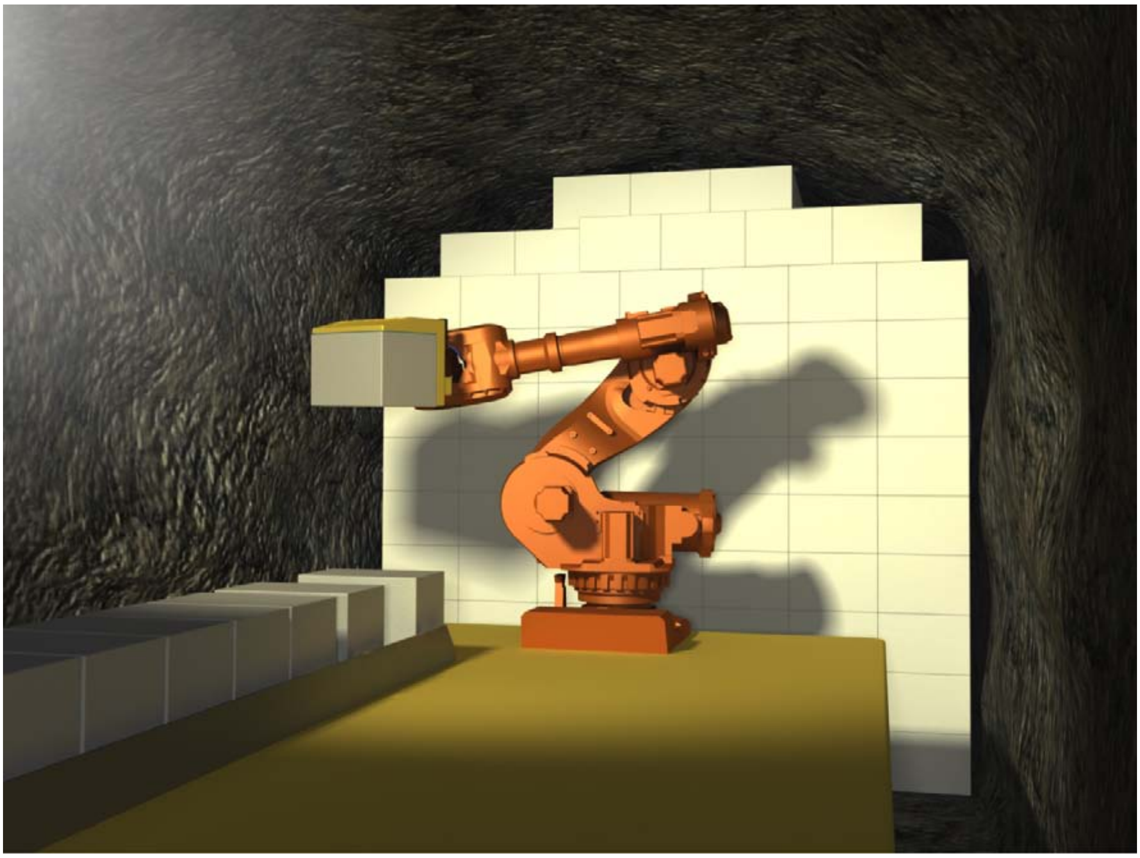


Figure 5-2. A mobile platform with a robot has been developed in order seal the deposition tunnel with backfill material and to meet the requirements.

5.2.3 Buffer emplacement

Background

The buffer consists of blocks and rings, as well as pellets, of bentonite. Equipment is needed to place the buffer in the deposition hole with a large degree of precision, to form a straight hole that the canister can be placed in. The steering gear of the tool for lift and location of the buffer was completed during 2010. The tool works with vacuum to hold the buffer and has shown good function in preliminary laboratory tests (see Figure 5-3).

Objectives

The aim of these projects is to design, manufacture and test equipment that can place the buffer in the deposition holes with the required degree of precision and without causing damage to it.

Experimental concept

A test programme is drawn up, as well as a plan and instructions for the execution of quantity and endurance tests. The test programme describes the design, number, sequence and documentation of necessary lifting equipment. The tests are in progress.

Results

Adjustments on the crane have been made. The buffer rings used for the initial tests were too porous and easily damaged. No vacuum could be achieved on the damaged rings. New rings have been ordered and delivered.

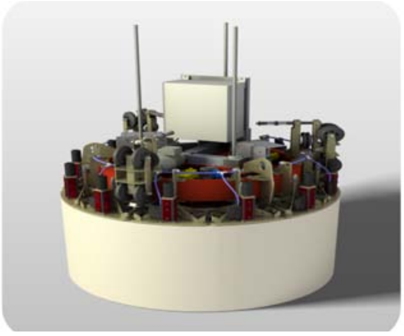


Figure 5-3. Lifting tool for buffer emplacement.

5.2.4 Multipurpose vehicle

Background

SKB has a frequent need for heavy load transports in the ramp at the Äspö HRL. To have these transports executed, a Multi Purpose Vehicle (MPV) for heavy transports was ordered in November 2010 and delivered in August 2011 (see Figure 5-4).

Objectives

The objective was to procure and take into service a vehicle for heavy transports to Äspö HLR.

Experimental concept

Apart from being used for regular transports in different projects the vehicle will be used as a platform during technology development of various systems. E.g. development and testing of the mission control system and development of equipment for backfilling. It will also act as a prototype for the future ramp vehicle for the deep repository.

Results

Delivery tests and functional tests have been performed. A cabin has been mounted and tried out. During 2011 the MPV has been used to transport e.g. the two canisters from the excavation of the Prototype repository.

Figure 5-4. In August 2011 a Multi Purpose Vehicle (MPV) for heavy transports was delivered to Äspö HRL.

5.2.5 Logistic studies

Background

The main objective of the logistic studies for the final repository for spent fuel is to simulate all activities at the repository during the operational phase. The studies include rock excavation, emplacement of buffer, canister and backfill, 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 this project was to find out if suitable software was available and if it is a practical way to carry out this type of simulations. The results of the project were used for internal information and as decision basis for continued logistics studies. Planning and preparatory work for continuation of the project has proceeded and in December 2011 the project directive was approved.

Objectives

Operation of the nuclear fuel repository will include large amounts of transports and movements of different kinds of objects. The logistic simulations will identify bottlenecks and in what sectors there is a need for optimization of operations. Simulations of different scenarios will form a basis for the choice of technical solutions.

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

- Time needed for various activities.
- Bottlenecks and sensibility for disturbances.
- 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, supervision and follow up of operation and maintenance.
- Organisation structure for the final repository including staffing.
- Costs.

Experimental concept

The aim of a further developed logistic study is to step by step simulate the complete operation of the repository. The simulations will also form a basis for detailed schedules for deliveries to and from the repository and will answer the questions of how and when deliveries of technology need to take place.

Results

The required software was purchased in 2011. During the year planning and discussions between stakeholders have continued. The process has resulted in a well planned and established project which will be implemented in close cooperation between stakeholders. The model will include the skip building, the skip hall, the reloading station and 4 to 8 deposition tunnels.

A logistics study of reception, transportation and deposition of decommissioning waste and operational waste at SFR (Final Repository for Short-lived Radioactive Waste) from year 2020 and onwards is done within the project for extension of SFR.

5.2.6 Mission control system

Objectives

Within this project, a prototype of a comprehensive automatic system for the management and control of transport and production logistics for the final repository is developed. Preparatory work has been made during 2010 and formally the project started in October 2010.

Experimental concept

The decision to develop a mission control system establishes a working method for the final repository that facilitates the use of automated vehicles.

Results

Definition of properties and program structure was finished during the first months of 2011. The mission control system and a related data base were developed during 2011 and the test of the system will start in 2012.

5.2.7 Transport system for buffer and backfill material

Background

A feasibility study to find a solution for transport of buffer and backfill material was carried out in 2010. The study included the transport 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 was made regarding human factors. An internal report from the feasibility study was produced.

Objectives

The final target of the project is to deliver an autonomous and remotely operated transport system for buffer and backfill material from the production premises to the deposition tunnels (see Figure 5-5).

Experimental concept

All the different parts of the transport system will be tested together and synchronized with the installation equipment for buffer and backfill.

Results

Work in the project has initially been focused on increasing the level of detail from the feasibility study and to work out a requirement specifications for the included equipment. Steel pallets have been procured.

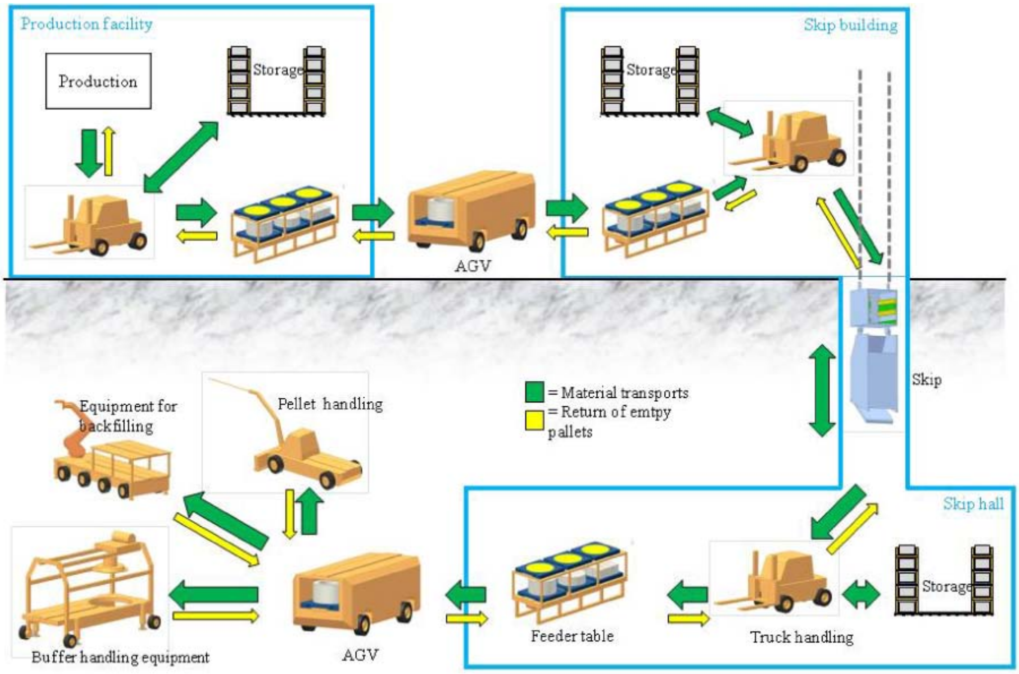


Figure 5-5. A sketch over an autonomous and remotely operated transport system for buffer and backfill material from the production premises to the deposition tunnels.

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.

During 2011 the development of the Äspö Facility has been continuous ongoing with the extension of the tunnel. During the year the pre-investigation in order to identify a suitable location for the extension has been made. The operation of the already ongoing experiments in the Äspö Hard Rock Laboratory has continued and some have been completed with respect to field work. For those now remains work to analyze, evaluate and report results from the experiments.

In the beginning of the year work was initiated in the new geotechnical laboratory and one of the first tasks was connected to the Prototype Repository project. During the summer the first canister from the outer section of the Prototype Repository was retrieved, and the second canister was extracted in December. During the fall the analysis and tests of the bentonite began and is still ongoing.

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.
- Conduct comprehensive visitor services and information activities in co-operation with SKB`s Communication Department.

The *Repository Technology (TD)* unit has the past years been 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-operation of projects undertaken at the Äspö HRL, providing services (administration, design, installation, 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 Communication Oskarshamn (KO) a part of the Repository Technology unit. However the group were transferred to the reorganised Communications department within SKB in May 2010. 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.

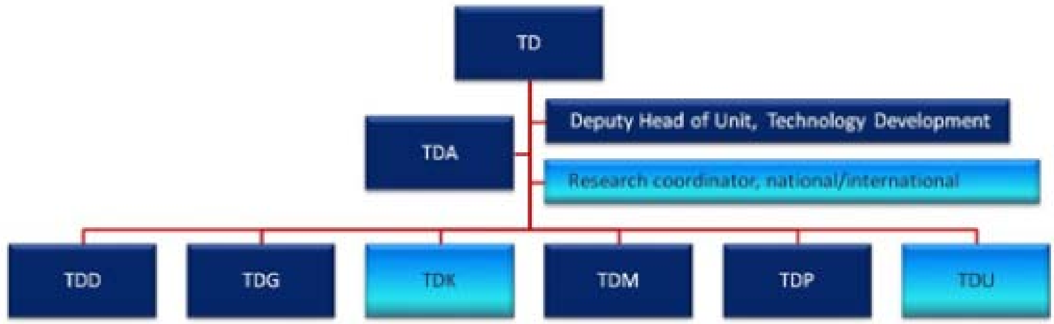


Figure 6-1. The reorganization of the Repository Technology (TD) unit entails a lot of changes and includes TDA (Administrations, QA and planning, TDD (Facility Operation), TDG (Geotechnical barriers and rock engineering), TDK (Chemistry Laboratory), TDM (Mechanical- and system engineering), TDP (Project- and experimental service) and TDU (Rock Characterization and Construction Technology).

During the later part of 2011 plans have been made to reorganize the Repository Technology (TD) unit and from the 1st of January 2012 extend the unit with two further operative groups – Rock Characterization and Construction Technology (TDU) and Chemistry Laboratory (TDK). The reorganization also means that a research coordinator for the national and international work will be placed in the unit.

The previously established groups (TDG, TDM, TDP, TDD and TDA) still have the same responsibilities as before. The responsibilities of the new groups are:

- Rock Characterization and Construction Technology, TDU, responsible for development and management of investigation and evaluation methods, measurement systems with tools and field equipments.
- Chemistry Laboratory, TDK, responsible for taking water samples and to do chemical water analysis.

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 Pre-investigation for tunnel expansion

Background

Additional spaces are needed underground to support the research and development commissioned by SKB´s two programmes; the Nuclear Fuel Programme and the LILW Programme. In addition a new experimental site is required for the ongoing development of the KBS-3H method. SKB International AB also requires new experimental sites to further develop Äspö HRL as an international research hotel. Within the growing cooperation with universities and colleges who are interested in conducting other types of research at Äspö HRL, the need for new facilities and experimental sites above as well as below ground has been voiced. The expansion of Äspö HRL 2011–2012 aims to coordinate these needs.

Objectives

The aim of the expansion is to create new and extended opportunities, through new experimental sites underground, for the continued technology development in full scale and in realistic environments. 185 m transport tunnel with experimental tunnels are being prepared for:

- Nuclear Fuel programme – Experimental site for testing of plug for deposition tunnel.
- Project KBS-3H – Experimental site for KBS-3H at repository depth (–420 m).
- LOMA programme – Experimental sites for the project Concrete and Clay.
- Nova FoU – Experimental sites for geoscientific basic research.

The expansion project also aims to strengthen the role of Äspö HRL as an open national and international facility for research and technology development in the nuclear industry as well as in other research areas/industries where the advantage can be taken of the facility's opportunities.

The work in the project will also contribute to competence development and knowledge transfer within SKB.

Results

During the spring 2010 a survey of the previously made tunnel mapping, groundwater pressure, and ground magnetic anomaly map for a suitable host rock for the expansion was made. The rock volume of the intended area is in the northeast part of Äspö HRL at the –420 m level. The rock is structurally relatively preserved and less influenced by deformation zones than the rock volume towards north and northwest within the "Äspö deformation zone" and the groundwater pressure is assumed to be higher in the rock around the main tunnel.

During 2011 two boreholes (227 m and 320 m) were drilled from NASA2050A and NASA3009A for hydraulic characterization. This gave further information on the area and the rock was found to fulfill the requirements set.

Three layout alternatives where produced and one of these were selected during 2011, consisting of three new transport tunnels with several experimental tunnels. One of these is an extension of the TASJ tunnel, and the others have been named TASU and TASP. Pilot holes have been core drilled in the tunnel direction for TASU and TASP.

During 2011 invitations to tender was sent out and a contractor has been selected for the excavation work, set to begin by end of January 2012.

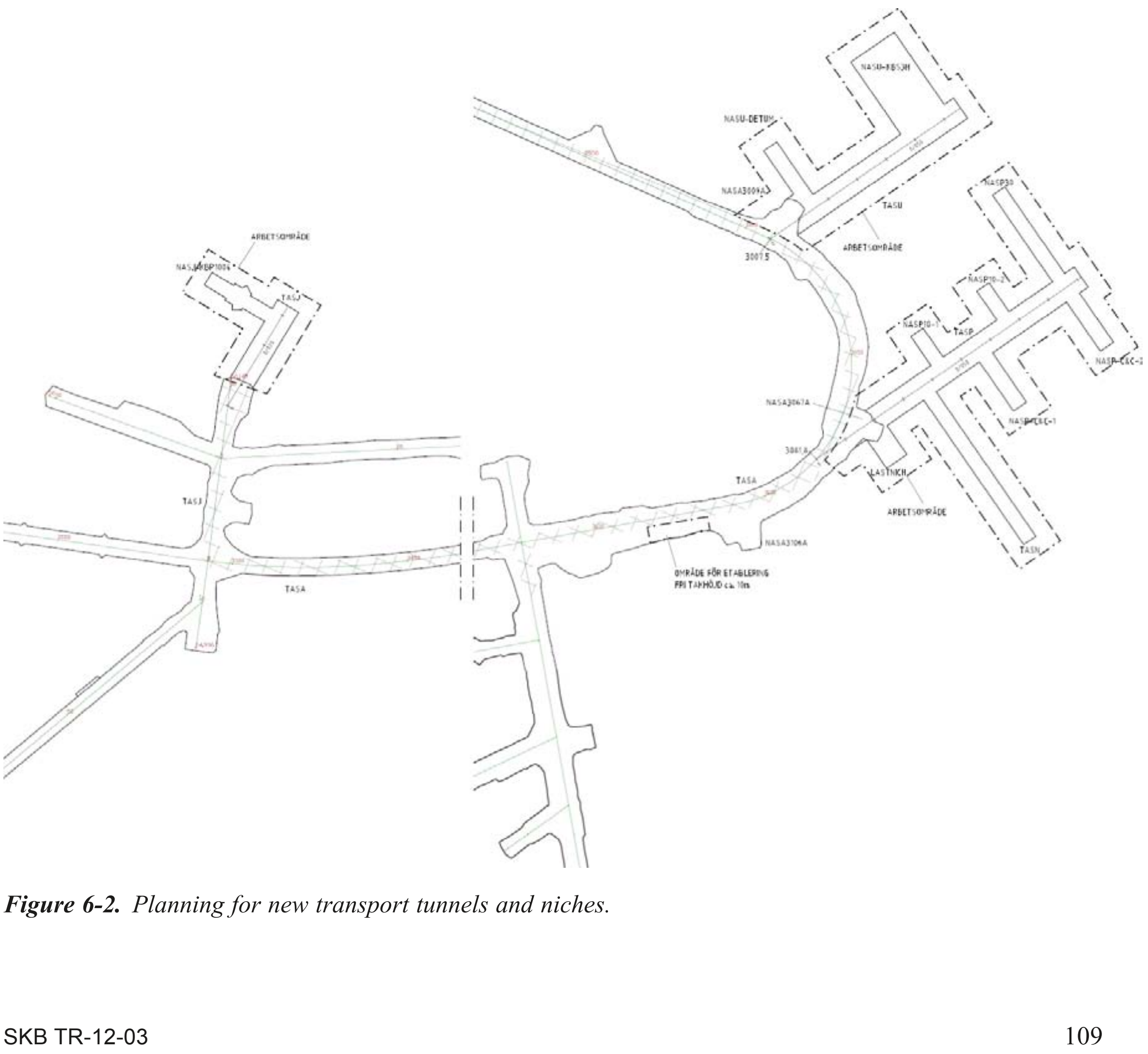


Figure 6-2. Planning for new transport tunnels and niches.

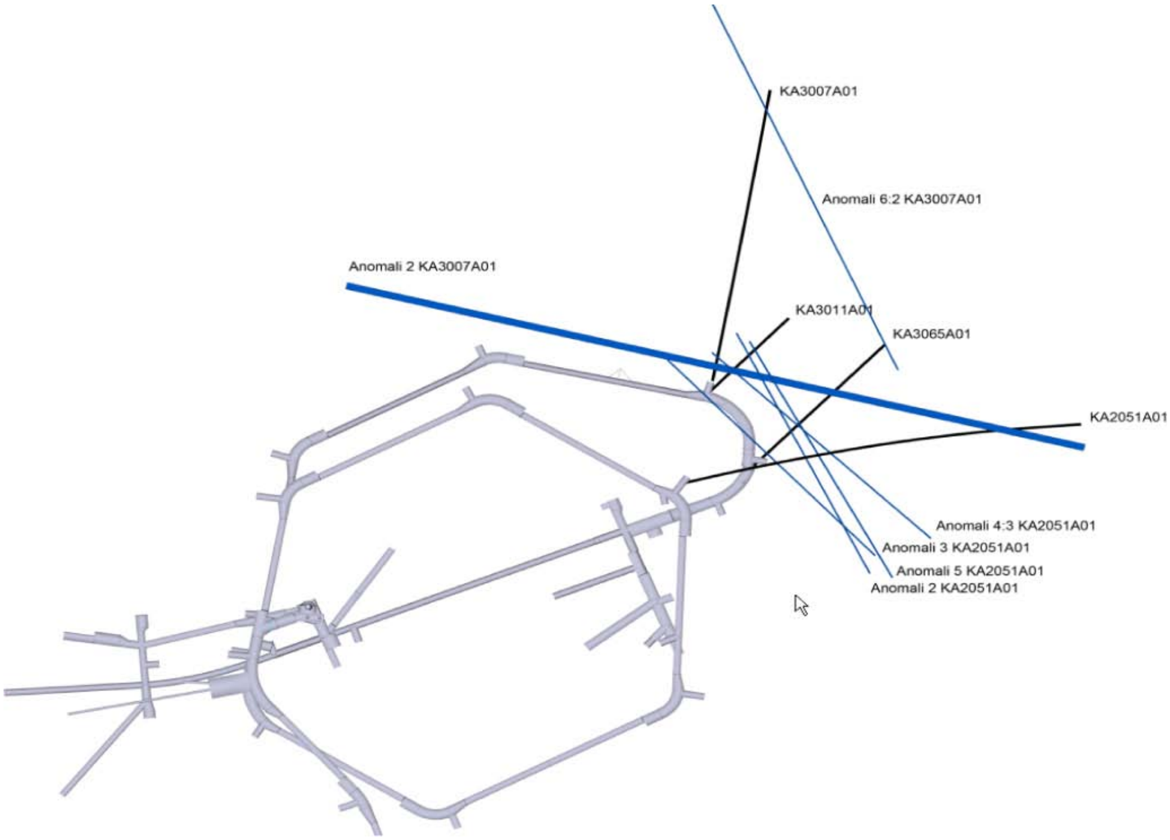


***Figure 6-3.** First hydro structural interpretation of possible high transmissive deformations zones.*

6.3 Bentonite laboratory

Background and objectives

Before building a final repository, further studies of the behaviour of the buffer and backfill under different installation conditions are required. SKB has built a Bentonite Laboratory at Äspö, designed for studies of buffer and backfill materials. The laboratory has been in operation since spring 2007. The Bentonite Laboratory enables full-scale experiment under controlled conditions and makes it possible to vary the experiment conditions in a manner 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 reference design for the backfill of deposition tunnels includes bentonite block, bentonite pellets and a foundation bed of bentonite clay. The tunnel floor needs to be flat and have sufficient bearing capacity to make it possible to stack the backfill blocks according to the reference design. To achieve a flat foundation the tunnel floor will be covered with a bed of pellets or granulate made of bentonite clay. The bed can be either compacted or none compacted.

A number of bed tests have been performed as a part of SKB´s development of the bed design. The main objectives are:

- To define all requirements for the backfill and its production and installation prior to start of the large scale tests, based on given prerequisites.
- To present the basis for a technical decision on new reference design based on project results.

The purpose of the performed bed tests was to define the bed requirements in the backfill installation to enable stable stacking of backfill blocks. The tests included stacking of blocks on different bed materials, on blasted and wire sawn floor, with and without concurrent water inflow.

Block stacking on different bed compositions

The purpose of the tests was:

- To evaluate the reference geometry of stacking on a non compacted bed.
- To study the feasibility of using pellets as bed material with sufficient stability in the block stack.

Block stacking on bed during water inflow

The purpose of the test was to study how the bed and the stability of the block stack were affected by inflowing water.

Block stacking on the upper part of the deposition hole and bevel.

The purpose of the test was to study how the bed and the block stack are affected by stacking over a deposition hole, with and without concurrent water inflow.

Results

The block stack was stable and no problems with placement of the blocks occurred in any of the performed tests. The tests show that the stacking geometry is very stable and not sensitive when it comes to foundation material and compaction of the foundation bed. The stability of the stack is caused by the stacking geometry with overlap joints; every newly placed block locks the underlying ones.

The test results show that the sinking is relatively evenly distributed over the bed, when the bed is uniformly deep. Blocks adjacent to each other have sinking of the same magnitude. This is a positive result since it is the relative sinking between block that is of interest, hence no problem with the stack stability will occur as long as the sinking are of same magnitude.

The inflowing water was mostly absorbed by the pellets around the simulated crack. The water was also pushed up to the sides of the block stack where it was partly absorbed by the pellets.

The largest sinking was observed in the bevel, where the pellets depth was deepest. This caused a compaction of the block stack over the bevel, which rather increased the stability of the block stack than decreased it.

Figure 6-4. *Upper part of the deposition hole and bevel.*

***Figure 6-5.** Block stacking on the upper part of the deposition hole and bevel.*

6.3.1 Impact of water inflow of backfill

Background

The backfill of deposition tunnels is proposed to consist of stacks of blocks of highly compacted smectite rich clay, surrounded by blown-in smectite rich clay 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.

Results

The bearing idea was to investigate how water entering from a local point at the confinement penetrates into the pellet fill. The experiments had the form of injecting water at different constant rates from a nozzle at the contact and measuring the pressure at the nozzle, as well as to excavate the pellet fill for identifying the flow paths at the end of the respective tests. The measurements showed, that the generated pressure, and distribution of penetrating water were functions of the inflow rate and time after start of injection. The main conclusion was that for rock contacting pellet fills the migration of water initially took place into the fill, and not along the contact between rock and pellets. This is in contrast with the ½-scale tests in which water migrated along the contact between the steel confinement and the fill from start.

The major conclusions from the work are: 1) field experiments for identifying flow paths in the pellet component of clay backfills show that water moves along the contact between the pellets and steel plates used for simulating rock, 2) tracers of suitable type can be used for detecting flow paths in pellet fillings, 3) air enclosed in pellet fillings under saturation can generate channels, 4) tests of water-saturated rock and contacting pellets, show that water is initially directed into the filling, and that channeling takes place even at very low inflow rates, after sufficiently long time, 5) more knowledge is required respecting the importance of the rock structure for which large-scale tests are needed.

The experience from the whole project was that the experimental setup and performance were successful and that the defined goal was achieved. The results, which will be published in two SKB R-reports, show that all the goals set have been achieved.

6.4 Facility operation

Background and objectives

The main goal for the operation of the HRL 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 2011 has been stable, with a very high degree of availability. An independent consultant has done an energy audit at the plant and a proposal on energy conservation measures were developed for operational planning. The upgrade of the object monitoring and personnel tracking system (RFID) has been made during the year. Efforts to develop a calibration facility for the curvature deviation measurements have begun see Figure 6-6. Major purpose of the facility is the needs of drilling very straight holes at the site of deposition tunnels. There are no such facilities in Sweden that will permit calibration of straight boreholes and for accurate curvature measurements. The main request for this type of curvature measurements has been made by the KBS3H project, where a lot of straight pilot hole is a prerequisite. During the last month of the year a road has been constructed at which the testing facility is planned to be placed.

Figure 6-6. *Facility for the curvature deviation measurements.*

The control system for tunnel ventilation has been replaced during the year. Previous management consisted of several older systems. Further three new rescue chambers also have been purchased during the year. They will be delivered in connection with the beginning of the tunnel expansion of Äspö HRL.

During the year, work on building a vehicle wash station begun. The old facility for washing vehicles was not adequate anymore. Invitations for building contract tender were sent out in December.

A treatment plant for the separation of drill cuttings has been purchased and recovery of the tunnels TASQ and TASS were completed after experiments were finished.

The new geotechnical laboratory has also been completed. Rebuilding of the goods reception was made in order to receive and cut bentonite samples from the Prototype repository outer section. Goods reception was then relocated to the previous drill core archive and most of the cores are now stored in "Verkstad 14". The constructions of the new facilities were completed and the new laboratory premises can now be used for different activities.

During the year, a new water and sewer construction was completed, see Figure 6-7. The old sewer was previously collected in a large container, and transported away by truck. The new sewer facility now allows to be pumped in a two-kilometre long pipeline to OKG's treatment plant. To become more independent of water supply from OKG, a water reservoir to meet emergency services requirements of approx. 100 m^3 was constructed.

Figure 6-7. *The new water and sewer construction allows to be pumped in a two-kilometre long pipeline to OKG's treatment plant.*

6.5 Communication Oskarshamn

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

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 Äspö HRL. 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. 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. During 2011 Communication Oskarshamn consisted of 13 persons. The unit has the responsibility for SKB´s exhibitions, for school information in Oskarshamn as well as in Östhammar, the magazine Lagerbladet, press release matters, development of the research communication in co-operation with the research unit of SKB and to carry out internal as well as external communication at the facilities Äspö Hard Rock Laboratory, Clab and the Canister Laboratory etcetera.

Figure 6-8. *During a day dedicated to female students the participants learned more about" Friction Stir Welding".*

Special events and activities

The facilitates in Oskarshamn were during 2011 visited by 9,471 visitors. The total number of visitors to all SKB facilities in Oskarshamn and Forsmark was 15,309 persons. The visitors represented the general public, teachers, students, professionals, politicians, journalists and visitors from foreign countries. “Urberg 500” was arranged during six summer weeks. During these weeks about 1,500 persons went on a tour underground.

During 2011 the unit´s school information officer went to schools and high schools within the municipality of Oskarshamn and met approximately 1,300 students and teachers. The unit also met 110 students in the municipality of Östhammar. A newsletter is sent out to teachers three to four times a year. All students in 9th grade in Oskarshamn are offered a visit to Äspö HRL and the Canister Laboratory and all students in the 3rd grade of high school are offered a visit to Clab.

During 2011, three issues of the magazine “Lagerbladet” were published. “Lagerbladet” 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 arranged a number of events during 2011. Äspö Hard Rock Laboratory celebrated 25 years during 2011. A day for the public was arranged in May with about 200 visitors. During the day, there was an exhibition with representatives from different projects etc. “The Geological Day” was arranged for students on September 9th and for the public on September 10th. Theme for “the Geological Day” was “Äspö – underground and above ground”. A nature guide and a geologist were lecturing in the underground and along the Äspö nature path. “Researcher´s Night” was arranged on September 23rd and was a part of “Oskarshamns Framtidsdagar”. The theme was “Can you make money on SKB´s research?” and about 50 persons attended. In November, about 90 competitors participated in “the Äspö Running Competition”. On December 3rd, “Ljus i urberget” was arranged. The visitors went underground where a choir entertained with Christmas carols.

Furthermore, the unit is involved in “Almedalsveckan” when the transportation ship m/s Sigyn is used as an exhibition. The unit is also involved in a number of other communication tasks.

***Figure 6-9.** The theme for “ForskarFredag 2011” was “Can you make money on SKB`s research”.*

7 Open research and technical development platform, Nova FoU

7.1 General

The aim is to describe major progress during the year 2011 for the research platform Nova FoU (Nova R&D). The description is made in terms of the mission, the status of the projects, spin-off effects, the organisation and the progress for the year 2011.

7.2 The Nova FoU mission

Nova in Oskarshamn gives university courses, conducts research and performs business development (www.novaoskarshamn.se) in the municipality of Oskarshamn. Nova is contributing to the long term growth in the region by creating networks between academia, business and society. Äspö Hard Rock Laboratory (www.skb.se) is a world unique underground research laboratory which is now open for more general research. Nova FoU is the organisation which implements this policy and facilitates external access for research and development projects to the SKB facilities, data and competence in Oskarshamn (Figure 7-1). The aim of Nova FoU is to create local and regional spin-off effects in favour for the society and business. Nova FoU is supported by SKB and the municipality of Oskarshamn. Nova FoU provides access to the following:

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

The aim of the research and development projects at 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).

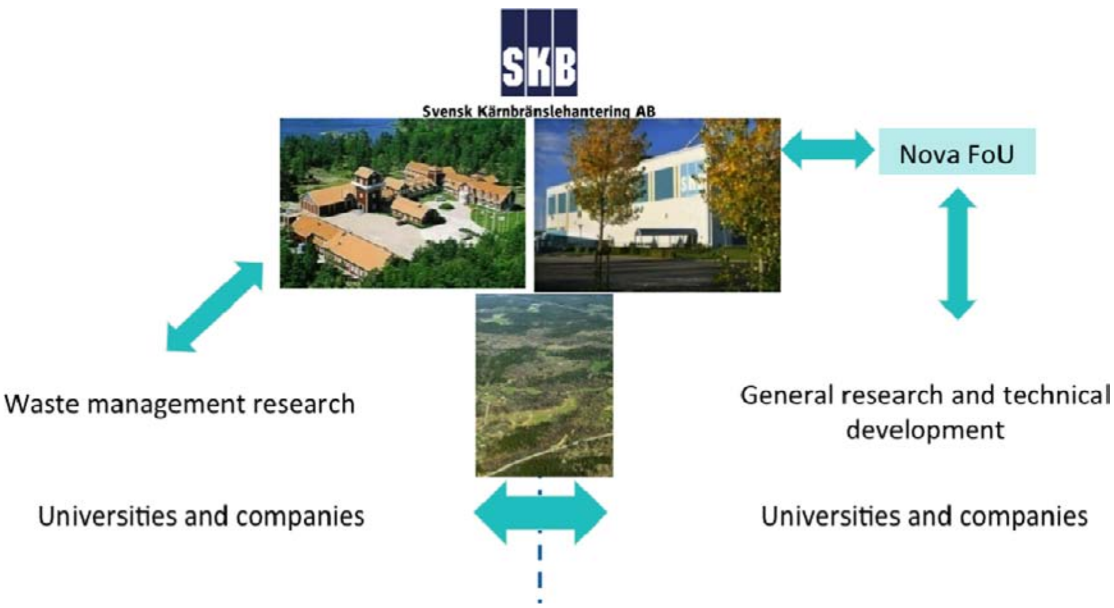


Figure 7-1. *Nova FoU provides access to the SKB facilities and data for universities and companies for general research and technical development. Nuclear waste management research is handled by SKB.*

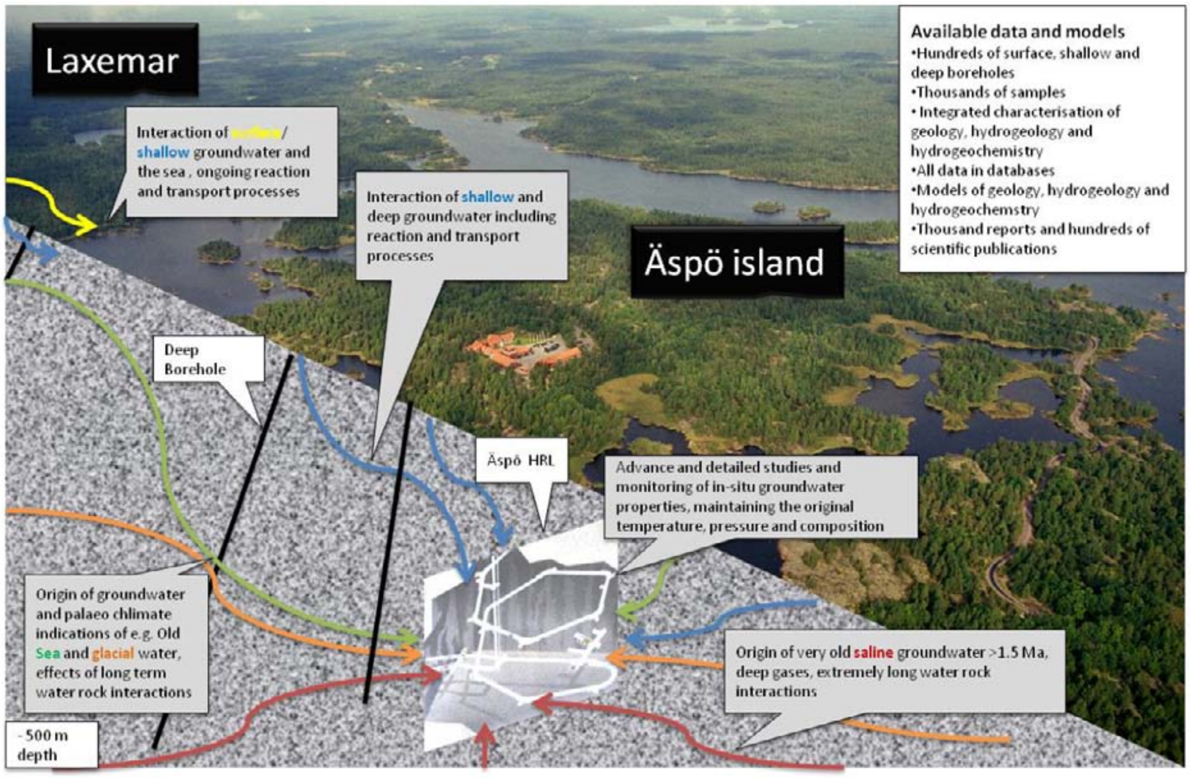


Figure 7-2. *The Äspö and Laxemar areas have been studied in terms of geology, hydrogeology, hydrogeochemistry and ecology. This information can be used for a number of purposes, for example to describe the water cycle and hydrogeochemical processes in 3D.*

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 are:

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 Nova FoU projects

The projects at Nova FoU range from detailed natural sciences studies to technical development and expert support in advanced projects. The status of the ongoing research and development projects within Nova FoU for year 2011 are described below.

7.3.1 Lanthanoids in bedrock fractures

Aim of the project

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.

Status of the project

The status of the project 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 M3 modelling, and (3) the relationship between lanthanoid concentrations and drilling-water % in ground-water samples have been studied (Figure 7-3).

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

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 the heavy lanthanoids are just as high as the light ones. It seems that a large part of the fractionation of lanthanoids in the calcites can be explained by the combination of fractionation of the dissolved pool existing in deep groundwaters (only current-day data exists) and partitioning into the calcites according to existing partition coefficients. Additional statistical work and interpretation will be carried out in order to further define the interaction of lanthanoids in groundwater and fracture minerals in crystalline bedrock.

Spin-off

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 kind of groundwaters.

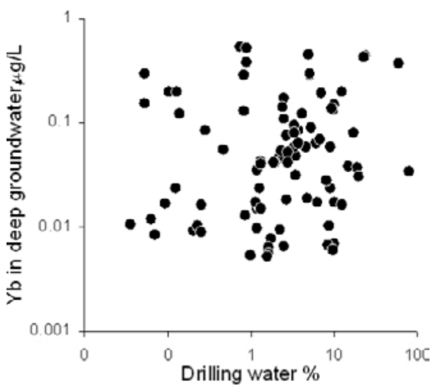


Figure 7-3. *Scatterplot of drilling-water percentage and lanthanoid concentrations in groundwater.*

7.3.2 Fluorine in surface and ground waters

Aim of the project

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 to: (1) describe and explain the high fluoride concentrations in the water in the lower reaches of the Kärrsviksån stream (this stream was included within Site Investigation Oskarshamn, Figure 7-4), (2) characterise and model fluoride abundance, transport and speciation in streams and overburden groundwaters in Laxemar and Äspö and (3) identify the sources of high fluoride concentrations occurring in many wells in the region (Kalmar County).

Status of the project

The status of the project for the reporting period: First paper, entitled "Impact of a fluorine-rich granite intrusion on levels and distribution of fluoride in a small boreal catchment", has been published in Aquatic Geochemistry (Jan 2012). During the autumn of 2011 two projects were initiated; (1) Temporal speciation of fluoride in three catchments in Laxemar area and (2) Distribution and controls of fluoride in overburden groundwater of the Laxemar-Äspö area. These two projects will be finalized and submitted for publication during 2012.

The major results are the findings and characterization of a temporal and spatial fluoride pattern within the Kärrsviksån stream and its catchment (Paper I), 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 mechanisms are 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).

Spin-off

The spin-off effects from this project will be increased information and knowledge on fluoride abundance and transport in surface and ground waters in Laxemar and Äspö, as well as elsewhere in Kalmar County, 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 fluoride concentrations well above the permissible limit 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 fluoride concentrations to rise 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 Kärrsviksån 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

Aim of the project

The aim of the project is to increase the understanding of the chemistry of ground water flowing through the deep fractures of the crystalline Proterozoic bedrock. This is a part of the Äspö Site Description Modelling (Äspö SDM) which is a SKB project. The different processes influencing the hydrochemistry in the fractures are: mixing (of several water types of different origin), transport, water-rock interactions and bacterial activity. Since the beginning of this project the focus was on the mixing process which is the one of the two dominant processes (together with transport) and therefore essential for the subsequent characterisation of the bacterial and inorganic reactions at a site scale.

Status of the project

For the reporting period, major attention has been on the data quality in order to identify and exclude possible contaminated groundwater samples. A new methodology has been developed for water classification of the groundwaters at Äspö based on the Cl content and $\delta^{18}O$ values. This method identifies and sorts qualitatively the groundwater samples resulting from intense mixing from those showing a dominant water origin of Saline, Glacial, Marine or Meteoric water. In addition, the chemical evolution of the time series available at Äspö was studied to characterize the evolution and mixing in the different part of the Äspö fracture network after the tunnel construction.

The major results from this work are:

- Waters are influenced by mixing but contain often the infiltrating end-member character.
- Saline, Marine and Meteoric waters are occurring in the fractures system at Äspö. In contrast, groundwater with glacial origin is less abundant rarer which suggests a significantly mixing with other groundwaters.
- The chemical and isotopic signature of the groundwater resulting from intense mixing tends to be dominated by Marine and Saline waters.
- A rapid intrusion of the Baltic Sea water is observed during the construction of the Äspö tunnel (Figure 7-5a). In a similar manner, the up-coning of the saline water is observed in the northern part of the tunnel spiral even if the Cl tend to stabilised or even decrease after 2007 (Figure 7-5b).

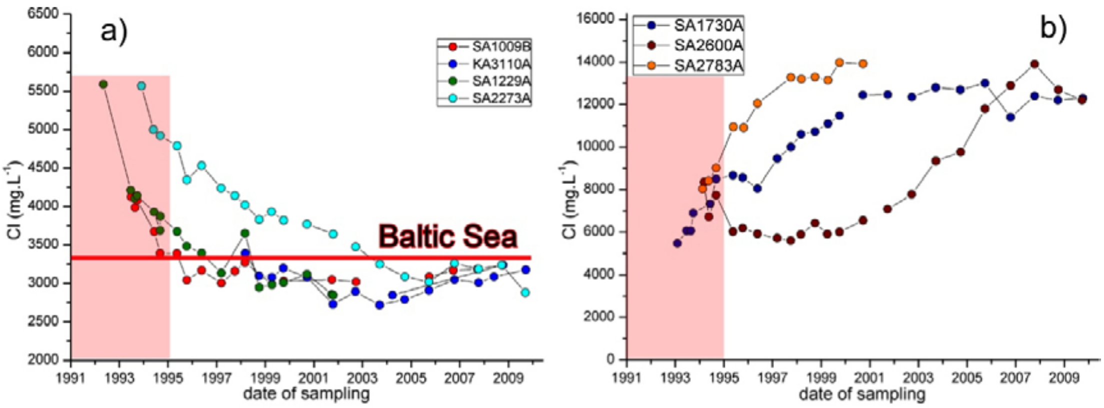


Figure 7-5. *Cl content in time series from the Äspö HRL with a) dominant marine and b) dominant saline water type. The borehole names are listed in the legends. The red bars represent the tunnel construction period and the red solid line the Cl content of the modern Baltic Sea.*

Spin-off

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 gives a better understanding of the groundwater evolution during and after a tunnel constructions in crystalline bedrock.
- The new modelling approach allows taking into consideration the compositional changes in e.g. marine component since the latest glacial age (18,000 BC).

7.3.4 Geobiology of microbial mats in the Äspö tunnel

Aim of the project

Major goals of the project are to study (1) the biodiversity of microbial systems occurring at different depths in the Äspö HRL, (2) metabolic pathways and biomineralisation processes, including EPS-controlled selective cation binding and complex formation, (3) inorganic and organic biosignatures for biogeochemical processes involving deep biosphere microorganisms.

Status of the project

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 mats and associated mineral precipitates. A part of the project will continue until the end of 2012. Long-term experiments are planned to continue for indefinite time.

Studies of aerobic and anaerobic enrichment cultures in the aquifer waters revealed previously described species as well as various novel freshwater halo tolerant or marine species that have as yet not been reported from Äspö. These organisms are tentatively believed to reduce sulphate, degrade different types of hydrocarbons, oxidize iron, reduce metals like iron and manganese (identification work still in progress) and oxidize various nitrogen species (e.g. *Nitrospira* spp., *Nitrotoga* spp.). Cluster analysis on 454 pyrosequencing data showed that the bacterial community is characteristic of each location, indicating that the aquifer water composition is the main control on the evolution of the community structures.

The majority of the cyanobacteria from green microbial mats developing in the flow reactors with light supply and on the tunnel walls in the deeper part of the tunnel are very different from known cyanobacteria species (50–80% sequence similarity). This suggests that the cyanobacterial

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

community has not been introduced by contamination from the surface, but has been isolated for a long time and may be endemic to the several thousands of years old, deep aquifer waters. However, it is as yet unclear how these prototroph could have survived such a long dark period.

The development of iron oxidizing microbial mats was studied at TASA 1327B (–183 m) and NASA 2156B (–290 m) and revealed a massive (up to 10^6 fold) accumulation of trace and rare earth elements (TREE) within the mineralized microbial mats after two and nine months, respectively. Iron mineral deposition is initially controlled by the metabolic activity of the FeOB and passive mineralization processes caused by the high biosorption capacity of the young EPS-stalks. Upon aging, ongoing iron oxyhydroxides impregnation causes a gradual depletion of the biosorption capacities of the EPS-stalks. As a result, indirect mineral precipitation becomes increasingly important over time, leading, inter alia, to the precipitation of gypsum.

Fracture minerals within an SKB drill core of the Äspö Diorite and Småland granites were investigated for fossil biosignatures of subterranean microbial activity using various analytical techniques. Thin (20–100 µm), dark organic layers lining the boundaries between different fracture minerals, corrosion marks, branched tubular structures, and TREE accumulation were interpreted as remains of a microbial biofilm system that established much later than the initial cooling of the Precambrian host rock.

Spin-off

Microbial systems in the Äspö HRL may serve as model systems for the biodiversity and structure of the deep continental biosphere.

Microbes showing increased capacities for the accumulation TREE may potentially be used for the recovery of precious trace elements, and for water remediation purposes.

Defining biosignatures of recent and ancient deep biosphere environments will be helpful for paleo reconstructions, which may also affect considerations about the long-term storage of nuclear waste.

7.3.5 Coastal modelling

Aim of the project

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.

Status of the project

Topic 1 Subsurface flow and transport from land to 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. Some preliminary results are shown in Figure 7-7 below.

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. During the fall, the plan is to complete the computations of the transit time distributions (TTDs) and present a first outline of a manuscript for a technical journal. Some initial results of modelled TTDs are shown in Figure 7-8.

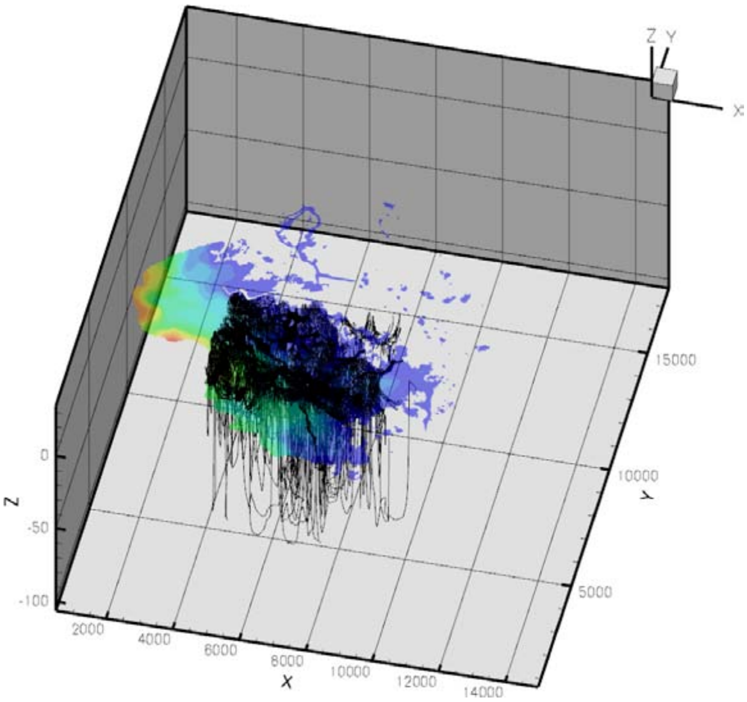


Figure 7-7. Figure showing land areas of the Forsmark model, pressure and particle trajectories from a rectangular injection area at the surface.

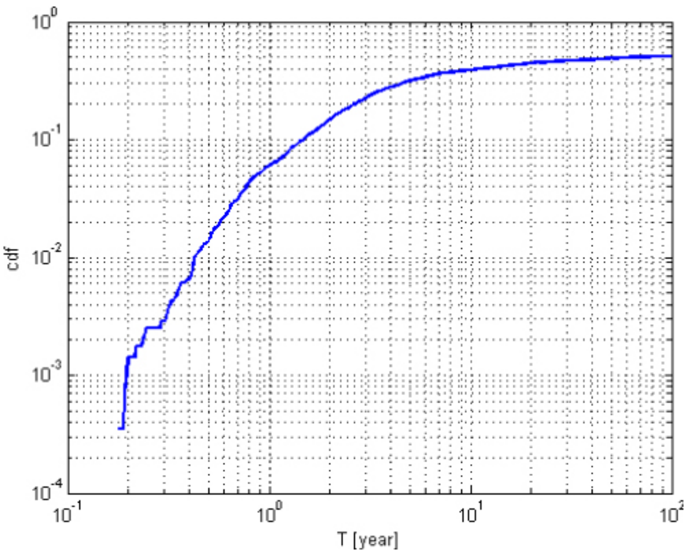


Figure 7-8. CDF of transport time in Forsmark model for equally distributed particles in overburden.

Topic 2 Lagrangian modelling of material transport along hydrological pathways from land to sea

This work is focused on providing a new theoretical framework for modelling hydrological transport. With mean properties and mean flow given or resolved by simulations (as considered under Topic 1), water and solute transport in a catchment can be analyzed in terms of flux/discharge. A Lagrangian framework for material transport along hydrological pathways is presented. Using this framework, we explore generic consequences of space-time flow variations, emphasizing the macro-dispersion along pathways. The solute is released from a finite but limited source (recharge) area. Two issues are of particular interest: i) Water travel time distributions obtained by forward and backward particle tracking in a space-time varying velocity field; ii) Conditions for implementing convolution in a space-time varying velocity field. Trajectories are simulated under generic conditions, with fully ergodic and only spatially ergodic velocity. It is shown that forward (water travel time) and backward (water age) statistical distributions coincide for statistically stationary space-time variations. Temporal variability will generally alter the statistical structure of the Lagrangian velocity fluctuations; once this is accounted for, convolution is applicable provided that independence of transition times between pre-defined segments is approximately valid. Finally, we illustrate the potential effect of space-time velocity fluctuations on tracer attenuation. Further work is needed to better understand the statistical structure of space-time velocity under more realistic scenarios of hydrological transport.

Spin-off

Regulatory implementation

There is a growing understanding to reach environmental goals and achieve overall good ecological and socio-economic status in coastal areas (e.g. EU Water Framework Directive) and there is a need for basin-wide integrated management strategies. This project would lead to novel developments toward more reliable and general tools for monitoring and implementing regulatory targets.

Environmental risk assessment

For environmental impact assessments there is a need for improved tools that can model and help the assessment of especially downstream and down-system effects .The same is also true for more strategic plans and policies. Long-term changes in land use, transport, water use, etc will have an effect on the water quality of the coastal zone and should be assessed. The strategic environmental assessment (SEA) process would also benefit from improved tools that interlink hydrological systems with transport and biogeochemistry, quantify attenuation and uncertainty and model downstream effects and processes.

Mitigating eutrophication

Effective mitigation must address external nutrient sources on land, combined with appropriate local/regional mitigation measures for internal nutrient sources/sediment. Several strategies for reducing internal sources are possible and have been proposed. There is a clear need to develop such technology, evaluate the feasibility and its effectiveness, combining experimental prototypes and modelling studies; adopting novel synergetic strategies and measures which have to be assessed and optimised. Such studies also require new tools for quantifying local to regional scale water flow, sediment and nutrient transport, coupled with ecosystem dynamic.

Technological development

Aeration of the sub-halocline waters using wave or wind energy, by enhanced mixing of waters from upper layers (oxygen rich) toward the halocline (oxygen depleted) or reversed. There is a clear growing interest for enhancing the filter function of the coastal zone for nutrients. The methodologies described above would provide novel tools for design of measures for enhanced efficiency of the coastal filter.

The ecological and economic potential for developers is huge, given that over 400 estuarine environments around the world suffer from permanent or temporal oxygen depletion, covering an area of more than 245,000 km^2.

Education

An important potential spinoff would be course programs using Nova’s facilities and framework, Äspö HRL and SKB experience as case studies, building on the experience within our KTH group with partners. The courses could address concepts and methods to effectively account for uncertainty within environmental, hydrological and coastal applications and modelling, directed toward students, researchers, active consultants as well as toward state agency and municipality employees working with environmental issues/regulation.

7.3.6 Integrated fire protection, the SAFESITE project

Aim of the project

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.

Status of the project

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 installation at Äspö has started to tests and study the conditions from blast and fire.

Spin-off

There is a great international and national interest from companies and organizations to follow the development of the SAFESITE project in Oskarshamn. Integration with the ALFAGATE 2 project and new commercial products and solutions.

7.3.7 Detailed fracture mineral investigations

Aim of the project

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.

Status of the project

A first part of the project has been to investigate calcite (Figure 7-9) precipitated in currently water conducting fractures at Laxemar, from which representative groundwater chemistry data exist. This has enabled a comparison to be carried out between the calcite and the groundwater, especially regarding the uptake of trace elements into calcite.

It therefore adds to the knowledge of trace element partition coefficients in calcite in natural granite systems – an understudied topic. This study is collaboration between Linnaeus University and University of Gothenburg and will be published in a scientific journal during 2012 and was presented at Goldschmidt Conference 2011.

Other parts of the project are in progress and include e.g.:

- Study of stable sulphur isotopes from currently water-conducting bedrock fractures at Laxemar in order to better understand depth and activity of past and present sulphur reducing bacteria in the bedrock aquifer. In situ stable isotope analyses will be carried out at NORDSIM in spring 2012 and the study will be submitted to a scientific journal in 2012. Collaboration involves e.g. SUERC, UK.
- Detailed chemical, isotopic and biomarker characterisation of calcite in fracture zones – on intra-crystal, intra-fracture, inter-fracture and inter-fracture zone scales from zones in granitoid fractures at great depth at Laxemar. Analyses in progress. Collaboration with University of Göttingen, University of Gothenburg, NORDSIM.
- Greenland analogue project; redox-studies from fracture coating samples. First sampling and analytical campaign finished and presented at Goldschmidt Conference 2011, second in planning. Collaboration with University of Helsinki and Conterra AB.

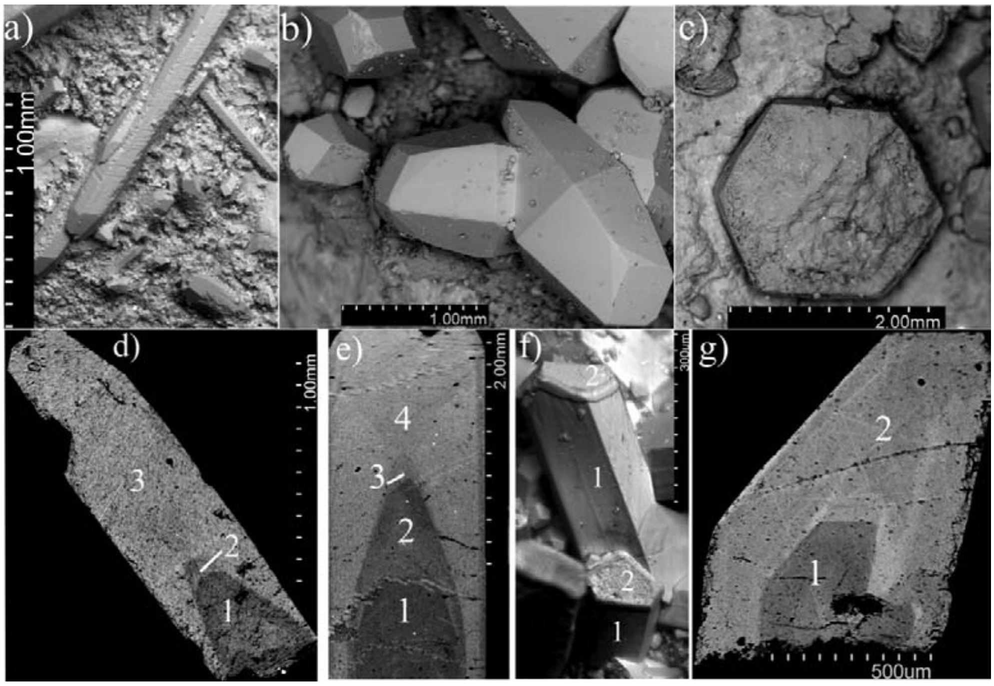


Figure 7-9. *SEM-images of calcite crystals from open fractures.*

Spin-off

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.

The results can be used as a reference and starting point for other detailed fracture mineralogical investigations and have a direct influence on the understanding of the long term stability and variability of groundwater chemistry at a site, as well as of hydrological and redox systematic in bedrock fractures. A spin-off can be that future investigations can use fracture mineralogy investigations in an applied way and well-grounded way.

Another spin-off effect is that the methodology evolved during these projects can be used at other sites as well, in a step-by-step analytical procedure established during these studies. A broad network of collaborations with laboratory expertise and other international experts in this field will, and has already been, established. The study of stable S-isotopes can also be of importance for other fields of research such as microbiology (microbe studies).

7.3.8 Expert group for the harbour remediation project in Oskarshamn

Aim of the project

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

Status of the project

Several expert meetings (Figure 7-10) have been held with the project leaders and personnel conducting the harbour remediation project. The expert group have reviewed the methodology, approach, monitoring program and documentation used within the project.

Figure 7-10. *The expert group supporting the harbour remediation project in Oskarshamn.*

Spin-off

The spin-off of the project is:

- Existing methodology technology is review and updated.
- This largest environmental project in Sweden attracts new competences to Oskarshamn.
- There is a potential to make the harbour remediation project to a demonstration site for the methodology used.

7.3.9 Hydrochemical interaction between a tunnel and its surroundings – development of prediction models

Aim of the project

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 hydro-chemical conditions will prevail during the construction, and operational phases of the facility.

Status of the project

During 2011 the project has comprised extensive field investigations at the Hallandsås tunnel project. Furthermore water sampling campaigns has been run at the Kattleberg tunnel project NE of Göteborg. The interpretations of the results are ongoing but generally verify effects in the groundwater quality due to construction works. The conceptualization of the resulting chemical processes and engineering implications are still treated.

The first steps in generic hydrochemical modelling have been taken. The model set-ups were based on real results from the Gårdsjö project database.

Initial contacts have been taken in order to collaborate with the project on corrosion protection of rock bolts at Äspö HRL. The project is run by Swerea KIMAB AB. There is a need for better understanding of the surrounding hydrochemical environment in the bolting project.

Spin-off

Research and development initiatives in the project will provide a basis for improving the content of environmental impact assessments in conjunction with underground projects.

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. The predictions provide a base for constructing safer tunnels with cost-effective maintenance.

7.3.10 Trace elements in fracture minerals and groundwater

Aim of the project

The main aim of the project is to characterize chemical and isotopic composition of fracture minerals and their enclosing bedrock in order to obtain better understanding of palaeohydrological conditions and the incorporation of microelements in the hydrothermal minerals. A minor part of the project is devoted to rare earth elements (REEs) speciation and calculation of different types of groundwaters with variable geochemical composition. Fracture minerals which are the subjected of investigation are from Laxemar-Simpevarp area and the groundwaters are from both Laxemar-Simpevarp and Forsmark areas.

Status of the project

The status of the work for the reporting period is: 1) The major part of geochemical/analytical procedures have been accomplished, which includes trace element analyses of bedrock and fracture minerals, stable isotopes $\delta^{13}C$ and $\delta^{16}O$ (in calcite) and $\delta^{34}S$ (in pyrite). 2) Part of the results has been processed, fractionation patterns and scatter plots of microelements for fracture minerals and bedrocks have been constructed. 3) Modelling of the REEs in underground was carried out with Visual MINTEQ 3.0 software and the results have been interpreted. 4) Additional isotopic analyses ($\delta^{13}C$, $\delta^{18}O$, $^{87}Sr/^{86}Sr$), U/Pb dating and fluid inclusion investigations in calcite will be carried out in the beginning of year 2012.

Spin-off

Spin-off from the project will lead to the better understanding of the nature of palaeo-hydrothermal solutions, mechanisms of the trace element incorporation in hydrothermal minerals and speciation of REEs in groundwater for granodiorite bedrock system. Outcome will be of particular interest for those who are working with trace elements in deep underground system and could be used as a reference. Some of the results from one of the ongoing project have been presented at the annual international geochemical conference, Goldschmidt 2011.

7.3.11 Corrosion protection of rock bolts

Aim of the project

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 fore 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 often within short time whereas the state of the parts in the bedrock 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 based on in situ conditions will be developed. The efficiency of available corrosion protection will be experimentally documented.

Status of the project

During the autumn, two tunnels, the Muskö road tunnel and Äspö HRL tunnel was selected as test sites for the exposure of rock bolts of different materials and with different corrosion protection.

Field exposure that began in October 2010 in Muskö tunnel and in December 2010 in Äspö tunnel included in total 166 rock bolts made of various materials and with various corrosion protection. Figure 7-11 shows an example of some embedded rock bolts of stainless steel.

There are in total 83 rock bolts per tunnel and 20 of them are exposed to scabs test. This means studs sprayed once a month with a 3% solution of sodium carbonate solution during one year, see Figure 7-12. An initial intake of both scabs-tested and non-scabs tested rock bolts will occur after one year of exposure (end of December 2012). The corrosion condition will then be evaluated visually and by measuring the corrosion rate by using mass loss measurements.

Figure 7-11. *Grouted rock bolts of stainless steel.*

Figure 7-12. *Mounted rock bolts in the Äspö tunnel are sprayed once a month during one year.*

At the release of the embedded rock bolts in the Muskö and Äspö tunnel the water content of each borehole will be measured. From some selected borehole water samples were collected for the determination of chloride content and conductivity. From the Muskö tunnel a mean chloride concentration of 4,060 mg/L was measured and at Äspö HRL the mean concentration of the groundwater was 11,900 mg/L.

In summary, the experiment with the embedded rock bolts has worked well. All test items have been delivered in time and the project is progressing according to plan.

Spin-off

The expected main result from the project will be a basis for rational selection of materials and corrosion protection measures for rock bolts and other products exposed to groundwater. In addition, experimentally verified specifications for the corrosion protection of rock bolts shall be prepared. Further consequences should be reduced investment and maintenance costs and a more efficient procurement process with better specifications.

7.3.12 Fossilized microorganisms at Äspö HRL

Aim of the project

The aim of the project is to search for and characterize fossilized microorganisms preserved in vein-filling minerals like carbonates and quartz in drilled samples from the Äspö Hard Rock Laboratory (HRL).

Status of the project

The project is in its initial stage. Samples have been assembled from various drill cores and thin sections as well as single crystals have been studied with optical microscopy and Environmental Scanning Electron Microscopy (ESEM). Putative fossilized microorganisms have been observed in some samples (Figure 7-13) and at the moment the biogenicity of these possible microfossils are being established with raman spectroscopy, and during 2012 probably also with ToF-SIMS as well. Initial analysis with raman has confirmed the presence of carbonaceous material which is a strong indication for organic remnants. The morphology of the microfossils suggests that they might be fossilized fungi (eukaryotes) rather than bacteria (prokaryotes), which is interesting from an ecological perspective and the diversity of the deep biosphere.

Isotope analyses have also been performed on minerals, like pyrite, associated with the microfossils.

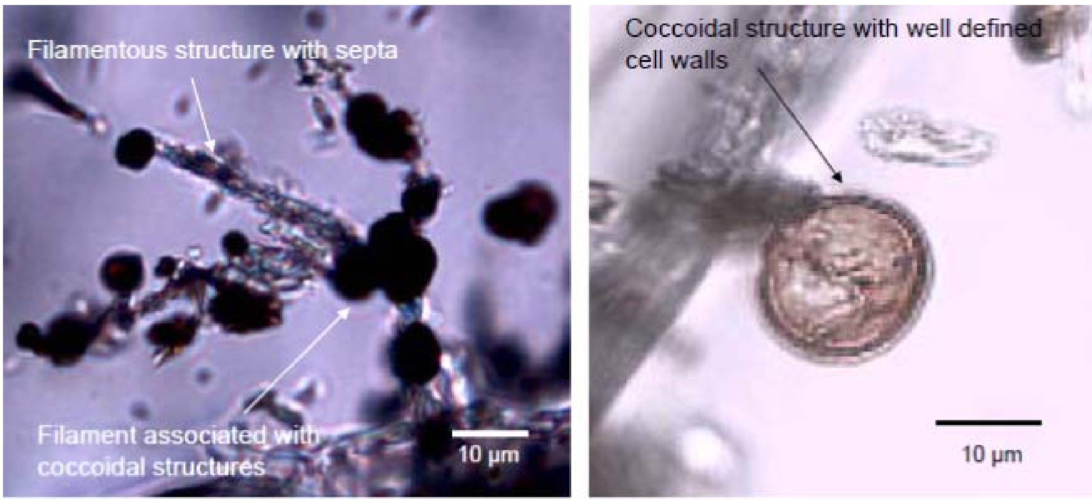


Figure 7-13. *Putative fossilized microorganisms in calcite.*

Spin-off

The outcome of this study will hopefully increase the understanding of microbe-mineral interactions of the deep biosphere at Äspö and increase our knowledge of the complexity of the deep ecosystems. The Äspö samples are part of an ongoing, more extensive study with the aim to develop methods and protocols to (1) distinguish between fossilized prokaryotes and fossilized eukaryotes in geologic material and (2) to use microfossils as palaeo-indicators.

7.3.13 Topology of grain structures in fault gouge

Aim of the project

The aim of the project has been to investigate the shape and size characteristics of gouge particles in borehole core samples.

Status of the project

During 2011 the proper measurements technique has been worked out and refined. It become obvious that the most interesting grains was found only below, roughly, 100 nano-meters. This meant that the originally planned x-ray tomography was not sufficient, and others techniques had to be tested. Finally it was revealed that only electron-microscopy was the method with sufficient resolution. Using mainly this technique it has now been established that nearly spherical particles from spontaneously in fault gouge on length scales below 100 nm. This is consistent with an exotic mathematical theory which demonstrates that it is possible to form space-filling structures with extremely low, or zero, shear stiffness. Within this project it has now been established that such structures may indeed form spontaneously in nature, and are not just theoretical constructions.

Spin-off

This finding which still needs a lot of elaboration may significantly alter our fundamental understanding of tectonic mechanics.

7.3.14 KLIV (Climate-land-water changes and integrated water resource management) – KLIV Intro as a pilot study to KLIV Demo

Aim of the project

Numerous water resources (lakes, streams, coastal waters, groundwater etc) are currently in less than good chemical and/or ecological condition. Restoring these waters to good condition and maintaining an acceptable status is one of the most pressing environmental challenges of today. This importance has led to the adoption of different water policies, including the relatively recent EU Water Framework Directive (WFD). However, the WFD implementation would benefit from better communication and interactions between the scientific community in the water resource area and various governance and management levels of water management. In addition, within research itself, there are considerable gaps that need to be bridged in our understanding of the main drivers and effects of hydrological-hydrochemical interactions and changes, and their water resource and pollutant load implications.

The KLIV project investigates critical questions regarding the improvement and sustainable management of water resources. General aims are to provide answers to such questions as: what has been and will be the temporal development of water flow and pollutant loading and why, what combined measures taken in the landscape can actually make a significant difference in reducing pollutant loads, and when should detectable improvement effects be expected? Based on these answers, with main geographical focus on coastal regions, KLIV also aims to develop decision-supporting methods and tools that can guide strategies for successful monitoring, pollution mitigation and change adaptation in sustainable water resource management.

KLIV constitutes an inter-disciplinary research environment in cooperation with a consortium/network of stakeholders from water authorities, municipalities, interest organizations, etc. An additional aim of the project is to utilize this network for facilitating relevant knowledge exchanges and practical use of new research-development results.

Status of the project

KLIV was accepted as a NOVA FoU project in early 2011, with a funding from Nova and Nova FoU. The core participants of KLIV have met four times (Figure 7-14). The project leaders have met with several stakeholders outside of the group to develop the stakeholder network, which has led to participation in joint funding applications with the Kalmarsunds commission and with the Regional Council in Kalmar County, for which decisions are still pending. In addition to several already ongoing and KLIV- supporting research projects of the different KLIV participants, the participants have also during 2011 started to join in formulation of new KLIV-project proposals, with new funding not yet received from such proposals.

Spin-off

Spin-offs are expected in terms of development of a NOVA- and Äspö HRL based virtual KLIV centre for research on sustainable water resource management, planned to start in 2012.

7.3.15 Fracture flow characterisation: Correlation of effective hydraulic conductivity and scan-line density of flowing fractures

Aim of the project

The aim is to explore the relationship between the effective hydraulic and the density of flowing fractures.

Status of the project

The project is at a data-analysis and write-up stage. The key data analyses are shown in Figure 7-15 and the results can be summarized as follows.

Previously, the possibility of estimating effective hydraulic conductivity from the density of flowing fractures was established from numerical simulations. Here, borehole log data, from Äspö, Sweden, are examined to further explore the relationship between effective hydraulic conductivity and the density of flowing fractures, and to characterize the fracture flow system. For the twelve selected boreholes, we examine the frequency distribution of the total fracture density as well as the density of flowing fractures. This enables us to estimate the connectivity strength of the flow paths. The analysis shows that both the connectivity strength of flow paths and the magnitude of fracture transmissivity decrease with depth. This can be explained by increasing proportion of close fractures as the compression stress increases with the depth. The proportion of fractures that control flow paths across the domain (connectivity strength) is low (less than 0.05). This, together with a power law distribution of fracture transmissivity, could be an indication that flow is controlled by a few large fractures.

Figure 7-14. *KLIV project meetings are used to plan the scientific requirements in future water resource management.*

From a perspective of modelling flow processes, the underlying fracture geometry can be based on a few large fractures. The analyses show that the effective hydraulic conductivity is not only a function of the density of flowing fractures but of the aperture distribution as well.

However, it remains a challenge to obtain representative measurements of the aperture distribution within a single fracture. This therefore shows that the problem (of relating effective hydraulic conductivity with the density of flowing fractures) is undetermined, as it will require information about the average fracture aperture.

Spin-off

The results provide some insight into the conceptual model for flow simulation in that the data seem to show that the flow processes can be estimated on the basis of a few large interconnected fractures. It seems possible that the fractures can be determined explicitly. Profiles of fracture density distribution along boreholes provide some insight into the propagation of fracturing and may indicate zones of different rock strength.

7.3.16 Documenting long-term biological and chemicals consequences of increased water temperatures in the Baltic Sea associated with global warming before they have happened

Aim of the project

Global warming is the unusually rapid increase in Earth's average surface temperature over the past century primarily due to the release of greenhouse gases associated with human activities. Models predict that greenhouse gas concentrations will continue to rise, and that average air, surface and water temperature will rise with them.

The aim of this project is to contribute with increased knowledge of long-term biological and chemical consequences of elevated temperatures, with particular emphasis on marine environments.

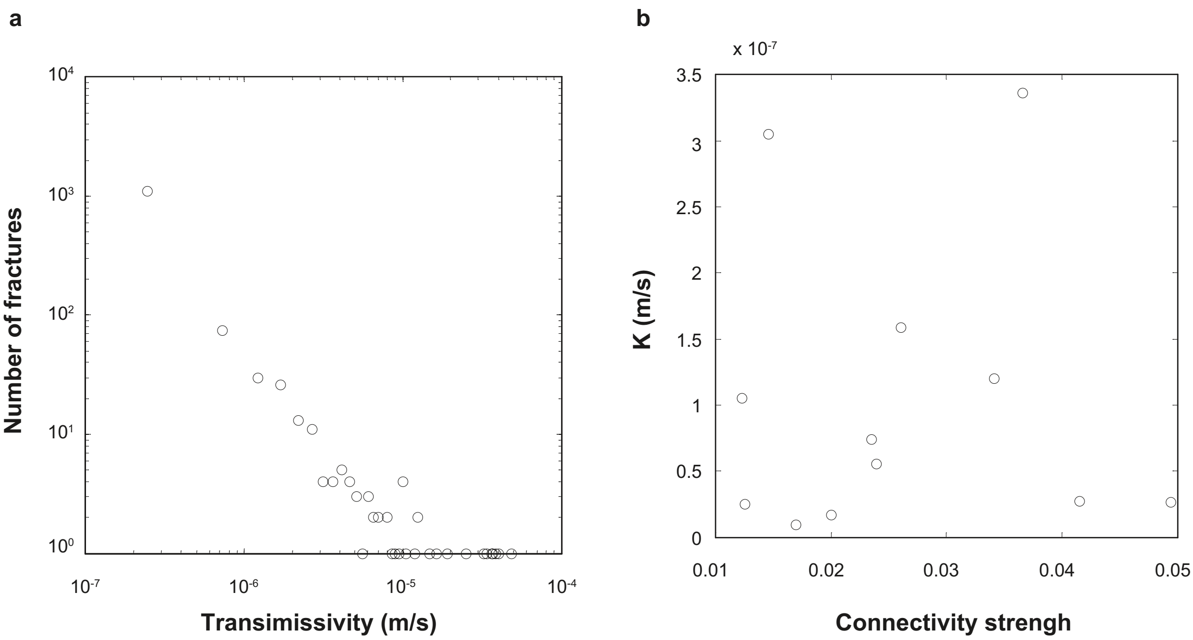


Figure 7-15. (a) Log-log discrete fracture transmissivity distribution for all the flowing fractures. The distribution can be modelled with a power law. (b) Effective hydraulic conductivity against connectivity strength. Both (a) and (b) would indicate that the flow processes can be modelled on a fracture geometry that is based on a few long and interconnected fractures.

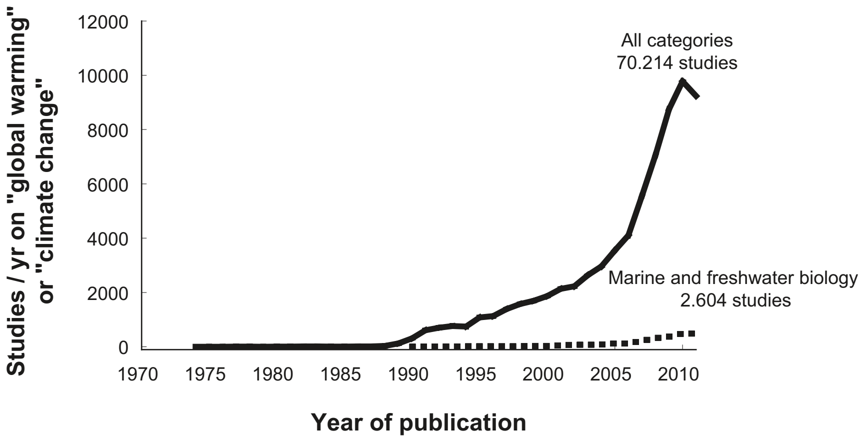


***Figure 7-16.** Trends in research output on global warming across all disciplines (filled line) and for marine and freshwater biology (dotted line). Figure shows number of publications per year and is based on data extracted December 22, 2011, from Web of Knowledge, Thomson Reuters.*

Status of the project

The status of this ongoing project for the reporting period is that we have outlined the framework and design for a review of published studies that will be performed in order to summarize and describe general patterns in past research with regard to perspectives, methodological approaches, and the type of systems and organisms that have been studied to date.

The major results of this recently initiated project are that: (1) across all disciplines and categories the number of published studies concerning global warming and climate change totals more than 70.000 (December 2011), (2) publication rate has increased from less than 10 papers per year prior to 1985 to about 10,000 papers per year in 2011; and (3) the number of studies that concern global warming and climate change specifically within the field of marine and freshwater biology has increased at a relatively slow rate, and currently amounts to about 2.500 studies (see Figure 7-16).

We will continue with more in-depth analyses of a subset of the available studies to identify knowledge gaps and fruitful lines of future investigations. We also intend to conduct an inventory of past base-line studies and ongoing monitoring programs, investigations and data bases associated with emissions of heated cooling water from the power plant at Oskarshamn, investigate how to obtain access to existing data, and evaluate how available data may be used to address crucial questions.

Spin-off

The spin-off effects from the project will be: (1) identification of biases and limitations in previous global warming research and associated gaps in current knowledge, (2) improved ability to design future investigations that will generate 'missing' data necessary to help fill existing knowledge gaps and (3) increased understanding of the consequences of increased water temperatures associated with global warming. Ultimately, an enhanced knowledge and understanding of biological and chemical consequences of increasing water temperatures may help protect biodiversity and be used within applied contexts, for instance by suggesting routes to alternative energy production and increased yield in aquaculture.

7.3.17 Waste heat for greenhouse production

Aim of the project

The general aim of the study is to develop competitive technology and production systems for greenhouse cultivation where waste heat from industrial processes is used to decrease energy costs and environmental load.

Specific aims of the project are:

- to gather, put together and compile the current knowledge in the area,
- to identify knowledge gaps suitable for a research cooperation between Swedish University of Agricultural Sciences (SLU) and Oskarshamn,
- to develop a working plan for continued work with sustainable technologies and cultivation systems,
- to create a suggestion of design of a pilot construction where innovative technology is used,
- to describe and formulate applications for funding of future projects.

Status of the project

Planned activities in the project include:

- An inventory of present technology suitable for making use of waste heat in greenhouse cultivation and also fish growing in greenhouses. This inventory will include (1) a deep literature study, (2) study visits to relevant industrial and research institutions in Sweden, and also abroad. A preliminary assessment suggests that Germany (Leibnitz Universität, Hannover), Finland (MTI/VTT) and the Netherlands (Wageningen UR) are interesting organisations to visit since they are in the front of the research.
- An inventory of possible national and international cooperation partners, and a compilation of their research regarding energy technology, technological systems, cultivation systems and also the market.
- Check up on the interest of the business category in question to establish a commercial cultivation/growing operation and in specific their interest for a pilot construction greenhouse operation in the Municipality of Oskarshamn. This will be achieved by inviting local entrepreneurs.
- Development of a plan of action for future work within the area regarding (1) development of a larger joint research application concerning relevant research areas. This includes a description of future research cooperation between Oskarshamn and SLU, Alnarp and possibilities to engage an industrial PhD student in cooperation, (2) draft description and suggestion of a pilot greenhouse construction in commercial scale.

The project was approved in the later part of the autumn 2011 and the literature study and planning of interesting study visits has begun. Strategies for identification of possible technology for using waste heat include climatization technology in combination with properties and design of cover materials, dynamic climatization and insulation as well as storage of heat.

Spin-off

Possible spin-off effects are:

- Reduced costs for greenhouse operations having access to industrial waste heat leading to establishment of a number of greenhouse operations for cultivation and fish growing using waste heat from industrial processes which creates more jobs.
- Less environmental load from greenhouse production since waste heat is used.
- Establishment of a pilot construction greenhouse operation using waste heat in the Municipality of Oskarshamn for demonstration of technology and for research.
- Intensified research concerning energy conservation in greenhouse cultivation and fish growing in greenhouses leading to further improvement in energy efficiency and environmental load and further development of systems.
- Further cooperation between Oskarshamn and SLU in a number of areas.

7.3.18 Structure and function of biofilms in the deep biosphere

Aim of the project

Microorganisms proliferate as biofilms on rock surfaces and aquatic environments in the deep biosphere. Cells in the biofilms alter the geochemistry of the environment via processes such as oxidation/reduction reactions that are important for e.g. scientific, environmental, ecological, and technical use. In this study, biofilms will be investigated to link their metabolism to the chemistry, geology and hydrology of the deep biosphere.

Studying deep sub-surface biofilms will achieve the following goals:

- Identify the biofilm microbial community and 3-dimensional structure in the Äspö HRL.
- Link the microbiology of biofilms to the observed chemical and geological transformations to create a model of the deep biosphere.
- Utilize the data for biotechnological applications for the final deposition of nuclear waste.

Status of the project

The project is in the start-up phase and a preliminary sampling of microorganisms has been taken from the Äspö tunnel. The total genomic DNA in the sample taken from the tunnel was extracted and evaluated for its quantity and quality. Lessons have been learned that will now be utilized in extraction and preparation of large amounts of DNA for complete genomic sequencing of the DNA (a "metagenome"). In addition, a technique for preserving the 3-dimensional structure of biofilms has been tested at a different site that will also be employed at Äspö HRL.

The next phase of the project will be to access biofilms within the Äspö HRL and prepare DNA for sequencing and biofilm samples for microscopic imaging.

Spin-off

The project will provide a systems biology investigation of the microorganisms present in the deep biosphere at Äspö HRL. From this, an analysis of the microbial populations present and their metabolic and functional potential can be inferred to begin the process of linking the microbiology of the deep sub-surface environments to the geochemistry.

Researchers will be able to utilize all the generated results as the sequencing data will be deposited in the publicly accessible NCBI database.

The research will be applicable to the nuclear energy industry where several other facilities are under investigation for deep sub-surface final repository of nuclear waste, including Olkiluoto, Finland. Sweden is world leading in relation to the final deposition of nuclear waste and attracts interest from around the world due to the progress that has been achieved. The majority of microbiological studies on radionuclide transport and biotransformation have been carried out in the laboratory, with little research on in situ systems. In addition, to fully understand the chemical patterns and dynamics of hydrological active bedrock fractures, it is of importance to couple mineralogy, hydrochemistry and microbiology. Whereas in previous and ongoing studies there has often been large effort to integrate fluid chemistry and fracture-mineral assemblages, there is a need for more extensive and in-depth studies regarding the interaction of the living world (microorganisms) and inorganic chemistry (groundwater and minerals etc.) in fractures at depths down to at least half a kilometre. In many cases, quantitative appraisals of microbial processes are not included in the evaluation of the long term storage of radionuclides in the deep sub-surface. This is potentially due to the 'biological' aspect that requires detailed understanding of the microorganisms present (especially the uncultivable portion) and quantification of factors such as availability of growth substrates, doubling times, metabolic reactions and DNA transfer.

The data will also be of great use to the research community interested in the deep biosphere as it will generate sequencing data for which there is geochemical monitoring of the site stretching back for many years. The interested researchers will include those involved in bioinformatics, microbiology, virology, ecology and hydrologists as it will provide a completely unique data set from several research disciplines.

7.3.19 Pre-study for sediment mining and remediation in Oskarshamn harbour

Aim of the project

The aim of the project is to carry out a pre-study towards a broad research proposal that will involve Postdocs, PhD students together with Master and under-graduation students as well. The pre-study is initiated to bring a theoretical background and proposal for an extensive research project that will generate knowledge and support to decision-makers on the selection of innovative, economical and environmentally sound ways (beneficial use) to tackle contaminated sediments in harbours and to see it as a potential resource. The main idea of the broad research and education project to be proposed in the near future by the Environmental Science and Engineering group (ESEG) is to use the Oskarshamn harbour as the main site of investigation and a teaching object in connection to the sediment remediation program to start in the year 2012.

Status of the project

During the two month period of the project, a database containing high-level scientific literature within a broad range of subjects related to contaminated sediments was created including literature regarding: (1) sediments contamination/chemistry, (2) sediment sampling, handling, quality assessment and characterization, (3) sediments toxicity tests and toxicity identification evaluation methods, (4) sediment quality guidelines, (5) bioaccumulation and bioavailability mechanisms and evaluation in lab-scale, (6) the use of hydrodynamic models coupled to transport/dispersion/fate/exposure modelling, (7) ecological and human health risks due to contaminated sediments in harbours, (8) remediation techniques focused on biological and physic-chemical techniques, (9) metal extraction and recovery techniques with focus on chemical and bioleaching processes, (10) Baltic sea most common problems in harbour/port areas due to contaminated sediments, (11) dredging technologies and operational aspects and (12) following-up of remediation projects in order to monitor changes and/or improvements in the remediated area.

Spin-off

Based on preliminary results obtained from the pre-study it can be stated that research investigations concerning harbour sediments contamination and remediation/recovery methods can bring to Linnaeus University possibilities of applying for 3–4 PhD students to be involved in the project in the near future. The broad literature survey obtained during the current pre-study has been used to line up PhD projects and to prepare major research applications to different sponsors including the EC Bonus 169 programme, KK-Stiftelsen, STINT and others. Assignments for the MSc students in the course Industrial Ecology related to Oskarshamn harbour have already been initiated and will be carried out during February and March 2012.

The PhD studies to be proposed in the future have the objective to bridge existing gaps and bring a better understanding regarding:

- Cost-effective remediation techniques considering environmental, ecological and technical aspects with the focus on persistent/recalcitrant compounds such as dioxins, PCBs, PAHs, TBT etc.
- The feasibility of new and innovative extraction/mining techniques of valuable contaminants from sediments for beneficial use (Cd, Cu, Zn, Ni, N, P, Co, As etc).
- Eco-toxicological effects based on tests with different test organisms (resident organisms is expected) considering the magnitude, the duration and frequency of exposures.
- Scientific-based methods to support decision makers in following-up remediation/recovery projects in terms of stressor/effects relationships, criteria for bio-indicators, the use of hydrodynamic models to support post-remediation monitoring etc.
- Knowledge on how/when dredging should be carried out and which technology is preferable to avoid transport and dispersion and reduce exposure of different aquatic organisms.
- Knowledge regarding the use of hydrodynamic models combined with models of transport/dispersion of contaminants to predict the fate of specific pollutants during dredging procedures in different site-specific conditions.

7.3.20 Participating in the FP7 project PETRUS II

Aim of the project

Linnaeus University will give the EU master course "Geological storage in Precambrian bedrock" by using Äspö HRL as a "class room". This is done in cooperation with other members in the EU project PETRUS II.

PETRUS II is an EC (European Commission) project with the objective of ensuring the renewal, continuation and improvement of professional skills in the field of radioactive waste disposal by building suitable frameworks for implementing and delivering sustainable training programmes. A total of 7.5 study credits will be given for the Swedish course.

Status of the project

PETRUS II has come to an end and the work-packages have been delivered. The final meeting for PETRUS II was held in Nantes on the 10th and 11th of January 2012. The Consortium decided to apply for a PETRUS III program, consisting of an implementation of the proposed education programme in PETRUS II. The Consortium decided on a smaller team, working with the new application, consisting of participants from Sweden, Finland, Spain and France. The team will start this work in the last week in January 2012. Planning meetings in Sweden will be held to be able to give the training course in September 2012 at Äspö.

Spin-off

The students on the course are from the countries in Europe which in a near future have to manage nuclear and radioactive waste. The training course at Äspö will market Oskarshamn and Äspö HRL as a demonstration site for handling of spent nuclear fuel.

7.3.21 Alfagate 2 – RFID wireless- WIFI integration in extreme environmental conditions

Aim of the project

The aim is to develop and apply RFID (Radio Frequency Identification) wireless WIFI integration in extreme environments to identify persons or objects (Figure 7-17). The project creates an open software structure which will be integrated and tested with other Äspö HRL systems. This will be used for safety purposes and to increase process or production efficiencies. The project partners are involved in the oil, gas and mining industry which also have similar needs and requirements.

Status of the project

We are in the start-up phase of the project. The project objectives for RFID 2 are to improve and develop the current technology together with the project partner Identic Solutions.

Spin-off

To expand the company NEOSYS in Oskarshamn to be able to give service and support for the products/system in Sweden. This will mean new employments as an important spin-off effect for the region. Cooperation with international companies such as Identic Solutions, Siemens and Sisco are an important spin-off and several international companies can follow. Continuing development and testing of future technology to meet SKB:s present and future requirements for final disposal and in existing plants is an important spin-off.

Figure 7-17. *Possible applications for the RFID and WIFI technology.*

7.4 The Spin-off effects from Nova FoU work

Examples of spin-off effects from the Nova FoU projects to the society are:

- **University education:** Planned master's education in the field geological storage within the EU program PETRUS2.
- **Research education:** PhD and post doctoral education.
- **Research:** Water management in regional scale to decrease the pollution to the sea according to new EU directives. Understanding of the fundamental geochemical processes in groundwater.
- **Technical development:** New technology to trace people and objects in 3D.
- **Commercialisation:** Identification and commercialisation of existing SKB technique.
- **Environmental technique:** The use of waste heat from industrial plants. Scientific support to the remediation of the harbour in Oskarshamn.
- **Society:** Cooperation model for society when establishing new industry plants.
- **Development:** Support the further development of the SKB laboratories.

7.5 The Nova FoU progress

The Nova FoU plan for year 2011 aimed at 17 ongoing projects. The actual situation at the end of year 2011 was 23 ongoing projects and 23 initiated projects. A total of 80 researchers from 11 national and international universities and six companies have projects at Nova FoU. The project value for the approved Nova FoU projects where 50 million SEK at the end of year 2011. In cooperation with SKB a new research laboratory at Äspö HRL was taken in use (Figure 7-18) and new research niches in the Äspö HRL tunnel are under construction.

Figure 7-18. The new research laboratory at Äspö HRL.

7.6 The Nova FoU steering committee and personnel

The Nova FoU steering committee during 2011 consisted of representatives of SKB and the municipality of Oskarshamn, Nova and KTH according to:

Mats Ohlsson (Manager of the Äspö Laboratory, SKB and Chairman of Nova FoU Steering Committee).
Peter Wikberg (Research Manager, SKB).
Ann-Christin Vösu (Municipality Chief Executive in Oskarshamn).
Bengt Karlsson (Rector for Nova Center for University Studies, Research and Development).
Margareta Norell Bergendahl (Professor, Royal Institute of Technology, KTH).
Marcus Laaksoharju is the Chief coordinator for Nova FoU.
Anna Rockström was employed as administrator in September 2011.

8 International co-operation

8.1 General

Nine organisations from seven countries will in addition to SKB participate in the cooperation at Äspö HRL during 2012. Seven of them; Andra, BMWi, NUMO, 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. 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 cooperation 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.

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. SKB is actively involved in the European technology platform IGD-TP (Implementing Geological Disposal of Radioactive Waste Technology Platform) which was launched in November 2009. The platform´s vision is that by 2025 the first geological disposal facilities for spent fuel, high-level waste, and other long-lived radioactive waste will be operating safely in Europe. The platform currently involves eleven waste management organisations and in addition about 70 participants from industry, research organisations, research centres, academia, technical safety organisations and non-governmental organisations in Europe. Research in the Äspö HRL is foreseen to be an important part of the joint work in the platform during coming years.

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 this framework, the main interest 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 2011 in three major experiments: TBT, Lasgit and ABM.

8.2.1 Temperature Buffer Test and Task Force on Engineered Barrier Systems

Andra is especially involved in the Temperature Buffer Test conceived during 2002, started beginning 2003, dismantled in 2010 and has already produced major expected THM results. Temperature Buffer Test dismantling gave a large amount of sampled material. Information on the bentonite blocks mechanical behaviour has already been collected, the result mapping of final hydration state is available. With access to the data from the dismantling operation and sample analysis, the THM modelling of the field test has been re-assessed during the first half of 2011. Based on the results of laboratory analysis, reports on the dismantling operations, the THM results and the HMC analysis are following the approbation process. They should be available by summer 2012.

8.2.2 Large scale gas injection test

Lasgit is now integrated in the FORGE 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.

8.2.3 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.

We have no new results compare to 2010. We are waiting for the next dismantling phase planned in 2012.

8.3 BMWi

In 1995 SKB the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie signed the co-operation agreement being the framework and the basis for the participation of German research institutions in the R&D activities in the Äspö HRL. The first prolongation was in 2003 and 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 related to the Äspö HRL programme: Federal Institute for Geosciences and Natural Resources (BGR), Hannover, DBE TECHNOLOGY GmbH, Peine, Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Dresden, 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, esp., 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.

The work carried out in 2011 is described below.

8.3.1 Microbe project

Introduction

The contribution of HZDR to the Microbe Project is focused on investigating the interaction processes of selected actinides (U, Pu, Cm) with planktonic cells and biofilms generated by Äspö relevant bacteria. The study focuses on: (i) generation and characterization of planktonic cells and biofilms produced by the Äspö bacterium *Pseudomonas fluorescens*, (ii) interaction of selected actinides with planktonic cells and those fixed in a biofilm, and (iii) spectroscopic characterization of the formed actinide species.

The activities concentrated on investigating (a) the interaction of U(VI) and Cm(III) with planktonic cells of *P. fluorescens*, and (b) the continuation of experiments characterizing both the growth of *P. fluorescens* biofilms and the effect of the addition of U(VI) to these biofilms.

Interaction of uranium(VI) with Pseudomonas fluorescens planktonic cells investigated by potentiometric titrations

P. fluorescens could be characterized in terms of the surface functional group densities and the corresponding pKa values using potentiometric titration. Subsequently this method was success-fully applied for the determination of relevant U(VI) surface complexes and their stability constants.

P. fluorescens (CCUG 32456 A) was cultivated in nutrient broth medium (DSMZ medium 1a) at pH 7.0 and 30°C. Culture purity was ensured by light microscopy, plating and *in situ* PCR with subsequent RFLP using the restriction enzymes HaeIII, CfoI and RsaI, as described in Moll et al. (2012). Cells were harvested in the mid-exponential growth phase, washed three times in a solution containing 0.099 M NaCl and 0.001 M HCl and then suspended in the same solution for titrations of *P. fluorescens* only. In case of simultaneous titration of *P. fluorescens* and U(VI), the cells were washed and suspended in 0.1 M $NaClO_4$ and the pH was adjusted to 3 by adding $HClO_4$. For all titrations a [dry biomass] of 0.3 g/L was used. In case of simultaneous titration with uranium, [U(VI)] was set to 0.1 mM. The total titrated volume amounted to 40 mL. The titration was carried out manually under N_2 atmosphere in a glove box at 25°C. CO_2-free 0.042 M NaOH was used as titrant. The exact titrant concentration was determined by counter titration with standard 0.100 M HCl. Titration curves were evaluated using the program HYPERQUAD2008 (Gans et al. 1996). The U(VI) speciation in presence of the cells in dependence on pH was calculated with the program HySS2009 (Alderighi et al. 1999).

Data resulting from titration of solutions containing solely *P. fluorescens* were fitted using a three-site model. Calculated pK_a values and site densities of the binding sites were 4.65 ± 0.13 (0.82 ± 0.06 mmol/$g_{dry\ weight}$), 6.62 ± 0.13 (0.36 ± 0.09 mmol/$g_{dry\ weight}$), and 9.18 ± 0.02 (0.78 ± 0.24 mmol/$g_{dry\ weight}$). Comparing these values to the pK_a ranges of different functional groups reported in (Cox et al. 1999), the respective surface functional groups can be attributed to carboxyl, phosphate and amine moieties. The parameters determined for surface functional groups of *P. fluorescens* (CCUG 32456) are comparable to those obtained for another strain of this bacterium, *P. fluorescens* (ATCC 55241) (Yoshida et al. 2004).

In Figure 8-1 the titration curve of U(VI) with *P. fluorescens* and the fit with HYPERQUAD is illustrated.

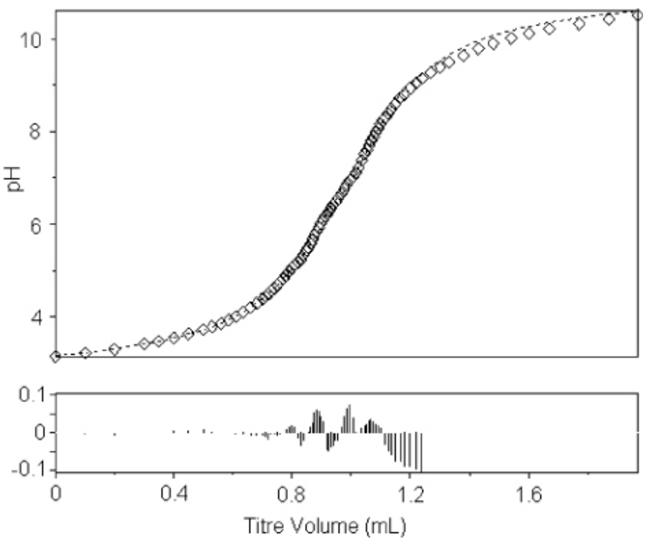


Figure 8-1. *Titration of 0.1 m M UO_2^{2+} and 0.3 g/L cells in 0.1 M $NaClO_4$ with 0.042 M NaOH. Data (◊), fit (---).*

Besides the determined pK_a values and site densities of the bacteria, the following hydrolytic uranyl species were included in the fit: $(UO_2)_2(OH)_2^{2+}$, $(UO_2)_3(OH)_5^+$, $(UO_2)_4(OH)_7^+$. Extracted U(VI) surface complexes and stability constants using HYPERQUAD are given in the following table.

Table 8-1. Calculated U(VI) surface complexes and stability constants.

Complex	xyz	log β (± SD)
R-COO-UO_2^+	110	6.66 ± 0.05
R-O-PO_3-UO_2	110	7.54 ± 0.18
R-O-PO_3H-UO_2^+	111	12.73 ± 0.06
(R-O-$PO_3)_2$-UO_2^{2-}	120	12.97 ± 0.07

Based on the calculated stability constants (Table 8-1) and the stability constants of relevant U(VI) hydrolytic species, a U(VI) species distribution in dependence on the pH (Figure 8-2) was calculated for a given [U(VI)] and [dry biomass]. This species distribution shows that complexation by cellular carboxylic groups plays a role over a wide pH range up to around pH 7. At pH 7 fully deprotonated phosphoryl groups are mainly responsible for U(VI) binding. If the pH is increased further uranyl hydroxides are the dominant U(VI) species in aqueous solution (in a CO_2-free system).

To validate the presented pH-dependent structural findings the evaluation of EXAFS data is in progress.

Curium(III) speciation studies with planktonic cells of Pseudomonas fluorescens

The goal of this work was a systematic study to explore the unknown speciation of Cm(III) with pyoverdin-free cells of *P. fluorescens* (CCUG 32456) by TRLFS.

TRLFS measurements were performed under N_2 atmosphere at 25°C. As a background electrolyte, analytical grade 0.1 M $NaClO_4$ was used. The Cm(III) concentration was fixed at 0.3 µM. In two runs, the biomass concentration was kept constant at 0.2 $g_{dry\ weight}$/L, while varying pH between 8.01.4 and 1.58.0, respectively. In two runs, the biomass concentration was changed at pH 3.05 and 6.08, respectively. Desorption studies were performed with 0.01 M EDTA solution (pH 5) as described in Panak and Nitsche (2001). TRLFS spectra were recorded using a unique pulsed flash lamp pumped Nd:YAGOPO laser system (Powerlite Precision II 9020 laser equipped with a Green PANTHER EX OPO from Continuum, Santa Clara, CA, USA). Further details about the laser system can be found in Moll et al. (2008).

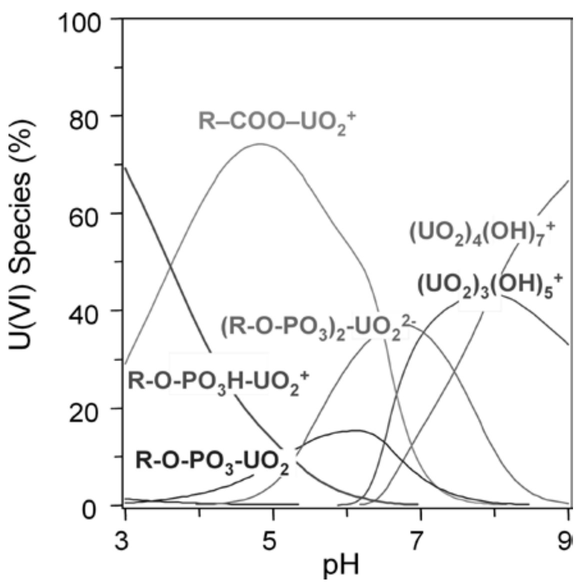


***Figure 8-2.** U(VI) species distribution in dependence on pH. [U(VI)] = 0.1 m M, [dry biomass] = 0.2 g/L.*

In aqueous solution, the emission bands of inner-sphere complexes of Cm(III) are generally red-shifted compared to the Cm^{3+} aquo ion (Figure 8-3). The spectroscopic speciation indicated strong interactions between Cm(III) and *P. fluorescens* cells. A strong decrease in the emission band of the free Cm^{3+} at 593.7 nm could be detected already at pH 1.43 and a biomass concentration of 0.2 $g_{dry\ weight}$/L. The dependencies found in the TRLFS spectra (Figure 8-3 B) suggested the occurrence of two Cm(III)-*P. fluorescens* species having emission maxima at ca. 599.6 (species 1), and 601.6 nm (species 2).

Within the investigated pH range, most likely bacterial carboxyl and phosphoryl groups are responsible for Cm(III) coordination on the cell envelope (Figure 8-4). Due to the strong inter-actions detected in the acidic pH region a protonated Cm(III) phosphoryl complex is likely to occur followed by a carboxyl complex at higher pH. The best fits were obtained with two 1:1 complexes, R-O-PO_3H-Cm^{2+} (log $ß_{111}$=12.7±0.6) and R-COO-Cm^{2+} (log $ß_{110}$=6.1±0.5). We extracted the cell-bound Cm(III) with 0.01 M EDTA solution (pH 5). Between 90 and 100% of the Cm(III) was released from the cells. These results show that the process is reversible and confirms the formation of surface complexes with functional groups of the cell envelope.

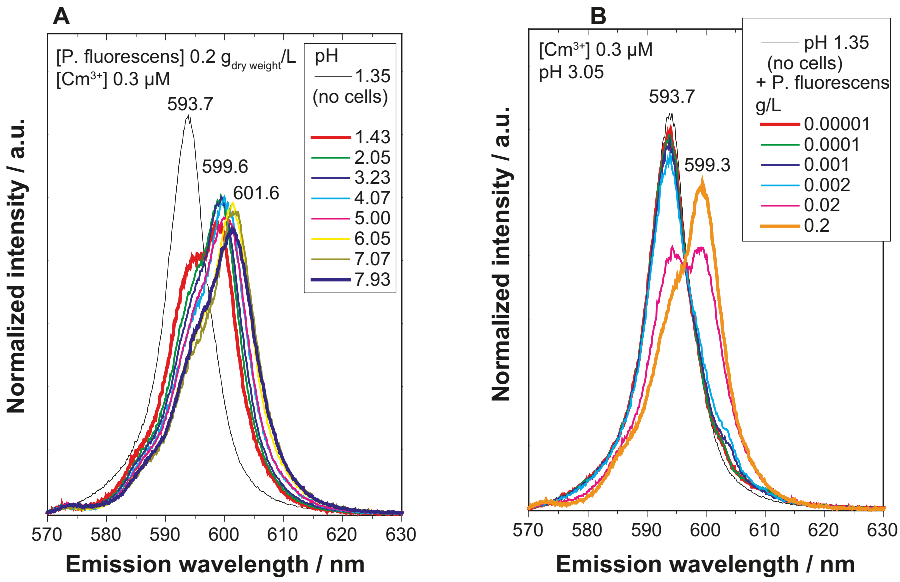


Figure 8-3. *Luminescence spectra of Cm(III) in 0.1 M $NaClO_4$ measured: A) as a function of pH at a fixed biomass concentration of 0.2 $g_{dry\ weight}$/L; and B) as a function of the biomass concentration at pH 3.05. The spectra are scaled to the same peak area.*

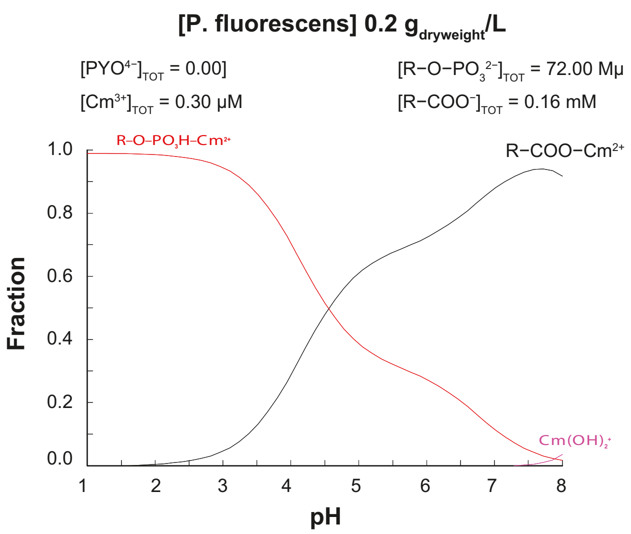


Figure 8-4. *Speciation of Cm(III) in aqueous solutions as a function of pH providing 800-fold (0.2 $g_{dry\ weight}$/L) excess of functional groups from the P. fluorescens cell envelope.*

To conclude, the biosorption studies showed strong interactions between Cm(III) and the cells already at low biomass concentrations of 20 mg/L between pH 3 and 8. Extraction studies with 0.01 M EDTA solution have shown that the biosorption of Cm(III) is a reversible process and the Cm(III) is bound by surface complexation. Two Cm^{3+}-*P. fluorescens* (CCUG 32456) species could be identified from the luminescence emission spectra.

The effect of uranium to Pseudomonas fluorescens biofilms

P. fluorescens (CCUG 32456) was cultivated in a synthetic nutrient medium consisting in 5 g/L peptone and 3 g/L meat extract with a pH 7 ± 0.2. In contrast to previous experiments, glucose was absent and the phosphate amount was low ($[PO_4^{3-}]$ = 12.7 mg/L). In the mid-exponential growth phase the culture was harvested and the optical density was adjusted to 0.2 at 600 nm. A volume of 3.6 mL of the *P. fluorescens* culture were added to 400 mL of the synthetic nutrient medium, kept in a glass plunger. The experiments were performed in air atmosphere under sterile condition. After three days a thin sterile biofilm has formed on the air/nutrient medium interface.

Geochemical and physical parameters of the biofilm were obtained by performing microprofilings by using microelectrodes. Concentration profiles of oxygen were measured in the biofilm by electrochemical microelectrodes of the micro-Clark design (Unisense, Denmark). The pH was measured using a miniaturized conventional pH electrode (PH-10, Unisense, Denmark) and the redox potential was determined by a miniaturized platinum electrode (RD-10; Unisense, Denmark). All of them were characterized by a very small tip diameter of 8–12 µm. The pH and redox potential electrodes were connected via a high-impedance millivoltmeter to a separate reference electrode (REF-50), an open-ended Ag/AgCl electrode with a gel-stabilized electrolyte (Unisense, Denmark). Since the oxidation reduction potential was measured, the values were corrected for the hydrogen electrode potential (+239 mV, after Cammann and Galster (1997). After the first measurements, U(VI) was added to the nutrient medium as 10 mM $UO_2(ClO_4)_2$ in ecologically relevant concentrations to a final U(VI) concentration of 0.1 mM. Further microprofilings were carried out after 48 h to determine the effect of uranium to the biofilm. The microsensor measurements of oxygen concentrations in the biofilm were recorded starting from the air/bio-film surface interface to the biofilm/nutrient medium interface. The results showed high concentrations of oxygen almost over the total thickness of the biofilm, which could be estimated to be 150–200 µm. The highest average oxygen concentration (220 µM) was determined at the top of the biofilm and decreased to 25 µM at the biofilm/nutrient medium interface. No oxygen was measured in the nutrient medium, below the biofilm (Figure 8-5).

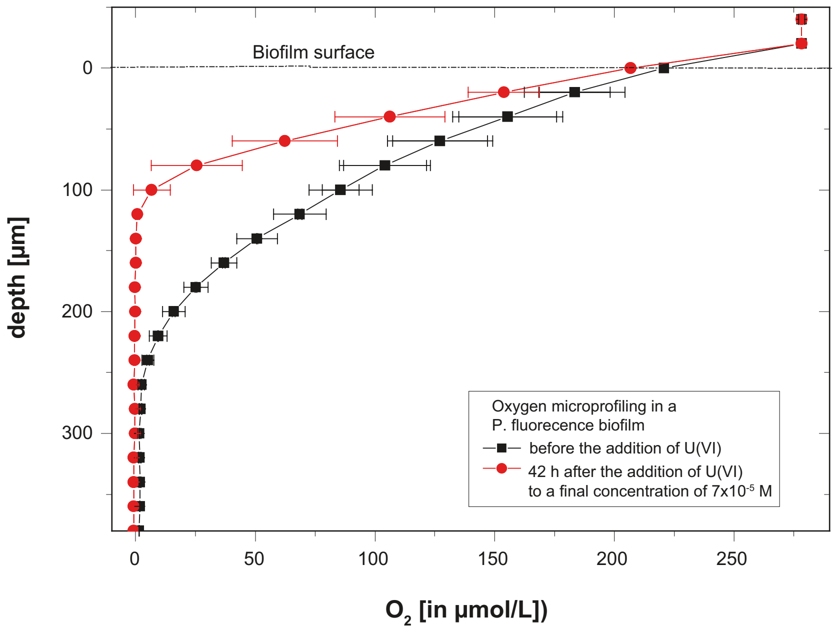


Figure 8-5. *Oxygen concentration profiles in the P. fluorescens biofilm before and 42 h after the addition of U(VI) to the nutrient medium to a final U(VI) concentration of 0.1 mM.*

After adding U(VI) to the nutrient medium, the oxygen concentration decreased faster from the biofilm surface to the biofilm/nutrient medium interface. The curve progression is relatively flat, so that already at a depth of approximately 120 µm the oxygen concentration dropped below the detection limit.

In staining experiments the fluorogenic redox indicator 5-cyano-2,3-ditolyl tetrazolium chloride (CTC) and the DNA-binding fluorochrome 4,6-diamidino-2-phenylindole (DAPI) were used to differentiate between respiring and non-respiring cells in the biofilm. Through confocal scanning laser microscopy (CLSM) examinations it became visible that the red-fluorescing CTC reducing bacteria were predominant (Figure 8-6). They were easily distinguishable from the total bacterial density, which were imaged via counterstaining DNA with DAPI and appeared blue. Since only actively respiring bacteria contain the red fluorescent CTC-formazan, our experiments indicated a significant higher respiratory activity of the bacteria after the addition of U(VI). This is a response and a prompt reaction of the bacteria on the addition of U(VI).

During the experiments 0.045 mM uranium (45%) was immobilized. To clarify if uranium was immobilized by the biofilm or if it was sorbed by the components of the nutrient medium, the analytical data for the nutrient medium after U(VI) addition were used to thermodynamically calculate the predominance fields of various uranium species at 25°C.

A pH–Eh diagram was constructed using the geochemical speciation code Geochemist's Workbench, version 8.0.12/Act2 (Figure 8-7). The database used was the thermo.dat accompanying the code, supplemented by the most recent NEA database for aqueous uranium species and by solubility data for the minerals uraninite and $CaUO_4$ (Guillaumont et al. 2003), and for the aqueous species $UO_2(H_2PO_4)H_3PO_4^+$ and $UO_2(H_2PO_4)_2$.When plotting the measured pH and Eh values in the pH–Eh diagram, which were measured in the nutrient medium after adding uranium, the formation of the aqueous uranyl dihydrogen phosphate species is predicted (Figure 8-7). Consequently, the results indicate that U(VI) was removed from the nutrient solution and immobilized in the biofilm. In further studies, e.g. energy-filtered transmission electron microscopy (EF-TEM), electron energy loss spectroscopy (EELS) and X-ray absorption spectroscopy, prove will still be performed. In addition, time-resolved laser fluorescence spectroscopy (TRLFS) will be used to confirm the formation of aqueous uranyl dihydrogen phosphate species in the nutrient medium.

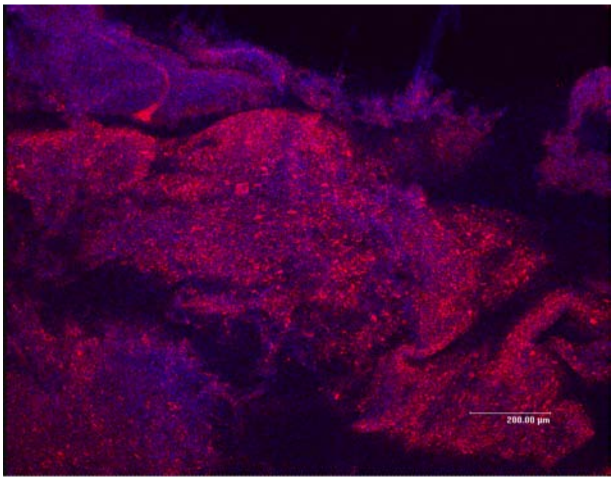


***Figure 8-6.** Confocal laser scanning micrograph of CTC reducing, actively respiring bacteria in red and counterstained cells (with DAPI) in blue of a P. fluorescens biofilm after addition of U(VI) to the nutrient medium.*

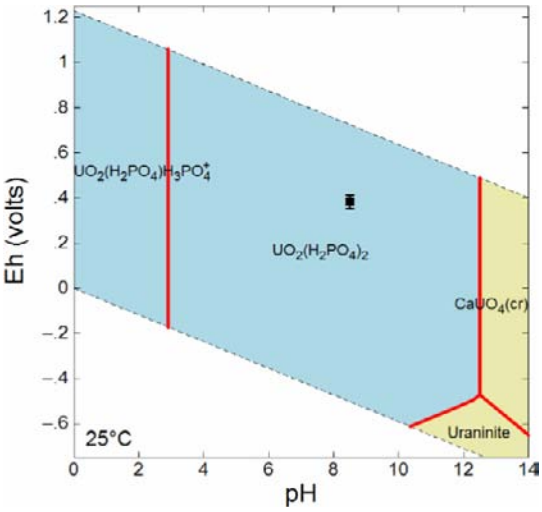


Figure 8-7. ph-Eh predominance diagram for the uranium contaminated nutrient medium after thermodynamic calculation using the geochemical speciation code Geochemist´s Workbench Version 8.0.12/Act2. The plotted pH and Eh data (including error bars) correspond to the measured values in the nutrient medium.

8.3.2 Prototype repository

In the Prototype Repository Project electric resistivity measurements have been 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. The measuring programme included 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.

In 2011, Section II of the Prototype Repository has been excavated and the canisters have been retrieved from the deposition holes 5 and 6. As a consequence, the geoelectric measurements have been reduced to measuring the backfill array in Section I. From the results, the section can be regarded as fully saturated; a region of slightly increased resistivity has, however, evolved during the last years close to the tunnel roof in this section. This is explained by a slight desaturation or a settling of the backfill, which resulted in a degradation of the electrode coupling. Such behaviour could have been induced by the continuous pumping of water out of section I.

BMWi is now partner in the project "Retrieval of the Prototype Repository at the Äspö Hard Rock Laboratory". In 2011, the work consisted mainly of following the excavation of Section II and attending the respective project meetings. As soon as samples of the electrodes (as far as they could be retrieved), the backfill, and the buffer are made available, laboratory testing will be performed by BGR and GRS, addressing following issues:

- Analysis of buffer material from the deposition holes for identification of mineralogical changes, changes in cation exchange parameters, and detection of possible secondary Cu corrosion products (BGR).
- Electrodes check for corrosion, cable breaches, and contact to the bentonite (GRS).
- Testing of buffer and backfill samples from the regions of the geoelectric measurements for water content and resistivity to confirm the tomography results (GRS).

8.3.3 Alternative buffer materials

BGR´s work in 2011 comprised the following: All chemical and mineralogical results of ten different ABM blocks produced from ten different bentonites were summarized in a scientific manuscript which at the end of the year was submitted to the Journal of Applied Clay Science (Kaufhold et al. 2011).

The main result of the study is that the different bentonites significantly varied in their reactions. Some showed Fe accumulation at the metal-clay interface, others not. Only in some instances anhydrite precipitation was observed. The Mg accumulation at the metal-clay interface, which was already observed in other projects as e.g. the LOT, is probably related to the formation of trioctahedral domains of the smectites. Interestingly, cristobalite occurring in some bentonites was dissolved near the metal-clay contact.

Still one of the fascinating results of the experiment is the fast and apparently far reaching cation exchange of all blocks, i.e. the population of the exchangeable cations in the interlayer was found to be more homogeneous in the analysed blocks compared to the rather heterogeneous cation exchange population before starting the experiment (Figure 8-8).

No horizontal gradients (perpendicular to metal-clay interface) of the type of exchangeable cations within the different blocks were found (Figure 8-9). Yet the project proved the importance of accurate measurements of the exchangeable cation population. Existing methods, however, are of 1) unknown precision if different laboratories studied the same clays and 2) of partly questionable accuracy if the clays studied have un-favourable mineralogical compositions. Therefore, to be able to assess the quality of results obtained by different methods and different laboratories, in 2010 BGR and SKB initiated a ring test for evaluation of cation exchange capacity (CEC) and exchangeable cation values which was conducted and interpreted in 2011. Results of this study now provide the possibility to properly assess the measured values. Moreover, two scientific manuscripts about the ring test results were submitted to Clays and Clay Minerals.

8.3.4 Temperature buffer test

After the THM-simulations with FLAC (Itasca 2000) have been completed, DBE TECHNO-LOGY GmbH intends to develop a calibrated discontinuous model for the geotechnical barrier material bentonite. Recently, a methodology for simulating the thermo-mechanical behaviour of claystone by applying the discontinuous numerical code PFC (Particle Flow Code) has been developed. A calibrated model for Opalinus clay as a host rock is already available. A corresponding model for the compacted buffer clay "bentonite" still needs to be developed.

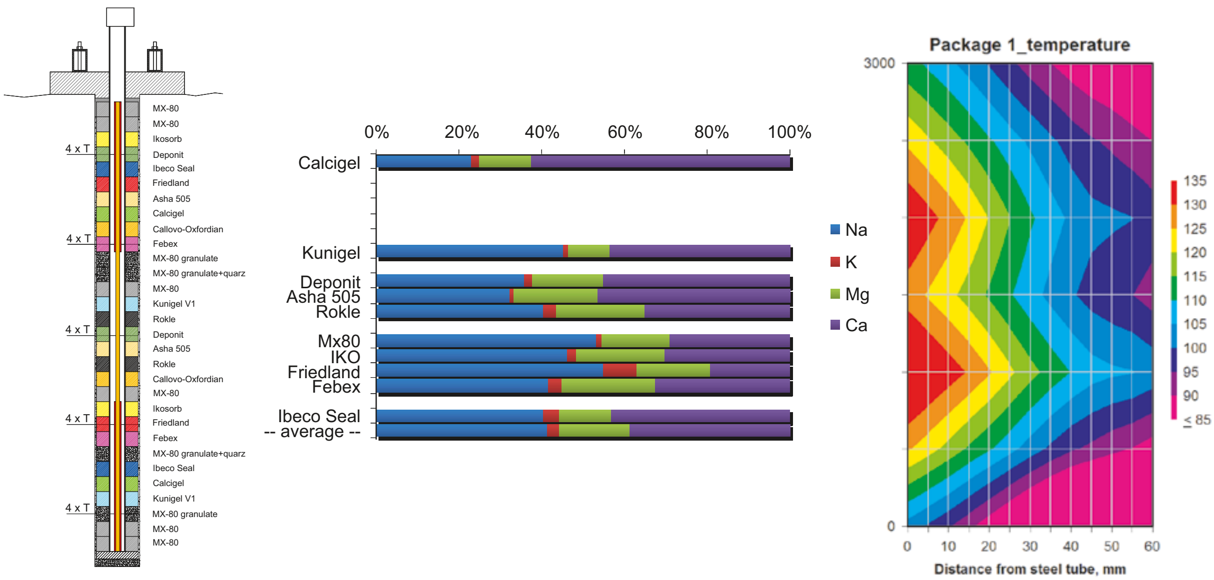


Figure 8-8. *Cation exchange population of clay blocks after retrieval of the first package. Initially the cation distribution was much more heterogeneous particularly for sodium and calcium.*

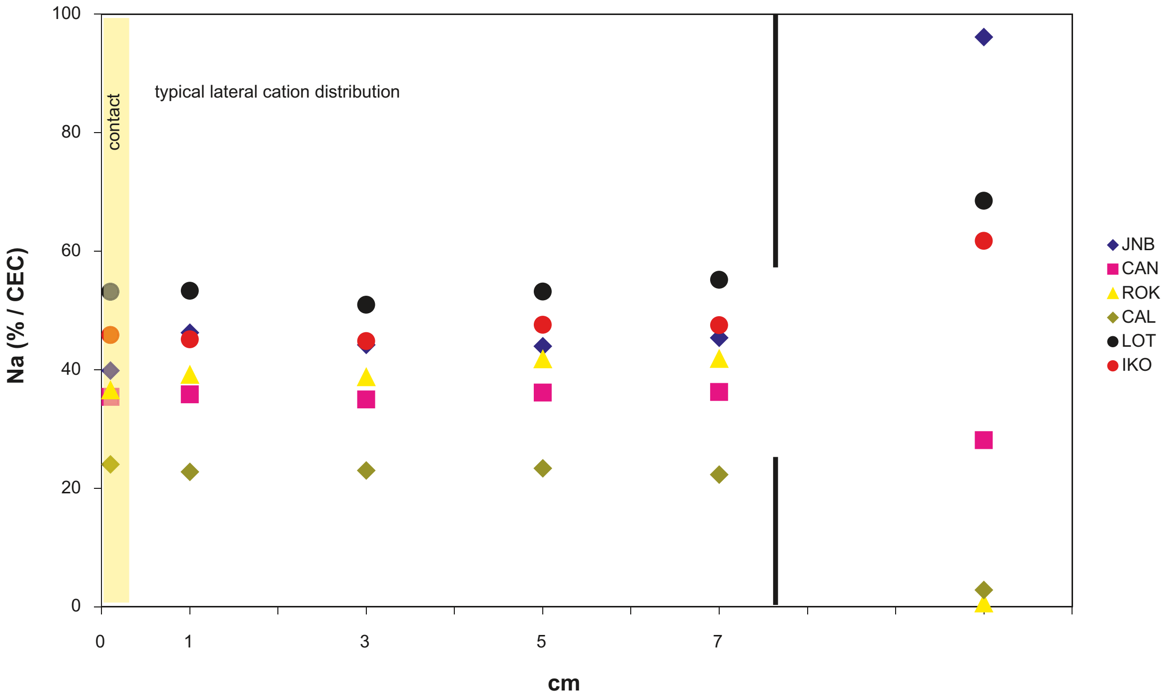


Figure 8-9. *Typical lateral exchangeable Na^+ distribution after retrieval of the first ABM package (in % of the CEC, = %/CEC); values of different block are shown. On the left side (0 cm) is the contact between clay blocks and the steel heater. Values on the right of the dashed line are reference values of the starting material.*

Monitoring data regarding temperature and pressure evolution within the bentonite buffer obtained during the Temperature Buffer Test together with the available simulation results were used to check the possibility for developing a calibrated discontinuous model.

The Particle Flow Code (Itasca 2008) is based on the distinct element method (Cundall and Strack 1979) and can be used to study rock behaviour by building particle assemblies and checking the breakage of bonds under stress. Rocks are modelled by spherical particles of varying diameters bonded together to simulate intergranular cohesion. The "parallel bond" used is assumed to be-have as a cylindrical piece of material with a finite radius, connecting two discrete elements that can break apart if the normal stress or the shear stress inside the bond exceeds its normal or shear strength, respectively. The contact forces between particles are computed for each contact in the assembly. The computing results of the forces and moments acting on the particles can be used to solve the Newtonian equations of movement for each particle. However, there is a draw-back as PFC models are limited in size by the very large number of particles needed to model even a comparatively small volume of rock.

It was considered that the problem could adequately be represented by a two-dimensional cross-section. So, a small-scale 2D particle model could be sufficient to represent the material behavior. However, temperature propagation from the canisters is a fully three-dimensional problem, with heat radiating horizontally first from the vertical cylinders, and then mostly vertically away from the plane of the repository. Also, the scale of the heat propagation is quite large, and cannot be represented with a particle model. This is resolved by performing a two-tiered computation, with a one-way coupling. First, a large scale continuum model simulates the THM behavior of an entire system. Its results regarding temperature and stress are then fed as boundary conditions into a local particle model that represents the horizontal middle-plane of the lower section of the borehole and the lower heater.

Continuous model (FLAC)

The large continuous model covers one axisymmetric segment of the borehole and the surroundings, which is equivalent to a 2D axisymmetric model. The model domains as well as the model dimensions are shown in Figure 8-10. The mesh of the model consists of 56.352 zones. In the vicinity of the heaters, the discretisation grid is fine (node spacing ~ 0.1 m within a radius of 5 m) and the zone size increases with increasing distance to the heaters as shown in Figure 8-10. The figure also shows the materials used. The peek and the cement plate are not included in the FLAC model, due to their small dimensions, in order to get larger model cells and to, thus, shorten the necessary calculation time. It is assumed that both features have negligible effect on the modelling results.

The initial and boundary conditions as well as the parameters used are described in the annual reports 2009 and 2010 (SKB 2009, 2010a).

Particle model (PFC)

In Figure 8-11 the 2D model domain for the particle model is shown. It represents a horizontal plane located in the middle of the lower canister (indicated in Figure 8-11). The bentonite between canister and borehole wall is represented by particles of different diameters. The material parameters for the particles representing the bentonite have been determined by laboratory investigations. Tensile strength tests have been performed on three different bentonite samples. Figure 8-12 shows the stress-strain relation obtained from the three samples. As can be seen in the figure, the tensile strength varies only in a small range of 0.93 to 0.97 MPa. The black curve represents the calculation, which was performed to fit the measurements of sample 1. The best values for the mechanical parameters of the particle model are given in Table 8-2. For the thermal properties of the particle model the same values have been used as in the continuous model. Thus, the heat propagation is similar.

Table 8-2. Mechanical parameters for the particle model.

Particles	Young modulus, GPa	4.1
	Density, kg/m^3	2010
	Friction coefficient	0.60
Parallel Bonds	Young modulus, GPa	4.5
	Average normal strength, MPa	0.95
	Average shear strength, MPa	3.05

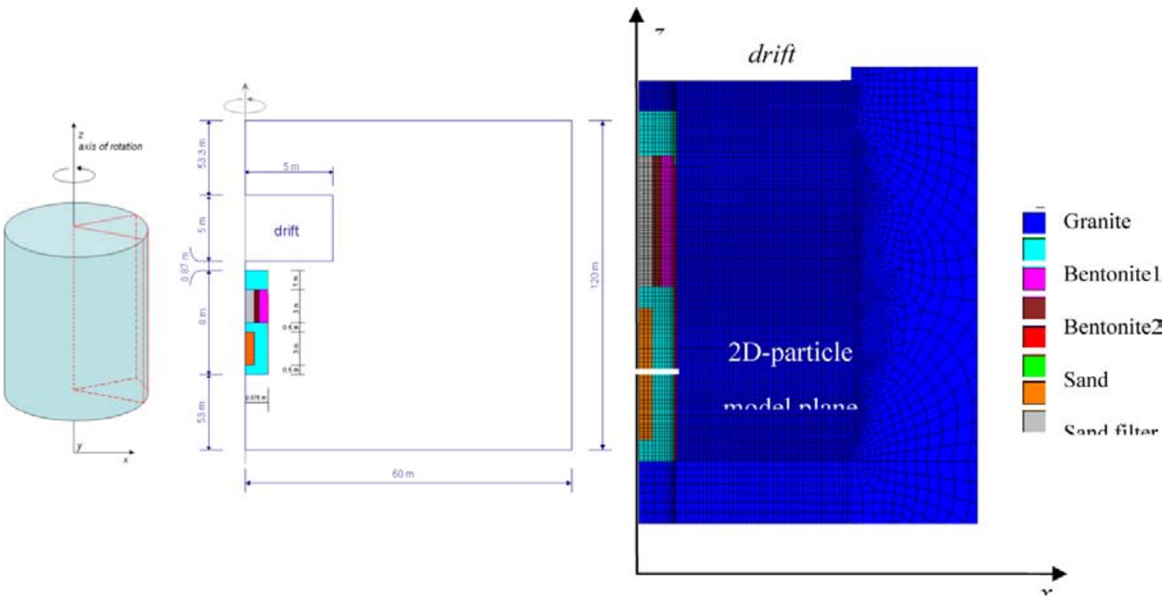


Figure 8-10. *Model domain (red border in figure top left), model dimensions (top right) and modelling mesh near the heater borehole (bottom).*

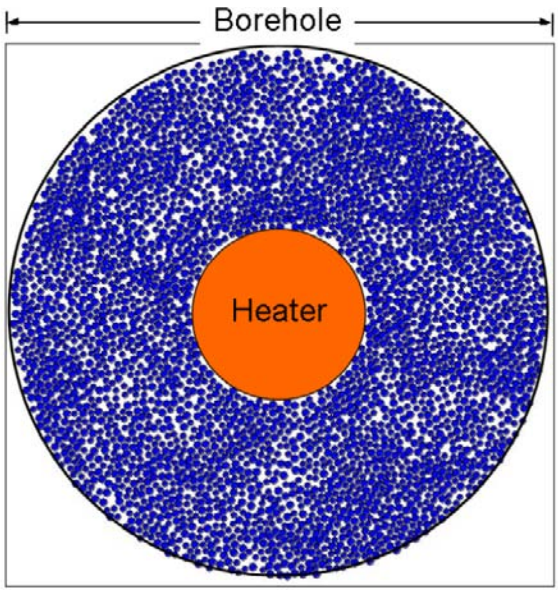


Figure 8-11. *Model domain for the 2D particle model.*

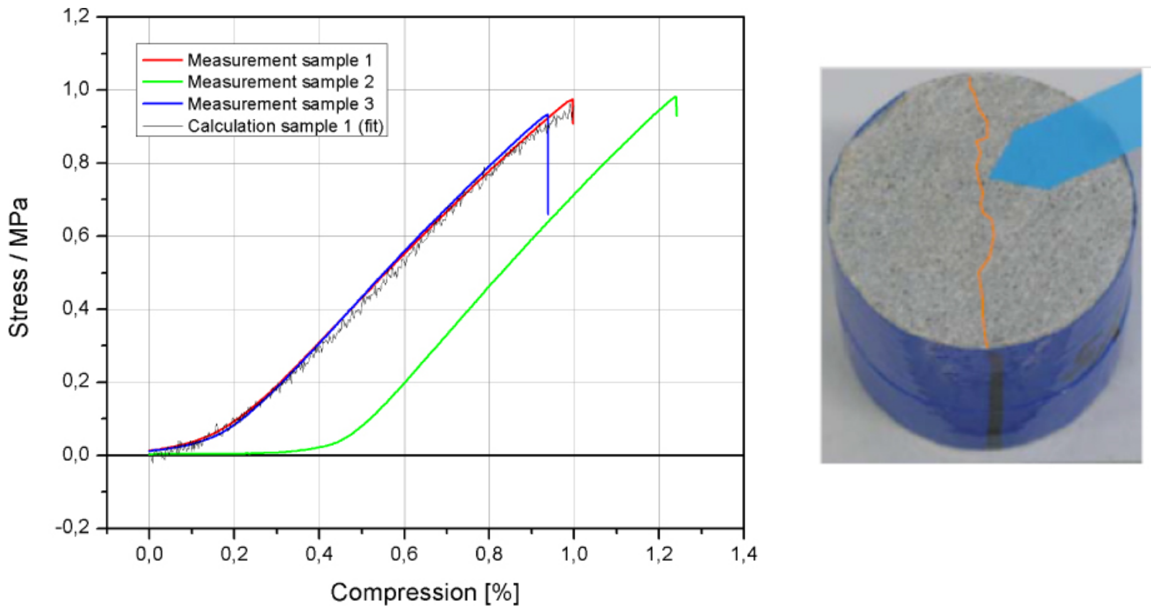


Figure 8-12. *Stress–strain diagram of three bentonite samples.*

In Figure 8-13, the FLAC and PFC calculation results are shown together with the measurement results at the pressure sensors PB204 and PB213 for the transient phase up to 250 days. As already stated (SKB 2011a), the simulation results of the continuous model did not represent the measured pressure evolution well. The stress development up to 200 days is underestimated by the model for PB213 (as for other sensors in the upper part as well). For sensor PB204, the stress is calculated too high, but the results of the sensor seems doubtful and therefore not considered for the particle model. The deviation between measured and calculated values (FLAC) is in a range between 1.25 MPa (sensor PB204) and 2.85 MPa (sensor PB213). The calculation results of the particle model for sensor PB213 are between the continuous model results and the measured results. Still, the pressure development in the particle model starts too early and is too sharp compared with the measurements (Goudarzi et al. 2008) and compared with the continuous model. In the later phase, the pressure development is still underestimated. The calculation results of the particle model are a bit noisy which is due to movements of individual particles. The fact that the particle model results are higher than the continuous model results could be due to the 2D-regime of the particle model. Any particle movement in the third direction due to the stresses are missing. A real 3D simulation is necessary for a better evaluation of the results.

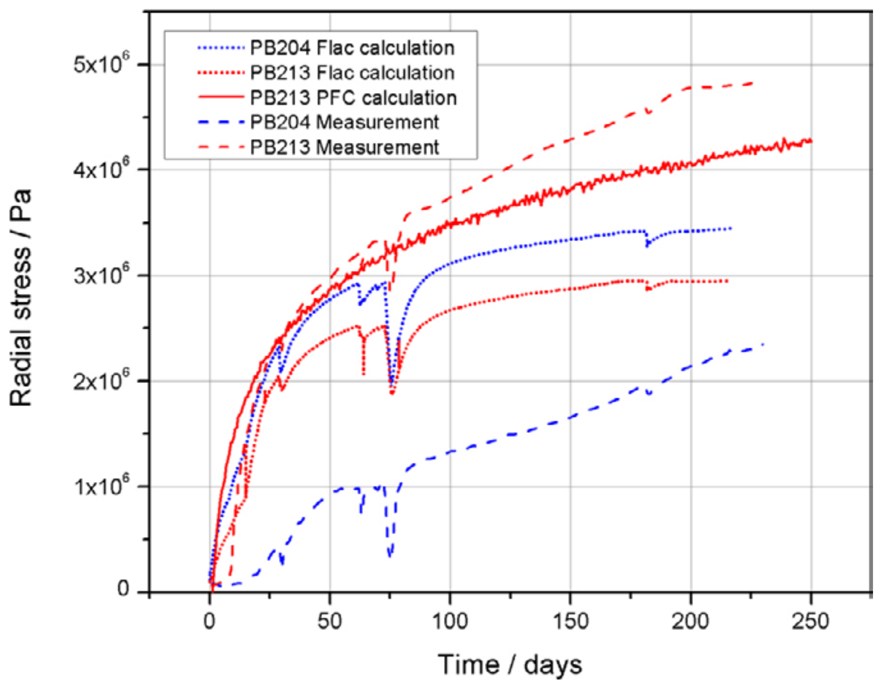


Figure 8-13. *Comparison of calculated and measured pressure evolution.*

Summary

It was intended to develop a discontinuous model for the geotechnical barrier material bentonite. Since large particle models are inadequate due to enormous computation time, a 3D continuous model was used to simulate the global THM system behaviour and then coupled to a 2D particle model for the bentonite. Using input parameters obtained from lab investigations on highly compacted bentonite samples, reasonable results were achieved from the particle model. Generally, it seems possible to develop a particle material model for highly compacted bentonite but the step into real 3D conditions to describe the material behaviour is still pending.

8.3.5 Large scale gas injection test

BGR's activities within the Lasgit project focus on the investigation of processes and inter-actions 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).

Besides the on-going code development to integrate the simulation of gas transport processes in clay-like materials, work on the modelling of the Lasgit experiment was continued in 2011. In a preliminary study an axisymmetric model is used to simulate the hydration stage and the first hydraulic and gas injections tests. Despite the geometric and physical simplifications, a relatively good agreement between numerical and experimental results could be achieved (Figures 8-14 and 8-15). The goal is to simulate the experiment in a three-dimensional model, taking into account the coupled hydraulic and mechanical processes in the buffer.

8.3.6 Task force on engineered barriers

A comprehensive status report on the theory behind the alternative vapour diffusion model for describing the resaturation process in compacted bentonite has been finalised at GRS. For qualifying the model it includes several benchmark calculations from the first phase of the Task Force with the experimental code VIPER, especially an interpretation of the transient moisture data in the Canister Retrieval Test.

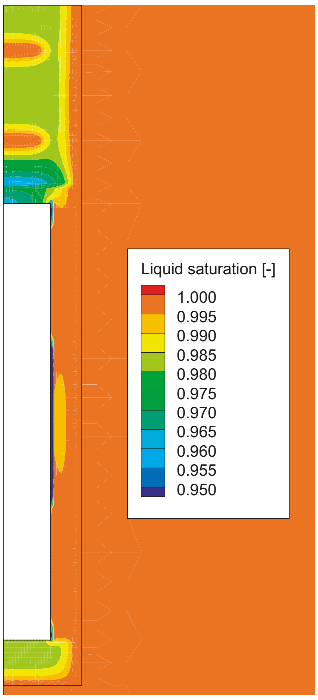


Figure 8-14. *Distribution of liquid saturation in bentonite buffer after 312 days.*

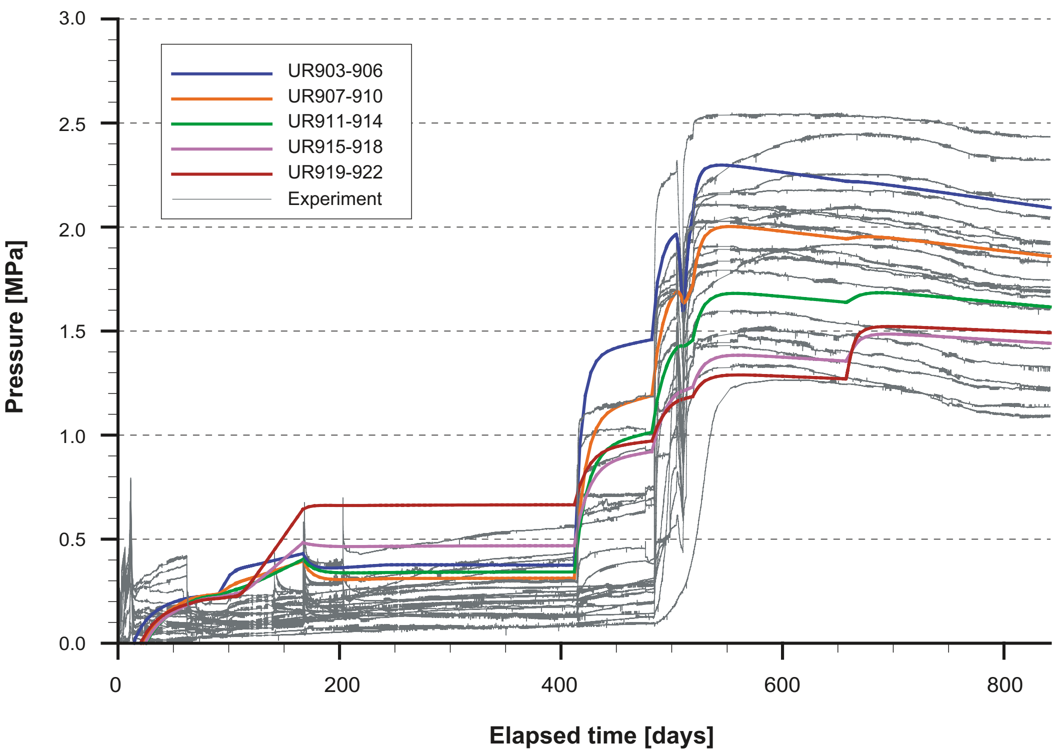


Figure 8-15. *Measured and simulated porewater pressures at borehole wall (day 0–849).*

The focus has then been shifted to Task 8 in which the interaction of groundwater flow in a fractured porous medium and bentonite re-saturation is investigated. Theoretical considerations about the drying of the rock through the surface of excavations and boreholes led to the development of an approach that decouples simulation of groundwater flow and bentonite re-saturation to a large extent and makes use of the single-phase flow code d^3f as well as the experimental re-saturation code VIPER.

The focus of BGR's activity within the Task Force on Engineered Barrier Systems was on the sensitivity analysis assignment. The objectives of this upcoming task are to study the effects of parameter value uncertainties and model simplifications on the results of THM-coupled calculations of engineered barrier systems.

After having defined a representative base case model, BGR worked on the preparation of a task description. The cases which are investigated in the sensitivity analyses include material parameter variations, changes in boundary and initial conditions, different considerations of physical processes and variations of the model geometries. The THM coupled calculations for the sensitivity analyses are conducted using the finite-element code OpenGeoSys.

First results of BGR's calculations were presented at the Task Force meeting in November 2011. Figure 8-16 shows an example of the results of the parameter variations. For each calculation case the thermal, hydraulic and mechanical results were evaluated in different points in the buffer and compared to the base case results. In the diagram the influences of the parameter variations on the hydration time in the buffer are displayed.

8.3.7 Task force on groundwater flow and transport of solutes

In the framework of Task 8b which was set up with realistic data from the HRL Äspö the capability of the code d^3f to simulate groundwater flow in a fractured porous medium was demonstrated. Figure 8-17 shows the 3D-pressure field and the velocity field in a horizontal cross-section.

Modelling a real system in the framework of the follow-up Task 8c was performed with the intention to model large fractures explicitly and to represent background fractures with an equivalent porous medium. A new method to derive heterogeneous equivalent porous media was under development at that time. Unfortunately, usability of this method was postponed due to unexpected difficulties so that a homogeneous medium was used instead. To match the seemingly unrelated and extremely varying inflow rates in the probing boreholes, two artificial fractures were introduced into the model as suggested in the update of the task description in summer. While the calculated pressure field looks quite similar to the results of Task 8b the overall inflow rates are too high. Therefore, future work has to be focused on calibration.

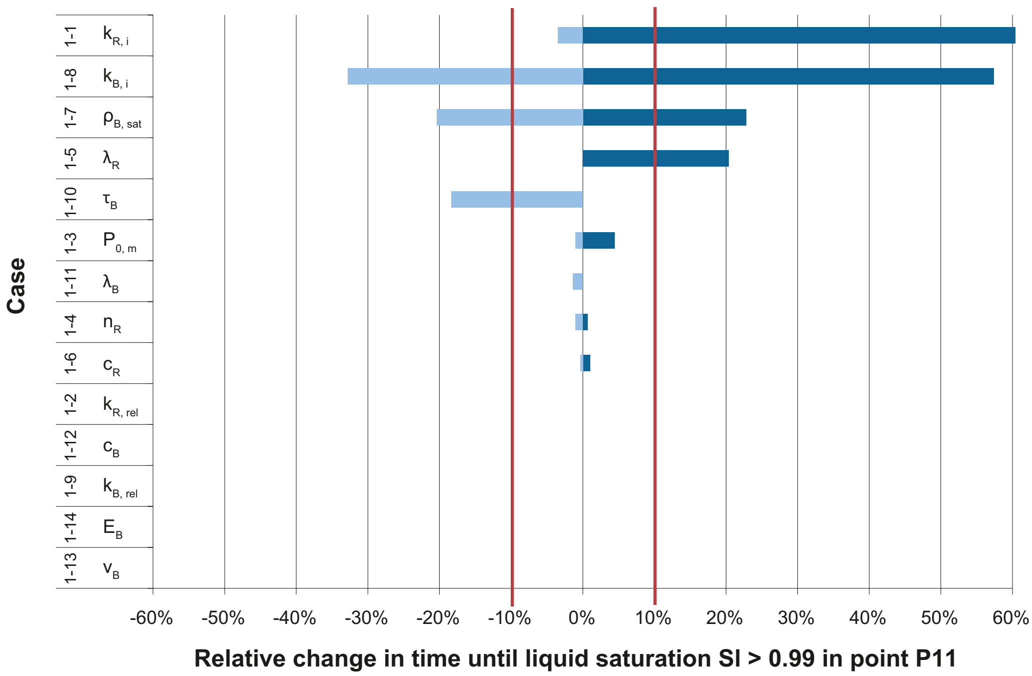


Figure 8-16. *Relative influence of changes in material parameters on the hydration time in the buffer.*

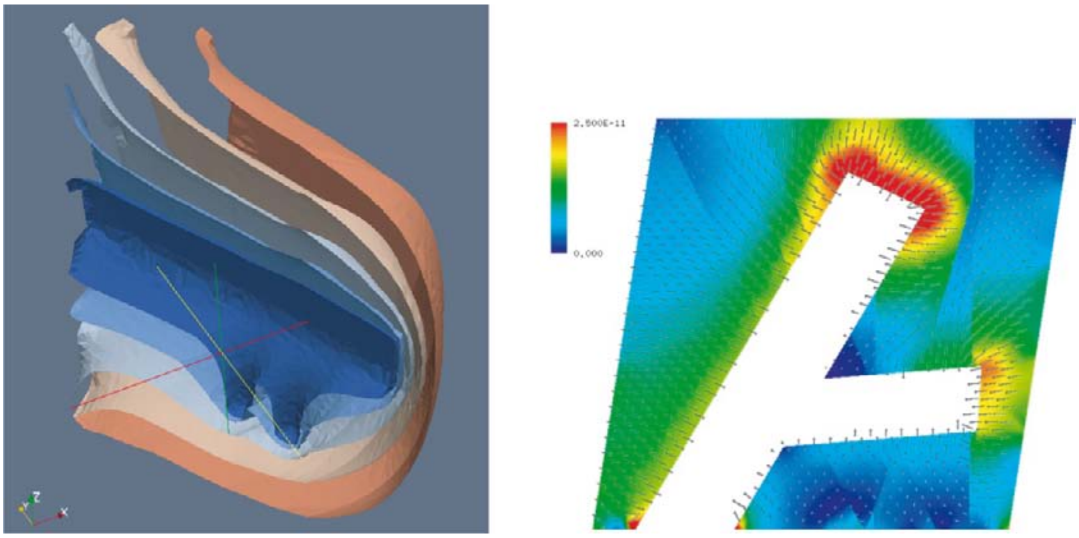


Figure 8-17. Pressure field (l) and velocities in a horizontal cross-section (r) for Task 8b.

8.4 CRIEPI

CRIEPI has been developing a numerical code "*FEGM*" to evaluate groundwater flow and migration of radionuclides in geosphere for performance assessment of geological disposal of radioactive wastes. In 2011, CRIEPI applied FEGM to the modelling work for Task 8b, TASO – Scoping calculation. TASO tunnel is a primary investigation area of the Bentonite Rock Interaction Experiment (BRIE). In Task 8b, the wetting phenomena of the bentonite in a borehole beneath TASO tunnel is dealt with. The modelled domain is a cube 40 meters on a side which incorporates the TASO tunnel (*see* Figure 8-18).

Tunnels, three deposition holes, an additional borehole and surrounding rock mass were considered in the model. The additional borehole was modelled as 3 metres deep and with a diameter of 30 centimetres. Seven geological structure model fractures and a hypothetical single fracture exist in the surrounding rock mass.

The hypothetical fracture is assigned as a circular feature of a diameter of 10 metres. The hypothetical fracture is horizontal and intersects the additional borehole at a depth of 1.5 metres below the tunnel floor.

The finite element mesh used for the numerical simulation is shown in Figure 8-19. The rock mass and bentonite were modelled with three-dimensional elements. And the geological structure model fractures and the hypothetical single fracture were modelled with two- dimensional elements. The mesh consists of 325,272 nodes, 1,887,962 three-dimensional elements and 28,999 two- dimensional elements. The domain within and near the additional borehole was subdivided into smaller elements.

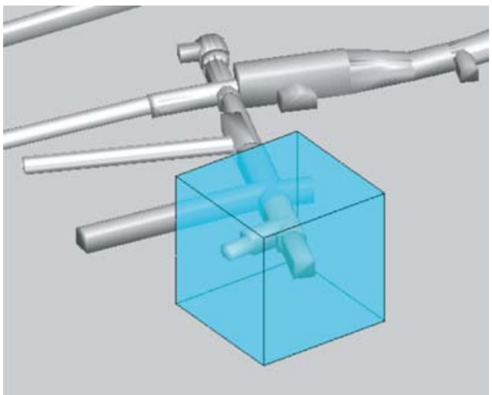
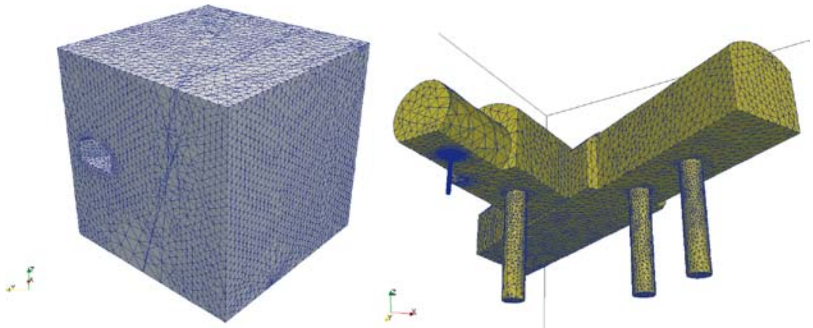
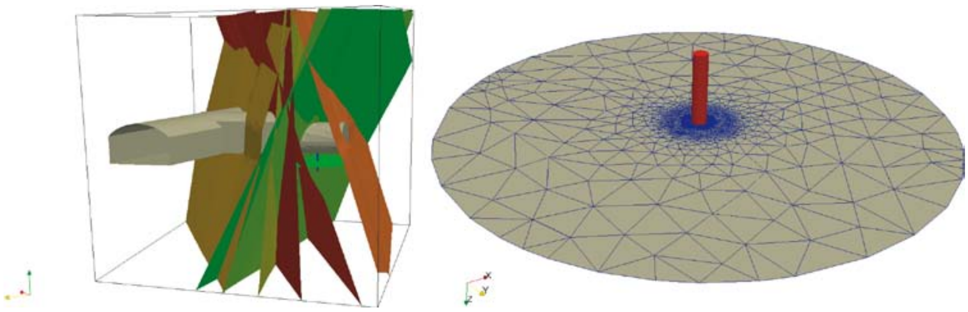


Figure 8-18. Modelled domain used for Task 8b.



(a) Overall view borehole *(b) Tunnels, deposition holes and an additional*



(c) Geological structure model fractures borehole *(d) A hypothetical fracture and an additional*

Figure 8-19. *Finite element mesh used for Task 8b.*

Hydraulic properties of each material are shown in Table 8-3 and Table 8-4. The unsaturated properties of bentonite, rock matrix and fractures were taken into consideration in the reference simulation case. The hydraulic heads calculated for the larger domain were assigned to the surrounding boundaries. Tunnel surfaces were prescribed at atmospheric pressure. The initial degree of saturation of bentonite was 0.36 which corresponds to an initial suction value of 100 MPa.

The following three cases of simulation were conducted:

- Case 1: Reference simulation case.
- Case 2: The hypothetical single rock fracture was eliminated from the model.
- Case 3: The unsaturated properties of the single rock fracture were ignored.

Table 8-3. Hydraulic properties of intact rock and bentonite.

	Intact rock (matrix)	Bentonite
Hydraulic conductivity	$1\cdot10^{-12}$ m/s	$6.4\cdot10^{-14}$ m/s
Porosity	$1\cdot10^{-5}$	0.44
Specific Storage	$1\cdot10^{-10}$ m^{-1}	$1\cdot10^{-11}$ m^{-1}

Table 8-4. Hydraulic properties of geological structure model fractures and a hypothetical single rock fracture.

	Geological structure model fractures	Single rock fracture
Transmissivity	$5\cdot10^{-8}$ m^2/s	$5\cdot10^{-10}$ m^2/s
Transport aperture	$1\cdot10^{-5}$ m	$1\cdot10^{-6}$ m
Storativity	$1\cdot10^{-8}$	$1\cdot10^{-9}$

Figure 8-20 shows the calculated water saturation around the additional borehole after one year in Case 1 and Case 2. And Figure 8-21 shows the calculated pore water pressure of bentonite along the central axis of the additional borehole in Case 1 and Case 2. In the reference case, Case 1, the bentonite is fully saturated 1.64 years after. On the other hand, in Case 2 where no fracture intersects the additional borehole, it takes half a year longer for the bentonite to be fully saturated.

There is a great difference in the progress of saturation of bentonite between the two cases around a depth of 1.5 metres where the single rock fracture intersects the borehole. Figure 8-22 shows the calculated pore water pressure of bentonite along the central axis of the additional borehole in Case 1 and Case 3. There is almost no difference between the two cases. The unsaturated properties of the fracture intersecting the additional borehole have little influence on the progress of saturation of the bentonite in the borehole.

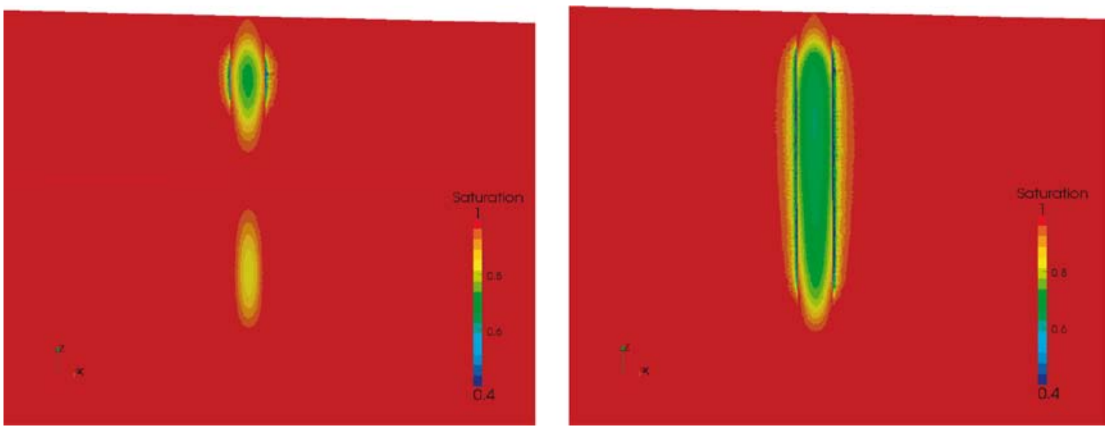


Figure 8-20. Calculated water saturation around the additional borehole after one year.

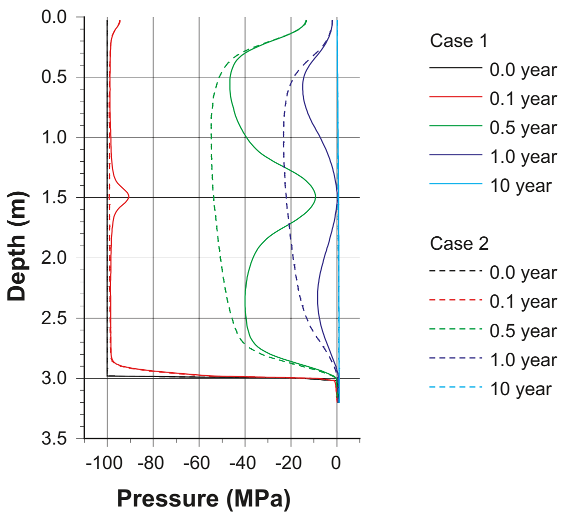


Figure 8-21. Pore water pressure along the central axis of the additional borehole in Case 1 and Case 2.

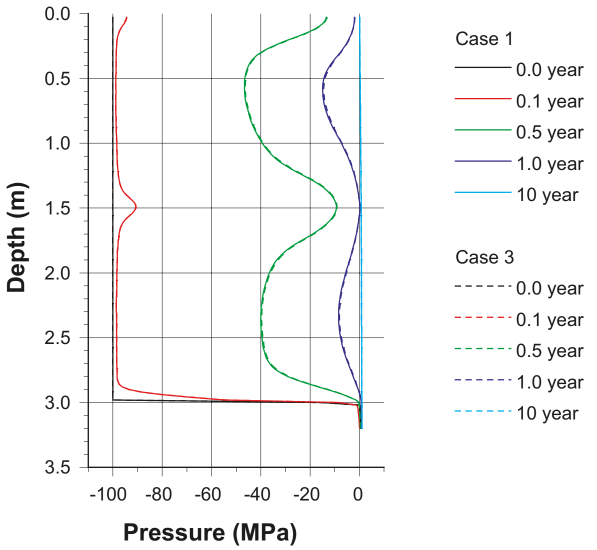


Figure 8-22. *Pore water pressure along the central axis of the additional borehole in Case 1 and Case 3.*

8.4.1 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 2011, THM benchmark simulation of Prototype Repository (PR) was carried out. There are three suggested tasks in benchmark of Prototype Repository. The first is 3D H-modelling of the PR before installation, the second is 3D T/H/TH-modelling of the PR after installation, and the third is THM-modelling concerning on deposition hole 6. CRIEPI started with the first task. Figure 8-23 shows one of the permeability distributions around the TBM tunnel and deposition holes which CRIEPI tested. Rock mass around TBM tunnel was divided into 11 regions, which were given different permeability. Rock mass around each deposition hole was also given a different permeability value. Permeability of total 17 regions was able to be calibrated after a few trials. The calibrated permeability values are summarized in Table 8-5. Generally permeability values around TBM tunnel are larger than those around deposition holes. Most permeable rock is distributed around tunnel face side of inner section. Figure 8-24 shows the calibrated results of water inflow. Water inflow was reproduced very well in all the measurement sections.

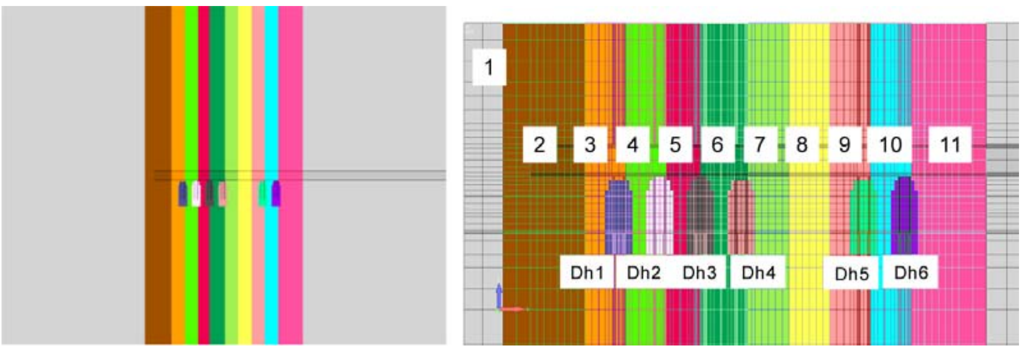
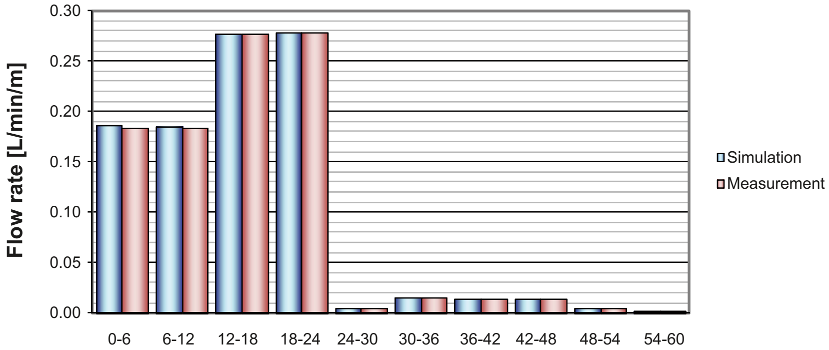


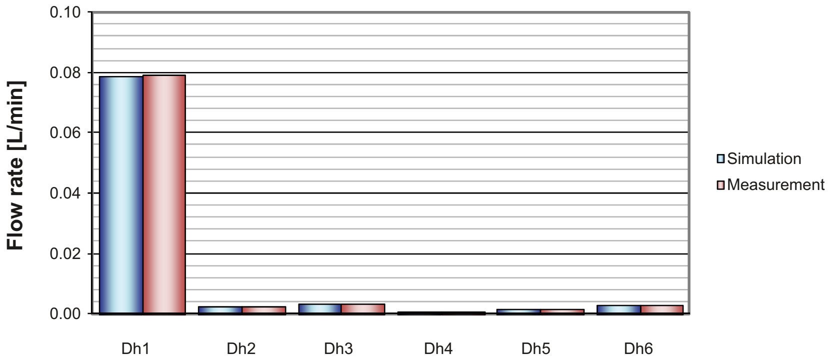
Figure 8-23. *Permeability distribution around TBM tunnel and deposition holes.'*

Table 8-5. Calibrated permeability values in each region in Figure 1.

No	Permeability	No	Permeability (m^2)
1	2.6×10^{-16}	10	8.6×10^{-18}
2	3.2×10^{-16}	11	4.5×10^{-18}
3	4.0×10^{-16}		
4	6.5×10^{-16}	Dh1	1.6×10^{-17}
5	6.9×10^{-16}	Dh2	5.4×10^{-19}
6		Dh3	6.9×10^{-19}
7		Dh4	1.6×10^{-19}
8		Dh5	3.3×10^{-19}
9		Dh6	6.8×10^{-19}



(a) Flow rate into TBM tunnel (Horizontal axis expresses the distance from the tunnel front face in m)



(b) Flow rate into deposition holes

Figure 8-24. *Inflow into TBM tunnel and deposition holes before installation.*

Next CRIEPI conducted the second task. Figure 8-25 shows the finite element mesh for 3D TH-simulation after installation of engineered barrier system. The mesh consists of 83,259 nodes and 77,412 elements. Backfill is divided into many blocks in order to represent the backfilling process. Rock permeability is determined after the calibration of the first task shown in Table 1. Simulation was conducted by numerical code LOSTUF.

Figure 8-26 shows the temperature evolution in R5 block at the mid-height of the canister in deposition hole 1. Numbers in the legend shows the distance from the central axis of the deposition hole (r) in the unit of mm. At r = 585 mm, maximum temperature is almost 70 degrees Celsius. The calculated temperature is in good agreement with the measured one. Figure 8-27 shows the suction evolution in R5 block in deposition hole 1. Zero or negative suction means that the media is saturated. Saturation was achieved almost 450 days after in R5 block in deposition hole 1 in simulation. Figure 8-28 shows the calculated suction evolution in backfill at the centre of TBM tunnel above 3 deposition holes 1, 3 and 6. It takes more time for saturation above deposition hole 6 than deposition holes 1 and 3 because of the difference of permeability in surrounding rock mass. Calculated water infiltration into the bentonite and backfill is a little faster than the measured one in the experiment.

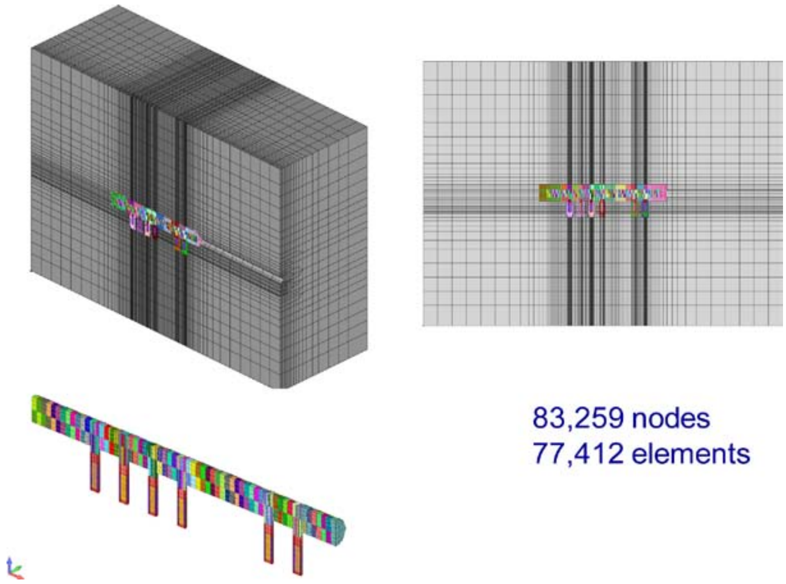


Figure 8-25. *Finite element mesh for the second task, TH-simulation after installation.*

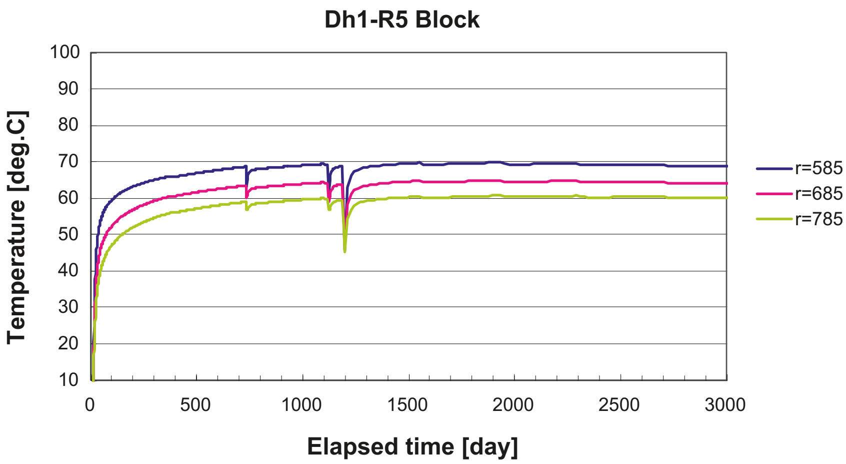


Figure 8-26. *Calculated temperature in bentonite at mid-height of the canister in deposition hole 1.*

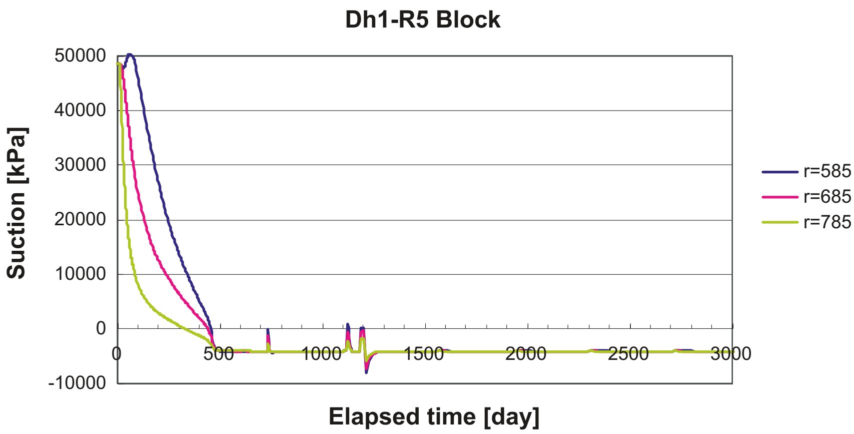


Figure 8-27. *Calculated suction in bentonite at mid-height of the canister in deposition hole 1.*

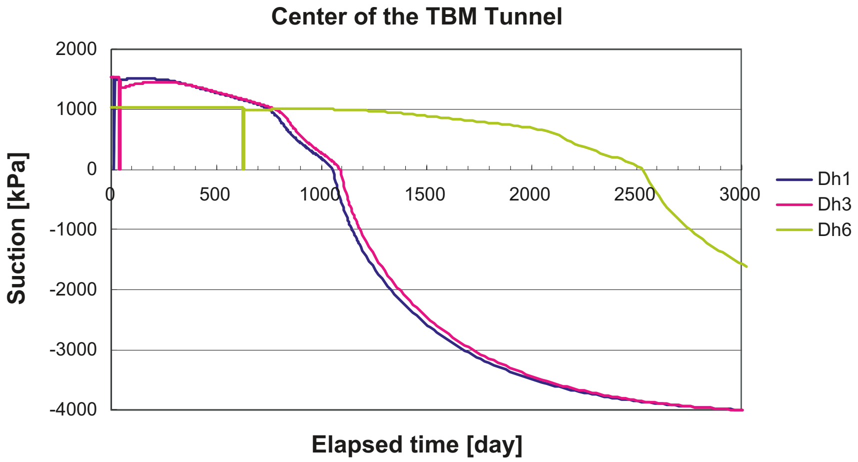


Figure 8-28. *Calculated suction in backfill above the three deposition holes 1, 3 and 6.*

CRIEPI has already started the third task of PR, THM axisymmetric modelling. In this task, CRIEPI will try to focus on the detail of mechanical behaviour in deposition holes including homogenization of bentonite and displacement of the canister. A series of sensitivity analyses has also been started in order to understand which material parameters and boundary conditions have great effects on numerical results.

8.5 JAEA – Japan Atomic Energy Agency

The role of Japan Atomic Energy Agency (JAEA)'s participation in the Äspö HRL directly contributes to JAEA's R&D mission. JAEA's research objectives at Äspö HRL during 2011 include 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 activities are designed to provide and support technical basis for geological repository program of high-level radioactive waste in Japan in terms of both implementer and regulator, which includes repository siting and safety assessment.

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 2011 focused on modelling for Task 7C, flow and transport at the single fracture (Olkiluoto, Finland), and conceptual development for Task 8, bentonite/ rock interface at the emplacement hole scale (Äspö Hard Rock Laboratory, Sweden). JAEA's goal for participation in Task 7C is an improved understanding of the characterization of single fracture flow and transport properties, focusing on of the Posiva Flow Fog (PFL) during hydraulic tests. Task 7C directly contributes to an improved understanding of performance measures relevant to safety assessment, such as the "F-factor", groundwater residence times, and transport pathways. JAEA's goal for participation in Task 8 is to improve understanding, characterization procedures, and analysis methodologies for the interface between engineered barriers and the host rock at the scale of a disposal pit.

During 2011, JAEA participation at the Groundwater Flow and Transport of Solutes Task Force meeting at Äspö, Sweden, March 15–17 was limited. However, JAEA did participate in a Task 7/ Task 8 modelling, workshop in Gothenburg, Sweden, November 25–26, 2011. However, results of Task7C modelling and initial conceptual modelling for Task 8 were presented at these meetings.

Task 7C – Hydrogeologic modelling at single fracture scale across the shafts

During 2011, JAEA implemented and evaluated detailed hydrostructural models for Task 7C. These models provided an extension of approached developed for simulation of heterogeneous flow structures at the ONKALO ventilation shaft sites. JAEA continued the development and documentation of characterization and analysis procedures for heterogeneous structures, and carried out flow and transport simulations with these structures at the single fracture (20 meter) scale.

Single Fracture Microstructural Model

The single fracture hydrostructural model developed by JAEA for Task 7C during 2011 was based on the concept of multi-scale Gaussian geostatistical roughness. This approach was built on workflow which incorporated:

- Conceptual roughness patterns based on the existing studies (ex. Tetsu and Sawada 2010), which indicate the effect of slicken sides, and slicken step at multiple scales and correlation lengths.
- Flow and aperture measurements and "Nappy Experiment" at the ONKALA KU2 raised bore shaft.

The multi-scale Gaussian fracture microstructural modelling procedure developed is illustrated in Figure 8-29. This model utilizes a conditioned sequential Gaussian approach SGeMS (Stanford Geostatistical Modelling Software; Remy et al. 2009). The required inputs for this model are (a) multi-scale variograms of aperture, (b) a distribution of aperture, and (c) constraint point values. Due to the lack of ONKALO-specific fracture roughness measurements, the microstructural model implemented for Task 7C utilized generic correlation lengths from a fracture roughness and aperture distribution measurement data of 50 cm scale of a single fracture excavated from Kamaishi in situ experimental site (Tetsu and Sawada 2010).

Four nested Gaussian fields are generated, with correlation lengths of 0.06 m, 0.1 m, 6 m and 15 m. The distribution of apertures and the constraint point values were both obtained from Site specific ONKALO data based on PFL transmissivity measurements at the KU shaft pilot boreholes and the "Nappy" experiment at the KU2 shaft. Figure 8-30 presents and examples of pattern of in-plane heterogeneity among ten realization models for both KU2 and KU3 shafts, coloured by transmissivity.

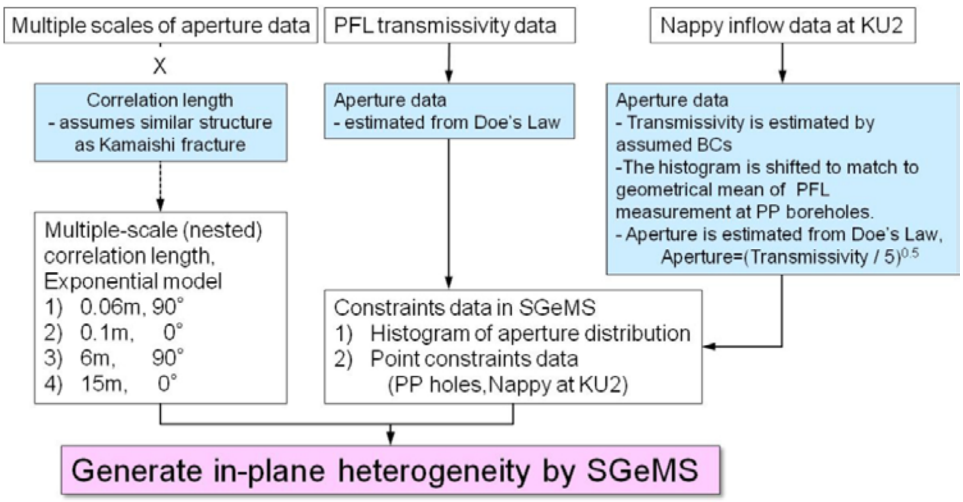


Figure 8-29. *Multi-scale Gaussian sequential simulation approach for implementation of Task 7C single fracture Microstructural model.*

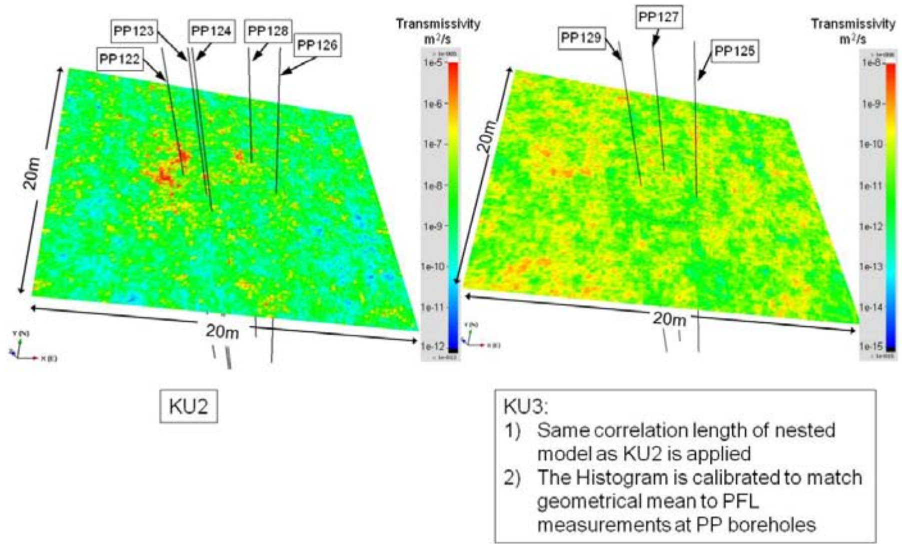


Figure 8-30. *Example simulated fracture roughness for fractures intersecting KU2 and KU3 shafts, colored by transmissivity.*

Task 7C Fracture Data Analyses

Flow simulations for Task 7C were carried in a 200 m×200 m×200 m block region, centred on the KU2 and KU3 shafts, respectively, with the background fractures, as shown in Figure 8-31. The stochastic background fracture parameters were estimated based on water conductive fracture data observed at pilot boreholes and the existing studies, see Figure 8-32.

Fracture transmissivity values for the FR1 single fractures were calibrated to match the geometrical mean to the PFL measured transmissivities, consistent with the Task 7C specification. Aperture, e [m] was estimated from transmissivity, T (m^2/s), by Doe's law, $T=(T/5)^{0.5}$. The target single fracture, FR1 was modelled 20 m×20 m scale of a single fracture, oriented to match to the trace observed at each shaft. Due to large apertures estimated from the KU2 "Nappy" experiments, relatively high transmissivities were simulated along the shaft wall.

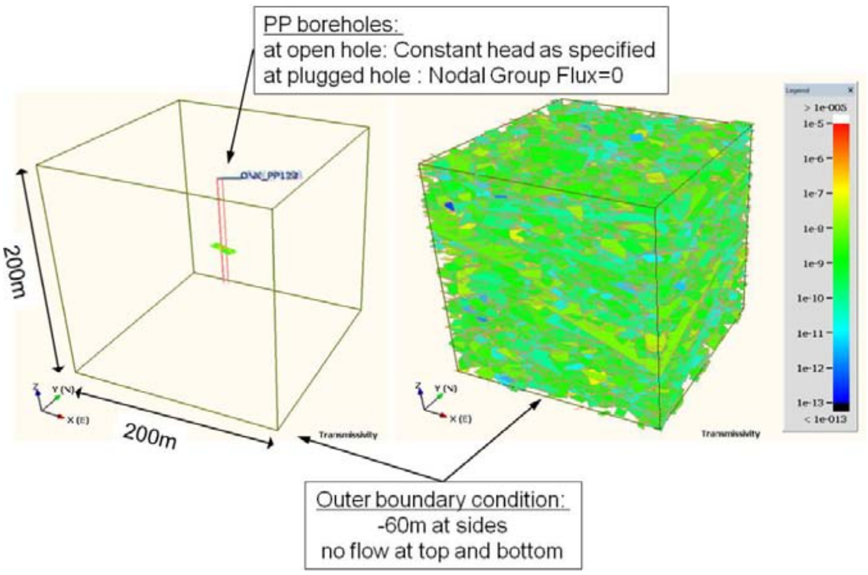


Figure 8-31. *Task 7C simulation region.*

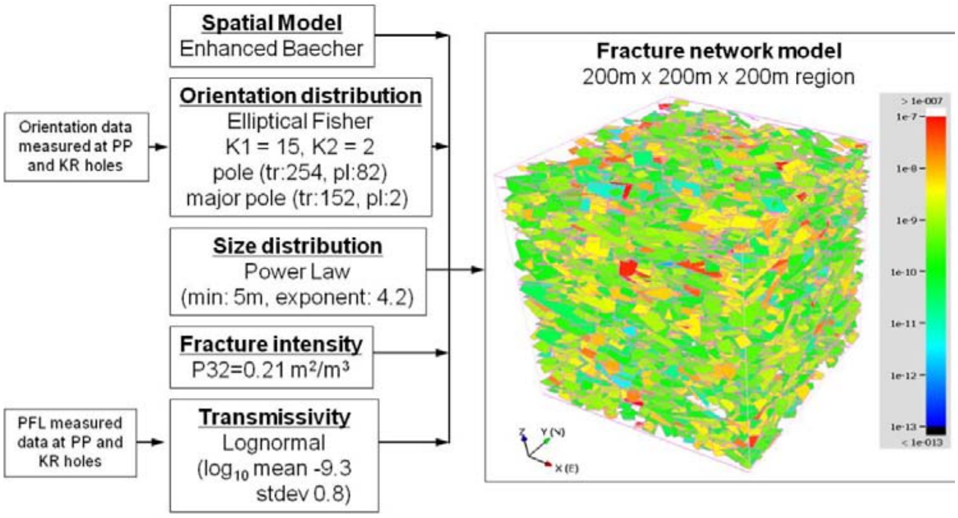


***Figure 8-32.** Stochastic parameters for the background fractures modeled for Task7C.*

No "Nappy" data was available for the KU3 shaft, and these values were therefore not conditioned. The aperture distributions for fractures at KU3 were therefore based on the KU2 aperture distribution, adjusted to be consistent with the geometrical mean to those of measured at three pilot boreholes for the KU3 shaft.

Task 7C Flow Simulations

Simulation cases are summarized in Table 8-6. JAEA's 2011 Task 7C simulations were carried out using the steady state flow boundary conditions as described in Figure 8-32.

Table 8-6. Task7C simulation.

Shaft	Borehole	Outer Boundary Head masl	Borehole head masl	PFL measure at FR1 mL/min.	Condition at other borehole	Simulation cases
KU2	PP122	6	–181.09	996	Other boreholes were plugged by packer	s-PP122
	PP123	6	–181.09	961	Other boreholes were plugged by packer	s-PP123
	PP124	6	–181.09	2870	Other boreholes were plugged by packer	s-PP124
	PP126	6	–181.09	2930	Other boreholes were plugged by packer	s-PP126
	PP128	6	–181.09	761	Other boreholes were plugged by packer	s-PP128
KU1	PP131	6	–177.52	–	Other boreholes were plugged by packer	s-PP131
	PP134	6	–177.52	367	Other boreholes were plugged by packer	s-PP134
	PP137	6	–177.52	–	Other boreholes were plugged by packer	s-PP137
KU3	PP125	6	–176.81	38	PP127, PP129 close	s-PP125
		6	–176.81	8	PP127, PP129 open	s-PP125-1
		6	–176.81	11	PP127 open (175 mL/min.). PP129 close	s-PP125-2
		6	–176.81	17 or 16	PP125 close, PP129 open (330 mL/min.)	s-PP125-3
		6	–176.81	135	PP125, PP128 close	s-PP127
		6	–176.81	21	PP125, PP128 open	s-PP127-1
		6	–176.81	158	PP125 open (90–110 mL/min.). PP129 close (overpressure + 2 bar)	s-PP127-2
		6	–176.81	–	No data shown	s-PP129
		6	–176.81	63	PP125. PP127 open	c-PP129-1

Example Task 7C simulation results are provided in Figure 8-33 to 8-36. These figures provide a comparison between simulation results (ten realizations) and measured flow rate for a series of PFL measurements during pumping tests at each KU2 pilot boreholes. In general, the stochastic fracture microstructural model realizations distribute close to, or in the range of measured values. However, PFL simulations for wells PP124 and PP126 do not provide as good a match as other wells. Simulations show a lower than measured higher flow rate at PP126 during pumping of PP123 and PP124, and simulated flow rates at PP124 are smaller than measured value during pumping of the PP126 and PP128 boreholes.

Figure 8-37 and 8-38 present example sensitivity simulations for an increase in transmissivity by one order of magnitude in a 1 meter radius region around the PP124 and PP126 wells. These simulations illustrate how increasing transmissivity around PP124 and PP126 boreholes increases the flow rate at those wells.

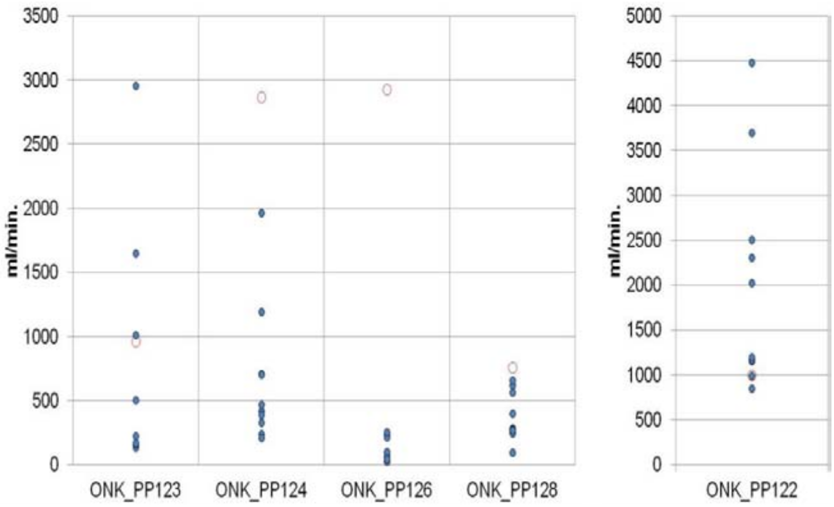


Figure 8-33. *PFL flow measurement during PP122 pumping, for the case s-PP122. Left figure is observation boreholes and right is pumping borehole. Simulation results are shown by solid circle and measured values are shown by red open circle. Left figure is observation boreholes and right is pumping borehole.*

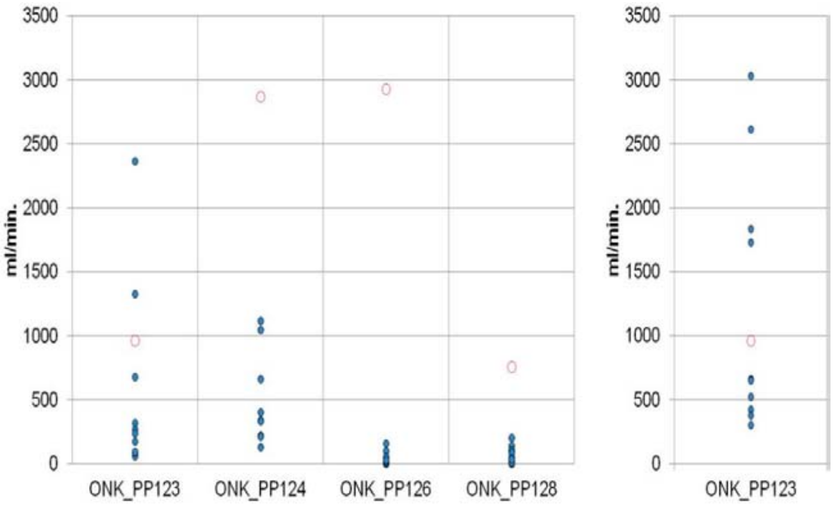


Figure 8-34. *PFL flow measurement during PP123 pumping, for the case s-PP123. Left figure is observation boreholes and right is pumping borehole. Simulation results are shown by solid circle and measured values are shown by red open circle. Left figure is observation boreholes and right is pumping borehole.*

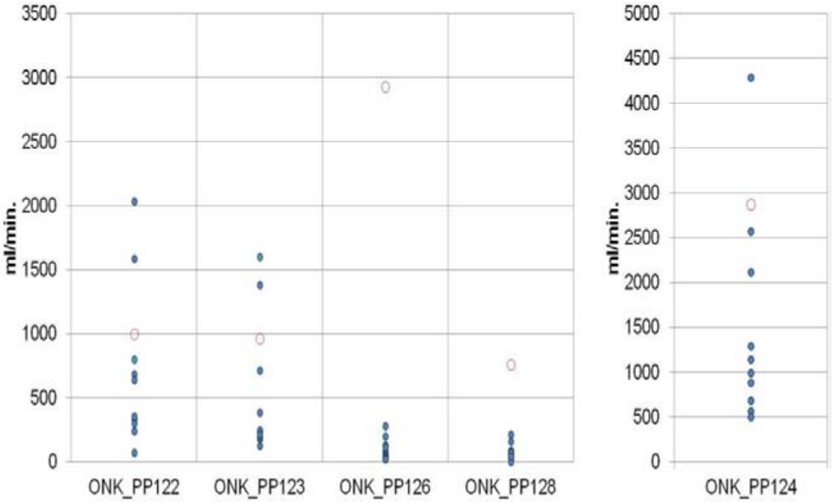


Figure 8-35. *PFL flow measurement during PP124 pumping, for the case s-PP124. Left figure is observation boreholes and right is pumping borehole. Simulation results are shown by solid circle and measured values are shown by red open circle. Left figure is observation boreholes and right is pumping borehole.*

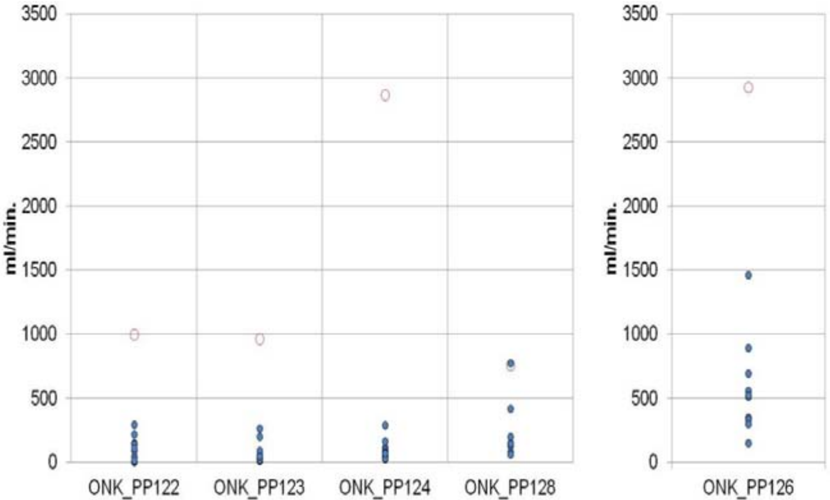


Figure 8-36. *PFL flow measurement during PP126 pumping, for the case s-PP126. Left figure is observation boreholes and right is pumping borehole. Simulation results are shown by solid circle and measured values are shown by red open circle.*

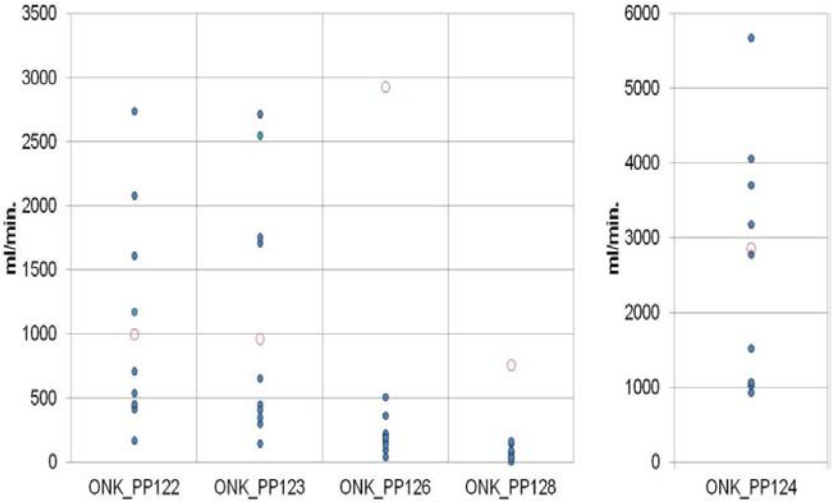


Figure 8-37. *Sensitivity calculation results with increasing transmissivity by one order around PP126 and PP124 in radius 1 m area. PFL flow measurement during PP124 pumping, for the case s-PP124.*

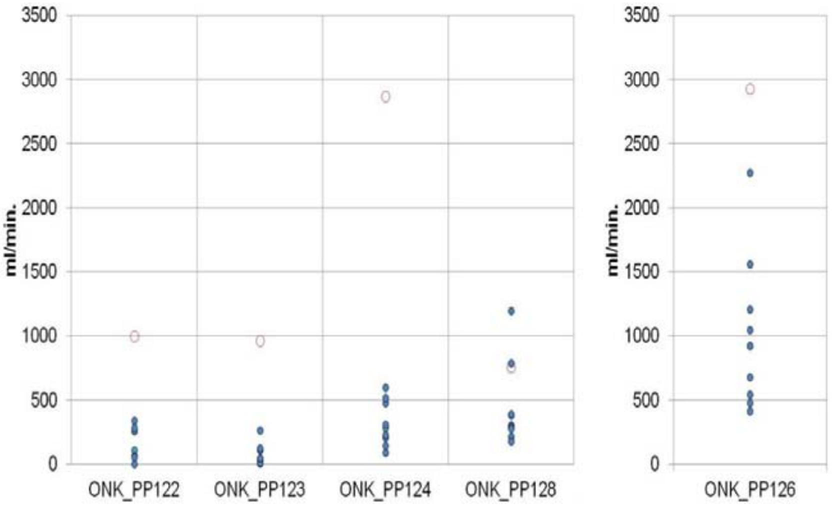


Figure 8-38. *Sensitivity calculation results with increasing transmissivity by one order around PP126 and PP124 in radius 1 m area. PFL flow measurement during PP126 pumping, for the case s-PP126.*

Simulations were carried out to evaluate the F-factor for the same heterogeneous fractures used for simulated PFL hydraulic interference tests. Figure 8-39 and 8-40 show the cumulative density function of F-factor for KU2 and KU3 fractures respectively. F-factor was calculated at the 20 meter scale, using particle trajectories under the steady state flow condition with fixed hydraulic gradient, 0.1 across the fracture, as required in the task specification.

Task 7C Conclusions

Important lessons from JAEA's 2011 efforts on Task 7C include the following:

1. Even though an un-supported variogram model was used, most realizations produced results similar to measured values. This may be because the models are sufficiently constrained for this purpose by the specification of a transmissivity distribution based on PFL log measurements, with local constraints on aperture values from "Nappy" experiments at KU2 and local PFL transmissivity values for PP holes.
2. While most realizations provided a good match to measurements, simulations of PP124 and PP126 did not cluster near measured values. Well PP124 and PP126 results could be calibrated by increasing transmissivity near boreholes, to increase the flow rate.

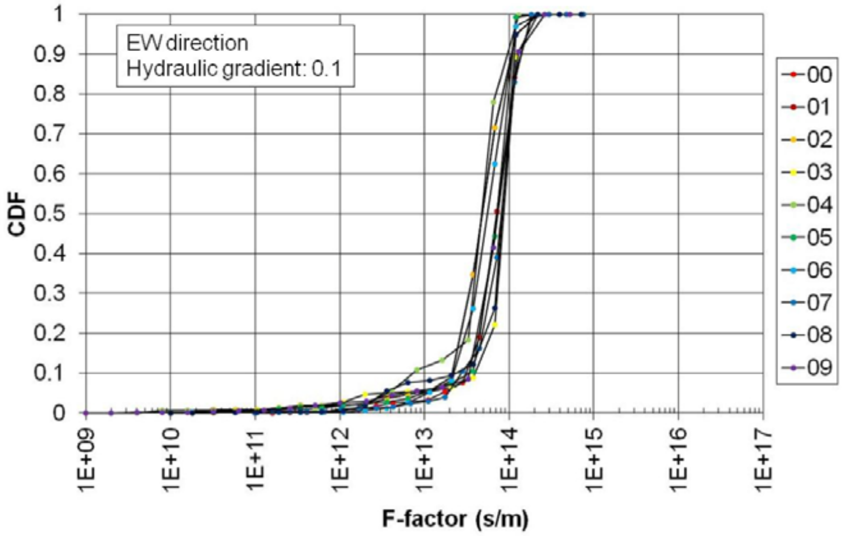


Figure 8-39. *F-factor calculated at KU2 model with 0.1 hydraulic gradient, EW direction.*

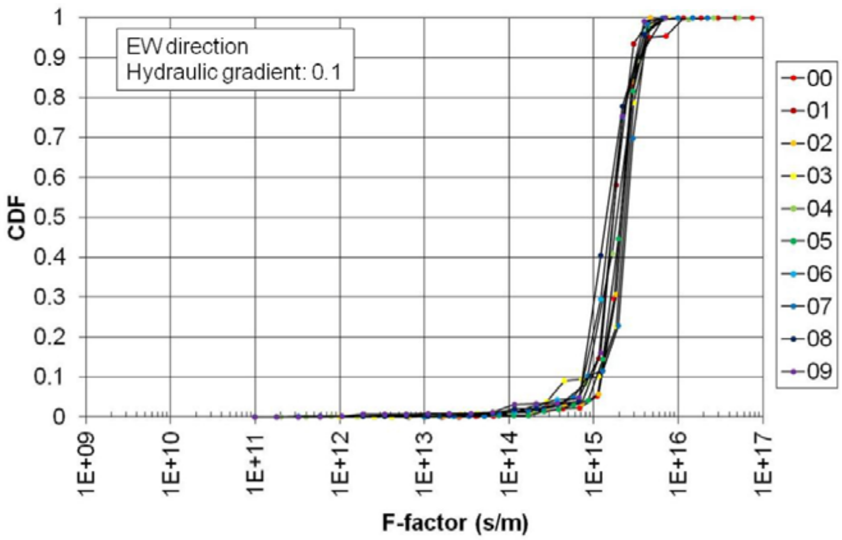


Figure 8-40. *F-factor calculated at KU3 model with 0.1 hydraulic gradient, EW direction.*

Task 8 – Modelling the interaction between engineered and natural barriers

JAEA initiated Task 8 conceptual development during 2011. JAEA's 2001 efforts focused on improving the understanding of the interaction of the proposed Task 8 modelling task and "BRIE (Bentonite Rock Interaction Experiment)" simulated canister emplacement holes with the fracture pattern. The main objective of Task8 is to contribute to 1) better characterization and modelling method of canister boreholes, and 2) better predictions of the wetting bentonite buffer.

During 2011, JAEA developed and implemented a discrete fracture network (DFN) model to study the characterization and evaluation canister boreholes, and to predict the heterogeneous in-flow distribution to buffer based on available data from TASO tunnel region, probe holes and canister holes.

Figure 8-41 show the conceptual illustration of rock mass modelling for Task 8 using a nested DFN approach. This model includes background fracture populations generated based on the Task 8 specification as shown by Table 8-7. The outer region the fracture population was filtered using a minimum fracture radius smaller of 6 meters. This value was selected based on sensitivity analyses.

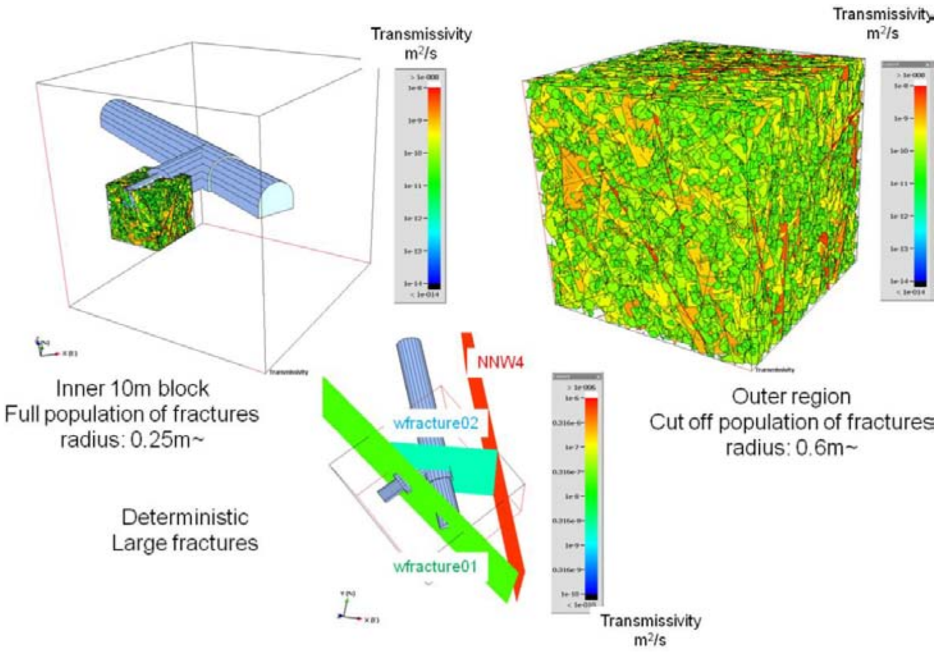


Figure 8-41. *Conceptual illustration of nested discrete fracture network (DFN) model for Task 8.*

Table 8-7. Stochastic fracture populations specified by the Task 8 specification.

Set	Orientation Trend	Plunge	Fisher k	Size r_0 (m)	k_r	Spatial Distributon	Intensity P_{32} (r_0, ∞) (m^2/m^3)
set 1	280	20	10	0.25		Baecher	1.1
set 2	20	10	15	0.25		Baecher	2
set 3	120	50	10	0.25		Baecher	0.75

One of the key processes which need to be understood for Task 8 is the microstructural model for heterogeneous fracture roughness. This roughness controls the pattern of flow into deposition pits, and also strongly influences multiphase and resaturation behaviour. JAEA utilized insights from previous work on heterogeneous fractures to build the microstructural model.

For preliminary conceptual Task 8 simulations, JAEA utilized the generic empirical functional relationship between the fracture size (S, meters) and transmissivity T (m2/s): $T = 7\ 10^{-11} \times S^{1.7}$. In addition, JAEA studied an alternative fit to Äspö size/transmissivity data using the function $T = 0.7 \times 10^{-11} \times S^{1.7}$.

Task 8 simulations carried out during 2011 by JAEA were carried out in steady state, using the following boundary condition assumptions:

1. Outer boundaries of 40 m×40 m×40 m model region: constant head –50 m.
2. Tunnel walls: constant head of the elevation of tunnel wall.
3. Boreholes: Open condition: constant head –417 m (assumes outflow is measured at the drift floor). Packed off condition: zero nodal group flux.
4. Pit: Open condition: constant head of the elevation of pit wall (assumes pumping out of water from the pit). Close condition: no flow boundary.

Figure 8-42 provides example simulation results for the assumption $T = 0.7 \times 10^{-11} \times size^{1.7}$. Figure 8-43 compares between a limited number of measured values (head and flow rate at the probe boreholes), for both transmissivity/size correlations. Differences between the transmissivity assumptions are small relative to variability between realizations.

Figure 8-44 presents examples of simulated fracture trace maps at the pit walls, and simulated flow distribution along the pits under the open condition of the pit.

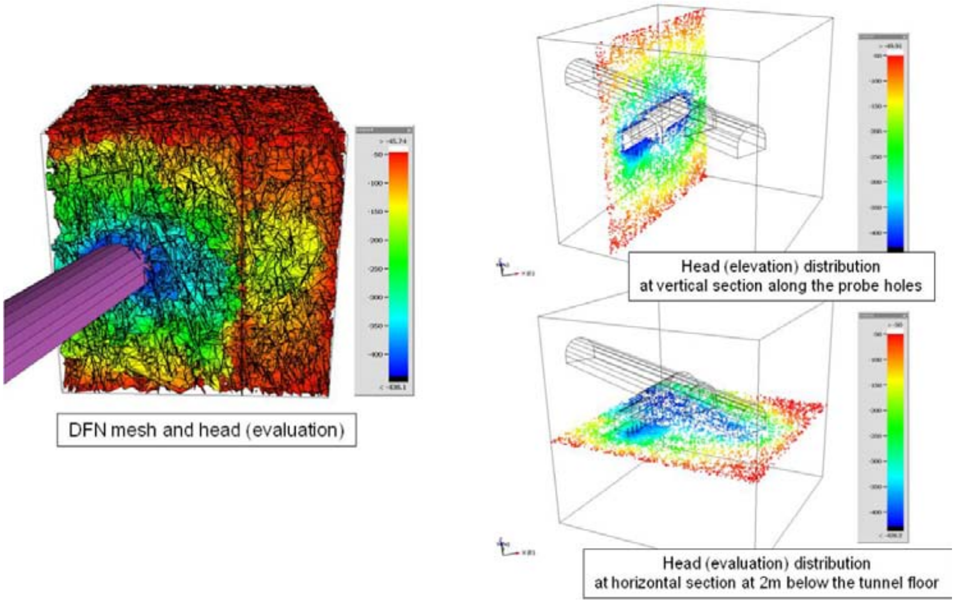


Figure 8-42. *Example steady state flow simulation. Figure on left shows the head distribution at outer boundaries. Figure on right provides cross section views along pilot boreholes and 2 m below TASO tunnel. Assumes T= 0.7×10*$^{-11}$*×S*$^{1.7}$*.*

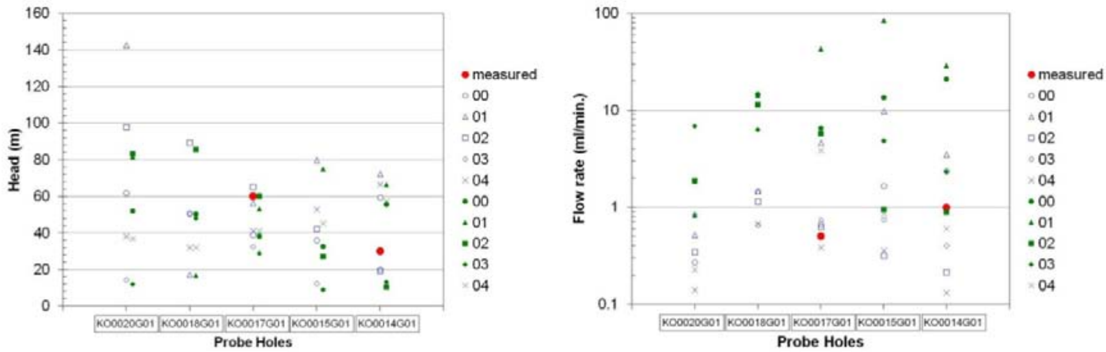


Figure 8-43. *Comparison between measured (red) head (left) and flow rate at the probe boreholes. Both of the transmissivity relationships T= 7×10*$^{-11}$*×S*$^{1.7}$ *(green) and 1 T= 0.7×10*$^{-11}$*×S*$^{1.7}$ *(blue) are shown.*

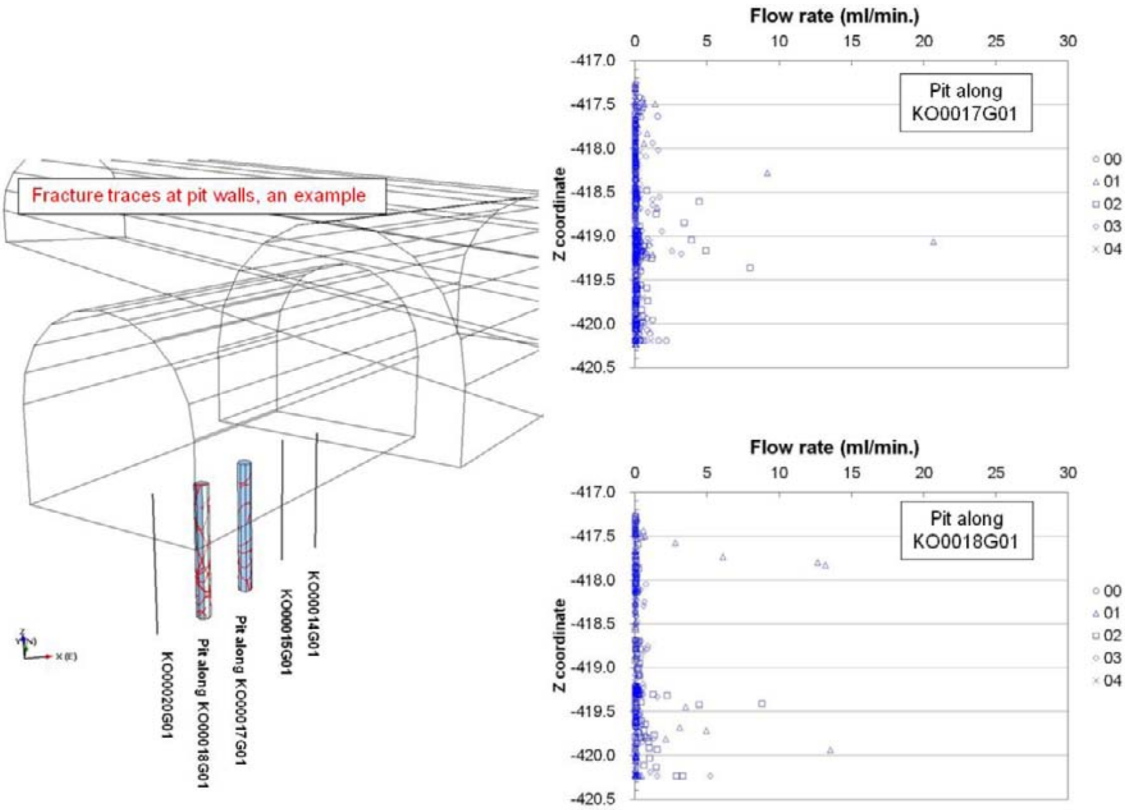


Figure 8-44. Examples simulated trace maps at the pit walls (left) and flow distribution along the pits (right) under the open condition of the pit.

8.5.2 Alternative buffer materials

The analyses of bentonite material (Kunigel V1) retrieved from parcel 1 in May 2009 have been continued. In addition to analysis of X-ray diffraction carried out in 2010, FESEM observation/EDS analysis and EPMA analysis were conducted to investigate mineralogical changes in the Japanese bentonite.

Figure 8-45 shows the results of FESEM observation and EDS analysis for the small specimen of interface between iron heater and bentonite sample (JAEA 2011). The color altered part of bentonite close to the heater was brown and the remainder of bentonite was gray. FESEM observations performed on bentonite surface revealed almost no variation in particle morphology in both the color altered and original parts. EDS analysis, however, indicated that the iron content of color altered part were higher than the original one. This suggests that the iron content increases in octahedral site of smectite in colour altered part. As another possibility, iron increase by ion exchange reaction (i.e. change to Fe-exchanged smectite) would be also suggested.

Figure 8-45 illustrates the iron distribution of interface between iron heater and bentonite sample, and the BEI (backscattering electron image) by EPMA (JAEA 2011). EPMA mapping and line analysis show the high concentration of Fe at the interface and gradual decrease of Fe toward the inner part of bentonite. The results suggest that the dissolved Fe migrated into the color altered part of bentonite from the iron heater. Additionally, the BEI detected the small distribution of alteration product (not well known at the present) around the interface. Detail analyses for such product by using AFM and HRTEM have been conducted in order to identify the mineralogy of alteration product.

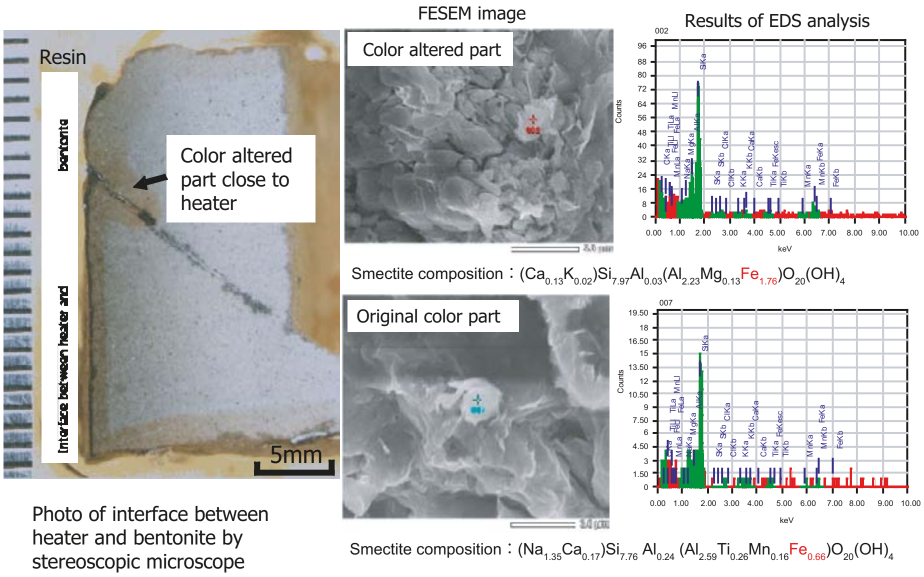


***Figure 8-45.** Results of FESEM observation and EDS analysis for Kunigel V1 retrieved from parcel 1.*

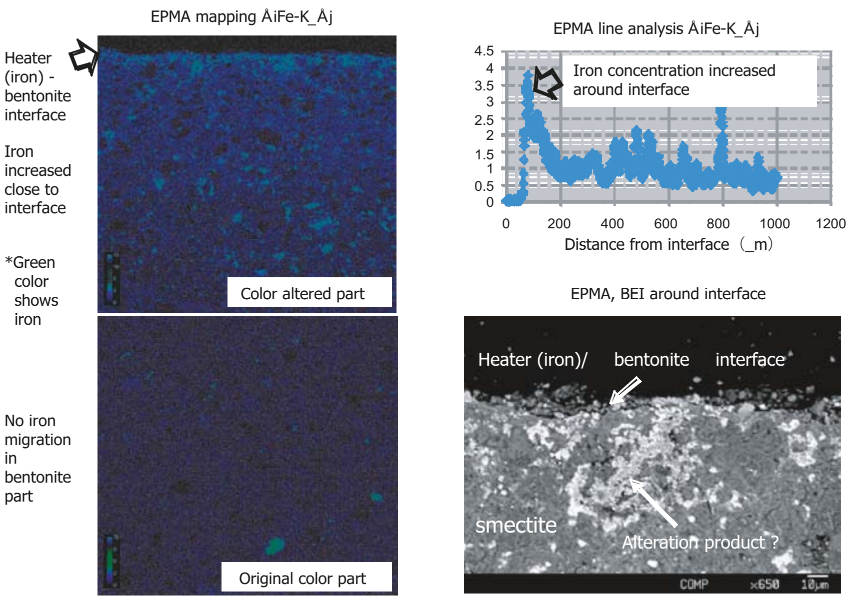


***Figure 8-46.** EPMA mapping and line analysis of Fe, and the BEI for the interface between iron heater and bentonite sample retrieved from parcel 1.*

8.6 NWMO

In 2011, the Nuclear Waste Management Organization (NWMO) effort under the Äspö Project Agreement was supported by Atomic Energy of Canada Limited (AECL), Université Laval and Geofirma Engineering. The results of this work are briefly described below.

8.6.1 Colloid

In 2011, the NWMO work program on colloids was directed to finalizing a summary report on the experimental work undertaken to advance the understanding of colloid migration on the performance of a Deep Geological Repository (DGR). The report describes the results from the NWMO's colloid transport and erosion experiments along with SKB's Colloid Dipole and Colloid Transport projects (2005–2010). These experiments were devised to quantify natural colloid concentrations as a function of ionic strength, improve the understanding of colloid stability in various ionic strength groundwaters, colloid facilitated actinide transport, and colloid generation from bentonite. This report will be issued in 2012.

The experimental results indicate 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 migration of stable colloids within fracture pathways is unlikely given low groundwater velocities fracture surface irregularities, heterogeneity in surface charge distribution and fracture aperture variability.

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

A modelling team from the Université Laval was participating in Task 7 using the numerical simulator HydroGeoSphere. Task 7 involved the multi-scale numerical modelling of hydraulic responses in the fractured crystalline rock environment located on Olkiluoto Island in Finland. A comprehensive data set was available associated with investigations for Posiva's Onkalo underground rock characterisation facility.

The 2011 work program was directed towards delivering a final draft report to the Task Force reviewer that integrates the Laval team's multi-scale modelling results for Subtasks 7A, 7B and 7C. The scales of each subtask decreased from about 15 km^3 for 7A, to the rock-block scale of 0.032 km^3 for 7B, and finally to the single-fracture scale of 36000 m^3 for 7C. A final task force report is expected to be published during 2012.

8.6.3 Large scale gas injection test

NWMO is providing modelling support for the Large Scale Gas Injection Test using the TOUGH2 code modified with pressure-dependent permeability and capillary pressure to simulate microfracturing. In 2011, 3D simulations using the modified TOUGH2 and homogeneous/heterogeneous permeability fields in bentonite were performed to model the 2009 gas injection test results, which showed complex gas propagation behaviour through the bentonite. Models using heterogeneous permeability fields are more successful than the homogeneous permeability field model. A heterogeneous permeability field model successfully simulated the pressure drop at the injection port and a rapid pressure increase at the rock-wall; however, the pressure increase at the rock-wall took a minimum of 5 days, much longer than in the experimental results (1.5 days) as shown in Figure 8-47. As well for all models, gas reached the rock-wall immediately adjacent to the injection port, rather than on the opposite side of the canister as observed. Several model modifications are recommended, particularly in the method by which pressure-induced permeability and capillary pressure are calculated, to improve the model's ability to simulate a distinct gas pathway at a location not immediately adjacent to the injection port.

8.6.4 Task force on engineered barrier systems

In 2011, the NWMO continued participation in the Task Force on Engineered Barrier Systems (EBS-TF); specifically the pre-installation hydraulic modelling activities related to the Prototype Repository. For this modelling effort, the NWMO used COMSOL, the widely used Multiphysics code. COMSOL is known to have a large number of users with a good library of modules developed for specific applications, such as geomechanics. Preliminary modelling results were compared with field results and preliminary modelling trials carried out by others. The NWMO continued with the pre-installation hydraulic modelling on an iterative basis, and found that closer agreements between the measured and simulated values were shown.

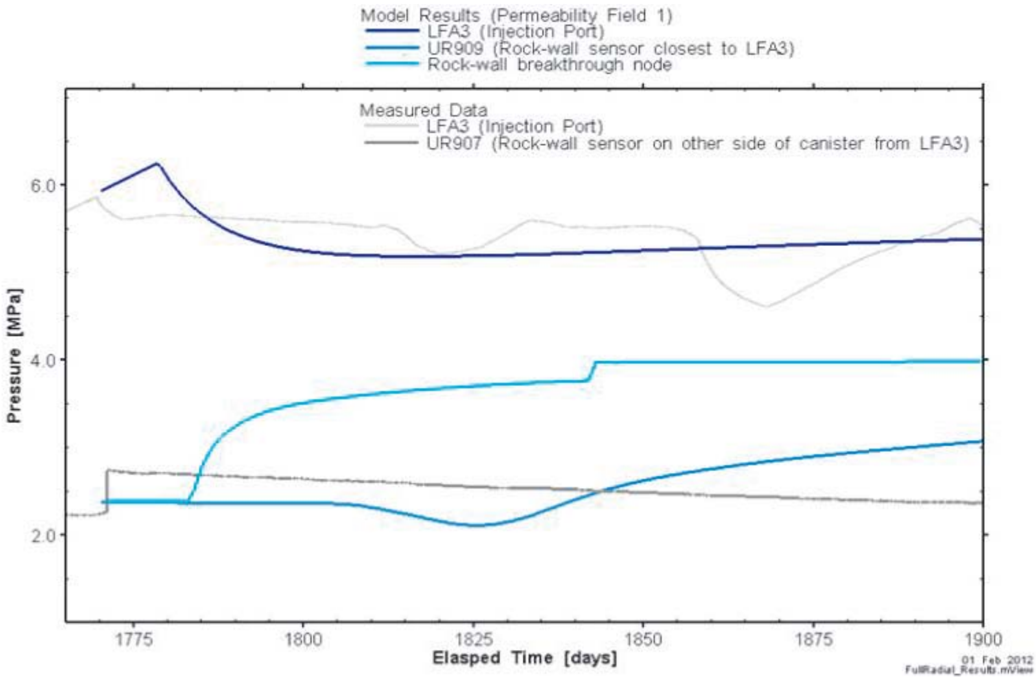


Figure 8-47. *Modelled Injection and Rock-Wall Pressures Using Heterogeneous Permeability Fields for LASGIT 2009 Gas Injection Test.*

8.7 Posiva

Posiva's co-operation with SKB continues with the updated co-operation agreement for years 2011–2014 signed in the autumn of 2011. The focus of the co-operation has been organized in areas related to construction and production of underground openings and development and testing of EBS components and to the safety related research. Within the new agreement also safety and licensing and performance assessment has a more considerable role.

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. The first demonstration tunnels produced with similar specifications as deposition tunnels has been excavated during 2012 and the EBS testing can be initiated with coming years also in ONKALO. Posiva's co-operation is divided between Äspö HRL activities and more generic work that can lead to demonstrations in Äspö HRL.

8.7.1 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 the project phase "KBS-3H Complementary Studies" was executed. Some of the targets to solve a number of pre-identified issues and to conduct component tests were solved and some of the targets were constrained. DAWE was selected for the reference design. Also full-scale system test with compartment plug was conducted at Äspö. During 2011 compilation of the final report "KBS-3H Complimentary Studies 2008–2010" has taken place. Representatives from both organizations have participated in the compilation. At the moment, the next project phase "KBS-3H System Design, 2011–2015" is under planning containing some full-scale tests at Äspö.

8.7.2 Large scale gas injection test

SKB and Posiva have conducted a joint Lasgit-project since 2003. Co-operation in conducting the experimental programme has continued during the year 2011 according to the plans agreed in steering committee meetings by continuing hydration and gas release tests. Similar approach will be used during the year 2012. The results will also be used in the EC project FORGE.

8.7.3 Long term test of buffer material

Posiva's contribution has been attending project meetings. Posiva's studies on pore water chemistry was reported in "Measurements on Cation Exchange Capacity of Bentonite in the Long-Term Test of Buffer Material (LOT)".

8.7.4 Alternative buffer materials

Posiva contributed to the project analyzing chemical processes in the porewater, mineralogical changes of buffer materials and changes in physical properties of buffer materials (swelling pressure, hydraulic conductivity). The clay materials Posiva analyzed were interest in the Posiva's studies are MX-80, Deponit, Asha and Friedland Clay. The results of the analyses were reported in during 2011 (Kumpulainen and Kiviranta 2011).

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

Äspö Task Force Task 7B – "Reduction of Performance Assessment uncertainty through block scale modelling of interference tests in KR14-18 at Olkiluoto" – was practically completed in 2011. Äspö Task Force Task 7C – "Posiva Flow Logging characterization and analysis of low permeable fractures and assessment of flow distribution pattern at shaft wall sections at ONKALO, Olkiluoto, Finland" – was also completed. In the Task 7C3 subtask the nappy experiment was reproduced with a range of numerical models, while in the Task 7C4 subtask the uncertainties contributing to the results (numerical model, geostatistical input) were assessed. The TS28 subtask was re-done with in-fracture heterogeneities applied as in the Task 7C simulations. The FEFTRA simulation package owned by Posiva and VTT was complemented with the feature of describing the transmissivity field over the large, identified, deterministic hydrogeological zones with spatially correlated, Gaussian distributions conditioned at the measured data. The Task7 project included the orientation, assessment and preliminary development steps of a genuinely new numerical method based on atomic basis functions (Fup-functions).

8.7.6 Task force on engineered barrier systems

During the year 2011 Posiva participated in the following tasks:

- dismantling of the Prototype Repository,
- modelling of Task 8 (BRIE) and
- sensitivity analyses for rock-buffer-canister-system.

Investigations of bentonite homogenization and doing the chemistry group benchmark cases were initiated but not reported.

8.7.7 Prototype repository

Posiva participates in the project on the dismantling of the outer section of the Prototype repository during 2011. Posivas main activities are to contribute to the modelling work and laboratory analyses related to behavior of buffer and backfill. Posiva also support the project management by coordinating the project committee, which is established to inform the multilateral participants, about achievements in the project.

8.7.8 Bentonite laboratory

SKB and Posiva are jointly developing the deposition tunnel backfill concept and part of the work will be done in Finland and part in Sweden. Projects like pellet optimization and handling of inflows during backfilling (technical methods) requires large scale testing and the Bentonite Laboratory at Äspö HRL is mainly the place for the tests.

8.7.9 Deposition tunnel plug

SKB has a detailed design for deposition tunnel plug and it will be demonstrated by constructing a full scale plug in 2011/2012. Information on performance of the plug and its requirements, excavation methods, concrete recipe is needed before plug construction. Posiva is developing an own plug design and part of the work will be done jointly. The decision on Posiva's role in plug demonstration will be done in 2011. Posiva is taking part to the construction of the full-scale plug test done in Äspö together with SKB. Posiva's plug development receives valuable information from the experiences gained in the full-scale demonstration done in Äspö.

8.8 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 2011, KAERI conducted the Task 7C 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 7C is related to simulation of groundwater flow in a single fracture.

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

The objectives of KAERI for the Task 7C are to consider the way how to characterize the hydraulic property of a single fracture using field data and to evaluate whether the conditional random generation approach can simulate the PFL and nappy experiments. For the simulation, the Fracture 1, which is the simulation target, was conceptualized as a two-dimensional plane, and a finite element domain was established for it. The hydraulic conductivity (K) field was established by cringing, and a stochastic approach was also applied as another approach for Task 7C, which was expected to consider the uncertainty of the K field. The random numbers following the analyzed statistics of the observed Ks were generated, and the generated random numbers were distributed to follow the semi-variogram of the observed Ks. The optimization method for disposition of the Ks was the simulated annealing method, and 30 realizations were generated as the K fields of the Fracture 1, and the Dirichlet boundary conditions were assigned to the lateral boundaries of the domain. The head values for boundary conditions came from the results of Task 7A. Using the established domain and K-fields, the Posiva Flow Logging (PFL) tests were simulated. The simulated PFL flows were different from the observed ones, and there was little difference between the simulated PFL flows using the K-field from the cringing and from the conditional random generation approach. There were also little variations in the simulated PFL flows among the realizations. These results may come from a small number of observed data with similar Ks. As a conclusion, KAERI tried to consider the uncertainty in characterization of a single fracture using the conditional random generation approach, but it was difficult to evaluate it with the simulated results because of the lack of data and calibration method.

8.9 Nagra

The Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle, Nagra, has the task to provide scientific and technical basis for the safe disposal of radioactive waste in Switzerland. Nagra has had agreements with SKB for participation in Äspö HRL since 1994 to include mutual co-operation and participation in Äspö HRL and Grimsel Test Site projects. The last agreement expired 2003 and Nagra left the central and active core of participants. Nevertheless, Nagra supports the Äspö activities and participates in specific projects.

8.9.1 Task force on engineered barriers systems

Nagra participates actively in both the THM- and the C-Group. A modelling group (Prof. Laloui and coworkers, EPF Lausanne) is involved in two benchmarks of the THM-Group, namely in the "Sensitivity Analyses" and in the "Homogenisation" task. As part of the C-group, developments of the code CrunchFlow (Carl Steefel/LBNL) were supported by Nagra. The model developments were presented in the context of an internal workshop in Berne. Furthermore, core infiltration experiments were conducted at University of Berne as input for C-related modelling benchmarks. The status of Nagra's THM-related modelling activities was presented in the November 2011 Task Force Meeting in Toronto.

The ongoing discussion on the conceptual description of pores in swelling clay has catalyzed the formulation of new benchmark exercises, the release of new experimental results and development of reactive transport codes. These activities have been listed as Nagra's contribution to the chemistry part of the EBS task force.

8.9.2 Alternative buffer materials

During this year the analysis of retrieved samples was completed. A status report has been published and documents from Nagra's investigation and analytical results from the retrieved ABM parcel.

8.9.3 Prototype repository

Nagra joined the Prototype Repository project in 2011 as one of the partners. During this year Nagra personnel participated in the Steering Committee meetings and in field visits during the excavation/dismantling operations.

8.10 Rawra

RAWRA contributes to the "Task Force EBS" project with two contractors, Technical University of Liberec (TUL) and Nuclear Research Institute (NRI). The team from TUL participates in the Prototype Repository task and in Task 8, with modelling of water inflow and bentonite hydration with both own developed and commercial software. The NRI team concentrates on the problems solved in the chemistry section of the project.

8.10.1 Task force on engineered barrier systems

Prototype repository (TUL)

The work of Technical University of Liberec is aimed on modelling of the Prototype Repository Task and the Task 8 which is based on the planned BRIE experiment.

In the Prototype Repository, the first phase of modelling the water inflow to excavation before the start of experiment is solved. They applied the multidimensional (hybrid) approach for fractured rock fluid flow, i.e. combination of rock matrix continuum and discrete fractures. The simulation is done with in-house developed software FLOW123D. Fully 3D approximation was used. The model has been calibrated to order of magnitude of measured inflow, distinguished between fracture inflow and matrix inflow, but without spatial distribution of conductivity and without assigning transmissivity to each individual fracture – this will be continued in the next period.

In the Task 8 we solved the sensitivity study of single borehole inflow with single horizontal fracture and surrounding rock. Same as above, the fracture is represented as 2D plane within the 3D rock model (multidimensional/hybrid approach). The results confirmed the expected distribution between fracture inflow and matrix inflow, depending on the prescribed transmissivity or conductivity respectively.

Next the water diffusion problem in the bentonite installed in the borehole was solved. The TUL team used the multiphysics commercial software ANSYS, where the non-liner heat conduction equation was used to represent the non-linear diffusion problem derived from the Richards equation model. In this case the saturation is the primary variable instead of pressure. They successfully compared own model with the data presented by Akeson in the Task 8 documentation.

Pore water chemistry of ROKLE bentonite: revision (NRI)

In the previous stages, the geochemical model of pore water chemistry of a non compacted and compacted Rokle bentonite was developed (Červinka and Vejsada 2010). The local Ca-bentonite (Rokle deposit, NW Bohemia) is considered as a potential material for both Deep Geological Repository (DGR) buffer and backfill. Because for understanding of many processes related to DGR the knowledge of pore water chemistry is necessary, the synthetic bentonite pore water composition was calculated and then the porewater was prepared to be used in experiments. In the first step, various preparation methods of synthetic porewater samples were tested. Even though the preparation of synthetic pore water may seem at first trivial, in some cases it is complex task. This contrast comes from the difference between the conditions of the model calculation (e.g. calculation to equilibrium without kinetics, the ideal temperature and pressures) and real preparation of bentonite pore water (e.g. impurities in chemicals, non ideal temperature and pressures, dissolution kinetics).

Table 8-8. Modelled pore water of compacted bentonite Rokle (1,600 kg/m^3), Ca-Mg-SO_4-Cl type, equilibrium with gypsum, with following composition (mg/l).

Na^+	K^+	Ca^{2+}	Mg^{2+}	Sr^{2+}	Cl^-	SO_4^{2-}	NO_3^-	HCO_3^-	F^-
44	25	881	213	0	1,078	1,585	0	13	1

The conceptual model of bentonite pore water chemistry was reviewed in terms of defining the conditions for a realistic scenario of DGR (e.g. pressure, temperature, saturation, liquid phase, etc). Based on these conditions the relevant processes contributing on the development of bentonite pore water chemistry will be selected. The main reason is a simplification of the geochemical model for its use in pore water evolution modelling.

In present time, the updated data are obtained for technologically processed Ca-bentonites from the same deposit. These data will represent the input into the geochemical model and the output would be the possible change to the pore water composition at given conditions (mainly reflecting the change in bentonite composition and chemistry).

Bentonite erosion in granite fracture: Ca-bentonites and their behaviour

The conceptual model is focused mainly on the situations, in which the bentonite is not fully saturated and it is in contact with fracture in surrounding granite, where the flow of the groundwater is present. During the saturation phase, the bentonite present either as highly compacted buffer or compacted backfill is not in the chemical and mechanical equilibrium with surrounding environment and the significant proportion of mechanical and chemical erosion of the bentonite can be expected. The main aim of our investigation is to size up the amount of bentonite particles eroded from the swelling bentonite by the flowing water in the fracture during the bentonite saturation and verify that erosion poses a significant risk for the Ca-bentonite to be used as the buffer. For experimental works, the Ca-bentonites (Rokle deposit, NW Bohemia) were used. The main part was focused on the study of bentonite mechanical erosion process and on the characterization of released clay particles (distribution, size, stability). Erosion experiments differed particularly in aperture size of granitic fracture and confirmed that the larger is the aperture, the easier bentonite penetrates into the fracture during the swelling, and this process leads to significant loss of bentonite. Also mineral phase separation occurred, mainly in settings of aperture size about 0.1–0.2 mm (see Figure 8-48).

Further experiments will focus in more detail on the bentonite erosion during the saturation phase with more accurately specification of erosion extent itself. The variables will be the size of aperture and water flow velocity.

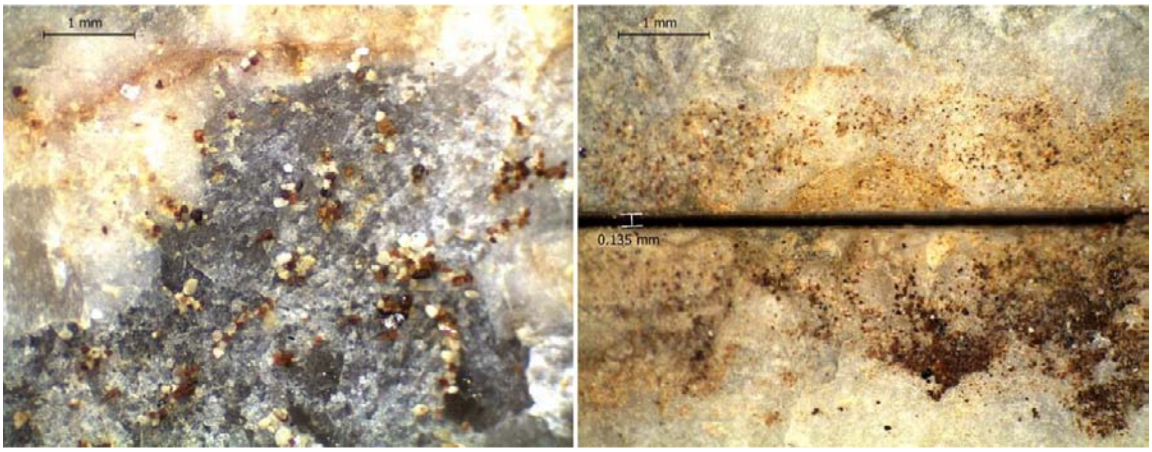


Figure 8-48. *Separation and accumulation of small mineral grains in the fracture (left) and on the edge of fracture (right). Pictures taken by optical microscope Leica S6 D.*

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9.1.1 Conference/meeting presentations

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9.2 Documents published 2011

During 2011 the following reports and documents have been published in the SKB series.

9.2.1 Technical Reports

During the year 59 Technical Reports have been published.