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Äspö Hard Rock Laboratory

Annual report 2012

Svensk Kärnbränslehantering AB

December 2013

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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 2012 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 activities further aim to provide basic geoscientific data to the experiments and to ensure high quality of experiments and measurements related to geosciences.

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 2012, work has been performed in the projects: *TRUE-1 Completion* (the final report for TRUE-1 Completion was completed during 2012 and is now on review) and *BS TASS – Follow up of TRUE Block scale structures* (expectation is to complete report during 2013).

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. All outstanding data originating from both the *'Matrix Fluid Chemistry Experiment'* phase and the *'Matrix Fluid Continuation'* phase are being systematically stored in the Sicada database; this will be completed before Easter 2013 and officially marks the conclusion to the project.

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. All outstanding data originating from these Fe-oxide studies are being systematically stored in the Sicada database; this will be completed before Easter 2013 and officially marks the conclusion to the project.

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. During 2012 the final report of the project was completed and reviewed and is currently being updated before printing. 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.

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 2012, the focus has been on: 1) finalizing porosity measurements of the eight minerals that have been selected for study. 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. 2) batch sorption measurements of two of five selected minerals and preparations for the remaining three minerals and also crushed Äspö material.

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 2012, the modelling work within Task 7 is more or less completed, and the focus is on result analysis, result presentation, reporting, and optional publishing. The Task 8 work mainly contained modelling of *BRIE* with different levels of detailed data. 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.

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. The outer test section was retrieved during 2011 after approximately eight years of water uptake of the buffer and backfill. The laboratory examinations of the taken samples started during 2011 and will be finalised during 2013.

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. Parcel #1 was retrieved after about 1.5 years operation at the target temperature and parcel #2 is planned to be retrieved in March/April 2013. The retrieval of parcel #3 is not decided but is preliminary scheduled to 2015. Three new test parcels were installed in November 2012.

The *Temperature Buffer Test,* a joint project between SKB and ANDRA, 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. A final report for the project was published during 2012.

SKB and Posiva are co-operating on a programme for the *KBS-3 Method with Horizontal Emplacement* (KBS-3H). A continuation phase of the concept development is ongoing and the aim of this phase is to reach a level of understanding so that comparison of the 3V/3H alternatives, and preparation of a PSAR becomes possible. The current project phase is planned for 2011–2016, it covers all areas of the KBS-3 method but the focus is on the KBS-3H specific issues. The sub-project consists of two main activities that were initiated during 2011, the Multi Purpose Test (MPT) which is also part of the EU-project LucoeX (which receives funding from European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013) and the excavation and preparation of a new KBS-3H drift at the –410 m level.

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 2012 the test programme of Lasgit concentrated on gas injection.

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 defect miniature canisters (defect copper shell with cast iron insert). The canisters are exposed to both natural groundwater and groundwater which has been conditioned by bentonite. Five canisters were installed in boreholes in the end of 2006/beginning of 2007 and since then several reports have been published on the installation procedure and on chemical, electrochemical and microbiological results. During 2011 one of the canisters was retrieved (canister number three). The main result for 2012 is the report on the analysis of experiment three.

In the project *Concrete and Clay* the aim of the project is to increase our understanding of the processes related to degradation of low- and intermediate level waste in a cement matrix, the degradation of the cement itself through reactions with the groundwater and the interactions between the cement/groundwater and adjacent materials such as bentonite and the surrounding host rock. During the time period 2010–2013 a total of about 15 experiments will be prepared and deposited at different locations in the Äspö HRL. During 2012 no experimental work has been performed within this project due to lack of experimental sites. Instead the planning of the remaining experiments which will be performed during 2013 has been initiated.

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 2012 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 *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 2012; one in Berlin, Germany on May 22–24 and one in Lund, Sweden on November 26–29. In the latter meeting one day was a joint meeting with the Task Force on Groundwater Flow.

The main objective with the *System Design of Backfilling of Deposition Tunnels* project is to ensure that the method selected for backfill including methods for inspection works as intended with reasonable efficiency. A large number of laboratory tests have been performed with different bentonites and pellet types to find a pellet with improved water storage capability. Pellet installation tests have been done in large scale to study the influence of the installation on the pellet properties. The concept for the installation of backfill is improved and the plan is to make a demonstration test in full scale underground during 2013.

The project *System Design of Dome Plug for Deposition Tunnels* aims to ensure that the reference configuration of the KBS-3V deposition tunnel end plug works as intended. By testing the design in a full-scale demonstration it is to be proven that the method for plugging of a deposition tunnel is feasible and controllable. In 2012, the experimental tunnel (TAS01) was excavated and the accurate plug location was determined. The installation of the inner parts of the plug began in late 2012. The test is part of the EU-project DOPAS, which receives funding from European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013.

Mechanical- and system engineering

At Äspö HRL and the Canister Laboratory in Oskarshamn, methods and 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 approximately 200 technical systems, machines and vehicles that are needed in the final repository have been identified and listed in a database called FUMIS. Extensive work has been put into assessing the degree of development and prototyping needed, costs, schedule, deadlines etc. Several projects within mechanical- and system engineering are ongoing.

Full-scale tests with fully automatic operation of the deposition machine have been completed. Several hundred recorded test runs of the full scale tests were started at the end of 2010 and continued through to 2012. A test report was completed during 2012.

A mobile robot is being developed for the installation of the 230 kg bentonite blocks used as backfilling material in the deposition tunnels. During 2012 an industrial robot was installed on the mobile platform and equipped with laser scanners. Software for the whole unit is under development and testing has been performed in the Bentonite laboratory.

Equipment needed for the installation of the buffer, in the shape of blocks, rings and pellets, with the required degree of precision, is being developed and tested in the Bentonite laboratory. The steering gear of the tool for lift and location of the buffer was tested during 2012 and is now undergoing further development as well as the concept for a carrier. Development of equipment for installation of pellets is ongoing.

There is a frequent need for heavy load transports in the ramp down to the underground areas at Äspö, as it will be in the future final repository. A Multi Purpose Vehicle (MPV) for heavy transports was delivered in August 2011 and is used both for heavy transports related to different experiments and tests in the laboratory, and e.g. as a prototype for a ramp vehicle.

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 is developed.

A transport system for buffer and backfill material is under development. Steel pallets and feed paths have been constructed and manufactured, and are tested at Äspö.

All these projects, as well as others, deliver input data to an extensive investigation of the logistics of the final repository, within which a prototype of the logistic system is developed.

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 2012 been extended with new underground openings. 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 also requires new experimental sites to further develop Äspö HRL as an international research facility. During October to December the rock excavation for the experimental tunnels were done. Total it is about 300 m new tunnel meters in Äspö Hard Rock Laboratory.

In *the Bentonite Laboratory* different methods and techniques for installation of pellets and blocks in deposition tunnels and tests on piping and erosion of buffer and backfill material are performed. During 2012 a number of tests have been performed to study the ability of geo textile to work as a distributor of inflowing water during backfilling. The Bentonite Laboratory has also been used for testing of the new robot equipment for backfilling in the project ÅSKAR.

The operation of the facility during 2012 has been stable, with a very high degree of availability. Construction of the new washing hall by the tunnel entry was initiated before the summer 2012. The washing hall is mainly intended for care of SKB's vehicles and for those contractors using vehicles underground. The facility operation group has also been working with several energy saving measures at Äspö HRL during 2012.

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 2012, 5,621 people visited the Äspö HRL and with the visitors at Clab and the Canister Laboratory included it results in a total of 8,687 visitors. The unit arranged a number of events during 2012. The national event "The Geological Day" was arranged at the Main library of Oskarshamn in September, with SKB as one of the participating organisations.

Open research and technical development platform, Nova FoU

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 Äspö Hard Rock Laboratory and Bentonite Laboratory at Äspö and the Canister Laboratory in Oskarshamn.

International co-operation

During 2012 ten organisations from eight countries in addition to SKB participated in the cooperation at Äspö HRL. Eight of them; Andra, BMWi, NDA, NUMO, CRIEPI, JAEA, NWMO and Posiva together with SKB formed the Äspö International Joint Committee (IJC), which is responsible for the coordination of the experimental work arising from the international participation.

Most of the participating organisations take part in the two Äspö Task Forces on:

- 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.
- 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.

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 2012.

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.

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 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 2012 har arbete pågått i projekten *TRUE-1 Completion* (slutrapport för projektet färdigställdes under 2012 och är under granskning) och *BS TASS – Follow up of TRUE Block scale structures* (förväntas slutrapporteras under 2013).

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. All kvarvarande data från både *Matrix Fluid Chemistry Experiment*-fasen och *Matrix Fluid Continuation*-fasen läggs systematiskt in i databasen Sicada. Detta arbete kommer färdigställas före påsken 2013 och markerar projektets avslut.

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. All kvarvarande data från dessa studier läggs systematiskt in i databasen Sicada. Detta arbete kommer färdigställas före påsken 2013 och markerar projektets avslut.

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. Under 2012 har projektets slutrapport färdigställts och granskad. Rapporten är nu under uppdatering inför tryck. Testerna var framgångsrika ur experimentell synvinkel och resulterade i stora dataset av god kvalitet, vilka förmodligen är användbara för ytterligare studier utöver syftet med detta projekt.

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 modelleringsansats. Ambitionen är att inkludera experimentella data för specifik ytarea och sorptionskapacitet för varje mineralfas som utgör granitiskt berg i modellen. Under 2012 har fokus legat på: 1) slutförande av porositetsmätningar av de åtta mineral som valts ut för studier 2) batch sorption-mätningar av två av fem utvalda mineral, samt förberedelser för de återstående tre mineralen samt krossat Äspö-material.

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 2012 har modelleringsarbetet inom Task 7 mer eller mindre slutförts, och fokus ligger vid analys av resultat, presentation av resultat, rapportering och eventuell publicering. Arbetet med Task 8 har mest inneburit modellering av *BRIE* med olika nivåer av detaljerad data. *BRIE*-projektet är pågående och har kopplingar till Task 8 genom dataleveranser, men även prediktiv modellering inom uppgiften som kan stödja projektet.

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. Laboratoriestudier av prover startade under 2011 och kommer slutföras under 2013.

Målet med projektet *Alternativa buffertmaterial* är att studera olika lermaterial som i laboratorietester har visat sig vara tänkbara buffertmaterial. Tre paket med olika kombinationer av lermaterial har installerats i borrhål i Äspölaboratoriet. Paketen ska värmas för att försiktigt höja temperaturen i bufferten till måltemperaturen 130°C. Paket #1 togs upp efter ca 1.5 års drift vid måltemperatur och paket #2 är planerat att tas upp i mars/april 2013. Upptag av paket #3 är inte planerat men är preliminärt tänkt till 2015. Tre nya testpaket installerades i november 2012.

Syftet med *TBT-försöket*, ett samarbetsprojekt mellan SKB och ANDRA, är att förbättra förståelsen av buffertens termiska och hydromekaniska utveckling under vattenuppmättnadsfasen vid temperaturer runt eller högre än 100°C. Experimentet har genererat data sedan starten 2003 och temperaturen runt den nedre värmaren hade i slutet av 2008 gått upp till 150°C. Försöket avbröts med början under de två sista månaderna av 2009 och all bentonit ner till cylinder 2 togs bort och provtogs genom kärnborrning. Basprogrammet, dvs. bestämning av vattenhalt och densitet, har genomförts parallellt med nedmonteringen och slutfördes under 2010. HM&C-karakteriseringsprogrogrammet lanserades efter nedmonteringen. Det huvudsakliga målet är att undersöka om några betydande skillnader kan observeras mellan exponerat material och referensmaterial. Projektets slutrapport publicerades under 2012.

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 en jämförelse mellan 3V/3H och förberedelser inför en PSAR är möjlig. Den nuvarande projektfasen är planerad till 2011–2016. Ett delprojekt fokuserar på systemtestet (Multi Purpose Test) som även är del i EU-projektet LucoeX, vars finansiering stöds från Euratoms Seventh Framework Programme FP7/2007-2013.

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 2012 fokuserade testprogrammet på gas-injektion.

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 defekta miniatyrkapslar (genomborrat kopparhölje med gjutjärnsinsats) som utsätts för både naturligt grundvatten och grundvatten som filtrerats av bentonit. Fem kapslar installerades i borrhål runt årsskiftet 2006/2007 och sedan dess har flera rapporter publicerats som beskriver själva installationen och kemiska, elektrokemiska och mikrobiologiska mätresultat som erhållits. Under 2011 återtogs en av experimentkapslarna, kapsel tre. Huvudresultatet för 2012 är en rapport på analysen av experiment tre.

I *"Betong- och lerprojektet"* är syftet att öka förståelsen för processer i samband med nedbrytning av låg- och medelaktivt avfall i en cementmatris, nedbrytning av cementen självt genom reaktioner med grundvattnet och växelverkan mellan cement, mark och angränsande material som bentonit och den omgivande berggrunden. Under perioden 2010–2013 kommer ca 15 experiment att förberedas och deponeras på olika platser i Äspölaboratoriet. Under 2012 har inget experimentellt arbete utförts på grund av väntan på experimentplatser. Istället har planering pågått för kvarstående experiment som ska utföras under 2013.

Syftet med *"Lågt pH-programmet"* är att utveckla cementprodukter med låg pH som kan användas i slutförvaret för använt kärnbränsle. Dessa produkter ska användas för tätning av sprickor, fogning av bergbultar, bergförstärkning i form av sprutbetong 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 2012 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 ägt rum under 2012; ett i Berlin, Tyskland under 22–24 maj och ett i Lund, Sverige under 26–29 november. Det senare mötet var ett gemensamt möte med Task Force för grundvattenflöden.

Huvudmålet med projektet *Systemdesign av Återfyllnad för Deponeringstunnlar* är att säkerställa att vald metod för återfyllnad fungerar med önskad effektivitet. Ett stort antal laboratorietester har genomförts med olika bentonit-material och pellet-typer för att hitta en pellet med förbättrad vattenupptagningsförmåga. Tester av pelletinstallation har genomförts i stor skala för att studera installationens påverkan på pelletens egenskaper. Konceptet för installation av återfyllnad har förbättrats och planen är att genomföra ett demonstrationstest i full skala i Äspölaboratoriet under 2013.

Projektet *Systemdesign av Valvplugg för Deponeringstunnlar* syftar till att säkerställa att referenskonfigurationen av KBS-3V deponeringstunnel och plugg fungerar som tänkt. Genom att testa designen i en fullskaledemonstration ska det visas att metoden för pluggning av en deponeringstunnel är genomförbar och kontrollerbar. Under 2012 har tunnelplats för test producerats och lämpligt plugg-läge fastställts. Installationen av pluggens inre delar påbörjades i slutet av 2012. Testet är del i EU-projektet DOPAS, som erhållit finansiering från Euratoms Seventh Framework Programme FP7/2007-2013.

Mekanik- och systemteknik

Vid Äspölaboratoriet och Kapsellaboratoriet i Oskarshamn utvecklas teknik och metoder för slutförvaring av använt kärnbränsle. Befintlig liksom nyutvecklad teknik kommer att användas. De omkring 200 tekniska systemen, maskiner och fordon som behövs har identifierats och har dokumenterats i en databas, FUMIS. Ett omfattande arbete har gjorts för att bedöma grad av nyutveckling, behov av prototypframtagning, kostnad, tidplaner etc. Flera utvecklingsprojekt inom mekanik- och systemkonstruktion pågår.

Fullskaliga tester med helautomatisk drift av en deponeringsmaskin har genomförts. Transport av 25 tons kopparkapslar i en strålskyddande behållare, genom deponeringstunneln fram till 8 m djupa vertikala borrhål där de efter en långsam vridrörelse, sänks ned med millimeterprecision.

För återfyllnaden av deponeringstunnlarna används 230 kg tunga bentonitblock som hanteras av en robotbaserad prototyputrustning, vilken är under testning i Bentonitlaboratoriet. Fullskaleförsök är planerade att genomföras i slutet av 2013.

Utrustning för att installera buffert i deponeringshålen, i form av block och ringar respektive pelletar, med kravställd grad av precision och densitet, är under utveckling. Utrustningen omfattar lyftverktyg, bärare av densamma, samt pelletinstallationsutrustning.

SKB har ett kontinuerligt behov av att utföra tunga lasttransporter ner till underjordslaboratoriet på Äspö liksom . För att utföra dessa transporter beställdes ett fordon kallat Multi Purpose Vehicle (MPV) under slutet av 2010. Fordonet levererades i augusti 2011 och har testats för olika ändamål under 2012 och 2013.

Inom projektet Mission control system (MCS) utvecklas en prototyp för ett omfattande automatiskt system för förvaltning och kontroll av transporter och produktionslogistik för slutförvaret.

I ett projekt utvecklas transportsystemet för buffert och återfyllningsmaterial. Kravspecifikationer för utrustningarna har tagits fram, prototyper av transportpall och matarbanor har konstruerats och tillverkats samt testas nu på Äspö. Vidareutveckling av dessa kommer att ske, liksom konstruktion av bland annat pellettransportbehållare.

Under 2013 har konceptet för omlastningsstation utvecklats där kapseln ska lastas om från ramptransport i kapseltransportbehållare till deponeringsmaskinen.

Samtliga dessa projekt, och en rad andra, ger även indata till en omfattande logistikutredning för slutförvaret som pågår.

Äspölaboratoriet

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 2012 har arbetet med tunnelutbyggnaden pågått. 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 nya experimentområden för att utveckla Äspölaboratoriet som en internationell forskningsanläggning. Under oktober till december utfördes bergarbete för att skapa de nya experimenttunnlarna. Totalt är det ca 300 nya tunnelmeter som tillkommit i anläggningen.

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. Under 2012 har ett flertal tester genomförts för att studera förmågan hos geotextil att avleda och distribuera inflödande vatten under återfyllnad. Bentonitlaboratoriet har också använts för att testa den nya robotutrustningen för återfyllnad.

Driften av anläggningen under 2012 har varit stabil med en mycket hög tillgänglighet. Konstruktionen av en ny spolhall i närheten av tunnelnedfart påbörjades före sommaren 2012, och färdigställdes under året. Spolhallen är avsedd för SKB:s fordon samt för entreprenörer som använder fordon i tunneln. Under året har driftgruppen även arbetet med flera energisparande åtgärder.

Det huvudsakliga målet för enheten *Kommunikation Oskarshamn* är att skapa en allmän acceptans för SKB, vilket görs i samarbete med andra avdelningar inom SKB. Under 2012 besöktes Äspölaboratoriet av 5,621 personer. Enheten arrangerade ett flertal evenemang under året, däribland ”Geologins Dag” som hölls i Oskarshamns Huvudbibliotek, med SKB som en av de deltagande organisationerna.

Öppen forskning och teknisk utvecklingsplattform, Nova FoU

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

Internationellt samarbete

Förutom SKB har tio organisationer från åtta länder deltagit i det internationella samarbetet vid Äspölaboratoriet under 2012. Åtta av dem; Andra, BMWi, NDA, NUMO, 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 flesta av de deltagande organisationerna medverkar i de två Äspö ”Task Force”grupperna: (1) ”Task Force on Modelling of Groundwater Flow and Transport of Solutes” och (2) ”Task Force on Engineered Barrier Systems”.

Contents

1 General

1.1 Background

The Äspö Hard Rock Laboratory (HRL), in the Simpevarp area in the municipality of Oskarshamn, constitutes an important part of SKB's work with design and construction of a deep geological repository for final disposal of spent nuclear fuel. This work includes the development and testing of methods for use in the characterisation of a suitable site. One of the fundamental reasons behind SKB's decision to construct an underground laboratory was to create an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to repository depth. Most of the research is concerned with processes of importance for the long-term safety of a future final repository and the capability to model the processes. 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 Äspö island where the tunnel continues in a spiral down to a depth of 460 m, see Figure 1-1. The total length of the tunnel is 3,600 m where the main part of the tunnel has been excavated by conventional drill and blast technique and the last 400 m have been excavated by a tunnel boring machine (TBM) with a diameter of 5 m. The underground tunnel is connected to the ground surface through a hoist shaft and two ventilation shafts.

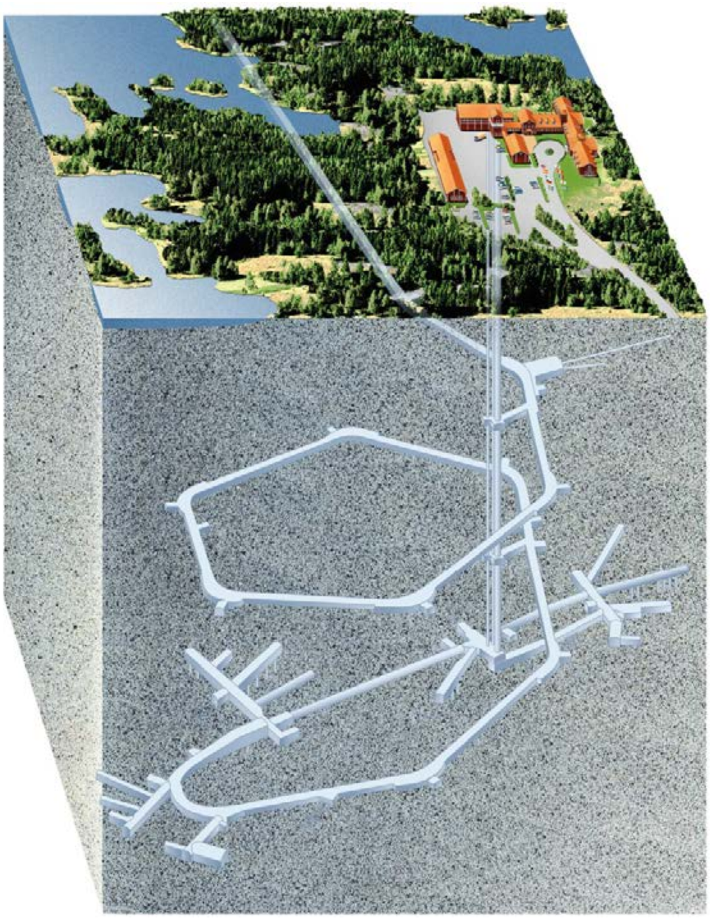


Figure 1-1. *Overview of the Äspö HRL facilities, including the new areas produced in the tunnel expansion, and the Simpevarp peninsula.*

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.

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 2010b). SKB's RD&D-Programme 2013 is currently in preparation.

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) as well as bi- and multilateral projects.

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

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

1.3 Organization

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 four units; the Technology Staff Support, the Repository Technology, Encapsulation/ the Canister Laboratory and the Research and Safety Assessment.

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

The *Repository Technology (TD)* unit is organised in the following groups;

- *Geotechnical barriers and concrete techniques (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 experiment 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.
- *Rock Characterization and Rock Engineering (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.

1.4 International participation in Äspö HRL

During 2012 ten organisations from eight countries in addition to SKB participated in the cooperation at Äspö HRL. Eight of them; Andra, BMWi, NDA, NUMO, CRIEPI, JAEA, NWMO and Posiva together with SKB formed the Äspö International Joint Committee (IJC), which is responsible for the coordination of the experimental work arising from the international participation.

Several of the participating organisations take part in the two Äspö Task Forces on:

- 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.
- 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 took part in work within the IAEA framework. The 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.

NUMO has during 2012 participated in the planning, of a full-scale Multi-Purpose Test (MPT) within the KBS-3H project. In 2013 NUMO will follow the installation of the test equipment. The participation involves one to two persons stationed periodically at the Äspö HRL to get general experience on the planning and operation of actual underground tests.

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. The expansion of the tunnel has resulted in several new experimental sites, some of which has been allocated to projects such as *KBS-3H* and the *System Design of Dome Plug*.

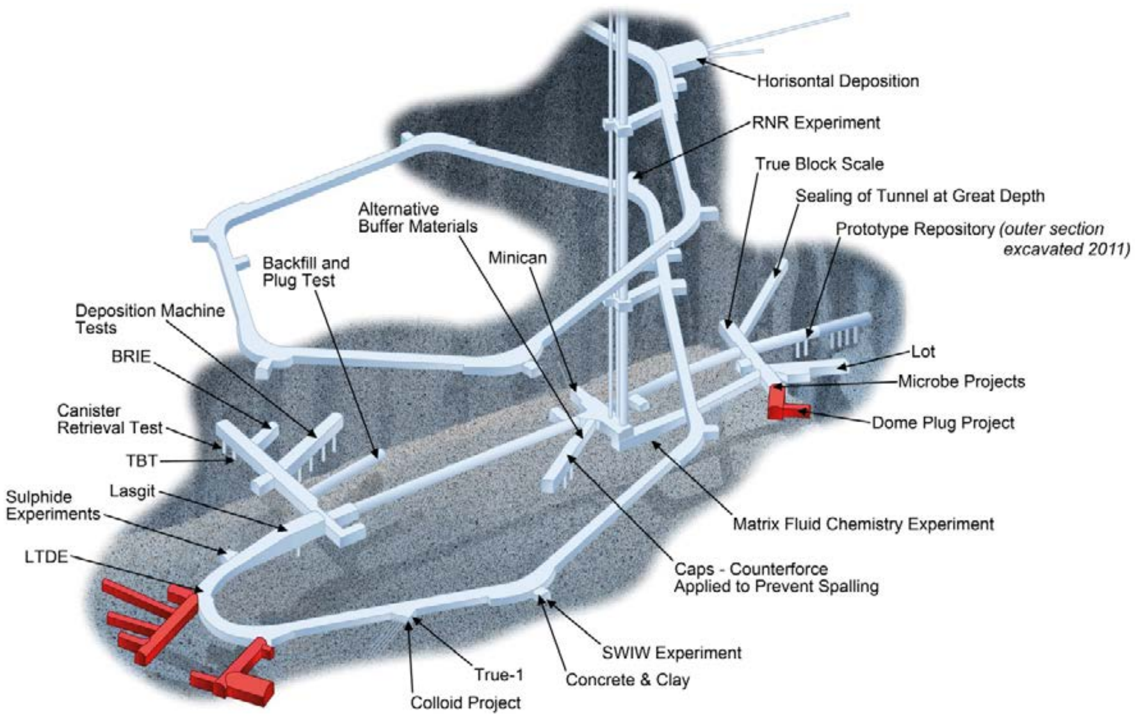


Figure 1-2. *Allocation of experiment sites from –220 m to –460 m level, with areas produced in the expansion of Äspö 2011–2012 in red.*

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 2010b). 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 2012.

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 was 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).

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

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 to work in accordance with SKB's management system.

1.8 Structure of this report

The achievements obtained at Äspö HRL during 2012 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;

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.

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, most updated descriptive model of the Äspö site includes data collected up to 2002 and was published in a series of reports in 2005 (Berglund et al. 2003, Vidstrand 2003, Laaksoharju and Gurban 2003, Hakami 2003).

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

- 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.

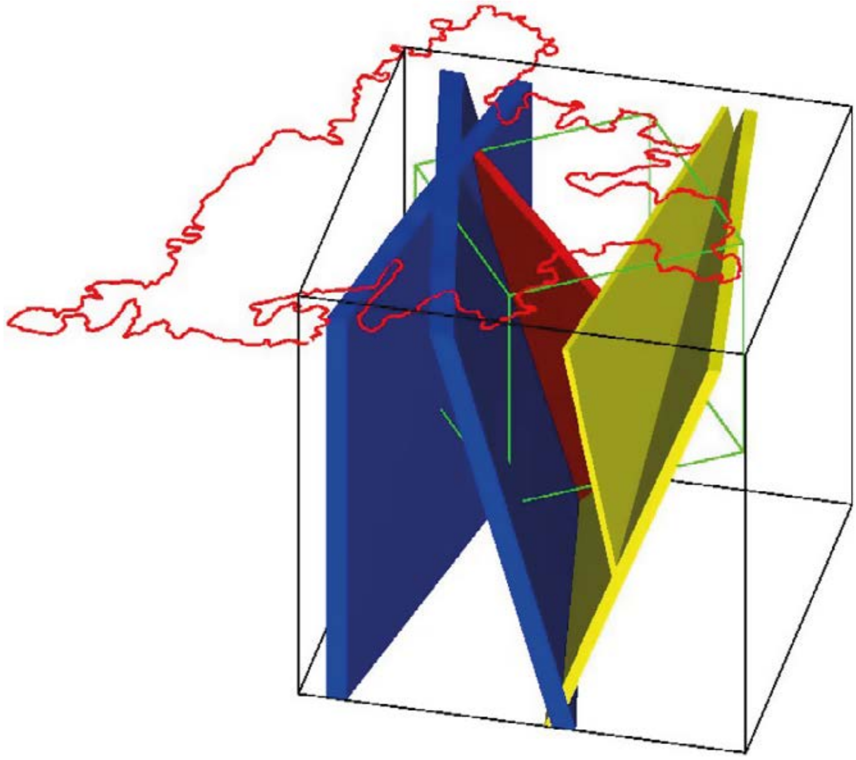


Figure 2-1. Modelling work to help understand the geological, hydrogeological and geochemical conditions of the Äspö site.

Experimental concept

- The nomenclature used for the different disciplines and for the structures in different scales shold 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

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 together with conceptual understanding of the relative movements of geological structures (Mattsson 2011), Figure 2-2. All water conductive fractures and water conductive deformation zones have been plotted in different sections along the tunnel. Hydrogeochemical data has been analyzed. Explorative analysis of the major components has been and is currently being done. Plots of Cl, Mg, δ^{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 in PhreeqC.

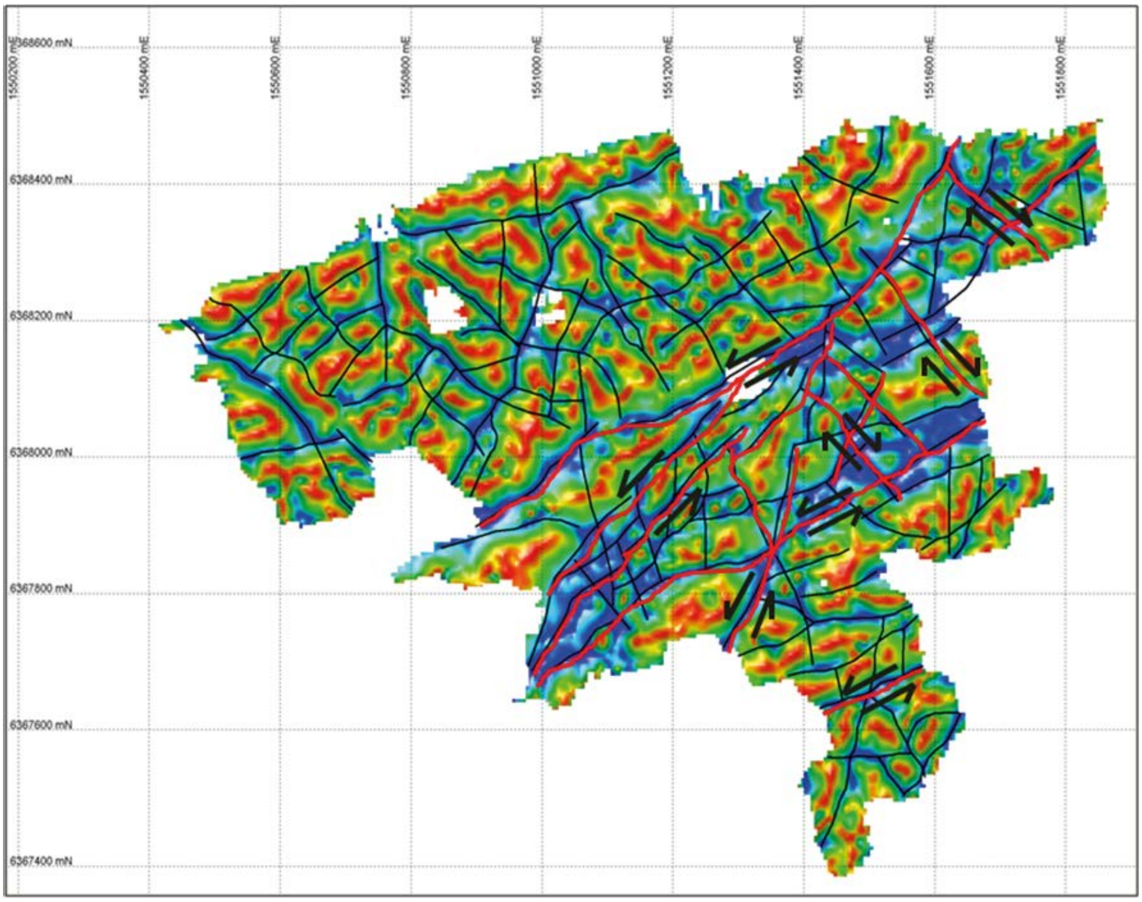


Figure 2-2. *Lineament interpretation of ground surface magnetic measurements performed in 1988 (Mattsson 2011).*

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.

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 and the project Expansion of Äspö HRL 2011–2012.

Results

The expansion of Äspö HRL has continued see further Section 6.2. The geological work has mainly consisted of photogrammetry and mapping with RoCS, see Section 2.3.2. Both front mapping and mapping of roof and walls in sections of tunnels TASU and TASP in advance of shotcreeting has been performed, see Figure 2-3.

Core samples for determing petrophysical properties of samples with our without fractures has been collected and shipped to laboratory for determing geophysical properties on behalf of the project DETUM-1, subproject Large fractures.

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 was 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. After finishing the feasibility study concerning modern geological mapping techniques SKB commenced a new phase of the RoCS project. The project now concentrated on finding or constructing a new system for geological underground mapping. Photogrammetry based on digital photography and/or laser scanning would be a part of that system. The resulting mapping system shall operate in a colour 3D environment where the xyz-coordinates are known.

Experimental concept

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

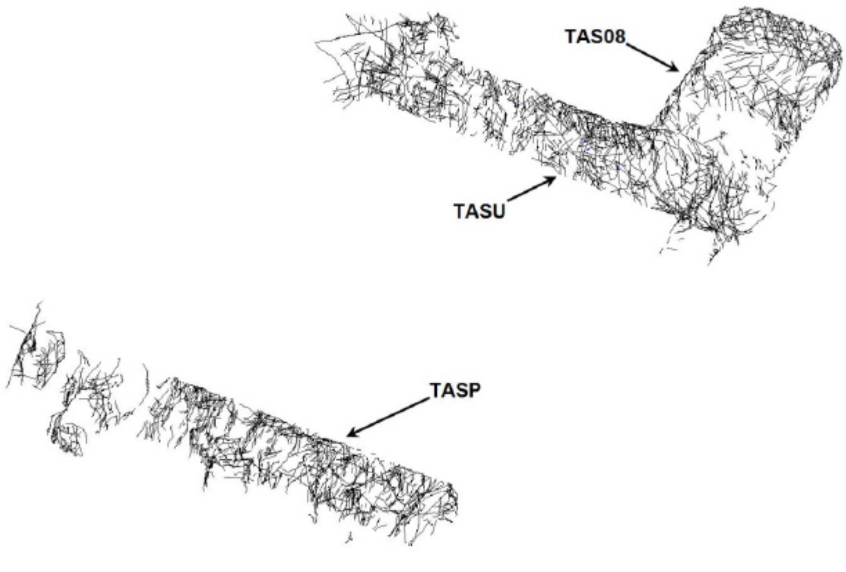


Figure 2-3. *Mapped fractures in TAS08, TASU and TASP.*

Results

No adequate geological mapping system that could full fill SKB's requirements could be found on the open market. SKB therefore decided to create their own system and use photogrammetry to accomplish 3D-models. In 2010 the Austrian company 3G Software & Measurement (3GSM) delivered the hardware and software for the photogrammetry part of RoCS. 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 company Ergodata that on SKB's behalf developed the core logging software Boremap was given the commission to develop the mapping module in RoCS. After a number of test versions eventually a version that was considered ready for professional tunnel mapping was launched in the beginning of 2012.

The system (photogrammetry and mapping) was used within the project Expansion of Äspö HRL 2011–2012 where a number of new tunnels/drifts were to be excavated. At first RoCS was used parallel with the "old" 2D mapping system TMS (Tunnel Mapping System). After some time, however, RoCS was considered stable enough to be used alone. A number of adjustments have been made during the year and more will be necessary to make RoCS the adequate tool for tunnel mapping, but it can alredy be concluded that it has many advantages compared to the TMS system. Today RoCS version 1.1.1.0 is used. The 3D-model with or without geological features can be used not only in RoCS but also in various 3D-visualisation and CAD-programs.

For each round (drilling, blasting and unloading) digital photos were taken to make it possible to create a 3D-model of the newly excavated section. However, while excavation of a tunnel took place only the tunnel faces were mapped after each round and only a 3D-model of the face was created in the tunnel by the geologist team (Figures 2-4 and 2-5).

Figure 2-4. *TASP-tunnel. Geological mapping with the RoCS system in tunnel environment.*

Figure 2-5. The geological features are drawn directly on the laptop screen and data are fed into the computer.

Photography of the whole round-section and creation of the 3D-model of the tunnel face needed about 20 minutes to accomplish. The geological mapping of the tunnel face took about 1.5–2.5 hours. Before photography and mapping could take place the tunnel section had to be cleaned, reference markers had to be placed on the walls and front and the markers surveyed to make it possible to place the model in the correct coordinate system. This took about 1 hour. Thus, the total time needed for the geological characterisation of each tunnel face was about 3–4 hours. This is much more than the time needed in the tunnel while using the TMS system, but on the other hand very little office work will be needed once necessary adjustments of RoCS have been made.

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 new data. The main features are the inclusion of data collected from various experiments and the adoption of the modelling procedures developed during the Site Investigations at Oskarshamn and Östhammar. The intention is to develop the site descriptive model (SDM) into a dynamic working tool suitable for predictions in support of the experiments in the laboratory as well as to test hydrogeological hypotheses.

Objectives

The major aims of the hydrogeological activities are to:

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

Experimental concept

Maintain and develop the understanding the hydrogeological properties and processes of the Äspö site as well as of the hydrogeological characterisation and analysis methodology at large as well as support of experiments and projects with hydrogeological expertise.

Results

The site descriptive modelling for Äspö SDM was prioritized to a lower grade in favour of other projects e.g. the project Expansion of Äspö HRL 2011–2012, see Section 6.2. In particular an interim deterministic hydrostructural model was developed for the project. The model was based on data prior to tunnel construction and constituted a prediction of the tunnel excavation. Hydrogeological input was delivered to experiments and other projects as well.

For the Äspö SDM project, see Section 2.2, a conceptual understanding of the genesis of large-scale deformation zones (> 1 km) was formulated and hydraulic properties were assigned to both deformation zones and rock masses.

2.4.1 Hydro monitoring programme

Background

The hydro monitoring programme constitutes a cornerstone for the hydrogeological research and a support to the experiments undertaken in the Äspö HRL. Monitoring was also required by the water rights court, when granting the permission to execute the construction works for the tunnel.

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 of 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 meterological parameters on 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

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 functioned well and the monitoring points in the tunnels have been maintained. The monitoring system has provided continuous support for the experiments and projects, e.g. the project Expansion of Äspö HRL 2011–2012, in their planning and execution and for the tunnel activites at large.

The system was necessary for the project Expansion of Äspö HRL 2011–2012 in keeping track of induced drawdown and for developing the hydrogeological model. For controlling the head the cored boreholes in the volume around the area for expansion was monitored and the head was specially controlled in a separate borehole, KA2050A, localized in the centre part of the excavated tunnel volume.

Nine monitoring boreholes were decommissioned and one new monitoring borehole was commissioned as a result of the tunnel excavations. Surface drilled boreholes are now all equipped with transducers/loggers.

Quality control of data is performed at different levels and scope; weekly, tertially and annually in internal, non-public documents.

2.5 Geochemistry

Background and objectives

The major aims within the geochemical work are to:

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

Results

A method for sampling trace elements in deep groundwaters has been developed with good results and the work will be compiled in a scientific publication in 2013. Further sampling with the technique DGT (Diffusive Gradient in Thin-film) is planned.

A work to develop a system for on-line measurements for pH, EC, Eh (redox), O^2 and temperature in the tunnel started in 2012 and tests are planned in four boreholes sections during 2013.

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 waters in core- and percussion drilled boreholes. After the completion of site investigation programme a reduced monitoring program was compiled for geochemistry in the area around Äspö. The selection of monitoring objects has been made to meet the needs of SKB’s geochemical information in connection with Äspö SDM and other projects, as well as for Nova FoU.

Objectives

The hydrochemical 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 2012 two groundwater sampling campaigns have been made in Äspö HRL. In May and November 17 borehole sections were sampled, 9 sections were rejected because of the project Expansion of Äspö HRL 2011–2012. The borehole KA2162B was removed from the program because of water shortages. SA1009B and SA2074A have very low flow but are still able to sample with a reduced chemistry class. All analytical results are expected to be reported during the first four-month period in 2013. Two examples of hydrogeochemical changes over time can be seen in Figure 2-6.

Sampling of surface water, soil tubes and precipitation has been performed at regular intervals. Core- and percussion drilled boreholes drilled from the surface have been sampled twice a year, in March and September.

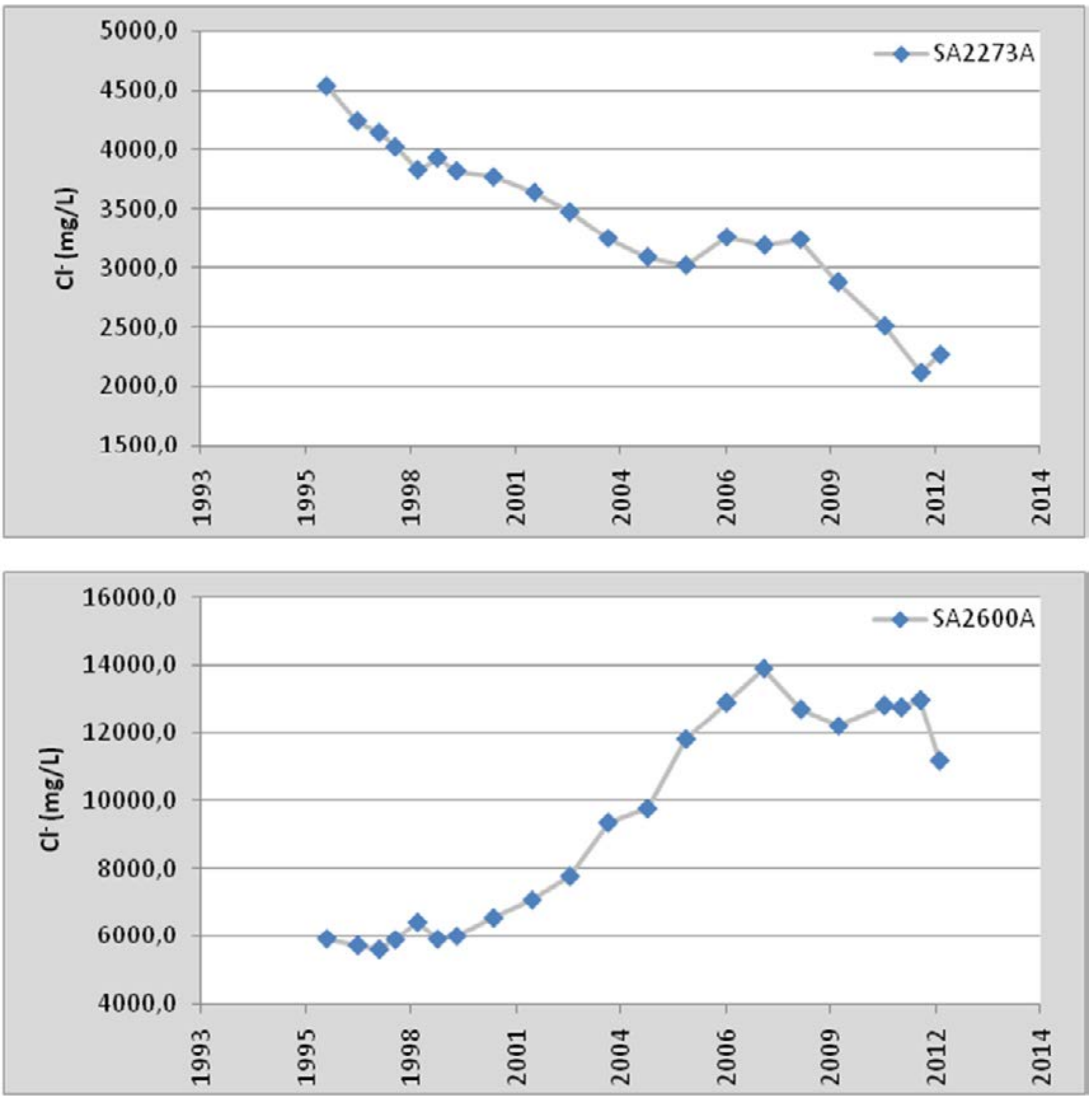


***Figure 2-6.** The concentration of Cl⁻ versus date of sampling from the boreholes SA2273A and SA2600A, sampled during the hydrogeochemical monitoring campaign from 1995 until 2012 in the Äspö HRL tunnel.*

3 Natural barriers

3.1 General

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.

3.2 Tracer retention understanding experiments

3.2.1 True-1 Completion

Background

The main activity within TRUE-1 Completion was the injection of epoxy with subsequent over-coring of the fracture and following analyses of pore structure and 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 deconstruction of the site.

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 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 included:

- Re-instrumentation of boreholes KXTT3 and KXTT4 in order to facilitate coming experiments, overcoring and analysis.
- Complementary tracer and hydraulic tests.
- Epoxy injection, over-coring and core-logging of KXTT3 and KXTT4.
- Analysis of core material using image analysis, mineralogical investigations and analysis of Cesium on fracture surfaces 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 2012, the three primary reports covering tracer tests (Nordqvist et al. 2012), epoxy injection with overcoring (Sigurdsson and Hjerne 2012) and analyses of core material (Hakami et al. 2013), have been updated after review and sent for printing. The final report for TRUE-1 Completion, Byegård et al. (2012), was completed during 2012 and is now on review. This report includes a summary of the primary reports, conclusions and updated conceptual models for Feature A at the TRUE-1 site. The main results presented in the final report strengthen and complement earlier findings made within earlier parts of the TRUE projects. The principle conclusions made in the final report may be summarized as follows:

- Feature A is heterogeneous in terms of transmissivity within the borehole array and has an undulating and/or stepwise character. The mean physical aperture is 0.45 mm, varying in the span 0–1 mm.
- The key elements of the micro-structural model of Feature A is repeated fracturing and associated wall rock alteration, i.e. several generations of fracture coatings with a dominant coverage of the main fracture surfaces of chlorite and clay minerals together with some wall rock fragments, and calcite with related accessory minerals on the fracture walls as well as highly altered rock adjacent to these fractures.
- The interpretation of performed tracer tests indicates that sorption of the relatively strongly sorbing tracer Cs may to some extent be irreversible, or slowly reversible on the scale of the TRUE-1 tracer tests.

The plan is to update the final report after review and print all four reports during 2013, 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 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 representativity 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 representativity of information from pilot boreholes.

Results

Nothing to add compared to account given in the annual report for 2011 (SKB 2012a). Finalization of the report has been delayed due to other commitments. Expectation is to complete top copy during first quarter 2013.

3.3 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 microfractures, 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 depth 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 microfissure 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 some thousands of years.
- Fluid inclusions have made no obvious contribution to the sampled matrix waters.
- Although stringent sterility measures were taken to minimise microbial activity, microbially 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 of the project, the 'Matrix Fluid Chemistry Continuation' phase, 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.
- To further characterise hydrochemically 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 3-1, was constructed to try and 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 porewaters (and gases) under pressure, and f) convenient sample holder to facilitate rapid transport to the laboratory for analysis.

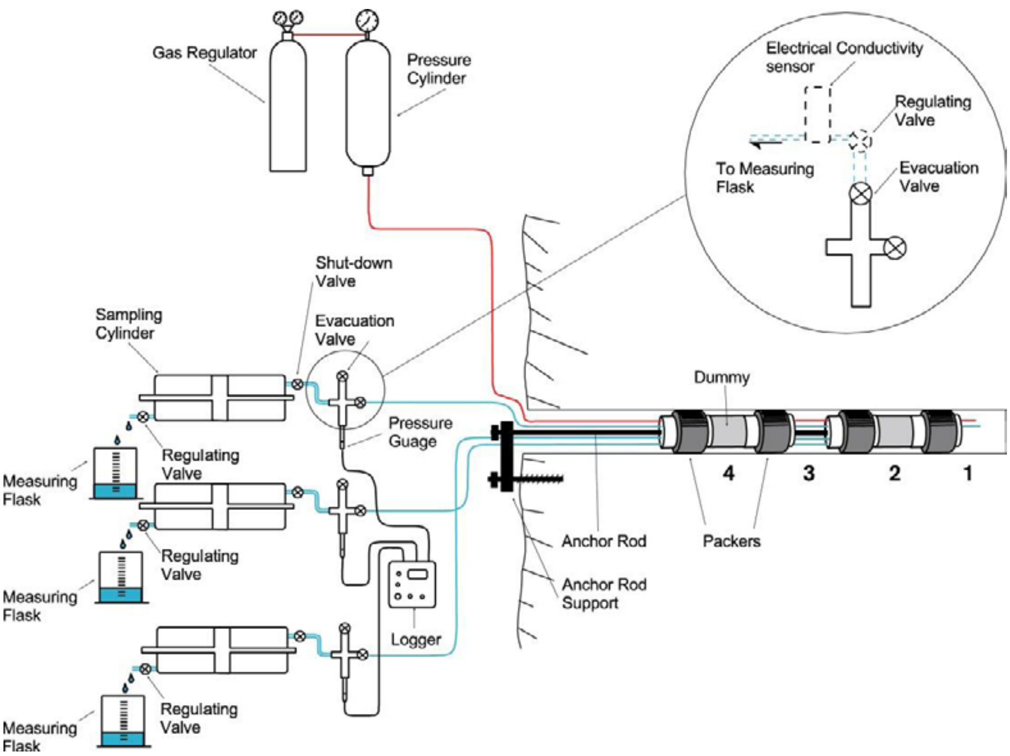


Figure 3-1. *Matrix Fluid Chemistry experimental set-up. Borehole Sections 2 and 4 were specifically selected to collect matrix fluid, although section was also successfully sampled; section S1, with the highest residual volume, could only be sampled for gas. Sections 1–4 were continuously monitored for pressure. The contact between Äspö diorite and Ävrö granite occurs in Section 3 at 8.5 m.*

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 microfractures and to concentrate on measuring the hydraulic parameters of the microfractures and the rock matrix.

Results

The most important hydrochemical, hydraulic and porosity aspects of the Matrix Fluid Continuation phase have been published in the open literature by Waber and Smellie (2008) and Tullborg and Larson (2006).

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 to 5.8E–13 m/s. This compares with 1.0E–14 to 5.8E–13 m/s in the rock surrounding the matrix borehole, indicating there is no large difference between the test sections containing visible microfractures or not. However, there is evidence in some cases that microfractures 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 microfractures and that preferential hydraulic microconductors may exist close to visible microfractures.

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 microfractures 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).

Furthermore, the long term experiment carried out over 7.5 years indicated that the matrix porewaters are less saline than the surrounding fracture groundwaters and do not have a marine component, i.e. the presence of shallower marine waters observed in the more transmissive fractures close to the Matrix Fluid Chemistry Experiment locality, resulting from drawdown effects during the excavation period, had not yet penetrated through the rock matrix.

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 during preparation than the thicker samples; this can also be due to a higher portion of microfractures 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.%.

Present status

All outstanding data originating from both the 'Matrix Fluid Chemistry Experiment' phase and the 'Matrix Fluid Continuation' phase are being systematically stored in the Sicada database; this will be completed before Easter 2013 and officially marks the conclusion to the project.

3.4 Fe-oxides in fractures

Background

The Fe-oxide studies described below were carried out by the members of the Nano Science Group at the Geological Institute, University of Copenhagen in close cooperation with the Swedish Nuclear Fuel and Waste Management Company. Some aspects of the studies contributed to two Master's Theses (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 provide clues about redox conditions during Fe-mineral formation or as a result of its inclusion in other secondary fracture minerals.

To provide a more direct application to specific problems relating to the Swedish waste disposal concept, 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 and subsequently published (Skovbjerg 2005, Christiansen 2004).

Comprising an additional 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. 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 (Dideriksen and Stipp 2005).

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 samples were used to establish the penetration depth of oxidising waters below ground surface at different sites (Dideriksen et al. 2007). 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 variaties 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 (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)-oxyhydroxide 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 ($GRso_4$) 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, formed 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 meltwaters).

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. 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 can not 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.

Present status

All outstanding data originating from these Fe-oxide studies are being systematically stored in the Sicada database; this will be completed before Easter 2013 and officially marks the conclusion to the project.

3.5 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. 2011). It has been discussed whether drilling and pumping activities and/or installation of monitoring equipment might influence the sulphide concentration. Sulphate reducing bacteria utilize some organic molecules and hydrogen gas in their metabolism when they reduce sulphate to sulphide. Anaerobic methane-oxidation is another process that produces sulphide but this process is not yet fully understood.

Objectives

The objective of the project as a whole 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 was performed in 2012 that focused on the possible effects from the borehole instrumentation on the microbial sulphide production in groundwater of drilled boreholes. Borehole instrumentations from two boreholes drilled in the 1990's were dismantled and investigated. The boreholes have different sulphide concentrations and an important objective was to compare the conditions in the boreholes and determine any differences in the instrumentation that can 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 (polyvinylchloride).

The investigation included visual observations of corrosion and degradation of plastics, analyses of total number of bacteria (TNC) and sulphate reducing bacteria (SRB) on surfaces, analyses of secondary minerals and stable isotopes in minerals and dissolved species in water. The conceptual idea was to trace the reaction pathways for microbial sulphide production and to elucidate if some material in the instrumentation could be a part of some reaction pathway.

Results

Evaluation and reporting of results from the investigation is in progress. Some preliminary results can be summarised as follows;

- The $\delta^{34}S$ in the dissolved sulphide and sulphate in the groundwater in both boreholes indicated on going SRB-activity in the section water but also in the fracture water. Analyses of $\delta^{34}S$ in precipitates of pyrite suggest that the sulphide production have been faster than the supply of sulphate from the fractures, in local micro-environments in the section where the water has been close to stagnant.
- Precipitates of Al-oxyhydroxides and Si-rich precipitates were found close to the PVC-tape (Figure 3-2). Precipitates of calcite were abundant on the stainless steel surfaces of the packers, the stainless steel acting as a cathode with higher pH than the surroundings. $\delta^{13}C$ values in calcite were either within or lower than the range expected for precipitates from the groundwater $\delta^{13}C$ composition. The lower values may be due to local fractionation of C during oxidation of organic matter to HCO_3^- which is eventually incorporated into calcite.

Figure 3-2. *Pipe string of aluminium, plastic tubing and black tape. Precipitates of Al-oxyhydroxides and Si-rich precipitates. Corrosion of aluminium beneath tape.*

- The pipe string of aluminium had been subjected to corrosion beneath the tape (Figure 3-2). It was obvious that corrosion occurred where plastic (tape or tubing) and metal was in contact. The corrosion process was similar in both boreholes.
- There was no significant difference in TNC or SRB numbers between the instrumentation in the two boreholes with high and low sulphide concentration (KA3110Aand KA3385A respectively). TNC and SRB were lower on the stainless steel surface of the packers than on the other material. There were no significant difference in TNC and SRB on the surfaces of plastics, aluminium and tape.
- It was not possible to make an identification of the species of the microorganisms on the equipment due to small amounts of DNA in the samples.

3.6 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 was 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 cesium normally used as tracers within the site investigations were also added. This synthetic groundwater was 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 was monitored. Before the withdrawal phase, a waiting pahse was employed for one of the two main Swiw tests. The combination of tracers, both added and natural, and test performance, with or without waiting phase, may then provide desired information of diffusion, for example if the diffusion is dominated by the rock matrix or stagnant zones.

Results

During 2012 the final report of the project was completed and reviewed and is currently being updated before printing. 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. There are clear and consistent differences between breakthrough curves for the tests with and without waiting phase, respectively, for all tracers. The differences are qualitatively consistent with what can be expected if diffusion takes place during the waiting phase. The late-time breakthrough for the added tracers clearly indicates diffusive mass transfer, shown by straight lines in log-log tracer breakthrough plots. The log-log slopes often approach the value of –1.5, which is the ideal value for single-rate matrix diffusion. An interesting observation is that sorbing tracers generally have somewhat flatter slopes and that the Swiw test with a waiting phase also results in flatter slopes. Basic simulations with a single-rate matrix diffusion model suggest that such a model is not sufficient to explain both early and late parts of the tracer breakthrough.

3.7 Äspo model for radionuclide sorption

Background

Today, geochemical retention of radionuclides in the granitic environment is commonly assessed by the use of 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 the effects of grain boundaries are questions that need to be resolved. Furthermore, it is desirable to verify possible localisation of sorption of radionuclides to specific minerals within the rock.

Objectives

In 2011, the overall objective of this project was revised, with the focus redirected to provide experimental evidence for the formulation of process quantifying models for geochemical retention of radionuclides, in granitic environments. This work has continued during 2012. Particularly, the operational objectives are:

a) to experimentally quantify how the sorption of some selected radionuclides depends on particle size and BET surface area for some important minerals that occur in Äspö rock and for some authentic Äspö rock material;

b) to experimentally identify the minerals in the Äspö rock material that mainly contribute to the sorption of some selected radionuclides and to clarify which information about localisation of sorption to grain interfaces and other structures at mineral surfaces that can be obtained from autoradiography and photography, in combination.

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 ("museum specimen") and also a drill core of rock material obtained during the Äspö-LTDE experiment. The concept follows the CA approach, where the behaviours of the individual pure minerals are studied separately and then the knowledge is synthesized to a model for 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 2012, the focus has been on: 1) finalizing porosity measurements of the eight minerals that have been selected for study. 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. 2) batch sorption measurements of two of five selected minerals and preparations for the remaining three minerals and also crushed Äspö material. Special attention have been given to the use of pH buffers in batch sorption, where pilot experiments with Äspö material indicate a clear advantage of using pH-buffered water phase over similar non-buffered batch experiments.

Results

Characterization of mineral samples

Figure 3-3 shows an example of data for labradorite particles for mean values of the particle size (PS) in mm and Non-Spherical-Particle (NSP) ratio in percent, both measured with a Particle Sizer instrument (Anatec), as function of the theoretical mean particle size, deducted from the size fraction.

For labradorite (shown in Figure 3-3), the measured mean particle size follows the theoretical mean particle size fairly well, even though the measured shape of the particles is, as expected, not completely spherical (80% of a spherical shape). In Figure 3-3, the inserted SEM pictures give examples of typical particle shapes for different particle size fractions.

Figure 3-4 shows an example of specific pore volume and pore size for labradorite for different particle size fractions, as measured with a N_2 gas adsorption instrument (Micromeritics ASAP2020) and evaluated through the BJH-model (Barrett et al. 1951).

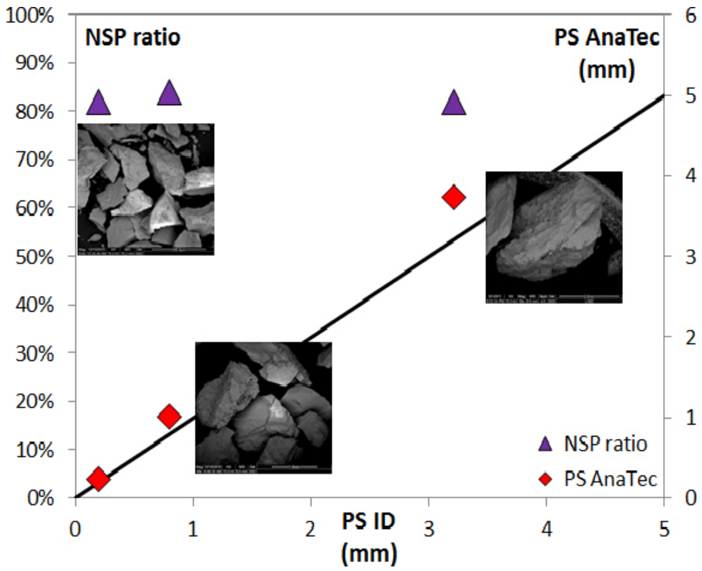


Figure 3-3. *Particle size in mm (diamonds, scale at right), NSP ratio in % (triangles, scale at left) and SEM pictures of the analyzed three particle size fractions (0.075–0.125, 0.5–1.0 and 2.0–4.0 mm) of labradorite as function of theoretical mean particle size. The line represents equality between actual and theoretical mean particle size (compare diamonds, scale at right),*

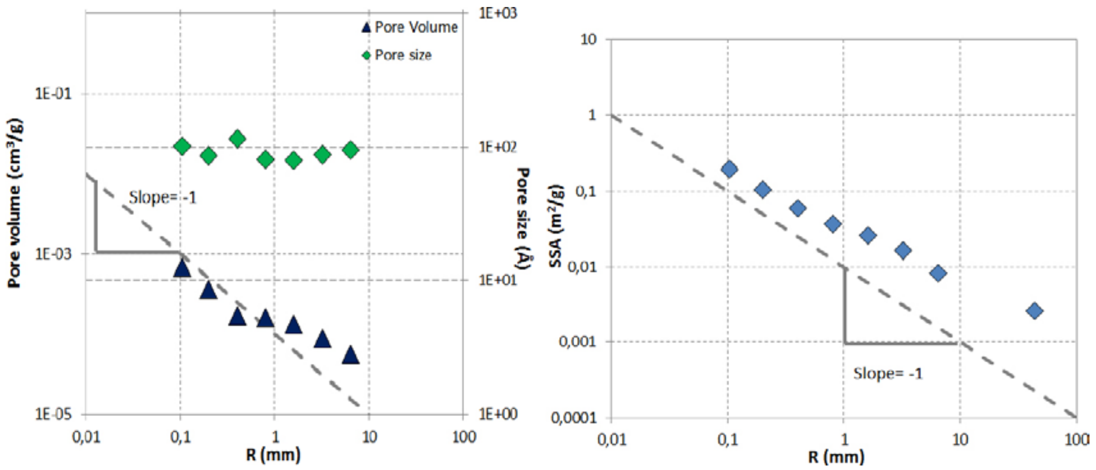


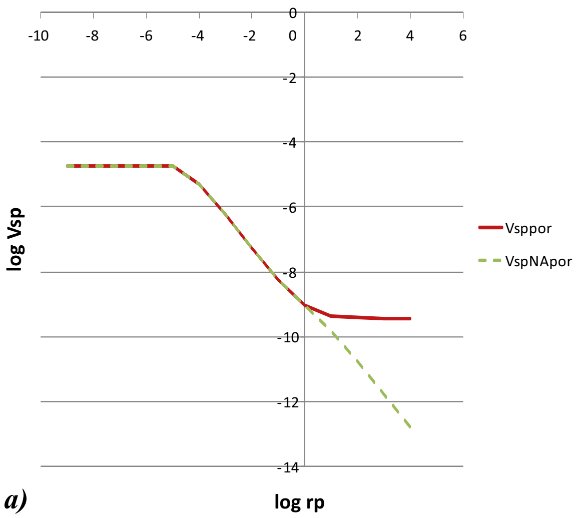
Figure 3-4. *Pore characteristics of Labradorite. (a – left): Measured pore volume ([cm³g–] ¹triangles, left scale) and average pore size ([Å] diamonds, right scale) of seven labradorite particle size fractions as function of theoretical mean particle size [mm].(– right): Specific surface area of the same seven labradorite particle size fractions as function of theoretical mean particle size. N.B. Logarithmic scale. Dotted lines arbitratily indicates a slope of –1.*

The pore volume data (Figure 3-4a) seems to follow a linear trend with a negative slope and, when comparing data, it seems to be closely related to the previously measured data for specific surface area (Figure 3-4b). Presently, the dependency 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 (compare André et al. 2008, 2009, Dubois et al. 2009, 2011). Figure 3-5 showing generic simulations of specific volume (Figure 3-5a) and specific surface area (Figure 3-5b) as function of particle size show, in part, similar trends as observed in the measurements (compare Figure 3-4), encouraging further assessment and testing of the model using this concept of particles consisting of radial zones of different porosities,

Batch sorption measurements

Before commencing with the sorption measurements of radiotracer and the mineral fractions, a modified batch sorption methodology using added pH bufferes have been tested. Cs and Sr sorption onto two different size fractions of Äspö diorite were studied in the pH range 5-9, comparing buffered and non-buffered conditions. Figure 3-6 shows results for R_d values [m^3/kg] for the sorption of Sr on the 0.09–0.25 mm particle size fraction with and without buffered aqueous solution. The results from the pH-buffered conditions clearly reveal a sorption isotherm for Sr onto granite with the expected behaviour, with increasing sorption with increasing pH. The non-buffered systems, on the other hand, do not show any trends at all, due to severe pH drift, making most of the samples to end up at pH 7–8. Note also the improved reproducability of the duplicate experiments for the buffered systems. Importantly, for the pH range 7–8 where data is available for both buffered and nonbuffered conditions, results for the different conditions are similar at a given pH. This shows that the buffers used do not affect the sorption severely.

In October 2012, the first batch sorption experiments with seven different size fractions of the minerals biotite and labradorite were started. During 2013 this is to be followed with apatite, chlorite and magnetite.



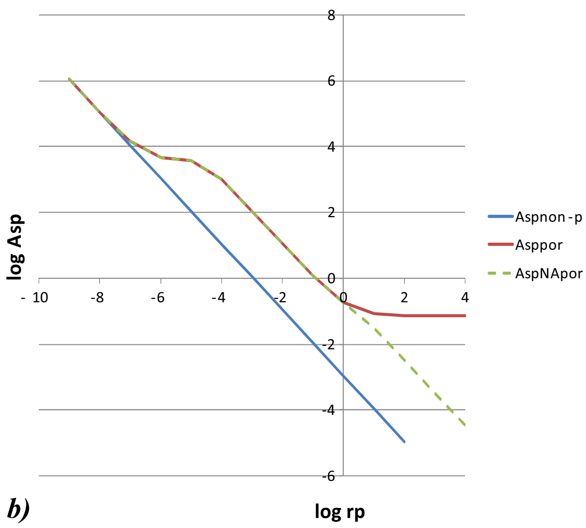


Figure 3-5. *Specific volume (a – left) and specific surface area (b – right) as obtained from a generic model simulation assuming particles with radial zones of different porosities. N.B. Logarithmic scales. Brown-red full drawn line:2-zone model, assumption of a disturbed zone at the surface of the particle surrounding a pristine core with lower porosity. Green dotted line: 3-zone model, assumption of a pristine radial zone sandwiched between a mechanically disturbed zone at the surface of the particle and a non-porous core. Blue line: non-porous particle (no pore volume) .*

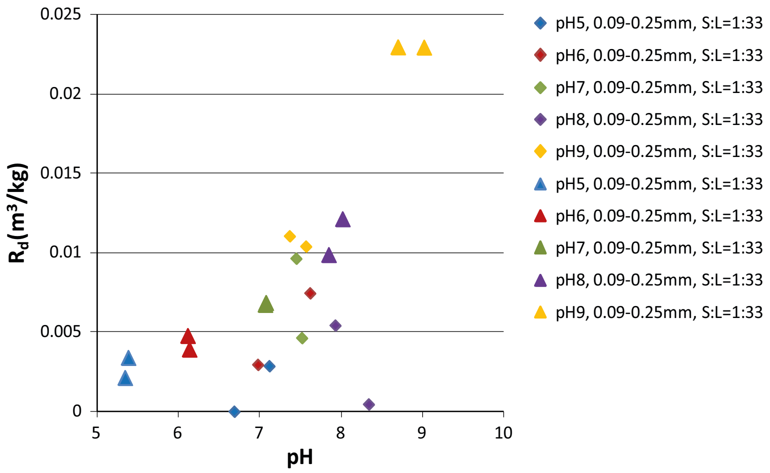


Figure 3-6. *R_d values [m^3 kg^{-1}] of Sr sorbing onto Äspö diorite as function of measured pH at the time of the R_d determination.Triangles mark pH buffered and diamonds mark pH non-buffered aqueos solutions of0.22M $NaClO_4$ at an initial pH of 5 (blue), 6 (brown), 7 (green), 8 (purple) or 9 (yellow).*

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

Background

The work within Äspö Task Force on modelling of groundwater flow and transport of solutes constitutes an important part of the international co-operation within the Äspö HRL. The group was initiated by SKB in 1992. A Task Force delegate represents each participating organisation and the modeling 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 utilised to support the modelling tasks. The modeling tasks and their status are as follow:

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

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

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

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

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

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

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

Task 8: The interface between the natural and the engineered barriers (ongoing).

Objectives

The Äspö Task Force is a forum for the organisations supporting the Äspö HRL project to interact in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock. In particular, the Task Force shall propose, review, evaluate, and contribute to such work in the project. The Task Force shall interact with the principal investigators responsible for carrying out experimental and modelling work for Äspö HRL of particular interest for the members of the Task Force. Much emphasis is put on building of confidence in the approaches and methods in use for modeling of groundwater flow and migration 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 together 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 modelling of the experiment BRIE (Bentonite Rock Interaction Experiment) project.

Results

During 2012, the modelling work within Task 7 is more or less completed, and the focus is on result analysis, result presentation, reporting, and optional publishing. The Task 8 work mainly contained modelling of BRIE with different levels of detailed data. 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 also provides a possibility to compare the modelling results to the experiment.

The 28th international Task Force meeting was held in Berlin in January. The presentations were mainly addressing modelling results on sub-tasks 8B and 8C. In addition, updated Task 7 results were presented. Review sessions on Task 7 and 8 were held. The discussions on the continuation of Task 7 and also the start up of Task 8 were constructive. Also, some thoughts on a possible Task 9 were presented. One idea was to model LTDE-SD that has been performed at Äspö HRL.

After that the Task Force GWFTS turned 20 years in August, the 29th international Task Force meeting was held in Lund in November. The presentations were mainly addressing modelling results on sub-tasks 8C. In addition, updated Task 7 results were presented. A review session on Task 8 was held. The discussions on the continuation of Task 8 and also the start up of Task 9 were constructive. It is possible that modeling of Posiva's experiment REPRO will be added to the plan for Task 9. Minutes of both venues have been distributed to the Task Force together with presentation material.

A workshop for mainly Task 8 was held in April where modelling approaches and plans for the future modelling were presented and discussed. The venue took place at Äspö. 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 as ITDs).
7B	Sub-task 7B is addressing the same as sub-task 7A but in a smaller scale, i.e. rock block scale. Sub-task 7B is using sub-task 7A as boundary condition. (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 (simplified reports).
8C	Updated predictions (results presented at Task Force meeting 29).
8D	Preliminary resulst (presented at Task Force meeting 29).

3.9 BRIE – Bentonite rock interaction experiment

Background

BRIE (Bentonite Rock Interaction Experiment) has its focus on the common boundary at the 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 (GWFTS) and the taskforce on engineered barrier systems (EBS).

Objectives

BRIE and Task 8 as a whole 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 characterization 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 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 important water-bearing fractures.

Results

Following selection and characterization of the test site in the TASO-tunnel, two 300 mm boreholes were drilled and investigated. Along each of the two boreholes one section with a fracture and one section with intact rock matrix were selected. Bentonite was installed in September 2012 and relative humidity, total pressure and pore pressure are monitored in the sections of interest. Pore pressure (hydraulic head) is also monitored in boreholes close to the ones with bentonite. Besides field investigations, characterization of the rock matrix is performed in the laboratory. During 2012 data was delivered to the modeling groups in Task 8 (Section 3.8).

During the planning of the BRIE experiment it was noted that it would be valuable to perform parallel water-uptake tests in laboratory, and the idea was to use the same MX-80 bentonite and the same dimensions (inner and outer radii), density and water content as in the field test. The objective would thereby be to provide data from an experiment with radial water-uptake, which would give a clear-cut description of the hydraulic processes in the bentonite in the BRIE experiment. Apart from this it would be a significant step in the attempts to validate the material model.

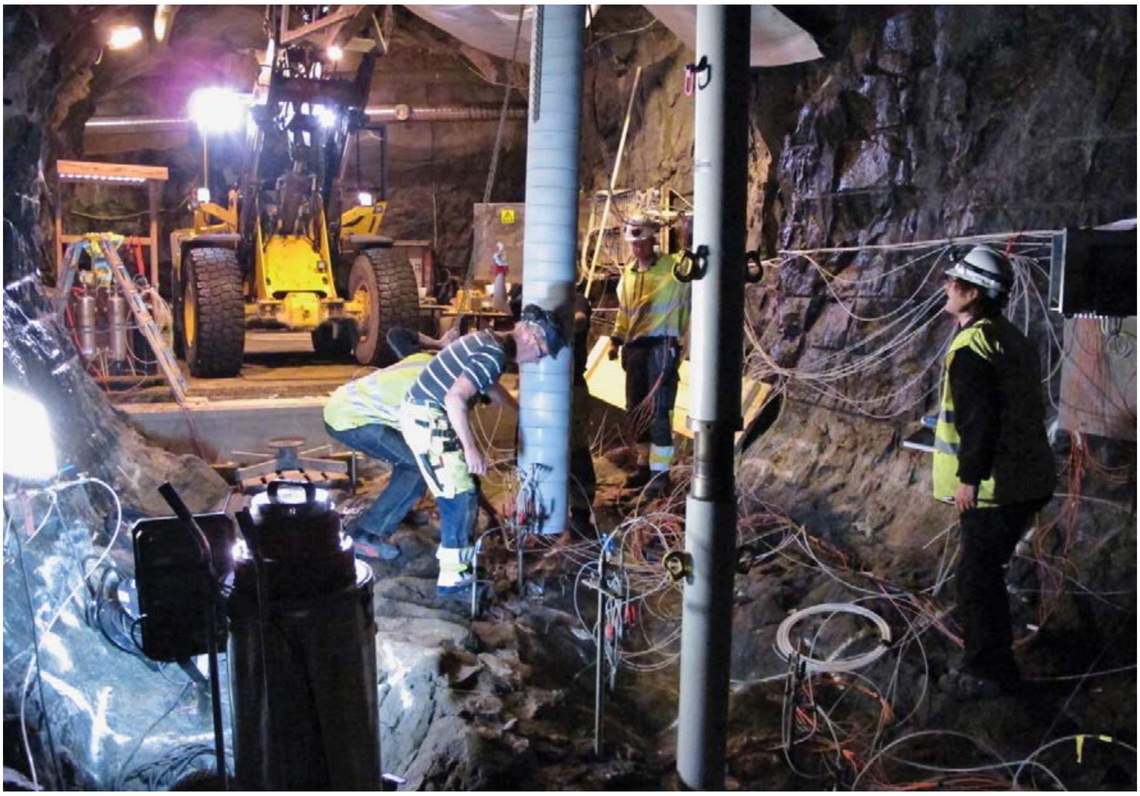


Figure 3-7. *Installation of bentonite in two boreholes (300 mm) in the TASO-tunnel (photo: Mats Lundqvist).*

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 2012 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.
- System Design of Backfilling of Deposition Tunnels.
- System Design of Plug of Deposition Tunnels.

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.

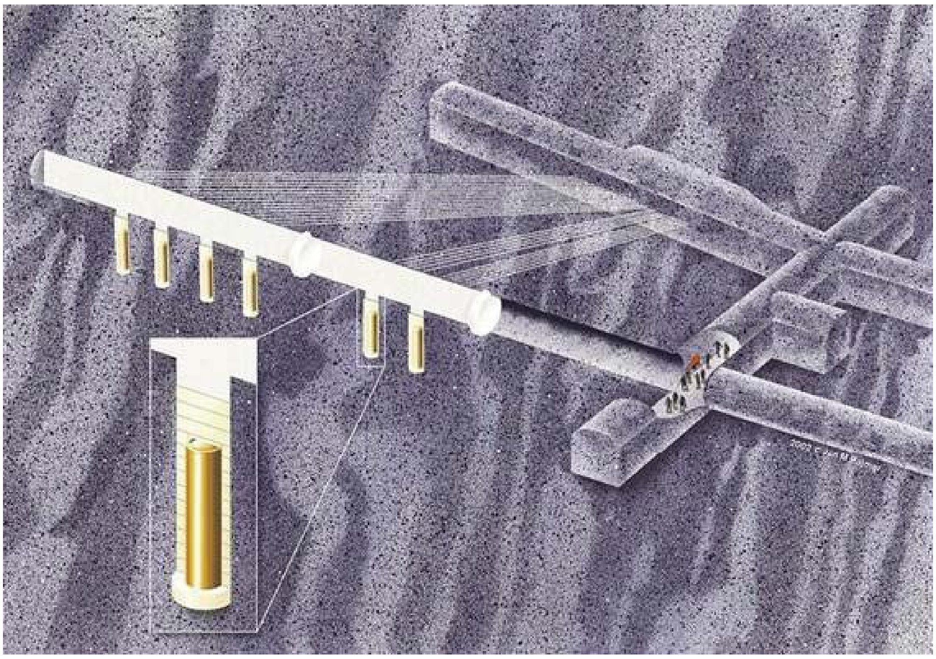


Figure 4-1. *Schematic view of the layout of the Prototype Repository (not to scale).*

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 retrieved 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 and #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 hole #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 around 1st January 2004. At that date the heating in canister 2 failed. It was then decided to turn off the power to all of the six canisters. Four days later, also damages on canister 6 were observed. The drainage of the tunnel was then opened again. During the next week further investigations on the canisters were done. The measurements showed that the heaters in canister 2 were so damaged that no power could be applied to this canister. The power to the rest of the canisters was applied 15th of November 2004 again. The drainage of the tunnel was kept open. At the beginning of August 2005 another failure of canister 6 was observed. The power to this canister was switched off until beginning of October 2005 when the power was switched on again. During 2008 new problems were observed with the heaters in canister 6, resulting in that the power was reduced to 1,160 W.

Measurements in rock, backfill and buffer

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

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

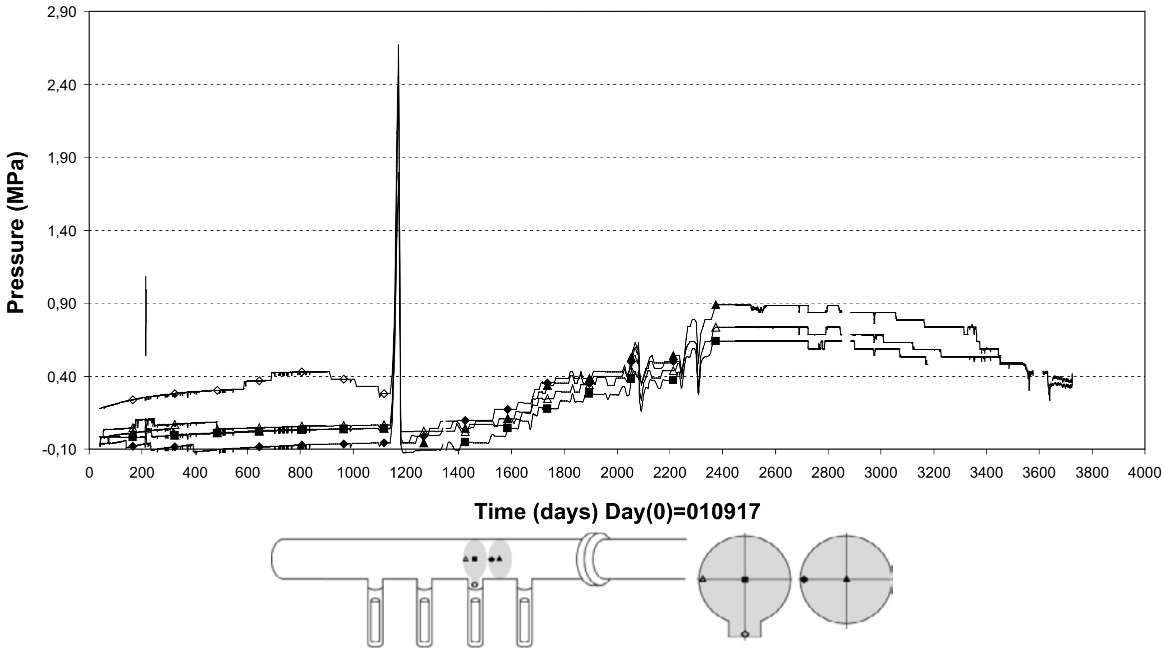


***Figure 4-2.** Examples of measured total pressure in the backfill around deposition hole 3 (17th September 2001 to 1st January 2012).*

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). These types of measurements are continuing.

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 2007). New gas and water samples have been taken and analysed during 2009–2010 (Lydmark 2010).

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 measurement 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.
- To find out how the contact between buffer-backfill and backfill-tunnel wall appears after more than 7 years wetting.
- 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.
- To determine the position and shape of the canister after the wetting period.
- If possible any damage and changes to the plug should be recorded.
- Biological and chemical activities in the buffer and backfill have been measured during the progress of the trial by sampling of water and gas. Samples will be taken to verify these measurements if possible during progress of the retrieval.
- Tests have been made on samples taken from this trial with the object of studying possible changes in the betontonite.
- Equipment for studying corrosion of copper in the buffer has been installed in one of the holes (hole 5). Measurements from this equipment have been 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 4-3 below.

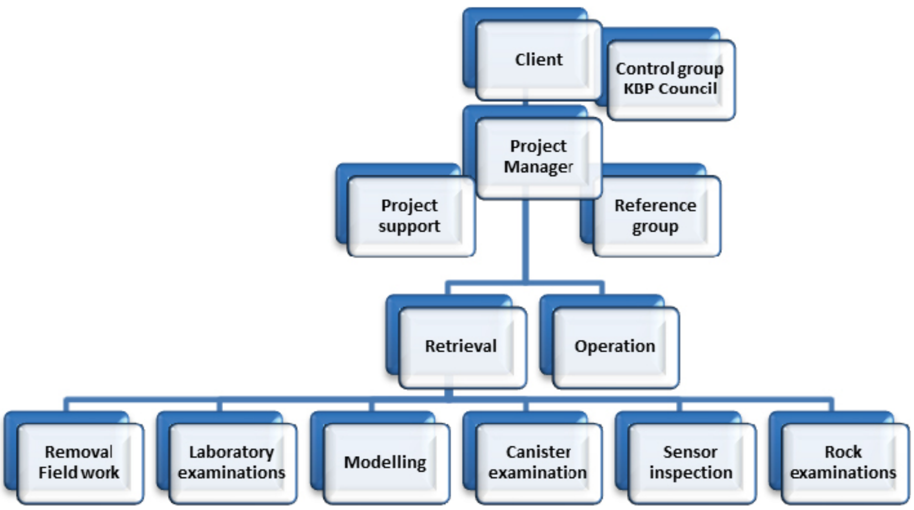


Figure 4-3. *Organisation chart for the project.*

The first subproject (Removal/Field work) involved the removal of the plug, excavation of the backfill and the buffer in the two deposition holes. The breaching of the outer plug started in December 2010 and finalized in February 2011. The plug was removed mechanically by core drilling and hydraulic demolition, see Figure 4-4. 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 1,100 determinations were made in 11 layers. An example of preliminary results from this work is shown in Figure 4-5. 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. After the excavation of the backfill had passed the deposition holes the excavation of the buffer started. The buffer was excavated by first core drilling from the upper surface of the buffer. 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. 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 4-6. Samples were also taken for further analysis in the laboratory.

The laboratory examinations of the taken samples (sub project two) started during 2011 and will be finalised during 2013. This work includes:

- Hydro-mechanical characterization of buffer material.
- Chemical characterization of buffer and backfill material.
- Microbiological investigations.

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

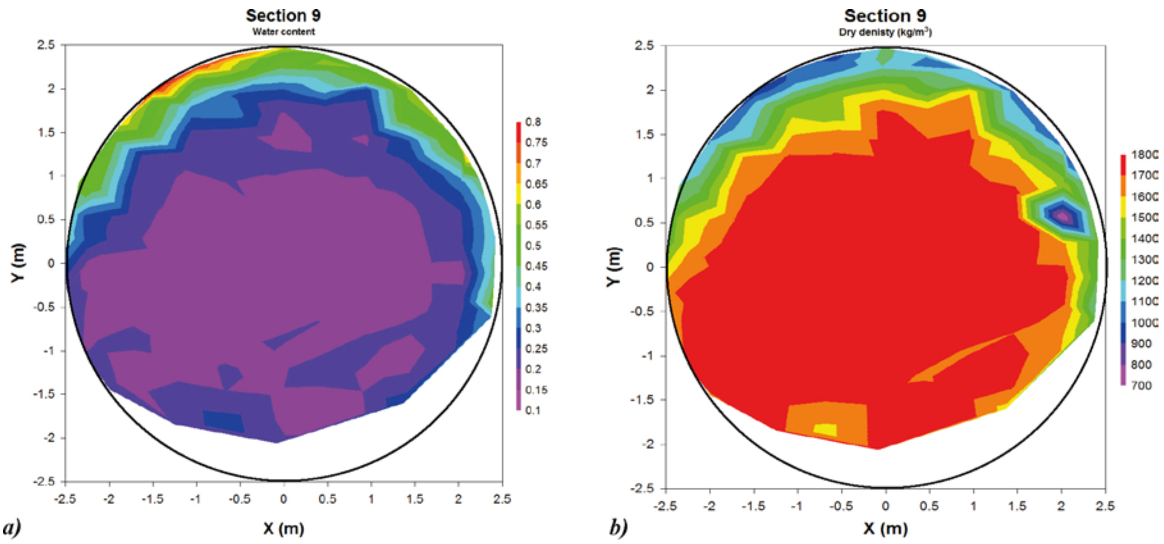


Figure 4-5. *Preliminary results from the determination of a) the water content b) the dry density of the backfill material in sample-Section 9.*

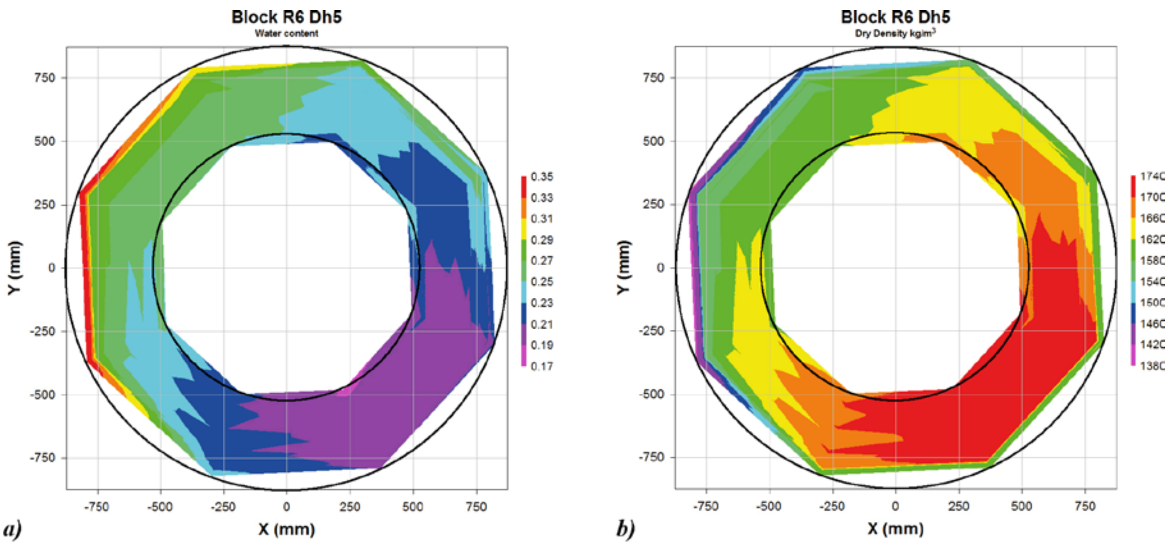


Figure 4-6. *Preliminary results from the determination of a) the water content b) the dry density of the buffer in deposition hole 5, block R6.*

An example of preliminary data from the laboratory work is shown in Figure 4-7 where the measured swelling pressures of the samples taken from the buffer are plotted as function of the dry density.

The modelling work of the Prototype Repository (sub project three) involves thermal, mechanical and hydro mechanical analyses of the rock, backfill and buffer. A stepwise solution strategy, including three steps, has been proposed for the task in which models at different scales and level of detail are used for solving the problem. Most of the modelling work is made within EBS-TF project, see Section 4.15.

The examination of the canisters (sub project four) involves investigations of samples taken of the canister surface, detailed deformation-measuring of the canister which will be made at the Canister Laboratory in Oskarshamn and examination of the cables and heaters installed in the canister. This work will be finalized during spring 2013.

51 sensors from the buffer and backfill have been retrieved at the excavation of the backfill and buffer and about 35 of them have been validated with varying success/quality with equipment which have been constructed and manufactured within sub project five, see Figure 4-8.

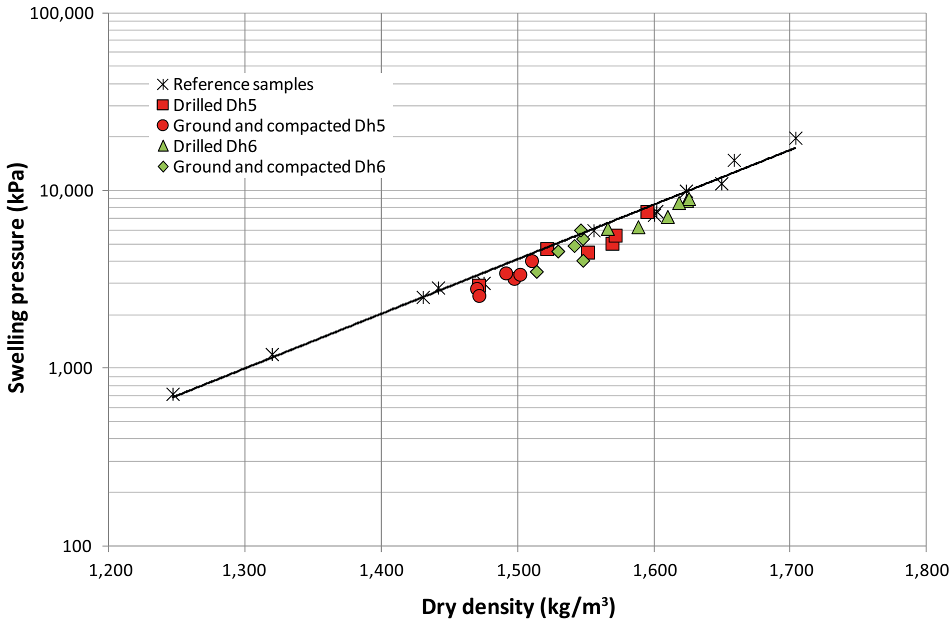


Figure 4-7. *Preliminary results from the determination of the swelling pressure reference samples and on samples taken from the buffer in deposition hole 5 and 6.*

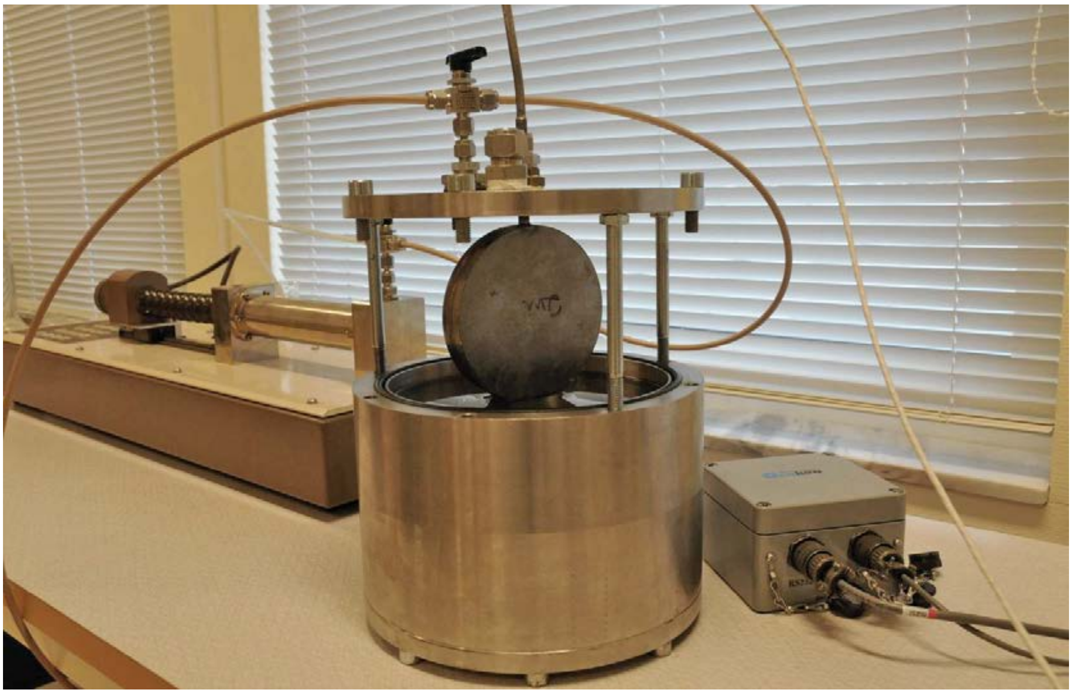


Figure 4-8. *Vessel used for verifying total pressure sensors.*

Within the sixth sub project, rock examination, numerical thermo-mechanical modelling of the rock mass surrounding the prototype repository has been performed. The modelling has been focused on investigating the risk of spalling in the deposition holes and on investigating deformations of discrete fractures intersecting the tunnel and deposition holes. Furthermore, modelling results have been compared with data from installed sensors in the rock.

Results from the models suggest that the spalling strength has not been exceeded except for positions in the uppermost few 10s of cm of the deposition holes. At an inspection of the holes, no evidence of any damage to the walls in hole 5 was found. In hole 6, some potential damage was observed at one location, which coincides with the region where high tangential stresses are expected. For models with discrete fractures, the results show that fracture normal stresses generally increase as a result of the thermal load. Fracture shear displacements are small and mainly elastic with local inelastic components around repository openings.

4.3 Alternative buffer materials

Background

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

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

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

Objectives

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

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

Experimental concept

The experiment is carried out in similar way and scale as the Lot experiment at Äspö HRL. The test parcels containing heater, central tube, pre-compacted clay buffer blocks, instruments and parameter controlling equipment were emplaced in vertical boreholes with a diameter of 300 mm and a depth of 3 m, see Figure 4-9. The target temperature in all tests is 130°C. 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, identical bentonite blocks are stored, covered in plastic, in order to monitor the effects of storage.

Test packages have been installed at two different occasions; in December 2009 (ABM) and in November 2012 (ABM45).

ABM

Three test parcels were installed in December 2009. Parcel #1 was retrieved after about 1.5 years operation at the target temperature and parcel #2 is planned to be retrieved in March/April 2013. The retrieval of parcel #3 is not decided but is preliminary scheduled to 2015.

Parcel #1 and# 2 were 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.

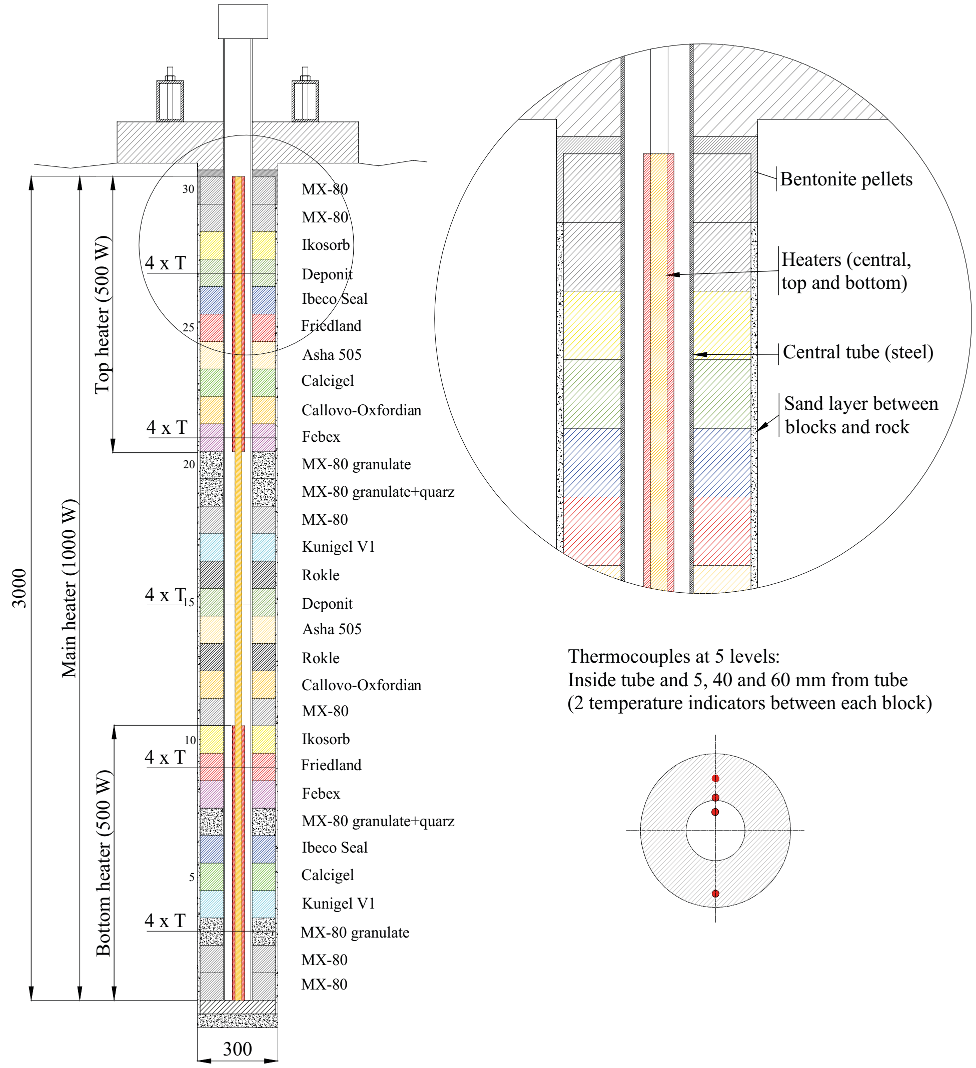


Figure 4-9. *Cross section showing the experimental set-up in the ABM test. The picture also shows the block configuration in test parcel 1.*

ABM45

Three new test parcels were installed in November 2012. Three new clay types were included, Asha NW BFL-L, Saponite and a Chinese bentonite, GMZ while Friedland, Callovo Oxfordian and the special cages with MX-80 granules were removed. All three test parcels are artificially wetted.

Special effort was made to remove lubricant on the inner part of the clay blocks. Copper and titanium inserts were installed in some blocks to further investigate metal-bentonite interactions.

Results

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

The analyses financed by SKB focused 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. Wheras 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 package 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 produced by the other participating organisations.

4.4 Temperature buffer test

Background and objectives

The Temperature Buffer Test (TBT) was a joint project between SKB and ANDRA with support from ENRESA (modelling) and DBE (instrumentation). The project aimed at improving the understanding and to model the thermo-hydro-mechanical (THM) behaviour of buffers made of swelling clay exposed to high temperatures (over 100°C) during the water saturation process. The test was carried out in a KBS-3 deposition hole at Äspö HRL. Two steel heaters and two buffer arrangements were investigated (Figure 4-10): the lower heater was surrounded by rings of compacted MX-80 bentonite only, whereas the upper heater was surrounded by a composite barrier, with a sand shield between the heater and the bentonite. The shield acted as a thermal protection for the bentonite, and as an important component for the retrievability.

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 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).

Experimental concept

The test was carried out at the –420 m level in Äspö HRL in a deposition hole (8.5 m deep and Ø 1.76 m). The *installation* of the test was performed in the beginning of 2003 (Johannesson et al. 2010), and consisted of different components (Figure 4-10): the heating system with two heaters (3 m long, Ø 0.61 m); the bentonite blocks (0.5 m thick; water content: ~17.5 %; void ratio: ~0.63 or ~0.57); slots filled with sand (in filter towards the rock wall, and in shield towards the upper heater) or pellets; the retaining construction with the plug, lid and anchor cables; the system for artificial saturation through the sand filter; and the instrumentation.

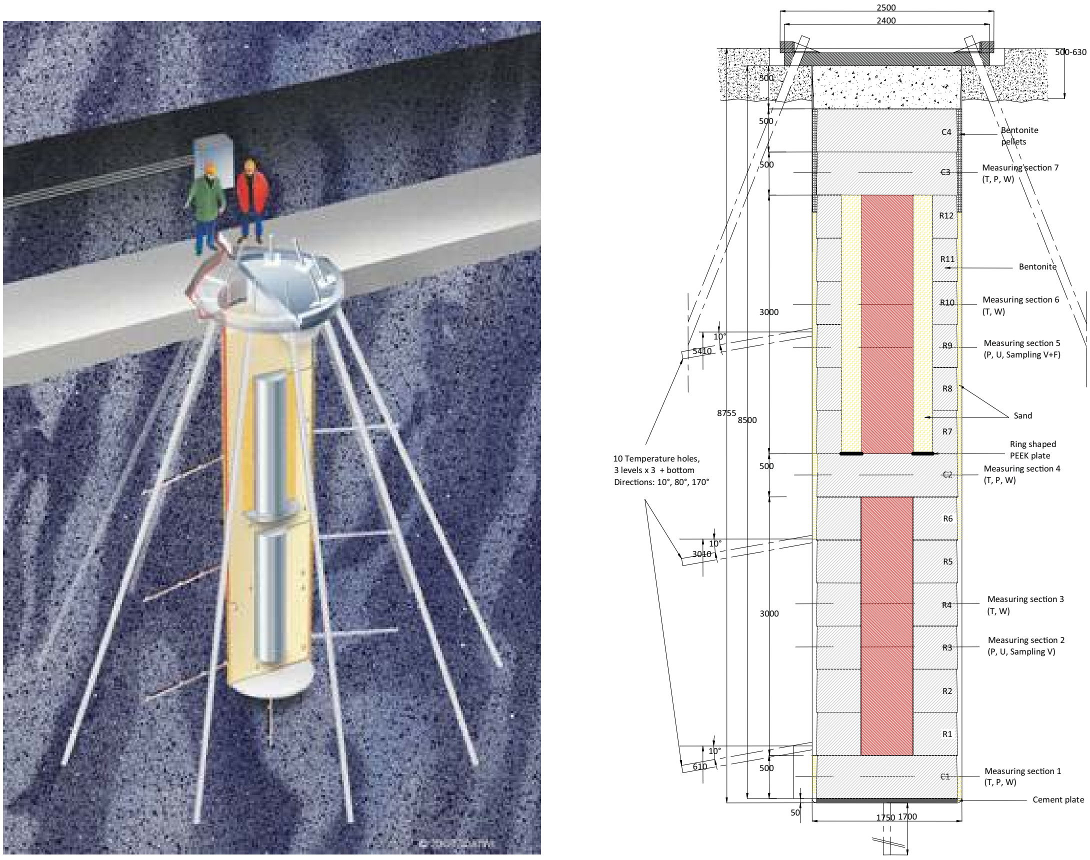


Figure 4-10. Principle design and experimental set-up of the Temperature Buffer Test.

The *operational conditions* evolved during the course of the test (Figure 4-11). During the first ~1,700 days the power output was 1,500 W (1,600 W during a limited period) from each heater. This was subsequently changed to 1,000 and 2,000 W, for the upper and lower heater respectively, and was kept at these levels during the last ~600 days. The second phase implied that the temperature in the innermost part of the bentonite around the lower heater reached approximately 155°C. The hydration of the bentonite was initially made with a groundwater from a nearby bore-hole, but this groundwater was replaced with de-ionized water after ~1,500 days, due to the high flow resistance of the injections points in the filter, which implied that a high filter pressure couldn't be sustained. The sand shield around the upper heater was hydrated from day ~1,500 to day ~1,800. The *sensors data* consisted of evolutions and distributions of temperature, relative humidity, total pressure, pore pressure, cable force and lid displacements (for the last sensors data report, see Goudarzi et al. 2010)

The dismantling operation was performed during a period from the end of October 2009 to the end of April 2010 (Åkesson 2010). One important goal with the dismantling operation was to obtain different types of samples: i) bentonite cores devoted for the so-called base program. These Ø 50 mm cores spanned over the entire height of each bentonite block and were taken in four directions at 50 mm intervals; ii) large pieces of bentonite, so-called big sectors, were devoted for the hydro-mechanical and chemical (HM&C) characterization program and represented the entire radial distribution; and iii) so-called end sectors, i.e. pieces taken close to the rock or the lower heater. A second goal was to investigate the retrievability of the upper heater, as facilitated by the possibility to remove the surrounding sand shield. The experiment was also documented in different aspects: by measurements of the coordinate of different joints and interfaces; verification of sensor positions and retrieval of sensors for subsequent function control; and by documentation of the operation through photography.

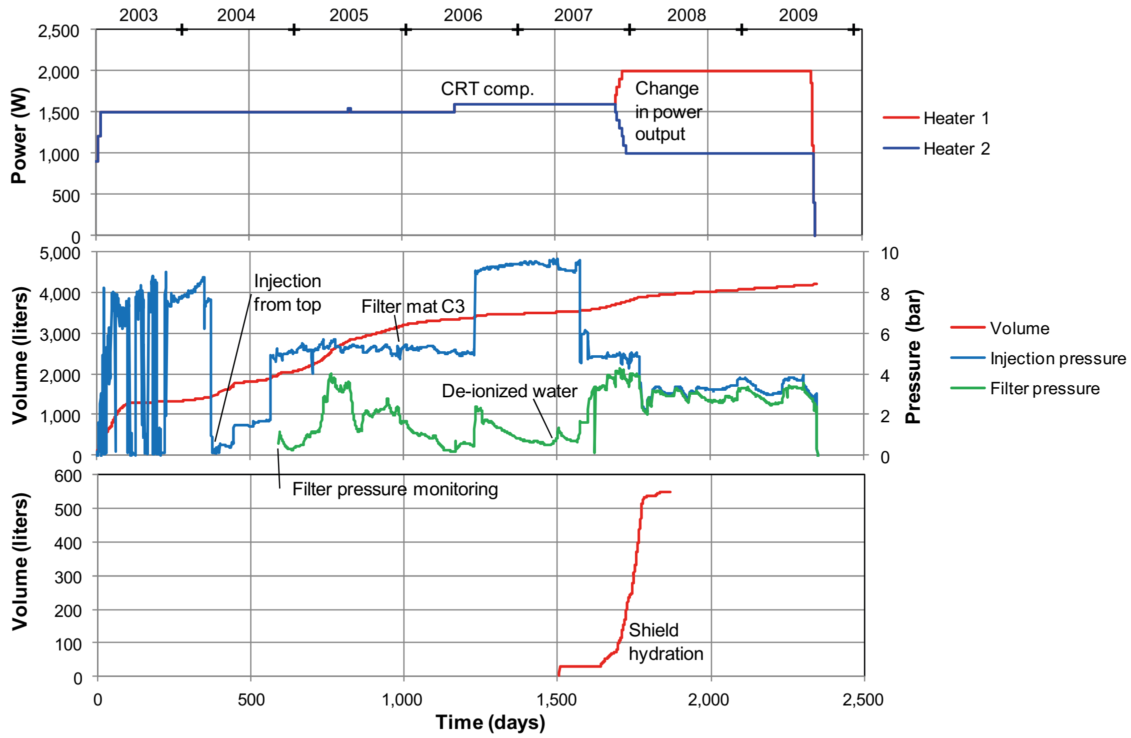


Figure 4-11. *Timeline of major events regarding power output (upper), filter injection system with total injected volume and pressures (middle); and shield hydration with total injected volume (lower).*

Results

The base program, i.e. the determination of water content and density, was performed in parallel to the dismantling operation (Johannesson 2010). The cores and end-sectors taken from the bentonite blocks were cut in smaller samples before the analysis. These analyses resulted in detailed distributions and contour plots of the determined properties (Figure 4-12).

The HM&C characterization program was launched subsequent to the dismantling operation (Åkesson et al. 2012a). The main goal was to investigate if any significant differences could be observed between the field test material and the reference material. The following hydro-mechanical properties were determined for the materials: hydraulic conductivity, swelling pressure (Figure 4-13), unconfined compression strength, shear strength and retention properties. The following chemical/mineralogical properties were determined: anion concentration of water leachates, chemical composition, cation exchange capacity and exchangeable cations, mineralogical composition (Figure 4-14), element distribution and microstructure, iron oxidation state. The analyses were performed on bulk samples, and in some cases also on Na-converted fine fraction (< 0.5 µm).

Several *THM modelling* tasks have been carried out since the beginning of the project: initial scoping calculations (Hökmark et al. 2005), predictions and first evaluations of the field test (Hökmark et al. 2007, Åkesson 2006a); as well as predictions and evaluations of two parallel mock-up tests (Åkesson 2006b, 2008, Åkesson et al. 2009). The final modelling task of the field test was resumed after the dismantling operation (Åkesson et al. 2012b). The main part of this work consisted of numerical modelling of the field test. Three modelling teams presented several model cases for different geometries and different degree of process complexity. Two codes, Code_Bright and Abaqus, were used. The work also included different evaluations of experimental results with the aim to validate a number of data sets (example given in Figure 4-15), and to assess the conditions in the tests prior to the dismantling operation. Finally, the validity of the material models was assessed. This task was a test of the different parts of the material models, especially for the bentonite, for their ability to reproduce the experimental data (example given in Figure 4-16).

A final report for the project was published during 2012 (Åkesson 2012).

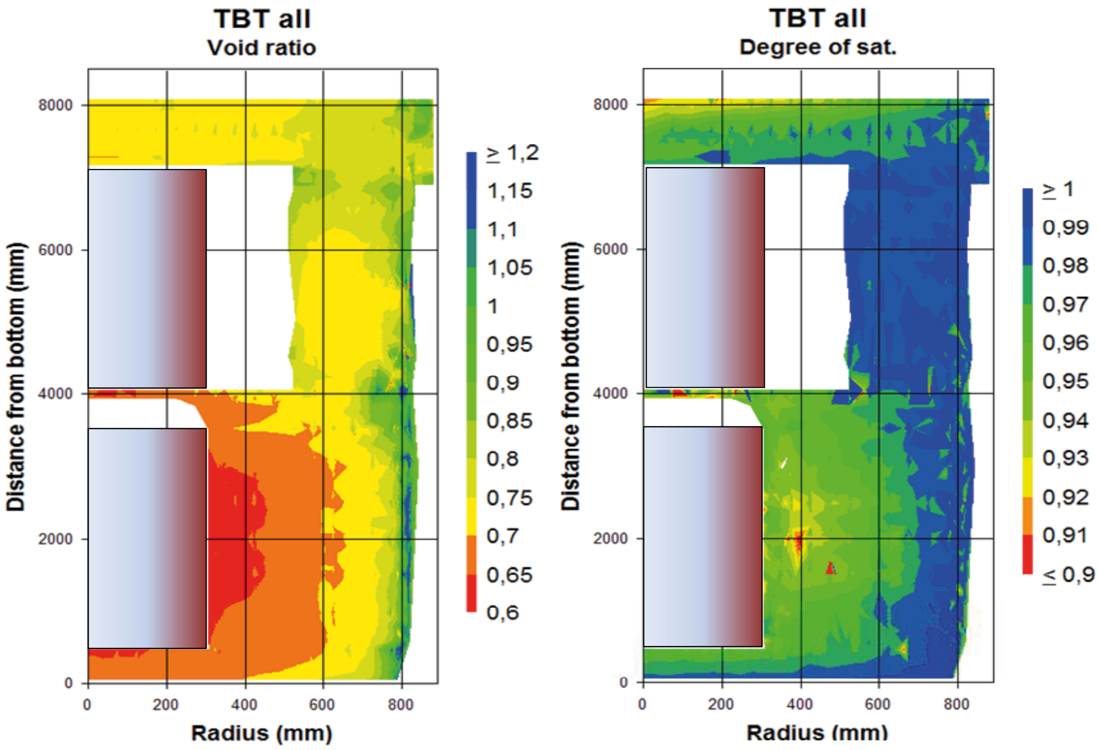


Figure 4-12. *Results from measurements of density and water content. Distributions of void ratio (left) and degree of saturation (right) at the end of the test.*

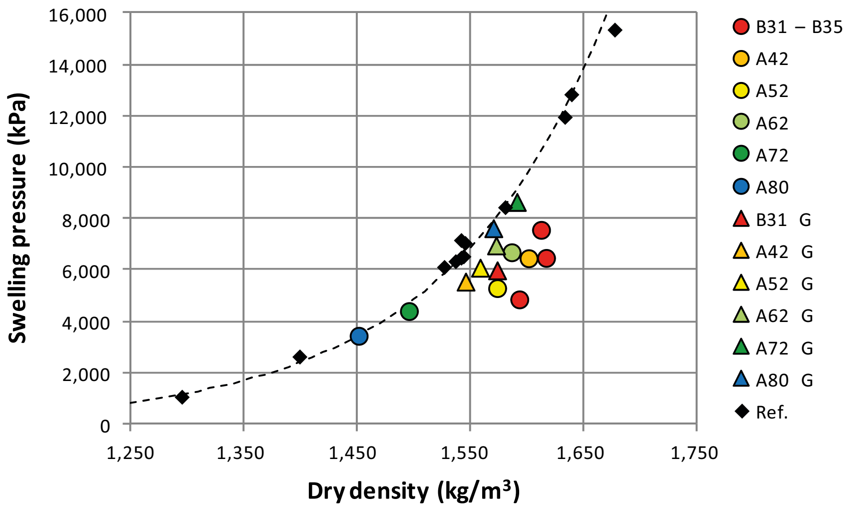


Figure 4-13. *Swelling pressure as a function of dry density. Field samples are denoted with colored markers: red to blue are used for the warmest to the coldest radial sample position (indicated by the labels); circles and triangles denote trimmed, and ground and re-compacted samples, respectively. References samples are denoted with black markers. The field test samples thus showed a reduced swelling pressure, especially for the innermost samples.*

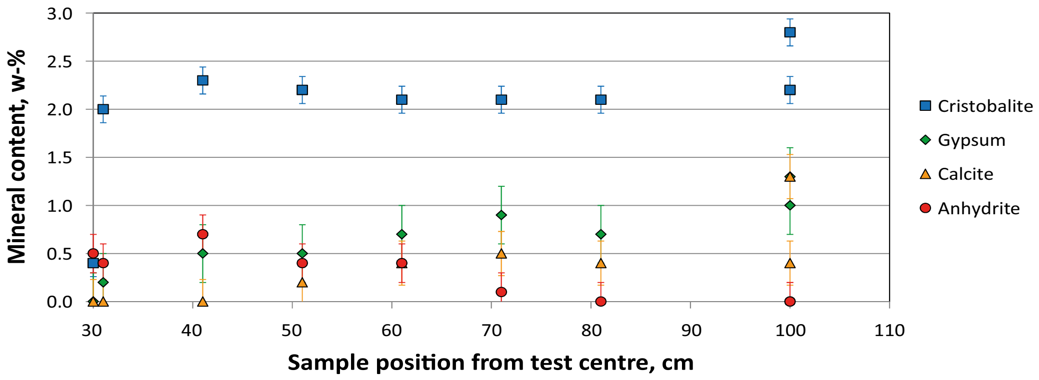


Figure 4-14. *X-ray diffraction (XRD) results evaluated with Siroquant software. Content of cristobalite, gypsum, calcite and anhydrite versus radial distance in the analyzed section. Results for the reference samples are plotted at 100 cm. Three tendencies can be observed: the calcium sulphate phase changed from gypsum to anhydrite in the inner part; calcium carbonate (calcite) was lost in the inner part; and cristobalite showed a marked decrease in the bentonite close to the heater.*

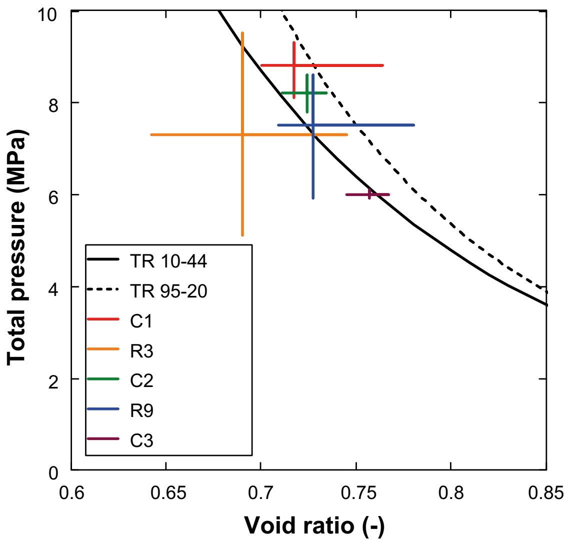


Figure 4-15. *Compilation of final pressures (minimum, mean, maximum) for each instrumented block versus the corresponding void ratios at dismantling (minimum, mean, maximum). Two swelling pressure curves shown for comparison. The void ratio profiles measured during the dismantling and the final total pressure readings were thus generally consistent with current swelling pressure curves.*

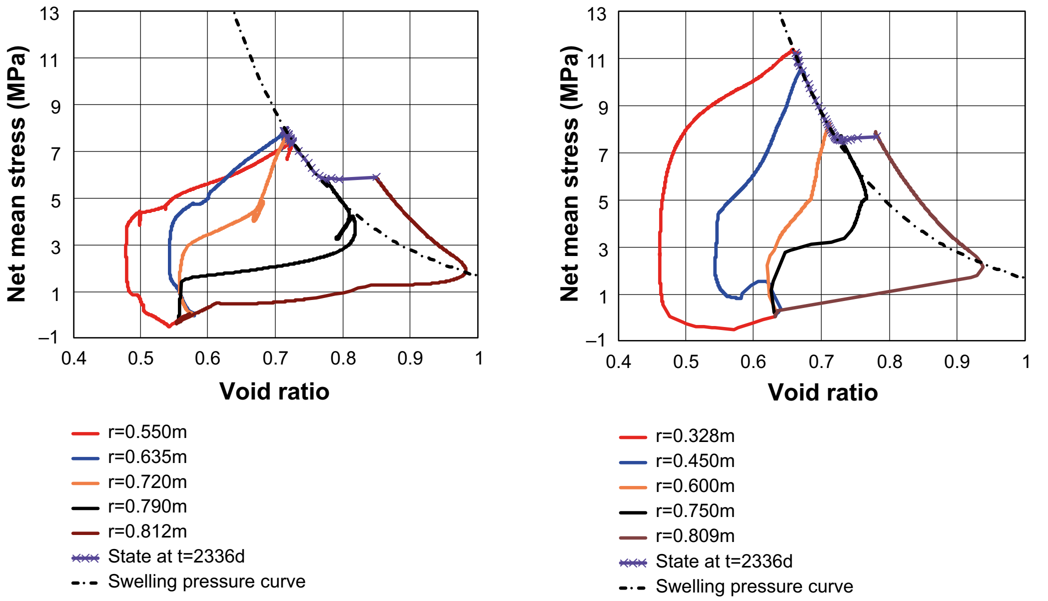


Figure 4-16. *Stress paths for different radii and final state in two numerical models together with adopted swelling pressure curve. Results for model of the upper package (left), and lower package (right). Swelling pressures, i.e. the relation between the void ratio and net mean stress during the final state, could thus be well reproduced.*

4.5 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 distance blocks, Figure 4-17 and Figure 4-18, 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) after which a KBS-3H reference design, DAWE (Drainage Artificial Watering and air Evacuation) was selected. The earlier stages provided positive results and a new phase, KBS-3H System Design, which is detailed in subsequent sections, was initiated in 2011. All development steps have been made in close cooperation between SKB and Posiva.

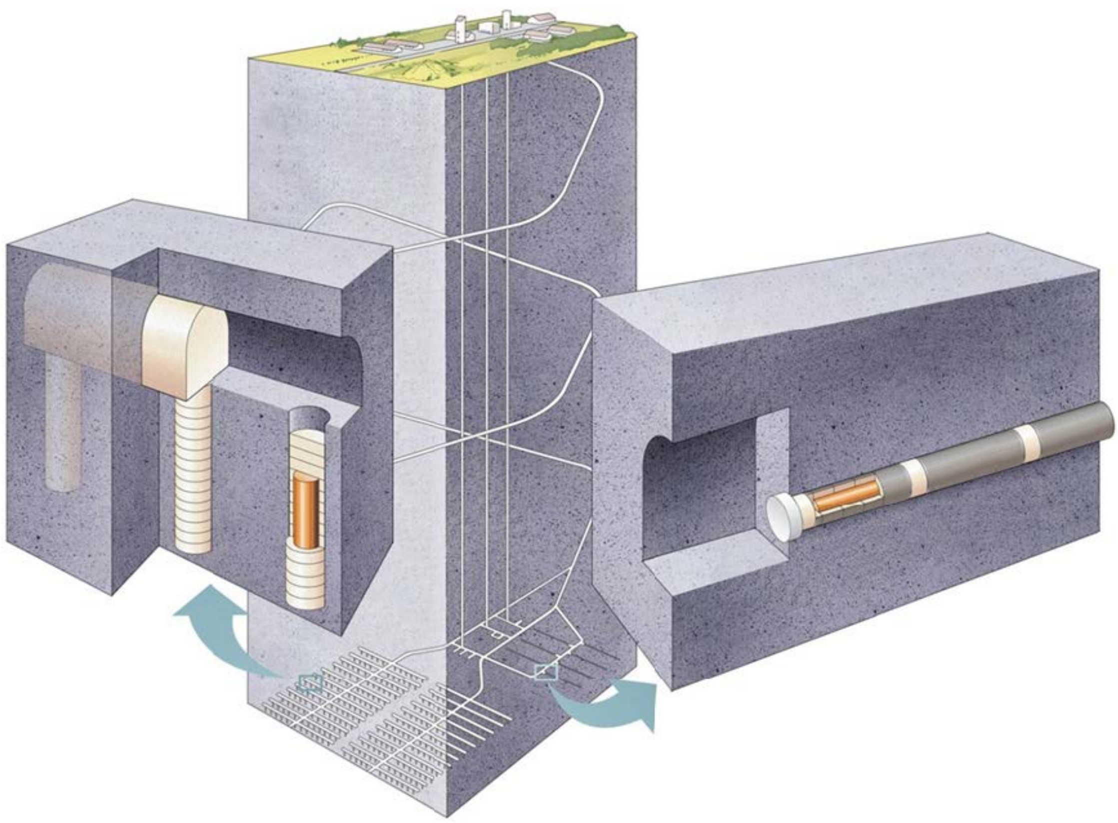


Figure 4-17. *Schematic drawing of the KBS-3V reference design (left) and KBS-3H (right).*

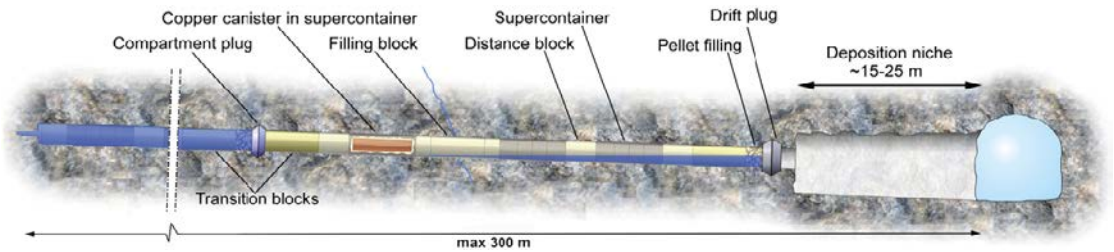


Figure 4-18. *KBS-3H reference design DAWE with its main components; the plugs with their transition zones, the Supercontainers, and the distance and filling blocks. The illustration shows an ongoing artificial water filling procedure.*

KBS-3H System design

The current project phase is planned for 2011–2016, it covers all areas of the KBS-3 method but the focus is on the KBS-3H specific issues.

Objectives

The goal of the KBS-3H System Design phase is to reach a level of understanding so that comparison of the 3V/3H alternatives, and preparation of a PSAR becomes possible. The plans are to reach this goal by the end of 2016. The comparison of design alternatives also includes environmental matters, costs and safety issues (long-term, operational and occupational safety). For components and sub-systems this will be achieved by assessing the design premises/basis, updating the requirements, verifying that the design solution meets and can be manufactured according to the requirements and based on this, reaching the system design level in accordance with SKB's model of delivery. The system design level also includes devising plans for industrialisation/implementation including control programs and risk assessments.

Vital in reaching the project's main objective is to produce the basis and carry out a safety evaluation for Forsmark and for Olkiluoto. This work will be based on earlier safety assessment work and make use of the SR Site for Forsmark and Posiva's safety case (produced by SAFCA) for Olkiluoto. This is expected to be achieved by the end of 2016.

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 also part of the EU-project LucoeX (which receives funding from European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013) and the excavation and preparation of a new KBS-3H drift at the –410 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 4-18. 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 4-19, 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:

- Test the system components in full scale and in combination with each other to obtain an initial verification of design implementation and component function.
- This includes the ability to manufacture full scale components, carry out installation (according to DAWE) and monitor the initial system state of the MPT and its subsequent evolution.

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.

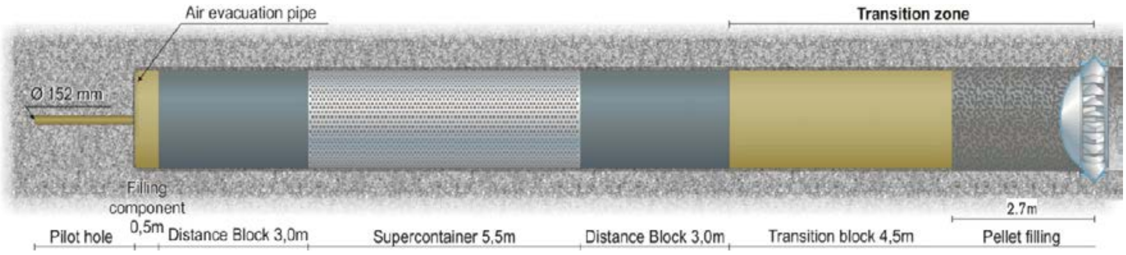


Figure 4-19. *Schematic illustration of the MPT layout. The length of the pellets filling has been increased from 1.3 m to 2.7 m, this is for practical reasons related to cabling and the manual installation. The KBS-3H reference design still has a 1.3 m long pellets section inside the plugs.*

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 developed 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 the TR-report (SKB 2012b). The System Design phase is based on the outcome presented in this report.

MPT

During 2012 the MPT has proceeded with several key activities:

- The deposition machines soft- and hardware has been updated and a considerably improved control and balance has been established for both Supercontainer and distance block dummies, Figure 4-20, final testing will be done early 2013.
- A buffer mould has been manufactured, bentonite has been purchased and a set of test blocks have been manufactured, Figure 4-21. Evaluation of the fulfillment of the block and bentonite material requirements will be done in 2013.
- Sawing of plug and sensor cable notches have been carried out as well as drilling of sensor holes, Figure 4-22.
- A Compartment plug has been manufactured and its fastening ring has been installed in the test drift, DA1619A02, Figure 4-23. The plug has passed the FAT.
- The MPT sensor design has been finalized and the sensors and data acquisition system has been ordered and FAT/SAT is planned in the beginning of 2013.
- Detailed planning for component assembly has been done and a test distance block will be assembled early 2013. This block will subsequently be test deposited in the drift using the deposition machine. Figure 4-24 illustrates preliminary planning for the Supercontainer assembly.
- Sectioned inflow measurements have continued throughout 2012 whenever possible with respect to the deposition machine, and the inflow is just above 0.02 l/min in the MPT section.

Excavation and preparation of a KBS-3H drift

A new KBS-3H niche has been developed as part of the Äspö expansion at the –410 m level, Figure 4-25. The new niche provides a location for KBS-3H drilling operations and the development of a new KBS-3H test site.

The project has also been involved in the development of a deviation measurement facility at the surface of Äspö HRL, this facility will be finalised during 2013 and will enable evaluation and selection of deviation measurement equipments for the planned KBS-3H drilling operations.

Figure 4-20. *To the left dummy distance blocks with the newly designed feet mounted and to the right the same blocks after deposition tests inside the drift, also illustrating the tight fit between the drift wall and the components.*

Figure 4-21. *Pictures from buffer manufacturing, to the left the new KBS-3H buffer mould and to the right a compacted bentonite 'ring' which will be used in the Supercontainer around the canister. After compaction the blocks are sent to machining to the correct dimensions.*

Figure 4-22. *The picture to the left illustrates the sawing of a compartment plug notch and to the right a picture from drilling of sensor holes. The right picture also illustrates the sawed out cable notches on both sides of the drift, these will be partially casted after the piping is installed.*

Figure 4-23. *To the left a picture from the compartment plug FAT and to the right the installation of the plugs fastening ring.*

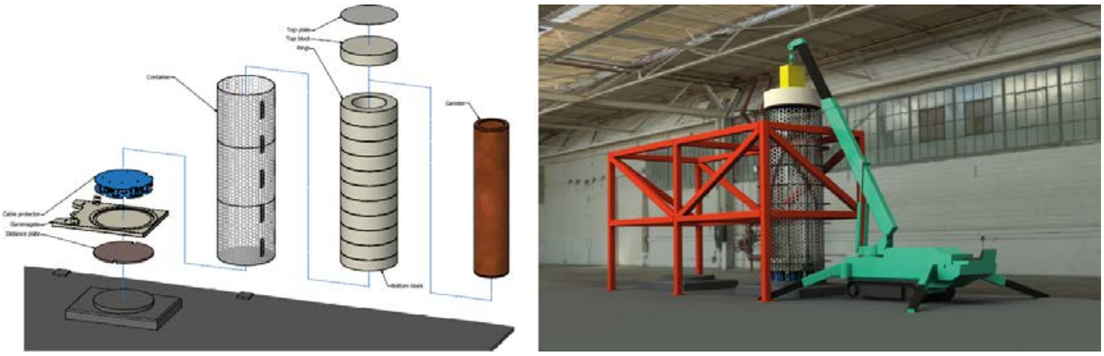


Figure 4-24. *Illustrations of the Supercontainer assembly sequence, the sensors are not illustrated. The Supercontainer will be built on a 'cable block' which has room for the sensor cables and will be connected to the Supercontainer during deposition in the drift.*

Figure 4-25. *New KBS-3H niche at the –410 m level at Äspö HRL.*

4.6 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 (FU910). Stage 5 started on day 2,073 and was completed on day 2,725. Focus then returned to the lower array (FL903) in late 2012.

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 4-26). 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

Figure 4-26. The Large scale gas injection test at the –420 m level in Äspö HRL.

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.

Results

During 2012 (day 2,525 – day 2,890) 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. In late 2011 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 & hydration state and position within the deposition hole.

Gas injection in FU910 was initiated on day 2,256 (8th April, 2011) 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. 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 4-27, gas breakthrough occurred on day 2,490.3 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).

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 4-27, 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. Several clear gas propagation events can be observed from the changes in stress and pore water sensors.

Figure 4-28 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. A series in pressure rises resulted in FU911 reaching a pressure similar to the gas injection pressure by day 2,590. The axial stress reading at sensor PC903 showed that gas had migrated to this sink by day 2,520. Finally, gas reached FL904 by day 2,580. This latter pressure increase shows that gas migration must have been along localised pathways as gas did not reach any of the intermediate filters.

The observations show that gas continued 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.

Following gas injection, a hydraulic two-stage constant head test was conducted. As with previous gas injection experiments this showed no significant change in permeability, indicating that the gas has no detrimental effect on the hydraulic performance of the buffer.

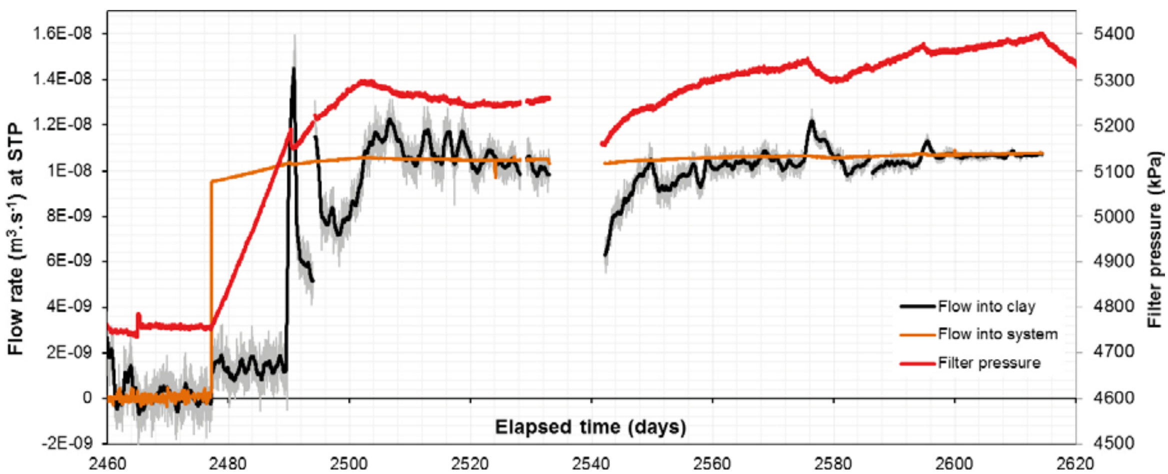


Figure 4-27. *Pressure response and flow of filter FU910, showing gas breakthrough at day 2,490. Similar to previous tests a sharp drop in pressure is seen at breakthrough. However, in contrast to previous tests, gas pressure in FU910 increased and reached a second peak before decaying.*

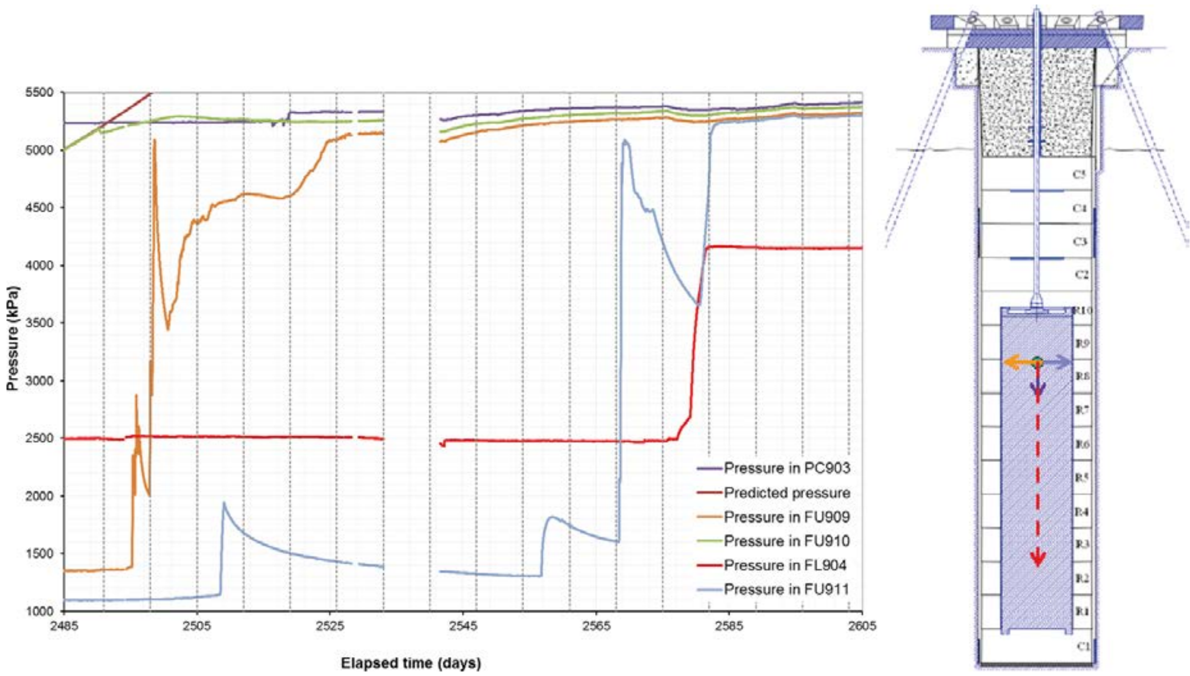


Figure 4-28. *Pressure response of all upper-array filters. Approximately five days after gas break-through the pressure in filter FU909 began to increase in a series of events. By the end of 2011 the pressure in FU909 was similar to that in gas injection filter FU910, suggesting very good connection between the two filters.*

4.7 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 space between the copper shell and the cast iron insert will determine the possible scenarios for radionuclide release from the canister. A possible scenario is that the formation of solid iron corrosion products could build up an internal load on the copper shell, which could lead to deformation. This has been studied experimentally in the laboratory (Bond et al. 1997) and been modelled (Smart et al. 2006).

In this project, miniature copper canisters with a cast iron insert will be exposed for several years in boreholes in the Äspö HRL. In order to model failure, defects have been introduced into the outer copper shell, making it possible to investigate the evolution of corrosion inside the canisters. Corrosion will take place under reducing, eventually oxygen-free conditions in the presence of microbial activity present in natural 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 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 space 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 4-29), 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 detect any expansion in the copper shell. The redox potential, E_h, is being monitored using a combination of metal oxide, platinum and gold electrodes.

The boreholes are located in a region with many fractures, 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 E_h probe.
- Corrosion rate of cast iron and copper, using linear polarisation resistance (LPR), AC impedance (ACI), electrochemical noise (ECN), and the electric resistance in a copper wire.
- Strain on the surface of two of the model canisters.
- Hydrostatic pressure in the boreholes.

Regular water samples are taken from within the support cages to monitor the development of the local water chemistry. The experiments will remain *in situ* for several years, after which they will be retrieved, 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 main result for 2012 is the report on the analysis of experiment three (Smart et al. 2012a). The fourth progress report (Smart et al. 2012b) was published in June 2012 and summarizes results of electrochemical measurements and analyses of water chemistry from 2008 to 2011. Analysis of dissolved gases and microorganisms were reported in Hallbeck et al. 2012.

Figure 4-29. *Model canister being lowered into support cage containing bentonite pellets in annulus.*

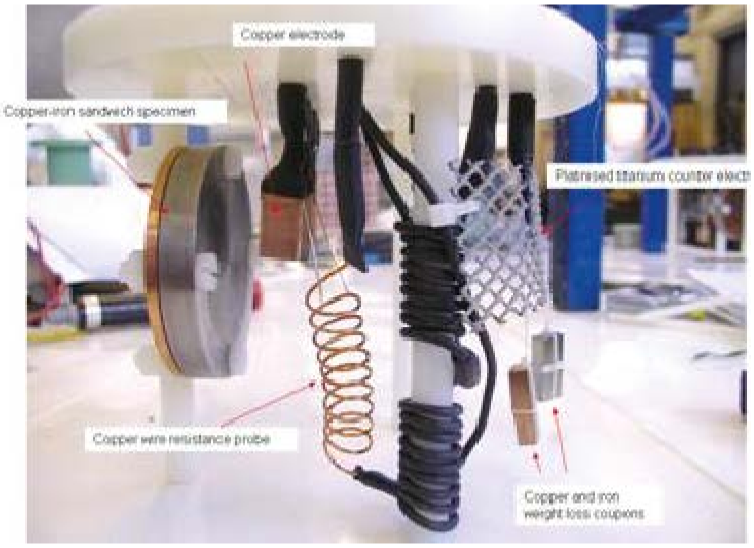


Figure 4-30. *Test electrodes inside support cage around model canister experiments.*

The main conclusions from these reports are:

- Microbial analysis shows that sulphate reducing bacteria (SRB) are present and active in the boreholes of the experiment (Hallbeck et al. 2012).
- The surfaces inside the experiment were covered (to various extent) with a black deposit (Smart et al. 2012a). Analysis of this deposit shows that it is mainly composed of iron sulphide and graphite.
- Measurements of redox potentials (E_h) show that the experimental environment became reducing over a period of a few months. Nevertheless, electrochemical measurements (LPR, ACI) predict high corrosion rates for iron as well as for copper. However, some values are so high that they are self contradictory, i.e. the thin electrode should have been penetrated if the interpretation of data had been correct, implying that the measurements have been disturbed in some way. Weight loss experiments (gravimetric analysis) of iron and copper coupons from canister three measure the actual corrosion rate and shows that the corrosion rate of copper (0.15 µm/y) was lower than earlier measurements from the in-situ experiments Prototype repository and LOT. Thus, the gravimetric analysis confirms that electrochemical predictions of corrosion rate have been subjected to erroneous influences. The most likely reason is that iron sulphide has formed as a precipitate on the copper electrodes, which has disturbed the electrochemical signals (LPR, ACI, ECN) and thus the interpretation of signals as corrosion rates.

- The corrosion of iron has been substantial due to the formation of large amounts of sulphide. Most part of the iron sulphide comes from corrosion of iron specimens mounted outside the canister (electrodes and other parts, see further Smart et al. 2012a). Only a smaller fraction is due to corrosion of the iron insert.
- Strain gauge measurements show no signs of expansion of the copper canister, which was thought to be a possible effect of corrosion of the iron insert. This is also confirmed by precise measurements of the canister dimensions before and after exposure.
- Water analysis shows compositional differences between the water inside the support cage and the external borehole water. The concentration of ferrous iron in solution has increased and pH has decreased from ~7.6 to ~6.7.

Figure 4-31. *Stefan Grandin Svärdh and Jonas Hallberg pulling out the steel cage from the KA3386A04 bore hole.*

Figure 4-32. *Equipment for sampling of the steel cage surface.*

Figure 4-33. *As the result of microbial activity and corrosion of cast iron, a precipitate of iron sulphide has formed on the instruments mounted inside the support cage.*

4.8 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 and pH of the ground water. 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 CO2 and CH4 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.

Reactions will also occur between compounds in the water and surrounding materials such as bentonite and minerals in the bedrock. These reactions can result in clogging of gravel beds used for drainage or as a so-called hydraulic cage, clogging of cracks in the bedrock or alter the properties of the bentonite.

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 2010–2013 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, Figure 4-34 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 4-35. 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 oxygen containing surface water.

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 2010 and 2011 a number of samples containing different material types have been prepared and deposited in the niches NASA 0507A and NASA2861A. The aim of these experiments is to study the degradation of metals such as aluminium, iron, steel andzinc and organic materials such as paper, rubber, cotton etc in a concrete matrix.

During 2012 no experimental work has been performed withing this project due to lack of experimental sites. Instead the planning of the remaining experiments which will be performed during 2013 has been initiated.

Figure 4-34. *The metallic specimens.*

Figure 4-35. *Deposition of a waste-containing concrete cylinder.*

4.9 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 2012/2013. The plug at Äspö HRL is partly included in the new EU project called "DOPAS", which receives funding from European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013.

Objectives

The purpose of the 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. 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". This project was completed during 2012 and reported in a SKB report R-12-02 (Alonso et al. 2012).

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 were preliminary planned to be over-cored after 1, 2, 5 and 10 years for evaluation of the behaviour of the low-pH grout but also corrosion of the rock bolts.

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 4-36 and Figure 4-37. 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.

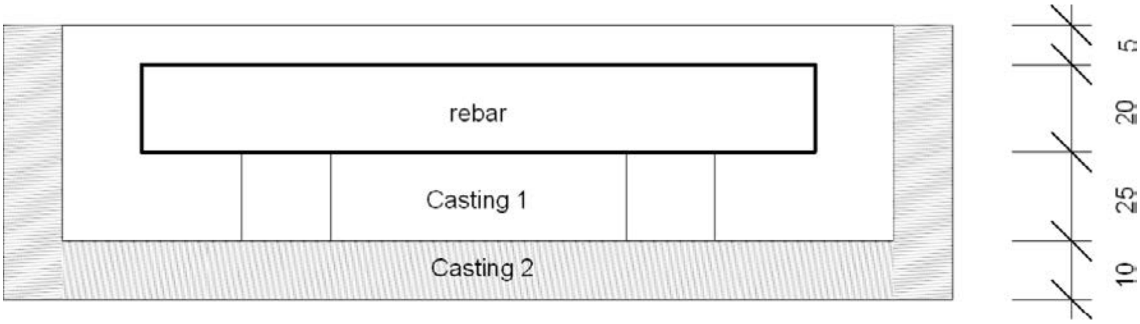


Figure 4-36. Specimen dimensions.

Figure 4-37. Mould and steel bars on supports before casting.

The specimens were then placed for field exposure in an open container in niche NASA2715 at the Äspö HRL, Figure 4-38.

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 2012 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.

Figure 4-38. Container in Äspö HRL with samples corrosion tests.

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 2013/2014. The first result of the corrosion experiments with carbon steel in low-pH concrete is however reported in Bodén and Pettersson (2011).

The report, Alonso et al. (2012), contains the agreed procedures for measuring of the pH values in low-pH concrete as the all organisations intend to use the same procedures it will be possible to compare results of these measurements and the products for a specific mixture. The result of the low-pH project and the use of a standard procedure/protocol for pH-measurement have also been presented at international seminaries in order to make the result of the project known and accepted.

4.10 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.

Experimental concept

THM

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

The present phase includes the following tasks:

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

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).

Results

Two Task Force meetings have been held during 2012; one in Berlin, Germany on May 22–24 and one in Lund, Sweden on November 26–29. In the latter meeting one day was a joint meeting with the Task Force on Groundwater Flow (regarding Task 8). For information about performed work within the different tasks by the international organisations, see Chapter 7.

The first phase of the Task Force was concluded in 2011 and the second phase started in 2010.

THM

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.

Three teams are working with this task. SKB is presently not involved in the task.

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 an Äspö test in a project called Brie (Buffer-rock interaction experiment), which was installed in 2012. This task is divided into several substasks and the modelling started 2010 and has continued during 2012. The project is described in more detail in Chapter 3. Five modelling teams are 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 laboratory swelling tests that have been made are modelled and used for checking/calibrating the mechanical model. In the second part one laboratory scale test that simulates bentonite lost in a deposition hole has been started and could be preceded by predictive modelling.

During 2012 some new tests in larger scales for part 1 have been performed and the results distributed. These results were used by the Team of SKB 2 and an updated material model established.

Figure 4-39 shows example of results with the updated model and comparison with measurements.

The configuration of the laboratory scale test for part 2 of this task was distributed in July and the test started in December. This gave opportunity for a blind prediction of the test, which was delivered by SKB team 2. Figure 4-40 shows the scale test during assembly.

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. Modeling of the water inflow in the repository before installation. (To calibrate the hydraulic conductivities in the surrounding rock mass).
2. Modeling 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. Modeling of the THM-processes in the outer section (concentrating on hole 6) during the operational phase and predict the state at the excavation that took place during 2011.

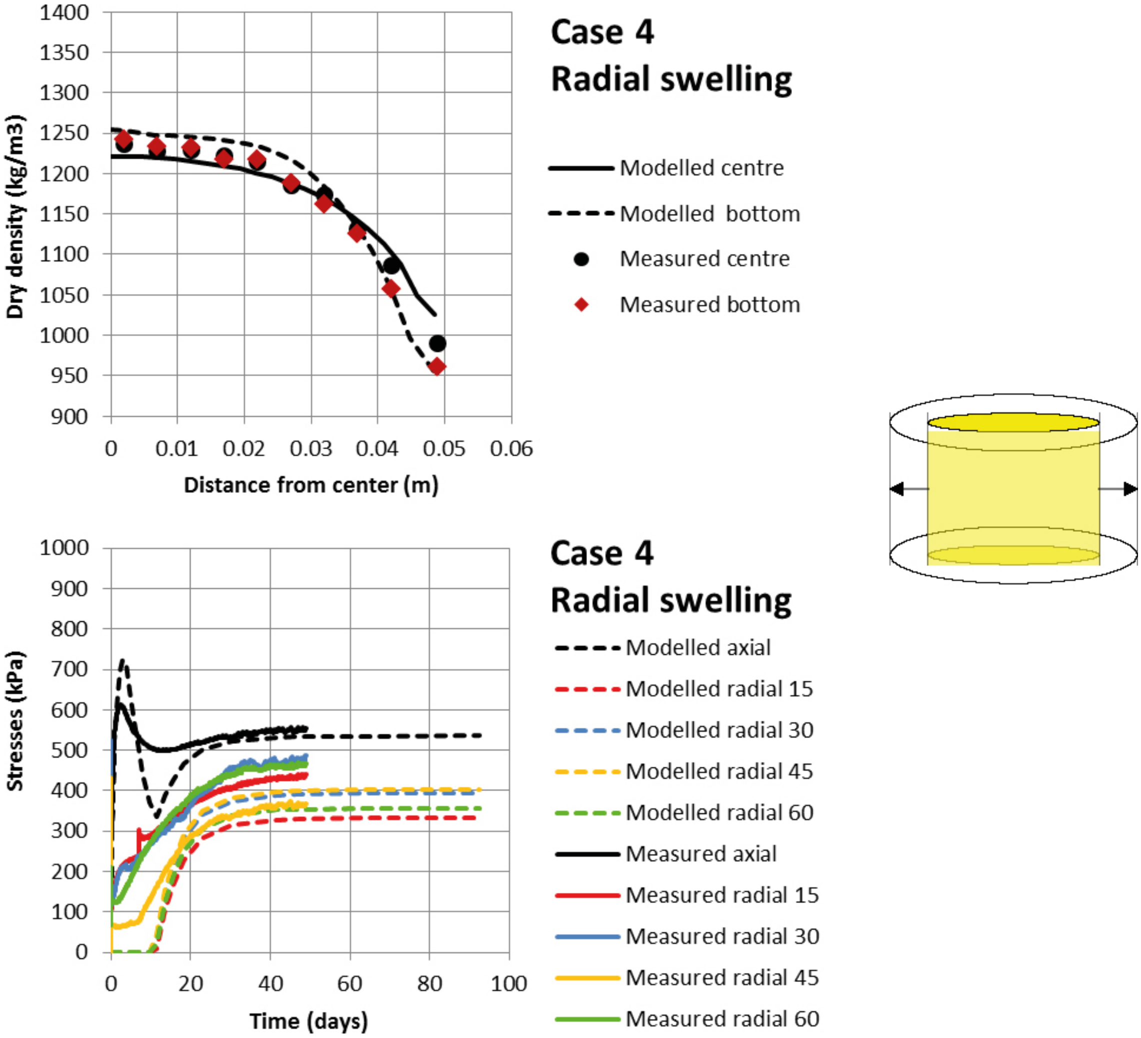


Figure 4-39. *Example of results from a homogenisation task (43% radial swelling). Upper: Void ratio distribution as function of the radial distance from the centre. Modelled with Abaqus and measured after termination (lines with symbols). Lower: Measured and modelled radial and axial stresses. Measured: solid lines; Modelled: dashed lines.*

Figure 4-40. *Assembly of the scale test for homogenisation modelling. The left picture shows the bentonite ring with the rectangular cavity.*

Five modeling teams are working with this task. Most of them have finished step 1 and are working with the following steps. A prediction of the water and density distribution in the outer section in the backfill and in the outer deposition hole at excavation was requested to the meeting in Lund. No complete THM-modelling results were available at the meeting. SKB team 1 presented TH-caluclations and the results of the water ratio distribution. The work will continue.

Geochemistry

The following issues have been dealt with during 2012.

Modelling and experimental work:

A course in CruchFlow was held in Bern in spring 2012.

Counterion diffusion in purified montmorillonite contacted to pure water has experimentally been demonstrated and modelled by Clay Technology.

Porewater chemistry of compacted bentonite from Rokle has been analysed and modelled by NRI.

Diffusion of water in bentonite has been modelled by use of Molecular Dynamics at Clay Technology.

THMC formulations and analysis by use of Code-Bright was presented by Leonardo Guimarães from the Federal University of Pernambuco.

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

Continued modelling concerning all four benchmark data sets has been performed at Clay Technology. The extension of the ion equilibrium approach to pressure and water flow responses due to externally applied water pressure gradients have been studied.

The Paul Scherrer Institut has performed experiments concerning "Diffusion of bivalent anions in compacted smectites".

Bentonite erosion into a granite fracture has been experimentally studied at UJW (Rawra).

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

Code development:

The in-house code developed by Clay Technology to handle ion-equilibrium has been further improved to model diffusion in bentonite.

4.11 System design of backfilling of deposition tunnels

Background

The KBS-3V repository consists of deposition tunnels with copper canisters containing spent fuel placed in vertical deposition holes. The canisters are embedded in highly compacted bentonite. After placement of canisters and bentonite, the deposition tunnels are backfilled with pre-compacted blocks of bentonite stacked on a bed of bentonite pellets. The remaining slot between the blocks and rock wall will be filled with bentonite pellets.

The concept for backfill, described in SKB's licence application for a Spent Fuel Repository in Forsmark, is developed further in this project.

The main objective with this project is to ensure that the method selected for backfill including methods for inspection works as intended with reasonable efficiency.

The work consists of investigations, calculations, laboratory tests, tests in the Bentonite Laboratory and underground tests at Äspö HRL.

Objectives

The project objective is to further develop SKB's reference concept for backfill by performing a system design and to ensure that the reference method works as intended with reasonable efficiency.

Experimental concept

The project is divided into 5 sub projects with the following main activities.

1. Design.
    a. Development of requirement specifications for backfill production and installation based on design premises from long term safety.
    b. Development of a quality plan for production and installation of the backfill.
    c. Modelling and tests to verify design and set requirements on the production and installation of backfill.
    d. Material studies on bentonite clays.
2. Pellet optimization.
    a. Optimization of bentonite pellet properties, in particular to improve the water storage capacity of the pellet filling.
    b. Development of a conceptual model for wetting of pellet fillings in deposition tunnels and verification of the model in large scale tests.
3. Block and pellet production.
    a. Production of bentonite blocks from different bentonite clays in factory tests.
    b. Industrial planning of block and pellet production in large scale.
4. Methods for water handling.
    a. Development of different methods for managing inflowing water from the rock during backfill installation.
5. Installation and large scale test.
    a. Design and construction of prototype equipment for installation of backfill blocks and pellets.
    b. Large scale test of backfill concept in tunnel conditions – A full scale demonstration test to backfill 12 m tunnel is planned underground in Äspö HRL in 2013.

Results

A large number of laboratory tests have been performed with different bentonites and pellet types to find a pellet with improved water storage capability. Pellet installation tests have been done in large scale to study the influence of the installation on the pellet properties. A conceptual model for wetting of pellet fillings has been developed. Improved understanding regarding water inflows and time aspects during backfill installation in deposition tunnels have been obtained.

A conceptual quality control program of the backfill has been developed.

Three batches of backfill candidate materials have been characterized within the project, one batch of Ibeco delivered in 2011 and two batches of Asha delivered in 2010 and 2012. Determinations of i.a. water content and CEC were performed on several samples. The Ibeco batch was a homogenous bentonite regarding water content and granule size distribution. The two batches of Asha were more inhomogeneous and the scatter in the determination of water content was large. However all three batches fulfilled the requirement on smectite content with good margin. Ibeco 2011 had an average smectite content of 64 %, Asha 2010 an average of 74 % and Asha 2012 an average of 76 %.

Large scale backfill blocks have been manufactured with good results. Experiences from block manufacturing tests of different bentonite clays shows that the block pressing unit needs to be tuned for every new material.

Prototype equipment for backfill installation has been designed and constructed and are ready for testing. Blocks will be installed with an industrial robot provided with a specially designed lifting tool, see Figure 4-41.

The concept for the installation of backfill is improved and the plan is to make a demonstration test in full scale underground during 2013. The demonstration of the backfill installation in tunnel conditions will give important and valuable information for the future development and detailed design of the backfill concept for the Spent Fuel Repository.

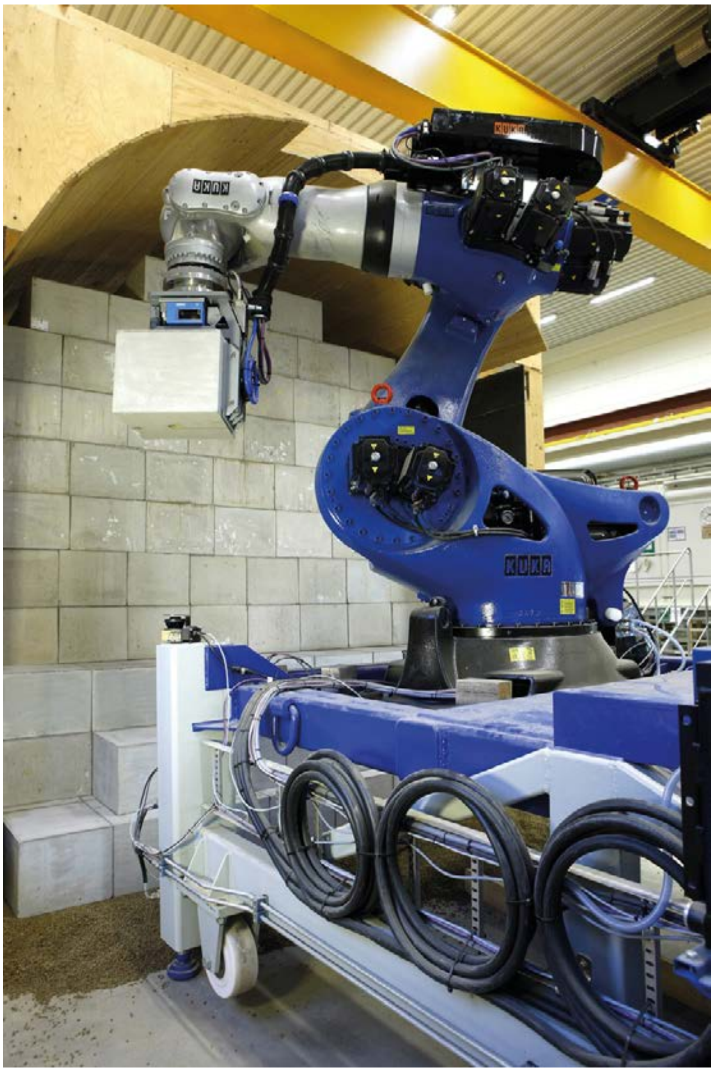


Figure 4-41. *Industrial robot for backfill block installation.*

4.12 System design of dome plug for deposition tunnels

Background

The reference design of the KBS-3V deposition tunnel end plugs consists of an arched concrete dome, a bentonite seal, a filter zone and delimiters. Furthermore, a backfill transition zone has been introduced to moderate the swelling pressure from the backfilling in the tunnel, with the purpose of attaining a static load on the plug. (SKB 2010a)

In the Spent Fuel Repository, the plugs will be made of low-pH concrete instead of conventional concrete. The reason for this is to avoid the negative effects that basic materials can have on bentonite clay properties. For this purpose, a specially adopted concrete recipe B200 was developed to meet the requirements of the design (Vogt et al. 2009). The conditions for reinforcement, cooling and contact grouting are hereby different compared to the use of standard concrete.

Additional input to this project is an investigative work where the plug has been evaluated with a focus on the concrete structure (Malm 2012). In conclusion, the report declares the potential of using an unreinforced dome design of low-pH concrete B200 to restrain the swelling clay and groundwater pressure in the deposition tunnel. The advantages of being able to perform a concrete dome without reinforcement is to avoid risks for corrosion of reinforcement and risk for cracks related to the reinforcement due to the shrinkage of low-pH concrete. In addition, time and cost savings are obtained at installation.

Objectives

The project aims to ensure that the reference configuration of the KBS-3V deposition tunnel end plug works as intended. By testing the design in a full-scale demonstration it is to be proven that the method for plugging of a deposition tunnel is feasible and controllable. The requirements on tightness of the plug are to be given a definite form.

The main goal of the full-scale test "Domplu" (Dome plug) at Äspö HRL is to determine leakage through the plug (and the contact surfaces between the rock and the concrete) at the design pressure of 7 MPa. Furthermore, a load-test of the plug up to 10 MPa will be performed.

Experimental concept

The experimental site for the Domplu-test is located at Äspö HRL –450 m level, where good and dense rock conditions prevail. The experiment is monitored by a total of about 100 sensors. More than half of the sensors are measuring the concrete dome stress performances, temperatures and movements while the remainder sensors are monitoring water pressure, total pressure, relative humidity and movements in the bentonite seal, filter and the backfill zone.

A key objective is to monitor the water leak through the plug over time (at least 36 months). For this purpose, a measurement system for leakage control has been developed and the water will be dammed up within a dense atmosphere (plastic sheeting) just downstream of the concrete dome and directed by gravity to a pendent scale for on-line registration of water flow. The experiment is pressurized artificially with water in the backfill behind the plug, stepwise up to 7 MPa for the tightness test, and up to 10 MPa for strength test verification. The experimental set-up and pressurization program is targeted to reflect the real conditions expected in the Spent Nuclear Repository.

Results

In 2012, the experimental tunnel (TAS01) was excavated and the accurate plug location was determined.

The rock excavation for the concrete dome abutment was carried out by wire-sawing, making an octagonal slot almost 9 meters in diameter.

The wire-sawing method is assumed to minimize risk of continuous EDZ and it provides smooth rock surfaces for the concreted dome. The tested rock excavation method was functional, but influence from rock stresses made the performance different compared to common sawing at shallower depth.

A temporary safety beam construction and steel nettings was used for workers protection during the excavation. When all sawing-cuts had been completed, the rock segments and the safety beams were removed simultaneously by blasting.

The entire slot was finally measured in detail by laser scanning. The results of the rock excavation will be evaluated during 2013.

The installation of the inner parts of the plug began in late 2012.

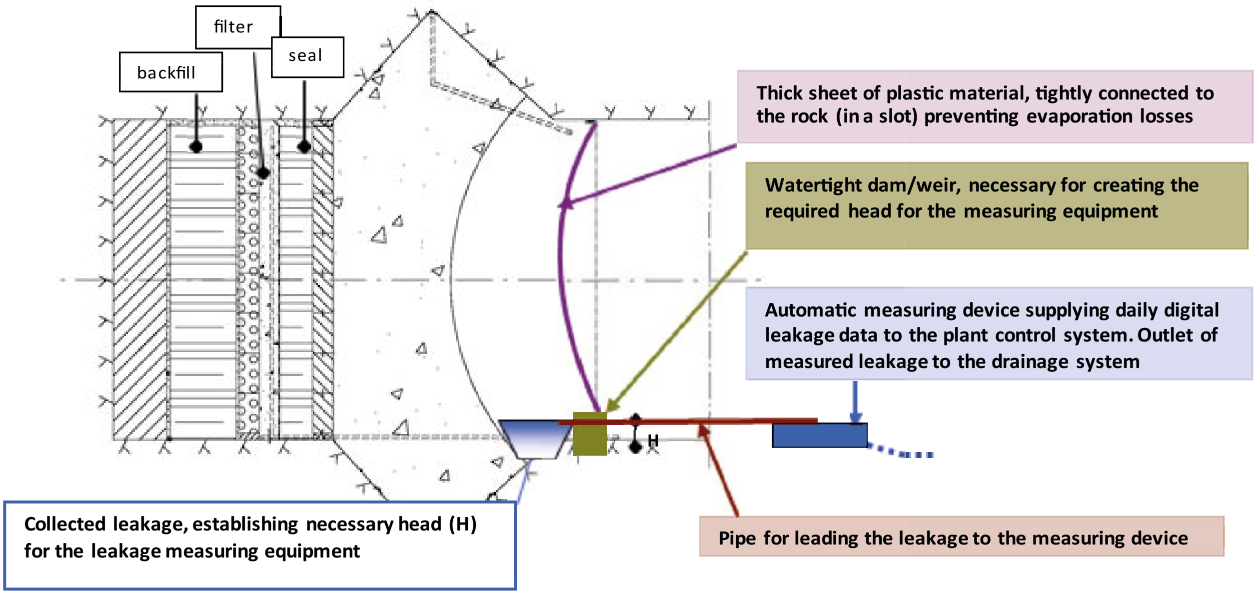


Figure 4-42. *Layout of the full-scale experimental set-up Domplu.*

Figure 4-43. *Part of the concrete dome abutment, excavated by wire-sawing.*

***Figure 4-44.** Detail photo showing (from left) filter of leca-beams and macadam, drainage (air) pipe, geotextile, bentonite seal of MX-80 (blocks and pellets) and concrete delimiters. All sensor cables are led in steel tubes.*

In March 2013, casting of the concrete dome will take place. The primary pressurization of Domplu starts when the shrinkage-gap between the concrete dome and the rock has been fully contact grouted. The contact grouting can be performed when the concrete dome has hardened and its autogenous shrinkage is about 99% complete, approximately 90 days after casting.

The test programme will commence in mid 2013 and continue throughout 2014. The measurements will include control of the amount of leakage-water and extensive recording of events in the concrete dome, bentonite seal, filter and backfill transition zone. The sensors data will be followed up and evaluated. A technical report is planned to be completed at the end of 2014.

The experiment will be under continued observation until at least 2016.

DOPAS (Full scale demonstration of plugs and seals)

The Domplu test is part of the EU-project DOPAS, which receives funding from European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013. DOPAS aims to improve the adequacy and consistency regarding industrial feasibility of plugs and seals, the measurement of their characteristics, the control of their behavior over time in repository conditions and also their hydraulic performance acceptable with respect to the safety objectives. DOPAS is carried out in a consortium of 14 organisations representing waste management organisations, research organisations, academia and consulting.

Figure 4-45. Installation of concrete delimiters, bentonite seal, macadam filter and sensors.

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. A total of over 200 different products and components known today are to be developed for the future final repository. 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.

Assessments hav been made of when the production of machines must begin and when they should be completed, as well as whether production of prototypes are necessary. The number of objects and affiliated information is due to change since the specifications are working documents. 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 Technical development at Äspö HRL

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 resulted 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 project phase recently finished was to perform long term tests with the machine, and to develop the systems for navigation and positioning. In the next phase the hoist and the grapple unit will be further developed, and Magne is also an important part of the development of mission and production control systems.

Experimental concept

Tests to collect data and to evaluate reliability, safety and availability were performed in a tunnel at Äspö HLR. Also the service requirements during continuous operation were tested.

Results

Recorded test runs of the full scale tests were started at the end of 2010 and continued through to 2012. When several full test cycles of 40 depositions had been performed without any kind of interruption or error the tests were regarded as completed. Approximatly 220 completed depositions were made within the long term test period and fine adjustment of the software was made. A test report was completed during 2012.

5.2.2 Equipment for backfilling

Background

After deposition of canisters in the future final repository, the tunnels will be filled with backfill material to seal the deposition tunnel. In order to perform this, and meet the requirements, a concept with a robot on a mobile platform has been developed (see Figure 5-2).

Robot handling of these large amounts of material 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.

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

***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.*

Objectives

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

Experimental concept

Software is developed as well as methods and equipment for measurement och control. The equipment is tested both over and under ground, and will be used to verify performance and identify if any parts of the process needs further development or redesign.

Results

During 2012 the following activities has taken place:

- An industrial robot was installed on the mobile platform.
- Software for robot on platform were developed.
- The systems were integrated with i e mission control system.

Development and testing is still ongoing in the Bentonite laboratory.

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 tested during 2012. The tool works with vacuum to hold the buffer and has shown good function in laboratory tests (see Figure 5-3).

Objectives

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

Experimental concept

Tests were performed with the lifting tool in the Bentonite laboratory. The test programme covered the design, number, sequence and documentation of necessary lifting equipment.

A total concept for buffer emplacement, blocks and pellets, is developed. The need for development of prototypes is assessed, and if needed, prototypes will be manufactured.

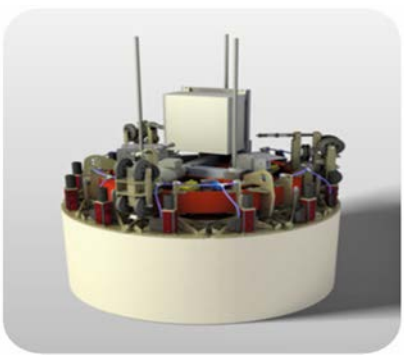


Figure 5-3. *Lifting tool for buffer emplacement.*

Results

A programme of quantity and endurance tests on the lifting tool has been performed and reported. Adjustments on the crane were made.

The development of a concept for a carrier of the lifting tool used for emplacement of blocks and rings and a concept for installation of pellets has started.

5.2.4 Ramp vehicle and multipurpose

Background

There will be frequent heavy load transports in the ramp down to the final repository. To have these transports executed, a Multi Purpose Vehicle (MPV) for heavy transports was ordered in November 2010 and delivered in August 2011. This vehicle is now tested for heavy load transports in the ramp att Äspö HRL.

Objectives

A verified concept and a tested prototype for heavy load transports in the ramp in the final repository.

Results

An ATB has been rebuilt and tests have been performed, transporting the modified ATB P in the ramp at Äspö HRL simulating different weights and centers of gravity.

5.2.5 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 was been made during 2010 and formally the project started in October 2010.

Figure 5-4. Ramp Vehicle carrying the modified ATB.

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.

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

Results

The system has been tested and further developed.

5.2.6 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

A concept for 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 was 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 and feed paths have been constructed and manufactured and are tested at Äspö.

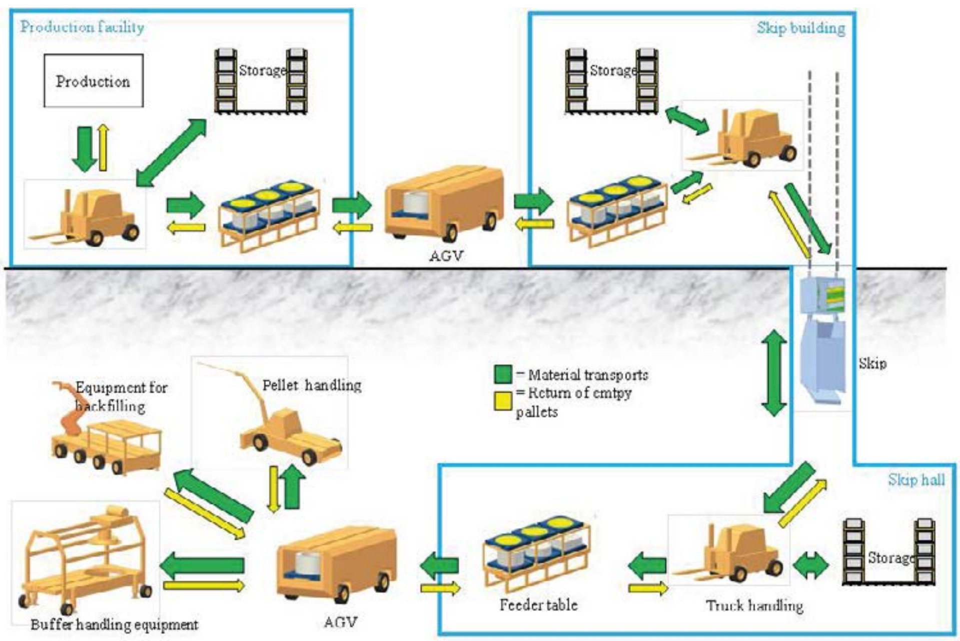


***Figure 5-5.** A sketch over an autonomous and remotely operated transport system for buffer and backfill material from the production premises to the deposition tunnels.*

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 2012 the development of the Äspö Facility has been continuous ongoing with the extension of the tunnel. During October to December the rock excavation for the experimental tunnels were done. Total it is about 300 m new tunnel meters in Äspö Hard Rock Laboratory and the layout for –410 m and –450 m level shows in Figure 6-1.

Important tasks of the Äspö facility are the administration, operation and maintenance of instruments as well as development of investigation methods. Äspö HRL is the residence of the unit *Repository Technology* but the unit includes employees in both Äspö and Stockholm. The main responsibilities of the unit are to:

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

The *Repository Technology (TD)* unit has the past years been organised in four operative groups and one administrative staff function. From the beginning of 2012, the unit was extended with two further operative groups – Rock Characterization and Rock Engineering and Chemistry Laboratory. The TD unit is currently organised in the following groups;

- *Geotechnical barriers and concrete techniques (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 experiment 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.
- *Rock Characterization and Rock Engineering (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.

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.

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.

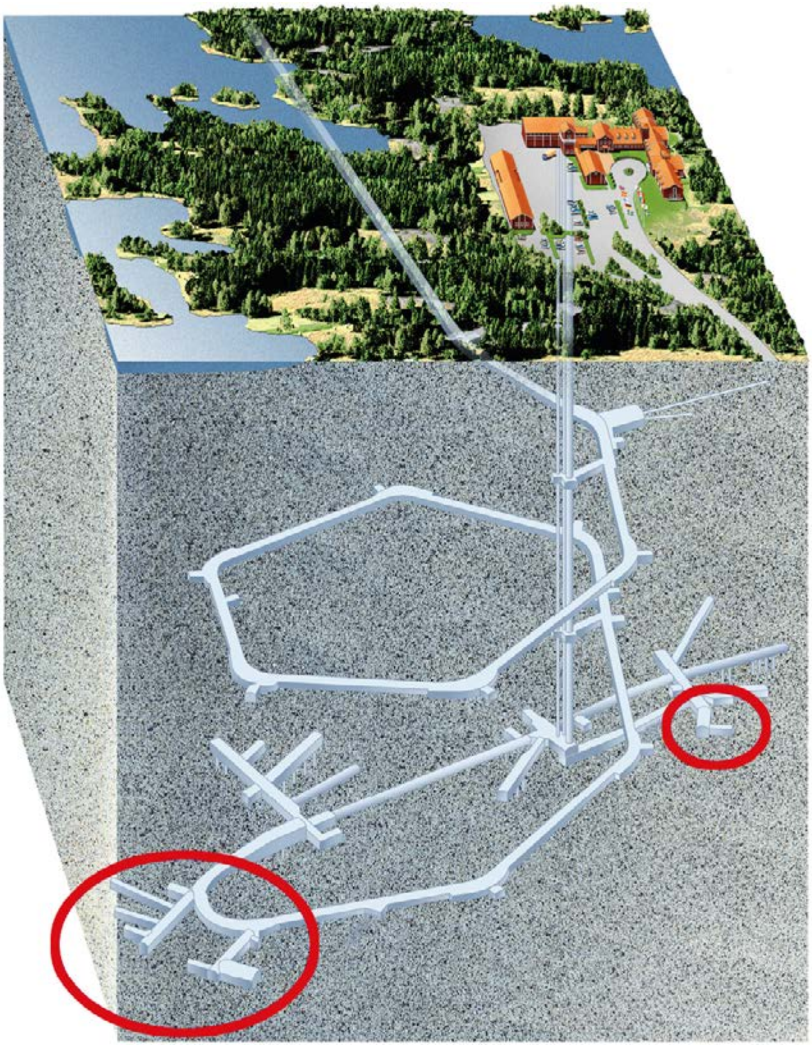


Figure 6-1. *Circled: the new areas in the Äspö tunnel.*

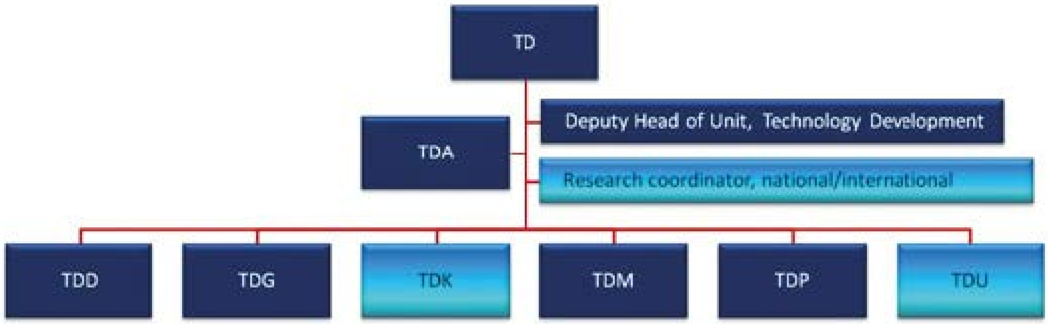


***Figure 6-2.** The reorganization of the Repository Technology (TD) unit entails a lot of changes and includes TDA (Administrations, QA and planning, TDD (Facility Operation), TDG (Geotechnical barriers and concrete techniques), TDK (Chemistry Laboratory), TDM (Mechanical- and system engineering), TDP (Project- and experiment service) and TDU (Rock Characterization and Rock Engineering).*

6.2 Expansion of Äspö HRL

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.

134 m transport tunnels with 174 m experimental tunnels are excavated for:

- Nuclear Fuel programme – Experimental site for testing of plug for deposition tunnel.
- Project KBS-3H – Experimental site for KBS-3H at repository depth (–410 m).
- LILW programme – Experimental sites for the project Concrete and Clay.
- SKB International.

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

The project has working with focus on tunnelling and how to optimize the rock excavation together with the mapping and still manage to handle time schedule and budget. During February to April the transporttunnel TASJ ande experimentel tunnel TAS01 was excavated. During May to October the transporttunnels TASU and TASP was excavated in the rockvolume of the intended area is in the northeast part of Äspö HRL at the –410 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.

A continous work through the excavation was modelling work to get information about the bedrock as input for deciding where the experimental tunnels should be placed based on requirements from each experiment.The geological and hydrogeological model of tha area of expansion at the –410 m level shows in Figure 6-3.

During October to December the rock excavation for the experimental tunnels were done. Total it is about 300 m new tunnel meters in Äspö Hard Rock Laboratory and the layout for –410 m and –450 m level shows in Figure 6-4.

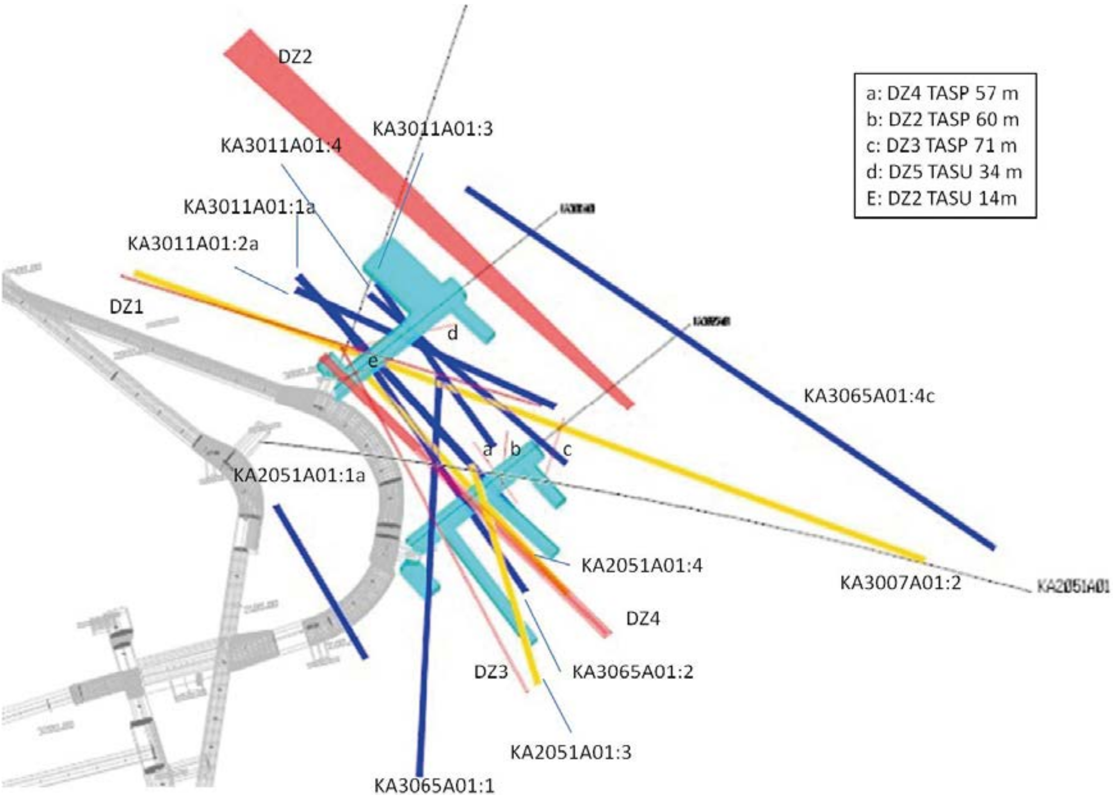


Figure 6-3. *Geometry for the area of transport tunnels TASU and TASP and experimental tunnels (in cyan) together with geological deformation zones and hydraulic conductive features, red features are geological deformation zones, yellow and blue features are hydraulic conductive features, yellow features ($10^{-6} < T < 10^{-5}$ m^2/s) show higher transmissivity than blue features ($10^{-7} < T < 10^{-6}$ m^2/s).*

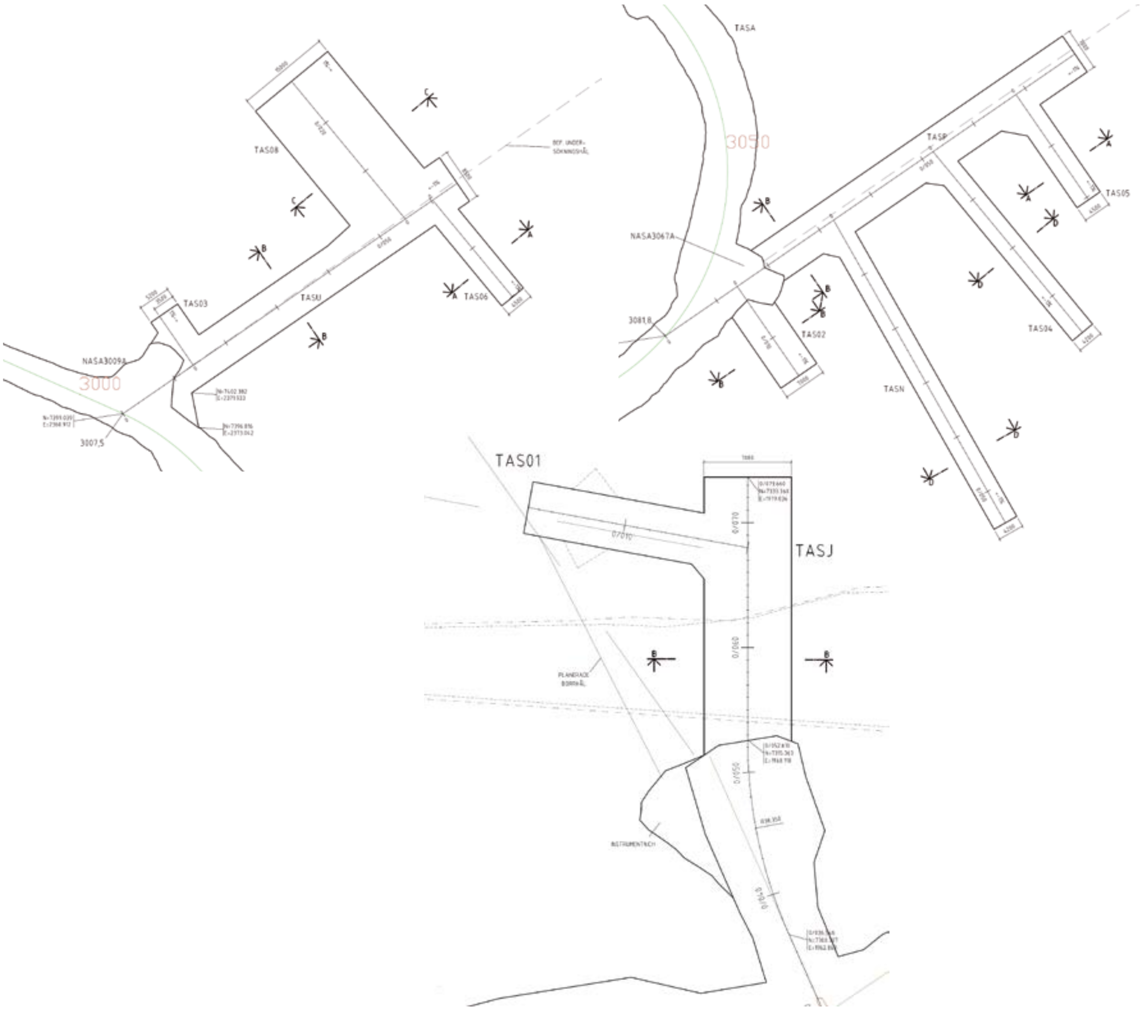


Figure 6-4. *Final layout TASU and TASP with experimental tunnels and TASJ with the TAS01 for the KBP1004 project.*

Figure 6-5. *Mapping with RoCS are conducted in the experimental tunnel for KBS-3H (TAS08).*

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

Steel tunnel tests at Äspö

One of the subprojects within the ÅSKAR project works with issues concerning water handling during backfilling of deposition tunnels. A part of this work has been to study if geo-textile, fastened over a water inflow point on the rock wall, can work as a distributor of the inflowing water and thereby increase the water storing capacity of the pellet filling. This would increase the available time for installation before water from backfilled parts hits the front.

In order to investigate whether the geo-textile works as planned, tests have been performed in the bentonite laboratory at Äspö. The tests were performed using the steel tunnel equipment. In total three tests were performed during the end of 2012. The tests included installation of a central form covered with plastic and bentonite mat, bentonite blocks stacked over the form and pellets that were blown into the remaining slots. Preliminary results have shown that the design works as planned. The evaluation of results is ongoing and a report will be made during April 2013.

Figure 6-6. *Dismantling test 3.*

6.4 Facility operation

Background and objectives

The main goal for the operation of the rock laboratory is to provide a facility which is safe for everybody working in, or visiting it, and for the environment. This includes 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 facility has has a stable operation during 2012, with almost 100% accessibility.

Construction of the new washing hall by the tunnel entry was initiated before the summer 2012. The washing hall is mainly intended for care of SKB'S vehicles and for those contractors using vehicles underground.

The ground work for the washing hall was made difficult by a number of hidden electrical cables and a poorly marked hydrogen pipe in the ground. The facility was put in operation during the later part of 2012.

During the year maintenance of the elevator is performed, including exchanging the elevator cable and a new attatchment on the elevator car.

A new mobile back-up power generator for the tunnel has been purchased and delivered. It is intended to replace a transformer in case of a failure. Test operation was performed after delivery.

Survey of the rock has been carried out for TASJ and TAS01. These tunnels were then handed over from the Expansion-project to the clients.

Maintenance of the Äspö facility has been performed, including painting facades and moss prevention on roofs. Upgrades and renovations have been done in conference rooms Måsskär, Vinö and Långö (which was divided into two rooms; Upplångö and Utlångö.

***Figure 6-7.** The new washing hall.*

The operations unit has been working with several energy saving measures at Äspö HRL during 2012;

1. Air/heat pumps to the contractors barracks 2012.

Air/heat pumps has been mounted in the two contractor barracks. The purpose is both to reduce energy use and to give up the electric radiators powered by direct-acting electricity.

2. Updating office lighting.

Work is continuously ongoing with regard to control and adjustment of lighting in office spaces. The lighting is updated to fluorescent lamps with presence sensor, dimmer function and in some cases also uplight function. An estimation of savings from these measures for all of the 70 office rooms at Äspö HRL is 378 kWh per week (approx. 20,000 kWh per year.)

3. Heating of new washing hall using drainage water from the rock.

The new washing hall near the tunnel entry was completed 2012. Drainage water from the tunnel, gathered in the near by sedimentation pool, is used as heat source by using a heat exchanger and ground source heat pump. The transformation factor is so effective that 60–75% can be saved in comparison with direct acting electrical heating. A new washing hall was an environmental goal, firstly to minimise emission to the recipient.

4. Heat recycling from drainage water.

During 2012, projection was started of a new heating system for the entire Äspö HRL above ground facility. The water, approx. 14 degrees Celsius, will be used to heat and cool the facility's buildings by using heat exchangers. Savings will cover the cost of the system after 6–10 years.

This measure is part of the energy survey from 2010, and has since been investigated further. The energy savings from this investment is estimated at approx. 615,000 kWh per year.

5. Increasing the number of energy measurement points.

The facility has 3 gauges for incoming energy. Plans have been made to increase the number of measurement points to allow for more detailed follow-up. This work was initiated during 2012 and is planned to carry on for several years, as it entails interference in the current facility.

6. Heating the road way outside the tunnel gate.

The road way outside of the tunnel gate needs to be heated during the colder months to prevent slipping. Currently, electric cables in the road way for this. A new heating system for the road way has been projected during 2012, using waterborne heat led through hoses under the road way. Estimated saving compared to the direct acting electricity used currently is approx. 50,000 kWh per year.

7. Control of tunnel ventilation.

A new fan has been installed at the –420 m level in the tunnel and there are plans to connect it to the RFID-system to be able to adapt the ventilation in the tunnel to the current needs. Need-based control of the ventilation was listed in the energy survey from 2010. The potential savings is estimated in the survey at 170,000 kWh per year or 170,000 SEK per year.

6.5 Communication Oskarshamn

General

SKB operates three facilities in the municipality of Oskarshamn: Äspö HRL, Central interim storage facility for spent nuclear fuel (Clab) and the Canister Laboratory. The main goal for the Communication unit in Oskarshamn is to create public acceptance for SKB, which is done in co-operation with other departments at SKB. The goal will be achieved by presenting information about SKB'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, but also questions regarding societal consensus. The information group has a special booking team at Äspö which books and administrates all visitors at SKB. The booking team also is at Oskarshamn NPP's service according to agreement.

In addition to above, the unit also has the responsibility for school information in Oskarshamn as well as in Östhammar, press release matters locally, 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. During 2012 Communication Oskarshamn consisted of 12 persons.

Special events and activities

During 2012, 5,621 people visited the Äspö HRL and with the visitors at Clab and the Canister Laboratory included it results in a total of 8,687 people. The total number of visitors to all SKB facilities in both Oskarshamn and Forsmark was 15,885 persons. The visitors represented the general public, teachers, students, professionals, politicians, journalists and visitors from foreign countries. The total number of foreign visitors 2012 was 1,593. The special summer arrangement "Urberg 500" was arranged during six summer weeks and during these weeks about 1,300 persons took the opportunity to visit the underground laboratory. Tours for the general public also took place some Saturdays during the year and on December 1st, "Lights in the bedrock" ("Ljus i urberget") was arranged. Candles lighted up the tunnel while music students from the school "Folkhögskolan" in Oskarshamn entertained at a depth of 450 meters.

During 2012 the unit's school information officer went to schools and high schools within the municipality of Oskarshamn to inform about SKB: s work. SKB has been represented at several school events in Oskarshamn during the year. Almost 60 female students on the high schools Oscarsgymnasiet in Oskarshamn and Lars Kagg in Kalmar have been participating in "Tjejresan", an initiative aiming to show the opportunities for a career within the technical field. Fieldtrips and meetings with employees are ways to increase the female student's interest for a field otherwise highly dominated by men.

All students in 9th grade in Oskarshamn are offered a visit to the Äspö HRL and the Canister Laboratory and all students in the 3rd grade of high school are offered a visit to Clab. Newsletters and targeted invitations are sent out to teachers every year. Teachers in Oskarshamn were for example offered a lecture about ice ages during the year and principals from the municipality of Östhammar were offered a trip to the facilities in Oskarshamn.

The unit arranged a number of events during 2012. The national event "The Geological Day" was arranged at the Main library of Oskarshamn in September, with SKB as one of the participating organisations. Children in primary school were invited and encouraged to bring stones of which a geologist could determine the rock specie. A meteorite exhibition was also held and 600–700 people attended to the event at the library. On the afternoon, approximately 60 persons took part in a popular feature in the form of a geological walk through Oskarshamn. "Researcher's Night" was arranged on September 28th at the Canister Laboratory and the theme was "Learn more about research and techniques used in the Äspö HRL". The participants were students from the Linnaeus University.

SKB was one of the inviting partners to the conference "Scientific Possibilities in the Oskarshamn Region in Kalmar County", that took place the 5–6 of November in Kalmar. The conference was an opportunity for interested parties to discuss the possibilities of a National Geosphere Laboratory (NGL) at Äspö HRL with surroundings and related research-supporting facilities. The conference was initiated by KTH Royal Institute of Technology and Nova Center for University Studies, Research and Development and the other inviting partners were The Municipality of Oskarshamn, Regional Council in Kalmar County and County Administrative Board Kalmar. Besides the National Geosphere Laboratory, Rad Lab Sweden and Use of Surplus Energy to enhance profitability in closed Aquaculture systems were discussed during the two days.

During spring and autumn, SKB held well attended lectures in Oskarshamn with different themes related to SKB: s work. The participants got the opportunity to learn more about how the disposal of spent nuclear fuel occurs in other countries, ice ages, radiation and the encapsulation facility.

On the 24th of November, 96 competitors participated in "the Äspö Running Competition" resulting in a new record time on the female side.

During 2012, 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.

Furthermore, the unit is involved in "Almedalsveckan" in Visby 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 6-8. *The theme for "Researcher's Night 2012" was "Learn more about research and techniques used in the Äspö HRL".*

Figure 6-9. *SKB was one of the inviting partners to the conference "Scientific Possibilities in the Oskarshamn Region in Kalmar County" that were held the 5–6 of November in Kalmar.*

7 Open research and technical development platform, Nova FoU

7.1 General

The aim is to describe major progress during the year 2012 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 2012.

7.2 The Nova FoU mission

Nova Center for Univeristy Studies, Research and Development 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 SKB facilities:

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

The platform also offers access to areas of interest for research and development within the Oskarshamns region such as the harbor remediation project in Oskarshamn.

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.

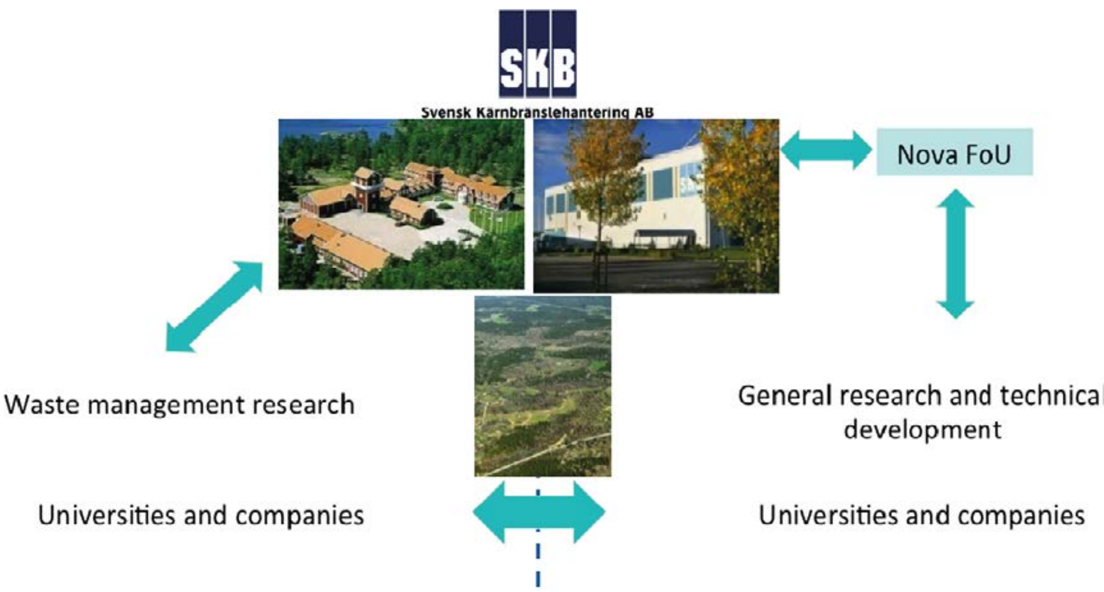


Figure 7-1. *Nova FoU provides access to the SKB facilities and data for universities and companies for general research and technical development. Nuclear waste management research is handled by SKB.*

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).

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:

7.2.1 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.

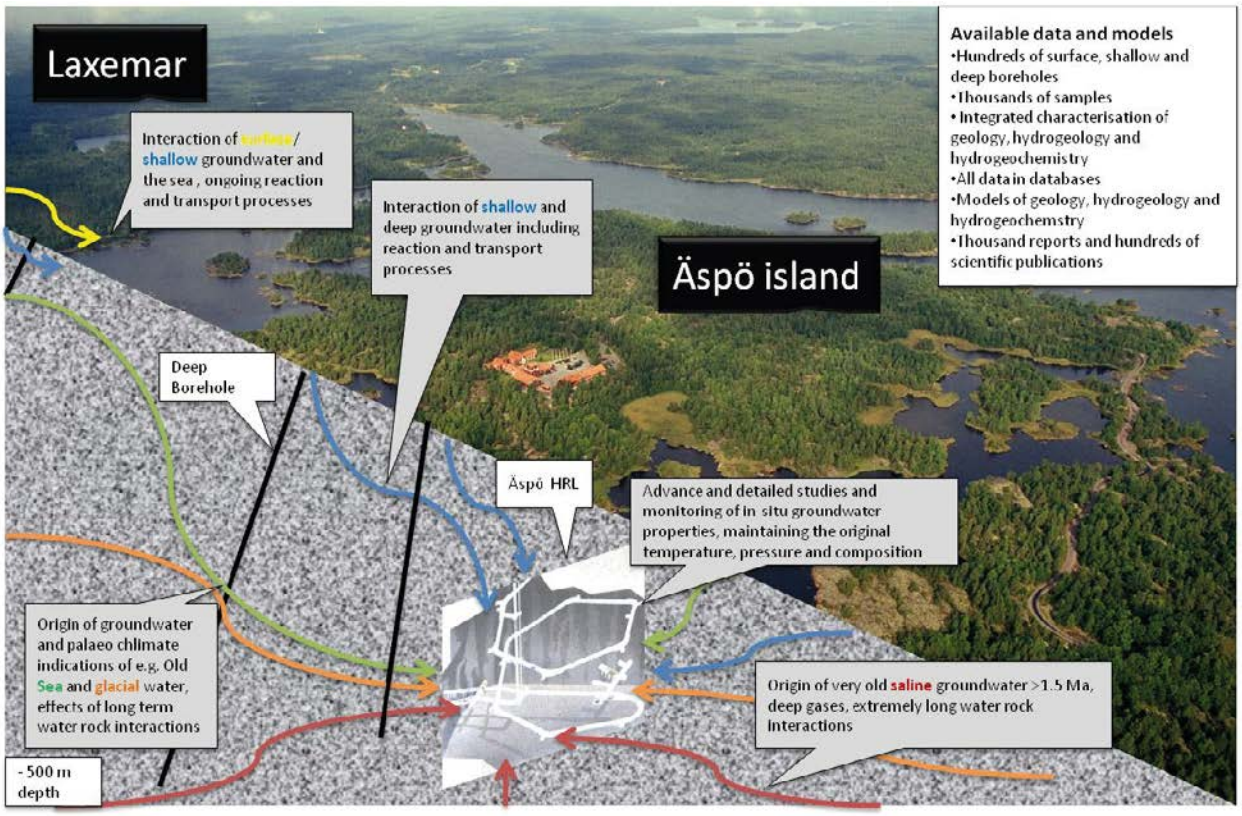


***Figure 7-2.** The Äspö and Laxemar areas have been studied in terms of geology, hydrogeology, hydrogeochemistry and ecology. This information can be used for a number of purposes, for example to describe the water cycle and hydrogeochemical processes in 3D.*

7.2.2 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 The status of the 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 2012 are described below.

7.3.1 Lanthanoids in bedrock fractures (Mats Åström, Linnaeus University)

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 project has come to the point that a manuscript has been submitted for consideration by a scientific geochemical journal. The title of the submitted manuscript is "Rare Earth Elements in Groundwater and Calcite Precipitates in Fractures in the Upper Kilometer of Proterozoic Granitoids in Boreal Europe". The authors are: Mats E. Åström, Frédéric A. Mathurin, Henrik Drake, Olga M. Maskenskaya and Birgitta E. Kalinowski.

In the manuscript we present and discuss the sources, distribution, abundance and fractionation of lanthanoids and yttrium in groundwater and the abundance and fractionation of the same metals in low-temperature calcite precipitates in fractures in the upper kilometer of granitoids. We argue that the lanthanoids dissolved in the fracture groundwater were not derived from the regolith, but rather from *in situ* solid phases bordering the fractures (including both fracture coatings and primary wall-rock minerals). We also argue that the lanthanoid concentrations in calcite, when applied to existing partition coefficient for lanthanoid uptake in calcite, indicate that the groundwater precipitating the calcites (within the past 10 million years) were similar to the present groundwaters in terms of Ln and Ca chemistry.

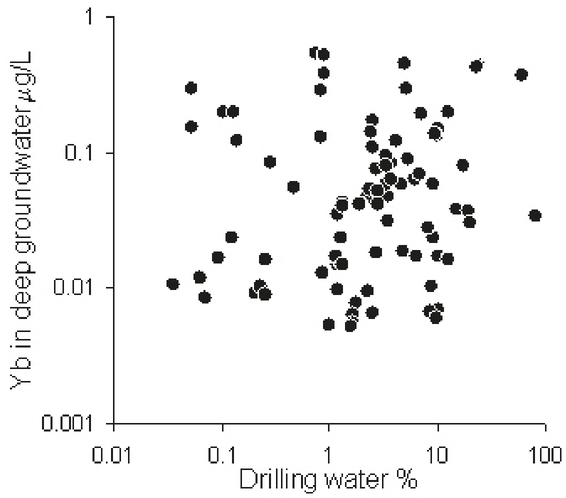


Figure 7-3. *Scatterplot of drilling-water percentage and Yb (a heavy lanthanoid) concentrations in groundwater. This plot shows that there was no significant correlation between drilling-water % and lanthanoid concentrations, which is a good starting point for further statistical analyses and interpretation of the behaviour of lanthanoids in the fracture system.*

Spin-off

The findings of this study are relevant in terms of the understanding of global lanthanoid cycles and technical/societal challenges, including:

1. The influence of submarine groundwater discharge on lanthanoid budgets of the oceans, considering that the investigated areas are located on the shore and thus are representative for deep-groundwater lanthanoid loads that ultimately discharge in the sea.
2. Nuclear-fuel waste repositories, which has to remain intact for at least 100,000 years and which in several countries will be constructed in the type of bedrock covered by this study. For the scenario of repository failure the lanthanoid results reported here can be used to assess the behavior of analogous radioactive actinoids potentially escaping through the technical barriers. For example, the overall low dissolved Ln concentrations in the groundwater (often occurring below detection limit), despite high lanthanoid abundance in several of the fracture-bordering solids, is indicative of generally high retention and low mobility of lanthanoids (and analogous actinoids) in the bedrock surrounding foreseen nuclear waste repositories.

7.3.2 Fluorine in surface and ground waters (Tobias Berger, Linnaeus University)

Aim of the project

The main aim of the project is to increase the understanding of the behavior 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 aims to: (1) describe and explain the high fluoride concentrations in the water in the lower reaches of the Kärrsvik stream (this stream was included within Site Investigation Oskarshamn, Figure 7-4), (2) characterise and model fluoride abundance, transport and speciation in streams in the Laxemar-Äspö area, (3) characterise fluoride abundance and temporal variation in shallow (soil) and deep (bedrock) groundwaters of the Laxemar-Äspö area and (4) describe and explain fluorine abundance in soils in order to better understand how this element is distributed and released from soils to shallow groundwaters and surface waters.

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

Status of the project

During the autumn of 2011 two projects were initiated; (1) Temporal speciation of fluoride in three catchments in the Laxemar area and (2) Distribution and controls of fluoride in shallow (soil) groundwater of the Laxemar-Äspö area. Project (1) will be finalised and submitted to a scientific journal during first half of 2013. Project (2) has during 2012 developed into a study also including deeper, bedrock groundwaters and a manuscript will be finalised during spring 2013. A third project reconnects to the fourth aim and was initiated during autumn 2012. We will thoroughly analyse fluorine in soil horizons (0 to ~1 m depth) across the Kärrsvik stream catchment area in order to investigate the distribution of this element across the catchment, along soil profile gradients and in different soil fractions. Samples have been collected and pre-treated and will be chemically analysed during first half of 2013. SEM-WDS microanalysis of fluorine in different bedrock minerals, i.e the "end-member" of fluorine in soils and waters, was carried out in February of 2012. Those results will be integrated in this study.

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). Project (2) presents the importance of fluoride abundance on aluminium speciation in boreal waters, which are characterised by seasonal pH declines and richness of dissolved organic matter. Dissolved aluminium is considered toxic to aquatic organisms and extensive complexation to fluoride might influence on the toxicological effects of this metal.

Spin-off

The spin-off effects from this project will be increased knowledge on fluorine abundance and transport in surface and ground waters as well as in soils and bedrock in the Laxemar and Äspö area, Kalmar County and other areas across the world with similar geology, 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. The findings may also lead to spin-off effects of economical value.

7.3.3 Modelling of groundwater chemistry (Frédéric Mathurin, Linnaeus University)

Aim of the project

The aim of the project is to increase the understanding of the chemistry of groundwater 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 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, a categorisation method for the assessment of data quality of groundwater from the Äspö HRL was performed. Additionally, the methodology developed in 2011 based on the classification of the groundwaters at Äspö according to their dominant origin was published (Mathurin et al. 2012a) and presented at the Goldschmidt conference (Mathurin et al. 2012b). From the general site characterisation obtained from these two complementary methods, characterisation of cation exchange processes were studied in more detail with a special attention on Cs (Mathurin, Drake, Peltola, Berger, Tullborg, Kalinowski and Äström, in preparation), which is a widely studied nuclide in the field of radioactive waste disposal and environmental sciences.

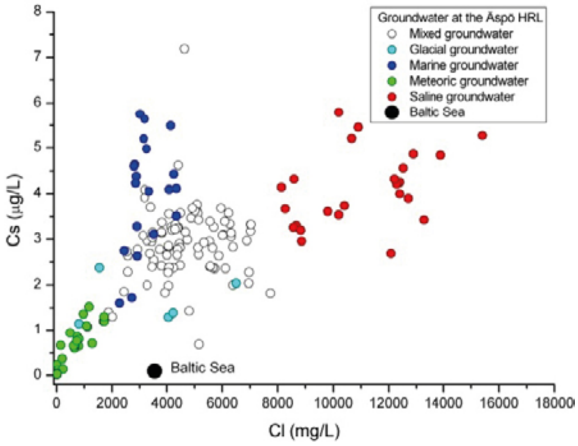


***Figure 7-5.** Cl concentration versus Cs concentration in fracture groundwater at the Äspö HRL. The color of the dots corresponds to the dominant water origin defined by Mathurin et al. 2012a.*

The major results from the Cs work are:

- High variability in Cs concentration appears in the groundwater collected at both the Äspö HRL and the Laxemar area.
- Higher concentrations of Cs (up to several µg/L) were found in old deep seated saline groundwater and groundwater with dominant marine origin (Figure 7-5).
- Cation exchange with illite fracture mineral was hypothesised as possible process leading to Cs enrichment in groundwater.
- From hydrochemical modelling, intrusion of Baltic Sea water (K and NH4 rich water), together with cation exchange, constituted a consistent explanation for the high Cs concentration observed in marinogenic groundwaters at the Äspö HRL.

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 tunnel constructions in crystalline bedrock.

7.3.4 Detailed fracture mineral investigations (Henrik Drake, Linnaeus University)

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 paleohydrogeological 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 paleohydrogeological 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 7-6) 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 a collaboration between Linnaeus University and University of Gothenburg and was published in *Geochimica et Cosmochimica Acta* and was presented at Goldschmidt Conference 2011.

A study of stable sulphur isotopes from currently water-conducting bedrock fractures at Laxemar has been carried out in order to better understand depth and activity of past and present sulphur reducing bacteria in the bedrock aquifer. In situ stable isotope analyses were carried out at NORDSIM (Nordic Secondary Ion Mass spectrometer) during 2012 and an article from this study has been accepted for publication in Geochimica Cosmochimica Acta (Variability of sulphur isotope ratios in pyrite and dissolved sulphate in granitoid fractures down to 1 km depth – evidence for widespread activity of sulphur reducing bacteria, Geochimica et Cosmochimica Acta, In Press, Henrik Drake, Mats E. Åström, Eva-Lena Tullborg, Martin Whitehouse, Anthony E. Fallick). Collaboration involves e.g. SUERC, UK.

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

- 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.
- Investigation of metal uptake in calcite grown on borehole equipment in the Äspö tunnel, and comparison with groundwater data. Collaboration with University of Gothenburg.
- Stable isotope characteristics of pyrite, calcite precititated on borehole equipment in the Äspö tunnel, and comparison with groundwater data.
- Chemistry and reducing capacity of fracture coatings in water-conducting fractures and fracture zones.

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.

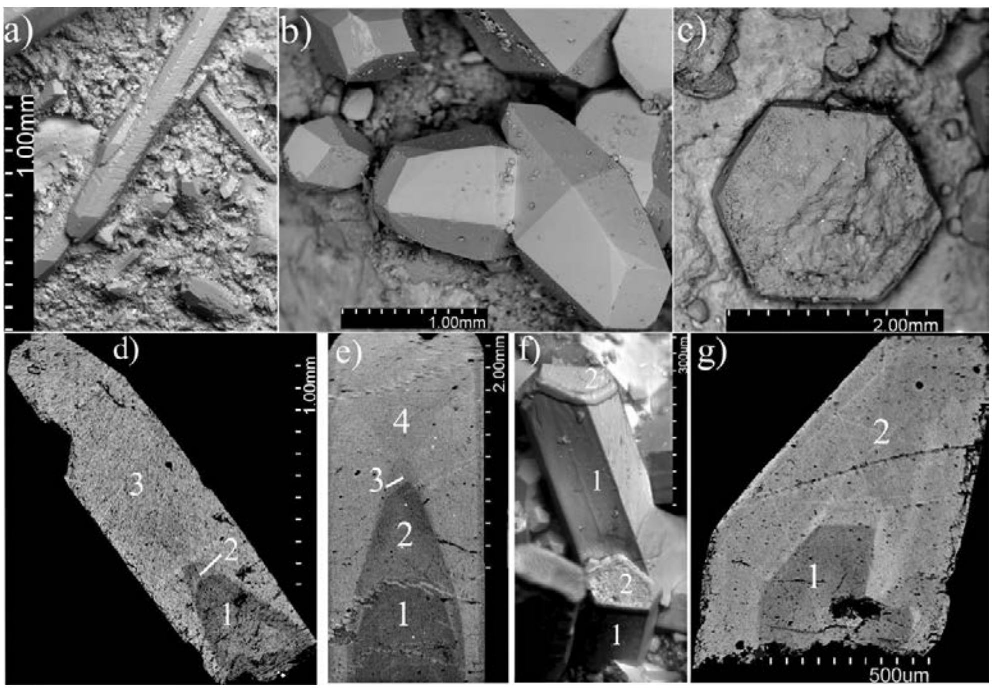


***Figure 7-6.** SEM-images of calcite crystals from open fractures.*

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 systematics 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).

7.3.5 Trace elements in fracture minerals (Olga Maskenskaya, Linnaeus University)

Aim of the project

The aim of the project is to characterize geochemical and stable isotope composition of fracture minerals which precipitated at several geological events and were emplaced in the crystalline bedrocks of the Laxemar area. The fluid that precipitated fracture minerals carries on geochemical and isotopic composition of initial hydrothermal fluid and could be changed due to interaction with the bedrock and mixing with fluids of another origin. Detailed study of bedrocks, originated intrusion and fracture minerals lead to understanding of the origin and factors that influenced the composition of paleohydrothermal fluids.

Status of the project

The most geochemical/analytical procedures have been accomplished for Mezoproterozoic, Neoproterozoic and partly for the Paleozoic generations of the fracture minerals, their originated intrusions and their host bedrocks. The major part of the results has been processed, which will lead to two publications in early 2013 devoted to the Mezoproterozoic and Neoproterozoic generations of hydrothermal minerals. Additional materials will be sampled and analysed in early 2013 for the Paleozoic generation.

Spin-off

Spinn-off from the project will lead to the better understanding of rare earth elements behaviour in paleohydrothermal systems. 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 of one of the ongoing project have been presented at the annual international geochemical conference Goldshmint201 (http://www.goldschmidt2011.org/abstracts/finalPDFs/1421.pdf/) which August 14–19, 2011 in Prague, Czech Republic.

7.3.6 Coastal modelling (Vladimir Cvetkovic, Royal Institute of Technology, KTH)

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.

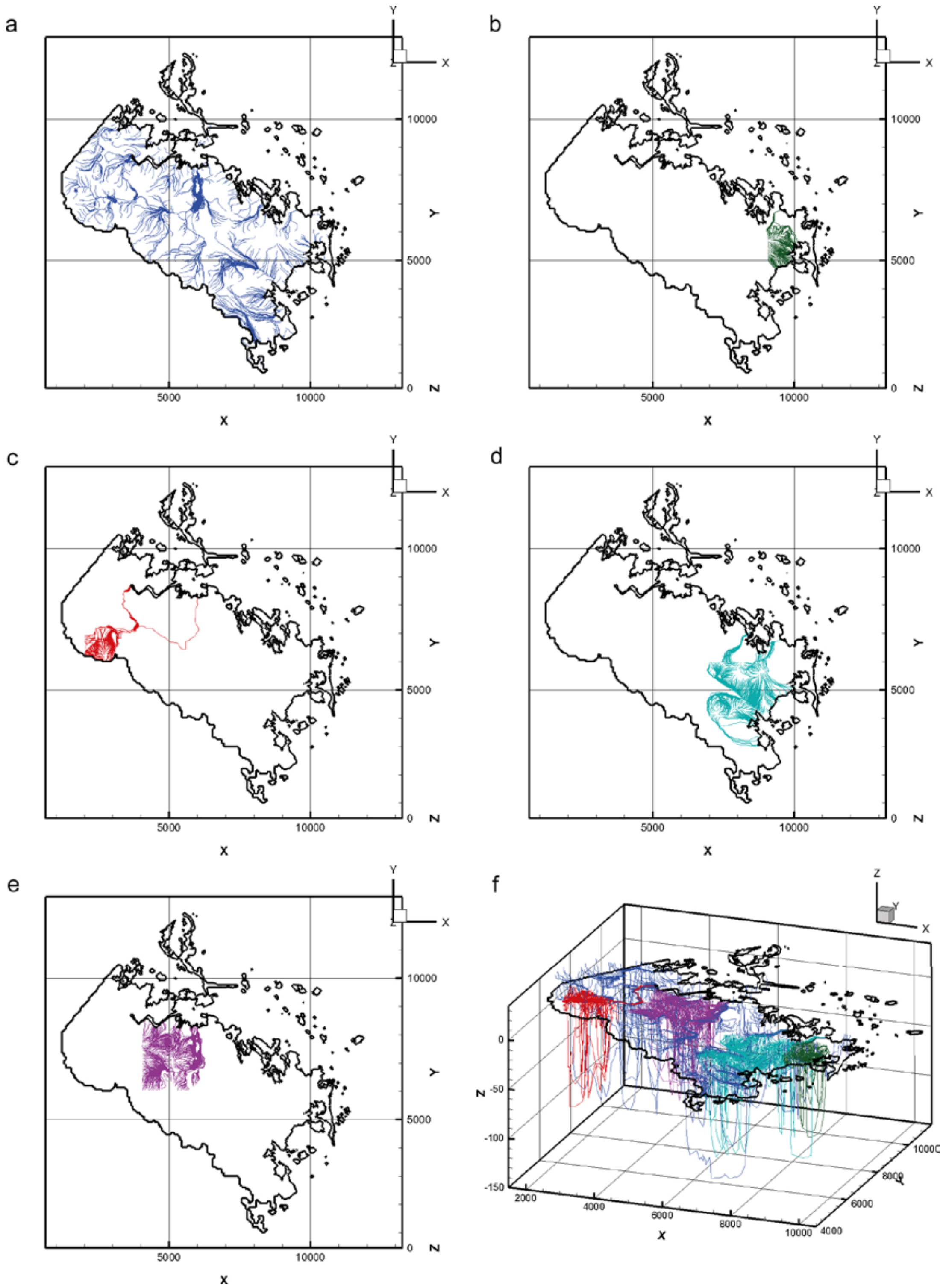


Figure 7-7. *Figure showing land areas of the Forsmark model, particle trajectories from different injection source areas at the surface.*

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.

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. Deterministic travel time distributions have successfully been combined with Lagrangian models, providing a flexible framework for transport modelling (Figure 7-9). Results have been presented at EGU 2012 and in manuscripts in preparation.

Outcomes

Oral prestentation at EGU2012: EGU2012-11297.
Lagrangian modeling of advective solute transport along hydrological pathways.
Approx 300 attendants.

Licentiate thesis: In the Pipe or End of Pipe?: Transport and Dispersion of Water-borne Pollutants and Feasibility of Abatement Measures.
Presented 30 May.

Two manuscripts in preparation for *Water Resources Research* and *Hydrology and Earth System Sciences.*

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.

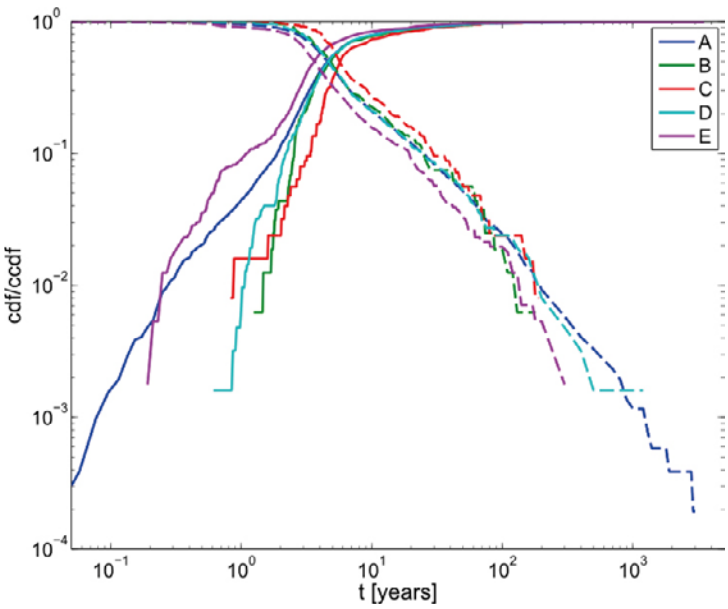


***Figure 7-8.** CDF of transport time in Forsmark model for cases in A–E in Figure 7-7 overburden.*

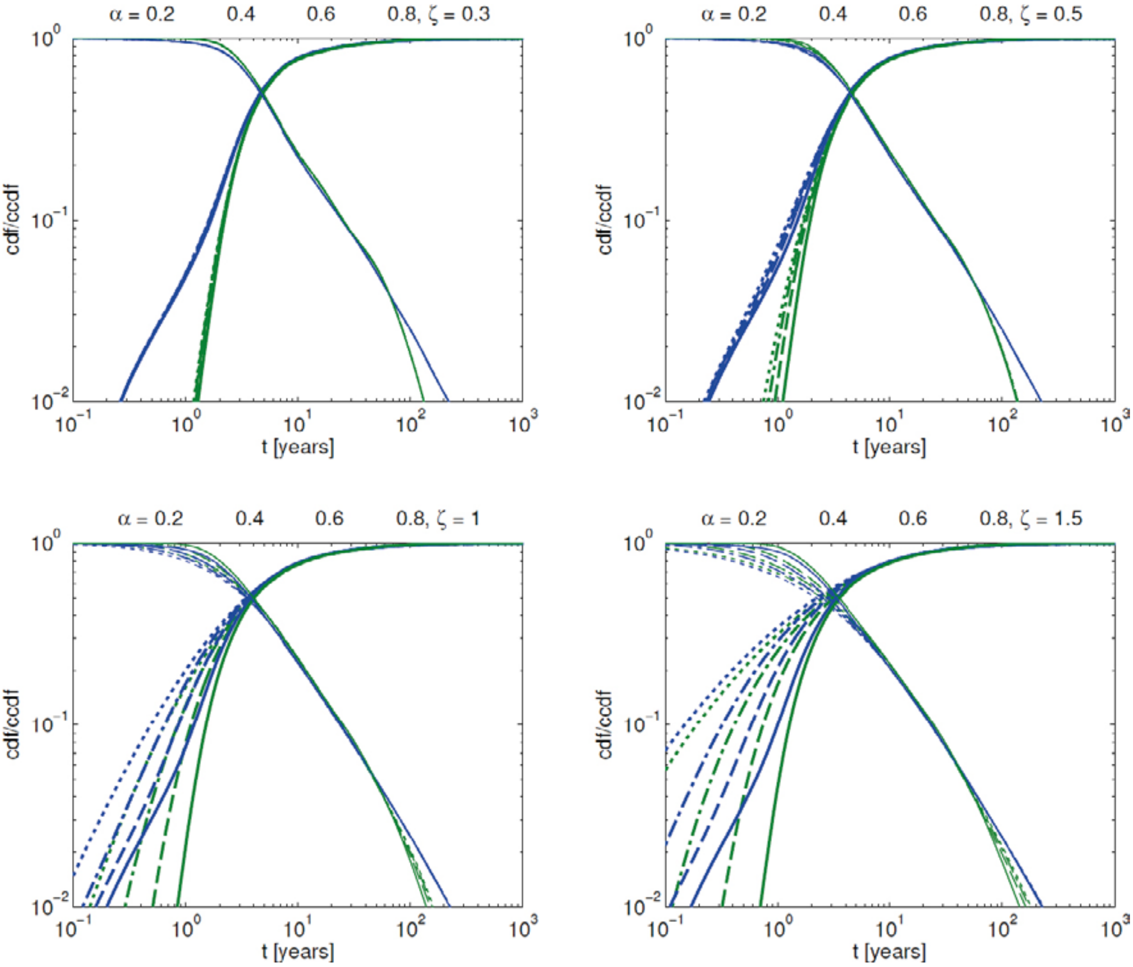


***Figure 7-9.** Results from combinations of deterministic travel time modelling and lagrangian dispersion.*

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.

An important potential spinoff would be course programs using Nova's facilities and framework, the Äspö laboratory 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.

7.3.7 KLIV – Climate-land-water changes and integrated water resource management in coastal regions (Georgia Destouni, Stockholm University)

Aim of the project

KLIV investigates critical questions for sustainable management of water resources, with main geographical focus on coastal regions. Main KLIV investigation sites include the Äspö HRL and wider Oskarshamn coastal region, and are more generally selected from or comprise the whole Swedish Water Management Districts of Southern and Northern Baltic Proper. Comparative catchment studies are also carried out in other regions and parts of the world. Main research questions, investigated across the different sites, catchments and regions, include:

- What are the time developments and spatial characteristics of regional climate and other environmental changes and their effects on water resources, and the anthropogenic loads of excess nutrients and pollutants to inland and coastal waters?
- What regional water resource changes (water availability/quality, flood/drought risks) should society prioritize and plan for adapting to?
- What measures in the landscape and what stakeholder behavior-participation changes can contribute to efficiently reducing anthropogenic nutrient and pollutant loads, and how much reduction can possibly be achieved at different times and landscape/coastline locations?

Based on the answers to these questions KLIV will provide new insights and knowledge on water systems and their management.

In particular, the KLIV research integrates the inland water system and its adjacent coastal waters, following the water flow and transport of tracers, nutrients and pollutants through their different water pathways from their respective entrance zones (sources of water, nutrient, pollutant) and through the hydrological catchments into the coastal waters. The main KLIV research hypotheses are then that:

i) This water-following research approach will provide new advancements, methods and tools for efficiently detecting-monitoring, modeling-projecting and improving-controlling water resource and ecosystem conditions.

ii) The results will contribute to efficient achievement of main environmental and water management goals, specifically regarding reduction of pollution and eutrophication, and protection, improvement and adaptation to climate change of waters and ecosystems in coastal regions.

Status of the project

The current, new KLIV project with G. Destouni as PI started in 2012 as a spin-off development from a previous KLIV project led by Kristina Lundberg and Anna Augustsson that ended in 2012. The new KLIV project extends over a 3-year period (2012–2015). During 2012, a new 2-year postdoc position with focus on KLIV was openly announced and filled at Stockholm University, with Andrew Quin as the successful candidate, starting his KLIV research in December 2012. The postdoc research will be focused on the variability and change in water flow and quality, their drivers and impacts, and needs and relevant measures – including in particular management of wetlands – for mitigating impacts and adapting to changes in participatory water management. This research aims at providing answers to such questions as: How have water flow and quality changed so far and why? What measures can efficiently reduce pollutant loads to water in the landscape? How are water flow and quality expected to develop in time under different scenarios of management measures, and climate and other changes in a region? The research will be carried out within the KLIV project, and also be linked to and co-supported by related strategic research programs at Stockholm University focusing on climate change effects on ecosystem services (EkoKlim) and Baltic ecosystem adaptive management (BEAM).

Furthermore, the core KLIV researchers have in 2012 published a series of relevant peer-reviewed publications listed explicitly below. Among these, we note for instance the high-profile paper published in *Nature Climate Change* on hydroclimatic shifts driven by human water use for food and energy production (Destouni et al. 2013. We note also that KLIV researcher G. Destouni has been awarded the Henry Darcy Medal of the European Geosciences Union (EGU), reserved for individuals in recognition of their outstanding scientific contributions in water resources research and water resources engineering and water resource management (http://www.egu.eu/news/45/egu-announces-2013-awards-and-medals/).

Spin-off

In general, KLIV is expected to provide new insights and knowledge on water systems and their management, and develop relevant decision-support methods and tools for efficient monitoring and mitigation of eutrophication and pollution, and adaptation to climate and other environmental changes.

During 2012, the KLIV research group has in collaboration with researchers from several other Swedish universities proposed and got support approval from the Swedish Research Council (VR) for developing a National Geosphere Laboratory (NGL) in the Oskarshamn region, including the Äspö Hard Rock Laboratory and surroundings, and associated other laboratory facilities and databases, with major participation by the other core KLIV researchers (read more, in Swedish, at http://www.skb.se/Templates/Standard_35327.aspx). Furthermore, The Swedish research council FORMAS has in 2012 approved support for another KLIV research group proposal, on "Basin-scale hydrological spreading of pollutants and wetland opportunities for reducing them under different hydroclimatic and other regional conditions" for the project time 2013–2015.

In addition, the KLIV research group has a leading role in the development and coordination of a newly formed international research network: GWEN – Global Wetland Ecohydrology Network: An Agora for Scientists and Study Sites (http://people.su.se/~gdest/gwen/), including scientists and study sites across many different parts of the world, including the main KLIV study site of the coastal Oskarshamn-Simpevarp catchment area (Figure 7-10).

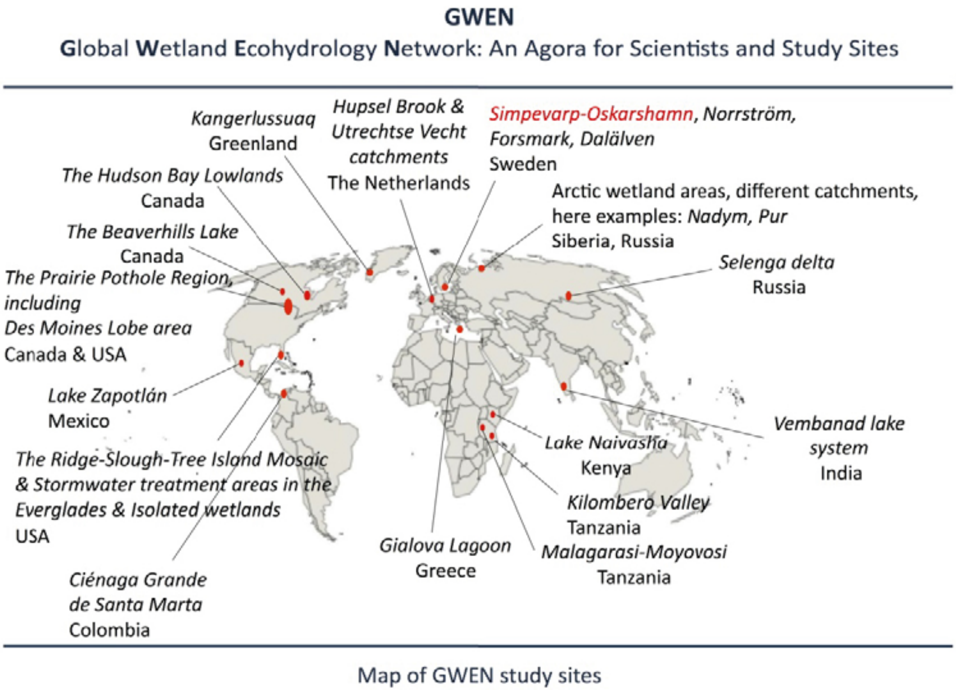


Figure 7-10. *Map of GWEN study sites in different parts of the world, including the main KLIV study site of the coastal Oskarshamn-Simpevarp catchment area.*

7.3.8 Hydrochemical interaction between a tunnel and its surroundings – development of prediction models (Lars O. Eriksson, Chalmers University of Technology)

Aim of the project

Previous experiences show that groundwater recharge in rock increases during the construction phase of underground facilities. 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 2012 the project has finalized extensive field investigations at the Hallandsås tunnel project. A scientific paper on groundwater chemical changes due to the excavation will be submitted in spring 2013. The article is written in collaboration with the Swedish Transport Administration.

Furthermore water sampling campaigns at the Kattleberg tunnel project NE of Göteborg were finalized. The interpretations of the results generally verify effects in the groundwater quality due to construction works. The conceptualization of the resulting chemical processes and engineering implications has been compiled into a scientific paper. The paper will be delivered to a selected journal in early 2013.

Generic hydrochemical modelling has continued. Initial model set-ups are based on real results from the Gårdsjö project database.

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.

7.3.9 Fracture flow characterisation: Correlation of effective hydraulic conductivity and scan-line density of flowing fractures (Ling Li, University of Queensland (UQ), Australia)

Aim of the project

The aim is to explore the relationship between the effective hydraulic and the density of flowing fractures within a fractured rock system.

Status of the project

The project is at a completion stage. We have previously examined the possibility of estimating effective hydraulic conductivity from density of flowing fractures based on from numerical simulations. In this project, borehole data, from Äspö in Sweden, are used to further explore the relation between effective hydraulic conductivity and the density of flowing fractures as well as 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. Field data show that the magnitude of fracture transmissivity decreases with depth. This can be explained by the increasing proportion of closed fractures as the compression stress increases. Borehole data also show that the density of flowing fractures is much smaller than that of all the fractures. Given that only up to 5% of the fractures control flow and that fracture transmissivity follows a power law distribution, we conclude that flow processes in Äspö can be modelled on a few large fractures. Analysis of the field data also highlights the need to refine measurements of flowing fracture interval, so that the uncertainty with the determination of the flowing fracture density and connectivity strength could be minimized. Borehole data show problems with correlating effective hydraulic conductivity and density of flowing fractures, which cannot be resolved because the fracture aperture distribution is unknown. It remains a challenge to obtain representative measurements of aperture distribution within a single fracture. These field data highlight the challenges with the task to establish relationship between the effective hydraulic conductivity (K) and the density of flowing fractures (d_{op}), as studied through the numerical simulations.

Spin-off

The results provide insights 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 insight into the propagation of fracturing and may indicate zones of different rock strength.

The data analyses contribute to the following manuscripts, which are under review.

Molebatsi, T., S. A. Galindo-Torres, D. Bringemeier and L. Li, 2013, Relation between hydraulic conductivity and scan-line densities in fractured rocks, *Mathematical Geosciences*, under review.

Molebatsi, T., S. A. Galindo-Torres, D. Bringemeier and L. Li, 2013, Combined effects of fracture system's connectivity and heterogeneity on effective hydraulic conductivity, *Mathematical Geosciences*, under review.

The investigators gratefully acknowledge the strong support received from the SKB staff during the project.

7.3.10 Documenting long-term biological and chemicals consequences of increased water temperatures in the Baltic Sea associated with global warming before they have happened (Anders Forsman, Linnaeus University)

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. The idea is to eventually use the plume of warm water from the nuclear power plant at Oskarshamn as a natural laboratory in order to study the effects that warming have on the ecological systems in the Baltic Sea.

Status of the project

We have performed a review of published studies 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.

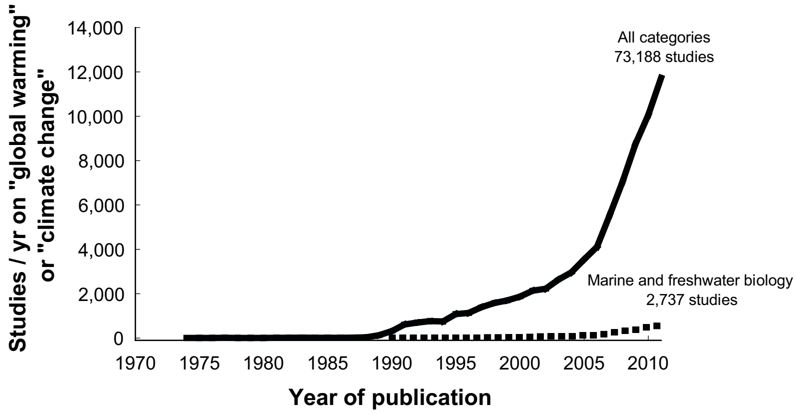


Figure 7-11. Trends in research output on global warming across all disciplines (filled line) and for marine and freshwater biology (dotted line). Figure shows number of publications per year and is based on data extracted February 2, 2012, from ISI Web of Knowledge.

The major results are that: (1) across all disciplines and categories the number of published studies concerning global warming and climate change totals more than 73,000 (up to 2011), (2) publication rate has increased from less than 10 papers per year prior to 1985 to nearly 12,000 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 environment and biology has increased at a relatively slow rate, and currently amounts to about 2,800 studies (see Figure 7-11).

We have studied and categorized all ca 750 published studies that focus on biology. The resulting data set has been entered into a spreadsheet and will be used for more in depth statistical analyses to identify knowledge gaps and fruitful lines of future investigations, intended for publication as a review. 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.

7.3.11 Drinking water scarcity in coastal areas – prediction and decision support tools (Bo Olofsson, Royal Institute of Technology, KTH)

Aim of the project

The aim of this project is to improve the understanding of kinematic (effective or flow) porosity in fractured, coastal bedrock with particular focus to coastal regions. The hydrogeological settings in such regions are often characterized by anisotropic, heteroscedastic conductive domains (the fractures), which often limit the sustainably extractable volumes of water or affect contaminant transport.

Status of the project

Currently, a statistically based model for characterising groundwater resources potential has been developed and tested using principal component analysis, non-parametric correlation analysis, and analysis of variance. The tool creates groundwater potential maps using geographical information systems (GIS) and was correlated against specific capacity data from the Geological Survey of Sweden's well archive with high confidence, using data which is readily available such as topography and geological maps.

Surficial fracture measurements have been conducted at several (64) locations to the south of Stockholm, and used to estimate kinematic porosity for an area. The estimated kinematic porosity values correlate with estimated hydraulic conductivity values in the region with high confidence. Combining this estimated porosity with geological data (soils and topography, for example) and climate data, water balance software which is executed in a GIS environment is currently being developed. This software will allow for scenario modelling (Figure 7-12) including: climate changes, extended or extreme seasonal variations, and increased environmental pressure on groundwater due to increased residency and water demand. Software to regionally estimate hydraulic conductivity tensors from surficial fracturing is also being developed.

Spin-off

Implications regarding this work could stretch from policy making regarding limitations on residency in areas where groundwater resources are under pressure, to environmental modelling and estimation of regional hydrogeological characteristics based low-cost data collection methods. Coastal regions often have very limited groundwater resources due to proximity to saline water bodies and the nature of the fracture network in the host rock. Thus, in order to prevent salinization or excessive drawdowns in these regions due to overuse, our aim is to better understand the volumes stored in these aquifers. Due to the heteroscedastic nature of the host rock, where spatial correlations often cease after only a few hundred meters, hydrogeological characterisation via traditional means is very costly. This methodology could provide a lower cost, reasonable alternative toolset for estimating regional hydrogeological characteristics.

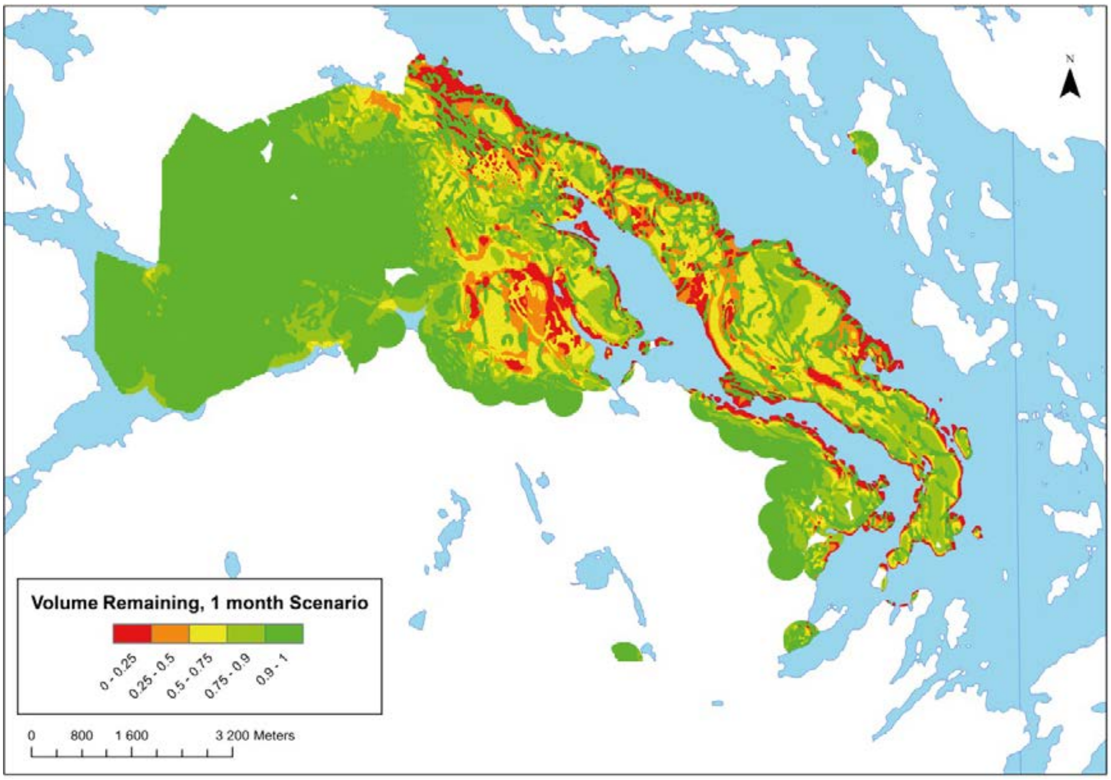


Figure 7-12. *An example of a one month extraction scenario in a coastal region. The figure shows an estimated ratio of stored volumes in a coastal aquifer remaining after a typical summer month.*

7.3.12 Geobiology of microbial mats in the Äspö tunnel (Joachim Reitner, University of Göttingen)

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 biomineralization 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 7-13), 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 end in spring 2013. Long-term experiments are planned to continue for indefinite time.

An evaluation of the **water chemistry data** was carried out and synthesized with existing data and groundwater models of the Äspö tunnel. Summarizing,the salinity of the three main aquifers tapped for the flow reactor experiments increases with depth. Ground waters at TASA 1327B and NASA 2156B have low Cl, Na, K, Ca and SO_4^{2-}, but high HCO_3^- concentrations (Figure 7-13) whereas the saline groundwaters at site TASF revealed high Cl, Na, K, Ca and SO_4^{2-} and low HCO_3^- concentrations (Figure 7-6). The concentrations of strontium (Sr) strongly increase with depth, with 4.9 µg (TASA 1327B), 17.5 µg (NASA 2156B) and 89.1 µg/g (TASF), respectively. Sr isotope ratios ($^{87}Sr/^{86}Sr$) were used to identify end-members in groundwater mixtures. These analyses revealed increasing water-rock interactions with raising depth, especially observed in the TASF aquifer.

Studies of **aerobic and anaerobic enrichment cultures** in the aquifer waters revealed previously described species as well as various novel freshwater halotolerant or marine species that have as yet not been reported from Äspö. These organisms are tentatively believed to reduce sulfate, 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 development of **iron oxidizing microbial mats** was studied at TASA 1327B and NASA 2156B. In respect to known iron oxidizing (depositing) bacteria (FeOB), a large diversity was found within the entire system. Among the identified species were *Gallionella* sp., *Sideroxydans* sp., *Crenothrixsp*., sp., *Acidithiobacillus* sp., *Thiobacillus* sp., *Acidovoraxsp*., a large diversity of Hyphomicrobiaceae including *Pedomicrobium* sp., and *Filomicrobium* sp. Additionally we found the recently isolated, marine iron oxidizing bacteria, *Mariprofundus* sp., to be present and even to dominate some of the sampled environments.

Pure cultures as well as microbial mats from the tunnel are investigated for microbial **biosignatures** with various analytical techniques (GC-MS, Raman, ToF-SIMS, LA-ICP-MS…). Data evaluation and biosignature identification is still in progress.

New data could be obtained analysing **$\delta^{33}S$ and $\delta^{34}S$ isotopes** of "feather structures", i.e. unusual multicelluar communities of **sulfur bacteria**, to understand metabolic pathways and concomitant S-isotope fractionation. The results are presented with data points of different colour (Figure 7-14). The colour emphasizes the different types of sampling locations sorted after their water flow rates (red dots: tunnel wall water discharges, green dots: low current reactors and blue dots: stagnant water body. Grey data points in the background were taken from the literature. Those originate from pure culture experiments. Thus, the resulting isotopic signatures are signals influenced by more than one metabolic sulfur pathway.

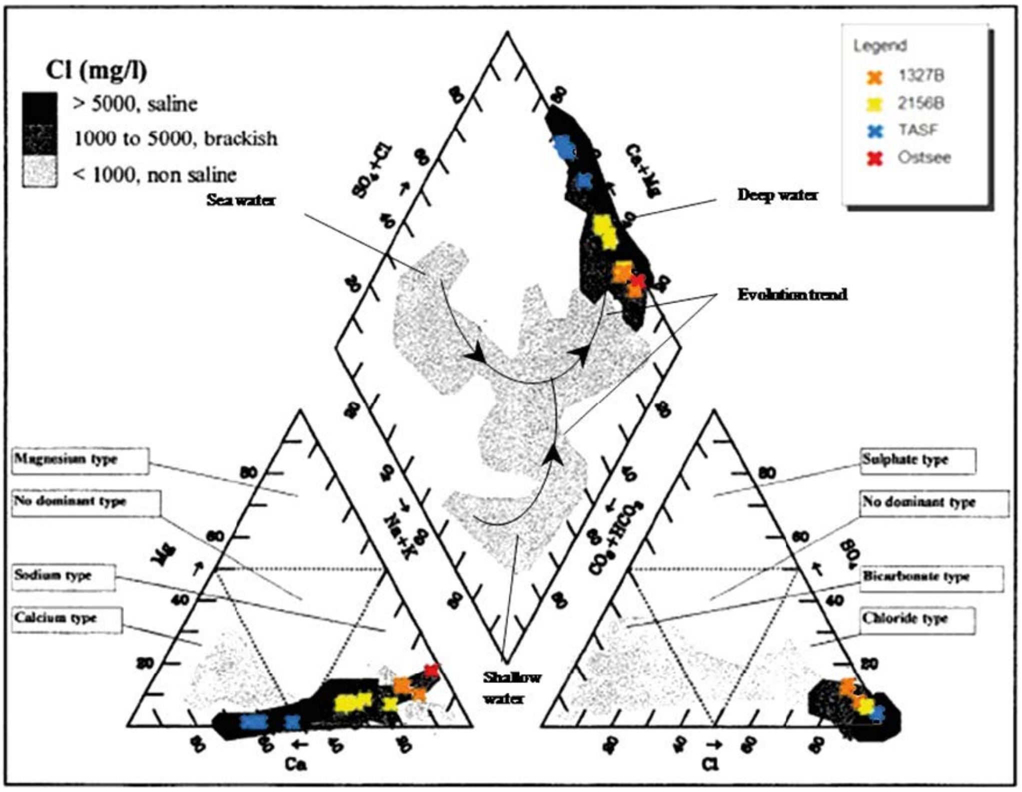


Figure 7-13. A standard Piper Diagramm shows the three types of aquifers investigated. They can be separated according to their salinity, especially the Ca and Mg content. Diagramm modifiet after Laaksoharju 1999.

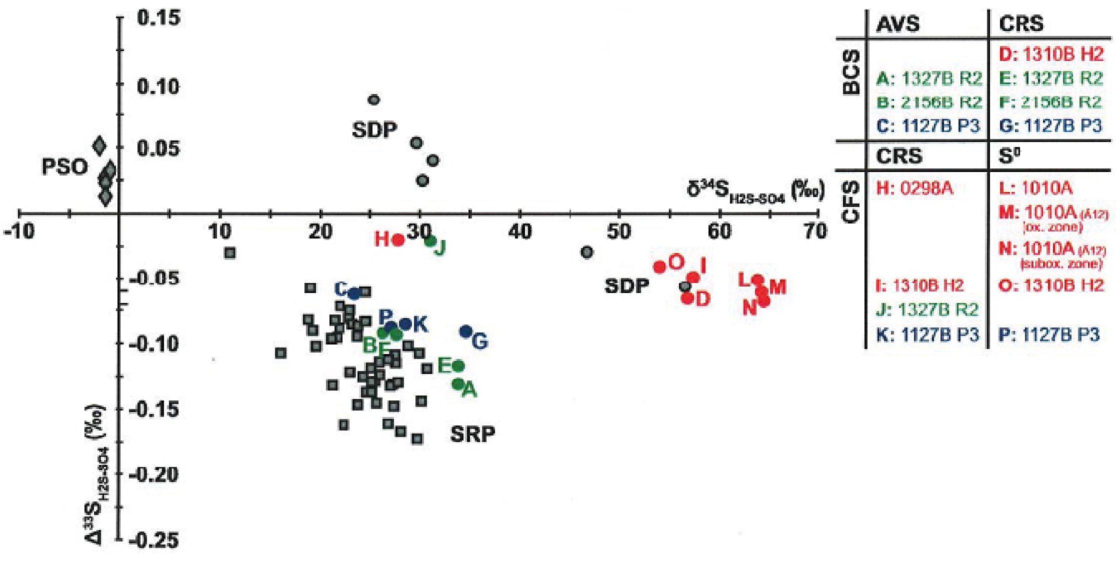


Figure 7-14. Δ33S versus δ34S plot reproduced and changed after Zerkle et al. (2009). Grey data show data from culture experiments. Squares illustrate sulfat e reducing prokaryotes (SRP) after Farquhar et al. (2003) and Johnston et al. (2005, 2007), circles illustrate sulfur-disproportionating prokaryotes alter Johnston et al. (2005, 2007) and diamonds illustrate phototrophic sulfide-oxidizing organisms. Red dots show tunnel wall water discharges, green dots show low current reactors and blue dots show stagnant water body (pond at NASA 1127B).

ToF-SIMS (time-of-flight secondary ion mass spectrometry) was employed in conjunction with scanning electron microscopy (SEM) in a time-serial experiment to analyse the **early stages of biofilm formation** in aquifer waters of the Äspö HRL. In that flow reactor experiment, clean artificial substrates were exposed to subsurface fluids for up to three months. This documented the immediate deposition of ultra-thin layers of proteinaceous organic matter (conditioning films, organofilms) on the substrates, before first solitary microbial cells attached after 1,000 min, and larger accumulations of microbial cells were observed after 90 days.

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.

7.3.13 Fossilized microorganisms at Äspö HRL (Magnus Ivarsson, The Swedish Museum of Natural History)

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 7-15) and at the moment the biogenicity of these possible microfossils are being established with raman spectroscopy, and during 2013 probably also with ToF-SIMS as well. Initial analysis with raman has confirmed the presence of carbonaceaous 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.

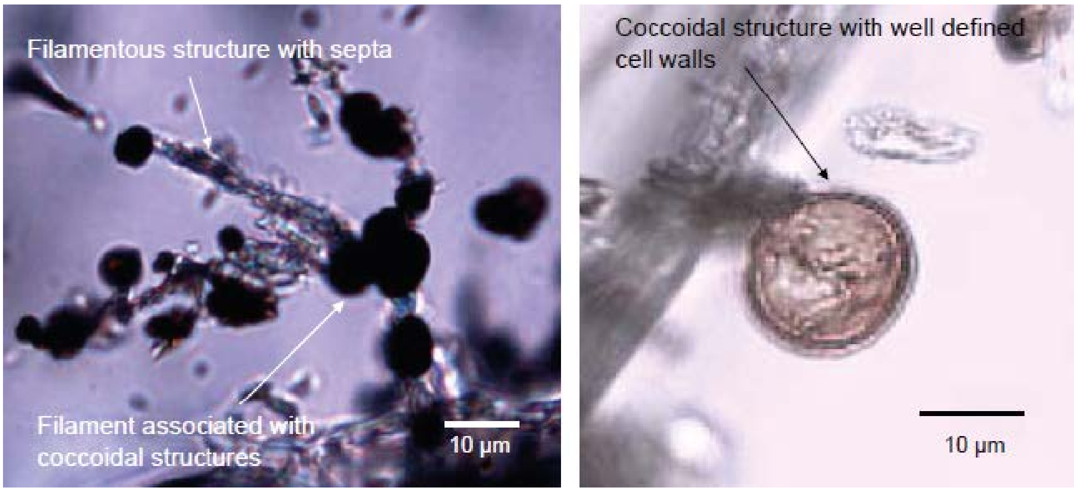


Figure 7-15. *Putative fossilized microorganisms in calcite.*

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 paleo-indicators.

7.3.14 Pressure filtration for collection of microbial nucleic acids in groundwater (Karsten Pedersen, Microbial Analytics Sweden AB, Mölnlycke)

Aim of the project

The aim was to develop and test a method for collection microorganisms in groundwater that deliver nucleic acids in enough quantities for quality assured sequencing.

Status of the project

Pressure filtration was executed without problems 19–20 July 2012 in the Äspö tunnel and nucleic acid extractions were successfully performed thereafter.

Spin-off

We obtained quality assured amounts of nucleic acids from microorganisms collected by the filters. We now have a method that can be used for collection of microbial nucleic acids in groundwater.

7.3.15 Integrated fire protection, the SAFESITE project (Angelos Achiniotis NeoSys AB)

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 (Figure 7-16) or fire together with access and logistical control of people and vehicles. True integration with the RFID (Radio Frequency Identification) system and other security systems are required.

Figure 7-16. *Smoke detector installed in the tunnel of Äspö HRL.*

Status of the project

The major results are that international companies such as Siemens and Niscaya have shown great interest and participate in the testing and verification of the system to be installed. The installation at Äspö HRL is used studying the conditions associated with blasting and fire.

During tunnel excavation activities in the beginning of year 2012 the test equipment was damaged. New equipment was recently installed and are now functioning according to the testing requirements developed within the project. During 2013, specific test protocols from stakeholders operating in harsh environments will be included in the study. Product developers are also testing products not yet available on the Swedish market.

The Safe site project will be part of the extension of SFR in Forsmark, which is the final repository for short-lived radioactive waste in Sweden.

Spin-off

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

7.3.16 Alfagate 2 – RFID WIRELESS- WIFI INTEGRATION in extreme environmental conditions (Angelos Achiniotis, NeoSys AB)

Aim of the project

The aim is to develop and integrate RFID techniques with WIFI technology in order to identify persons or objects in extreme environments (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 requirements.

Status of the project

Testing of the hardware have been performed during 2012 and will continue 2013.

Spin-off

- To expand the company NEOSYS in Oskarshamn and to be able to give service and support for the products/systems in Sweden, this will lead to new employments regional development.
- Cooperation with international companies such as Identic Solutions, Siemens and Sisco are an important spin-off and several international companies can be involved in the future.
- Continuing development and testing of future technology to meet SKB's present and future requirements for final disposal is an important result of the project.

7.3.17 Corrosion protection of rock bolts (Bror Sederholm, Swerea KIMAB AB)

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 for cast-in bolts is uncertain as is the corrosion protection capacity of the coatings now used, due to insufficient data. On openly exposed damaged part of the rock bolt is frequently observed whereas the state of the hidden and crucial part 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 method that is relevant for corrosion resistance of rock bolts based on in-situ conditions is developed. The efficiency of available corrosion protection will be experimentally documented.

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

Status of the project

The first assembly of rock bolts in Muskö and in the Äspö HRL tunnel was carried out in December 2011 after one year of exposure. Corrosion properties of rock bolts of carbon steel, stainless steel (three stainless steel grades EN 1.4311, 1.4162, 1.4362) and hot-dip galvanized and hot dip galvanized and epoxy-coated rock bolts have been evaluated during 2012. After a one-year corrosion test the following can be stated:

- On the bare rock bolts consisting of carbon steel the corrosion has only been found on visible parts of the bolt exposed. No corrosion occurs on the embedded rock bolt.
- The uniform corrosion rate of carbon steel bolts varied between 2.3 and 3.5 µm/year in the Muskö tunnel and between 2.6 and 3.2 µm/year in the Äspö tunnel. For the rock bolts of carbon steel sprayed with 3% NaCl the corrosion rate varied between 4.3 and 5.3 µm/year in the Muskö tunnel and between 4.3 and 5.9 µm/year in the Äspö tunnel.
- For the visible parts of the rock bolts consisting of carbon steel sprayed with 3% NaCl once a month during a year (Figure 7-18), the maximum pitting corrosion depth was 433 µm in the Muskö tunnel and in the Äspö tunnel the maximum pitting corrosion depth was 465 µm.
- For the unsprayed rock bolts of carbon steel the maximum pitting corrosion depth was 217 µm in the Muskö tunnel and in Äspö the maximum pitting corrosion depth was 183 µm.
- For the stainless steel rock bolts no visible corrosion was found in the Muskö or in the Äspö tunnel.
- For the galvanized roof bolts white rust was found on the visible parts of the rock bolts and in the interior environment.

- The uniform corrosion rate of galvanized roof bolts varied between 6.1 to 7.2 µm/year in the Muskö tunnel and in the Äspö tunnel between 5.8 and 6.9 µm/year. For the galvanized bolts sprayed with 3% NaCl the corrosion rate varied periodically between 7.9 to 8.6 µm/year in the Muskö tunnel and between 8.8 and 9.2 µm/year in the Äspö tunnel.
- The epoxy-coated rock bolts are completely undamaged after one year of exposure in the Muskö tunnel and in the Äspö tunnel. No visible defects such as blistering, cracking and peeling was observed on any of the epoxy-coated rock bolts.

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 are prepared. The consequences should be reduced investment and maintenance costs and a more efficient procurement process with better specifications.

7.3.18 Development of a system used for quality control of rock bolt reinforcement (Leif Gustafsson, Malmfälten i Norr AB)

Aim of the project

Production drifts within the mining industry (sub-level caving) are meant to exist for only a short period of time. The requirements for rock reinforcement are that the drifts shall be completely safe. Still, small cavities are allowed in the grouting mass as long as the drifts are completely safe.

Based on measurements with the Cavimeter equipment/method, the aim is to be able to classify grouted bolts in accordance with the following:

A-bolt – contains no cavities and is completely safe.

B-bolt – contains small cavities, but the rock bolt is completely safe despite this.

C-bolt – contains cavities that entail that the load-bearing capacity is under the limit. The bolt must be supplemented with a new rock bolt

Figure 7-18. *Mounted rock bolts in the Äspö tunnel are salt sprayed once a month during a period of one year.*

Status of the project

Field tests

An activity plan is submitted to SKB for approval. The drilling of 20 boreholes and the grouting of rock bolts with varying degrees of grouting was carried out in January-February 2013. Special equipment for pull tests for grouted rock bolts with varying degrees of grouting was under development during 2012. The pull tests were carried out in April 2013.

Computer simulations

Simulations of equivalent field tests as those in Äspö have already begun and are planned to be completed in February 2013.

Final report

A final report is planned to be completed in March/April 2013.

Spin-off

The plan is that the Cavimeter method shall be the internationally dominating measuring method for ensuring the quality of drifts/tunnels and rock spaces with respect to safety and to assure the quality of the contractors to perform rock reinforcement.

In the future the Cavimeter equipment can be assembled on the bolting unit and be a part of the work to ensure high-quality fieldwork.

7.3.19 Geophysical detection of EDZ/HDZ around tunnels (Matthew Perras, Queen's University, Canada)

Aim of the project

Geophysical methods have been considered as candidates for investigating the EDZ and HDZ, due to the non-invasive nature of the methods and the expected changes in the physical properties of rockmasses with accumulated damage. Many of the investigations to date, however, have been borehole based methods (cross-hole seismic tomography, cross-hole seismic velocity, cross-hole resistivity, etc.). The majority of investigations not using boreholes have focused on the principles of seismicity (i.e. active refraction surveys, or passive acoustic emission measurements). Other geophysical methods have the potential to be used without boreholes, although they have not been a focus in the literature. Some non-destructive resistivity & induced polarization (RES/IP) surveys have been performed in Opalinus Clay in Switzerland (Kruschwitz and Yaramanci 2004, Nicollin et al. 2010), although they have not involved a calibration based on damage development during lab testing and have used limited survey configurations. Ground Penetrating Radar (GPR) surveys for fracture detection in repository host rocks using high and low frequencies have been performed previously. Although EDZ delineation using this technique has been performed, it requires more testing and validation (Silvast and Wiljanen 2008, Heikkinen and Kantia 2010). By collecting the RES/IP and GPR data together, along with additional calibration and verification information, the application of these methods can be tested and improved.

The ultimate goal, via a collaborative field experiment is to correlate the spatial distribution of damage around an excavation with geophysical properties and to recommend a methodology for damage monitoring and detection using geophysical methods. It is also hoped that the damage levels detected can be correlated with laboratory strength thresholds. This will allow for non-invasive detection of the EDZ and the HDZ which can be utilized in optimizing cut-off design.

This is a joint project of Queen's University (which currently is funded by the Nuclear Waste Management Organization of Canada (NWMO) for EDZ research) and the Norwegian Geotechnical Institute (NGI). Site support for field work at the Äspö HRL was provided by SKB.

Status of the project

Geophysical and geotechnical data were collected at two sites within the Äspö HRL at Oskarshamn, Sweden. The niches for work provided by SKB were NASA 2376A and NASA 2715A. These data are currently in the process of being analyzed and documented.

Potential Spin-off Work

This research project is a preliminary proof of concept phase of a potentially larger project. Research in 2013 will focus on developing a better understanding of the field results obtained at Äspö through lab-based testing and calibration. In addition to this work, there are many other potential spin-off effects. Some of these are summarized below:

1. Applications for further research in 2013.
2. Optimizing existing geophysical equipment for EDZ/HDZ detection.
3. Developing methodologies and equipment specifications for geophysical detection of EDZ/HDZ underground excavations.
4. Other applications:
   a. Tunnel liner degradation (concrete – rock contact), important in pressure tunnels.
   b. Underground oil or gas storage.
   c. CO_2 sequestration.
   d. Compressed air alternative energy plants.

In future, the results of the 2012 preliminary investigation can be used as a proof of concept to further develop the above aspects with support for other interested parties. The other applications are specific to those other than nuclear waste storage underground. The concept could be used for remediation of existing underground infrastructure, such as pressure tunnels where the concrete liner may deteriorate over time. Some of the other projects are emerging areas of interest (CO_2 sequestration and Compressed air) which could potentially benefit from the knowledge of how much damage exists in the rockmass surrounding potential sites of interest.

7.3.20 Expert group for the harbour remediation project in Oskarshamn (Marcus Laaksoharju, Nova FoU)

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 7-19) 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.

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.

Figure 7-19. The expert group supporting the harbour remediation project in Oskarshamn.

7.3.21 Pre-study for Sediment Mining and Remediation in Oskarshamn Harbour (William Hogland, Linnaeus University)

Aim of the project

The aim of the project is to carry out a pre-study towards broad research proposals that involves postdocs, PhD students together with Master and under-graduation students as well. The pre-study was initiated to bring a theoretical background and proposal for extensive research projects that generate knowledge and support to decision-makers on the selection of innovative, economic and environmentally sound ways (beneficial use) to tackle contaminated sediments in harbors and to see it as a potential resource. The main idea of the research and education project proposed by the Environmental Science and Engineering Group (ESEG) at LNU is to use the Oskarshamn harbor as the main site of investigation and a teaching object in connection to the future sediment remediation/mining program to start in the year 2013. The fundamental approach of the project is shown in Figure 7-20.

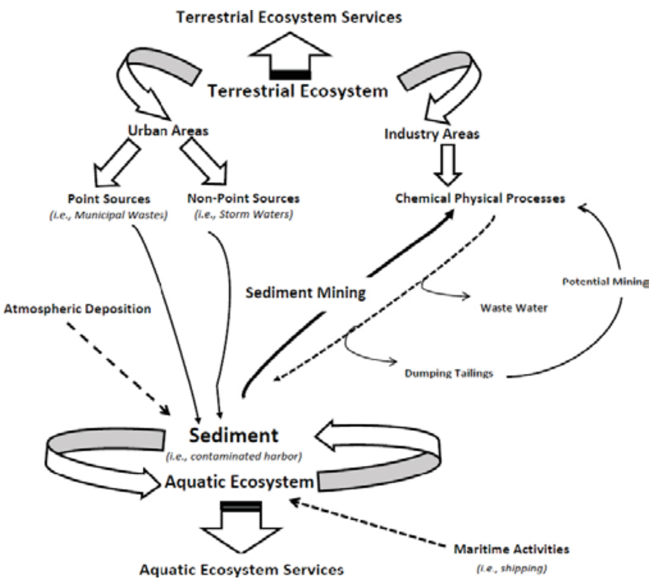


Figure 7-20. Conceptual diagram of the link between different loops (sediment, urban and industry areas, atmospheric deposition, maritime activities) and ways (sediment mining to return them to the anthropogenic closed loop systems).

Status of the project

During the past year of the project, a database containing high-level scientific literature within a broad range of subjects related to contaminated sediments has been studied. Harbor mining was included as assignment in the MSc course in Industrial Ecology during 2012 at LNU and the following study themes were created related to the project remediation of the harbor of Oskarshamn:

- Social dimensions of the harbor area and it's environmental problems.
- Harbor sediments as a Swedish, Baltic Sea, European and Global problem.
- Methods and technologies for bottom sediment dredging.
- Methods for stabilization of dredged bottom sediment, re-use (beneficial use) and related environmental issues.
- Toxicity effects of harbor sediments.
- The history of the harbor sediments.
- Methods for remediation and extraction of hazardous substances from harbor sediments and the beneficial use of these as resources.
- Pollution and sediment generation in the harbor of Oskarshamn.
- Bilge water handling and environmental improvements.
- Transport of contaminated sediments and pollutants from the harbor of Oskarshamn to the Baltic Sea.
- The wastewater handling in the harbor of Oskarshamn.
- Description of the harbor of Oskarshamn in an urban ecological concept.

The work by the students have been presented orally in front of the student group and in a written report. Three MSc thesis work are written of which two are finished and the third just started.

Spin-off

Based on preliminary results obtained from the pre-study it can be stated that research investigations concerning harbor sediments contamination and remediation/recovery methods have given LNU possibilities to write three large research applications and the fourth is on its way. The broad literature survey obtained during the current pre-study has been used to line up PhD projects and research applications send to different sponsors including Mistra, KK-Foundation, Kamprad Foundation and another is planned to EU Bonus programme for 2013.

The PhD studies to be proposed 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.

Within the frame of the project the following have been produced so far:

1. Report: Oskarshamn Harbor – Student assignments in the MSc course Industrial Ecology 2012, Linnaeus University.
2. MSc thesis "Speciation of metals in contaminated sediments in the Kalmar County, Sweden: An initial approach toward sediment mining" by Homayoun Fathollahzadeh, 2012, http://stud.epsilon.slu.se, Supervisors: William Hogland and Bhatnagar, Linnaeus University.
3. MSc thesis work "Improvement of dredging methods, removal and recovery of Heavy Metals – Characterisation of sediment properties and their pollution and attempt of removal of iron by bioleaching" by Jean-Christophe de Bortoli, École Nationale du Génie de l'Eau et de l'Environnement de Strasbourg, National Engineering School of Environmental and Water Management, France, Supervisors: William Hogland and Bhatnagar, Linnaeus University.

7.3.22 Waste heat for greenhouse production (Sven Nimmermark, SLU)

Aim of the project

The project has been performed with the aim to study possibilities, technique and possible production systems for competitive greenhouse production where waste heat from industrial processes is used to lower energy costs and environmental impact. Possibilities to use waste heat from the nuclear power plant in Oskarshamn have been a special focal point. Specific aims of the project were:

• To gather, put together and compile the current knowledge in the area.

• To identify knowledge gaps suitable for a research cooperation between 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

An inventory of present technology suitable for making use of waste heat in greenhouse cultivation has been done and a report is available. Strategies for identification of possible technology for using waste heat include climatization technology in combination with properties and design of covering materials, dynamic climatization and insulation as well as storage of heat.

Still large quantities of energy are used in Swedish greenhouse cultivation, although considerably less than for some years ago. The energy consumption for the Swedish greenhouses ranged to 627 GWh in the year 2011 which can be compared to 1,140 GWh in the year 1999. Later years a noticeable change to bio fuels has taken place but fossil fuels still has a share of 41% 2011 and of this oil stands for 25% and natural gas for 14%.

I the society there are large amounts of low tempered waste heat from power plants and industrial processes which is not used today and one way to use this resource and lower the environmental impact from energy use is to use such waste heat for greenhouse cultivation purposes or other cultivation.

Cultivation in advanced greenhouses puts high demands on the climate in order to make it productive and profitable. For a good yield and a good quality of a greenhouse culture the climatic conditions needs to be suited to the demands of the specific plants in question. Growing and development are regulated by the balance between light, temperature, humidity and availability of carbon dioxide. Temperature demands vary between cultivars, and for optimizing the photosynthesis a certain temperature level is required both night and days. However, there are possibilities to use so called dynamic, light regulated climatic control with higher day temperatures and somewhat lower night temperatures, making it possible to lower the energy consumption and making more beneficial use of low tempered waste heat.

Newer Swedish greenhouses being built are mainly of the type Venlo (Figure 7-21) with sections mounted together to large quadratic houses which have large rationally used areas. For such houses the energy consumptions are, due to their lower surface area per square-meter cultivation area, lower than for traditional wide free-standing Swedish greenhouses, and the energy consumption is further decreased by the use of screenings and advanced control and regulation systems. Venlo greenhouses are often built with single glass as covering material with good light transmission, which in a proper way facilitate the light demands of the plants. Also acrylic and polycarbonate panels with twin wall sheets are frequently used, and then especially in sidewalls of a greenhouse. An interesting new twin walled covering sheet with a zigzag profile (Lexan® ZigZag™) combines a good light transmission with a good insulation quality. For cultivation of plants with lower demands of the climate, often simple tunnel greenhouses are used and they are frequently covered by a plastic foil.

Conventional Swedish greenhouse cultivation use heating systems with heating pipes and these systems are usually designed for high supply/return temperatures (80/60 or higher). For use of waste heat other systems are required, i.e. air heating systems where the demands on supply and return temperatures are lower. In the US a number of greenhouse operations using low tempered waste heat were built for study purposes during the energy crisis in the 1970s and 1980s, and also a research facility for use of waste heat from the Browns Ferry nuclear power plant near Athens Alabama was built. The waste heat originating from the cooling water of the nuclear power plant was, when reaching the greenhouse, as low as 14–21°C in January. The systems built used large surfaces for heat exchange between the waste heat and the systems used in the greenhouses. In many of these cases fan coils were used in the operations and for use of the waste heat from the nuclear power plant a so called pad and pan system was used with evaporation of the waste heat from wetted pads and after that an extra second heating from a fan coil was available. This system with direct supply of heat resulted in a very good heat transfer, but also a very high humidity which caused problems. Operations built for use of waste heat in the US during the mentioned period were used a number of years, but information reveals that there was a limited commercial interest. The commercial interest is of course linked to economic prerequisites locally and at the time in question. The studies made during the 1970s and 1980s did not result in any commercial greenhouse cultivation linked to low tempered waste heat from nuclear power plants and the greenhouses built in e.g. Athens are no longer existing.

Figure 7-21. *Interior view in a Venlo greenhouse with single glass as covering material. Photo: Sven Nimmermark.*

In studies made at Alnarp during the 1980s strawberries were cultivated with different plastic coverings in soil heated with pipes containing water with temperatures ranging from 20 to 30°C. The heating resulted in an earlier harvest especially for strawberries grown in soil covered by a plastic foil or in small plastic tunnels. Heating without covering resulted in just a few days earlier harvest.

Use of waste heat for reduction of energy costs must be rated against other alternative energy sources, and other measures for energy conservation. Greenhouse owners are actively looking for alternative energy sources, and e.g. raw materials from forests like chips, bark, and chippings, as well as chips from wooden waste and saw dust are energy sources which can be used. Also an increased insulation result in a reduced energy demand. As an alternative to heat conservation in greenhouses by screenings during night time, studies have also been made of non conventional methods like use of polystyrene pellets blown into the greenhouse coating during nights, and also with foam having an insulating capability. In these studies pellets and foam have been removed during night time in order not to reduce the light.

In Germany a low energy greenhouses are studied in a special Zineg project. In one of those greenhouses a closed greenhouse concept using solar collectors, a heat pump and an energy storage is studied. Interestingly, the yield in this greenhouse has been higher than in a control greenhouse were more light is available.

After start of using a deep water intake for cooling of the Oskarshamn nuclear power plant the lowest temperature of the outgoing cooling water amounts to just about 11°C during wintertime and the highest temperature is about 21°C. A possibility to use low tempered waste heat in greenhouse cultivation is supply of it close to the walls and the roof in a slot between the covering material and a screening. With such a system, the heat transmission losses can be reduced when the outdoor temperature is lower than what can be achieved with the waste heat. However, calculations suggest that the energy savings will be low for conventional greenhouse crops for food production because of the low temperatures available when using the deep water intake. For this case other cultures like berries, cut flowers and fungi where lower temperatures can be used are more interesting. If the temperature of the waste heat is just 5°C higher the prerequisites for a beneficial energy saving is very much better.

There is a need to develop suitable technology for greenhouse cultivation using low tempered waste heat. In a research facility designed for this purposes such technology as well as the combination fish growing and greenhouse cultivation could be studied.

Spin-off

During the year 2012 a future "Swedish Surplus Energy Collaboration" between SLU, Alnarp and the Municipality of Oskarshamn and a number of other actors has been initiated. This should lead to intensified research in the area as well as practical use of waste heat in the green sector.

Possible spin-off effects of the current project 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 research and demonstration of technology.
- 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.

7.3.23 Participating in the FP7 project PETRUS II (Tommy Claesson, Linnaeus University)

Aim of the project

Linnaeus University will togheter with KTH give the master course "Nuclear technology and 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. The course was rescheduled and includes now cooperation with Professor Waclaw Gudowski, Nuclear and Reactor Physics, KTH. The course will take part both at KTH and at Äspö Hard Rock Laboratory. Lectures will take place at KTH in the beginning of June and the fieldwork will take place at Äspö HRL one week later.

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 10:th and 11:th 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 new application, PETRUS III, has been send to the EU commission for evaluation.

Spin-off

The students on the course are from the countries in Europe that in a near future will 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.

7.4 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 of nuclear technology and geological storage.
- **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 underground environments and to study rock weaknesses and corrosion problems underground.
- **Commercialisation:** Identification and commercialisation of research results and 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 2012 aimed at 20 ongoing projects. The actual situation by the end of year 2012 was 23 ongoing projects, 6 projects ready for approval and 12 new project proposals. A total of 90 researchers from 11 national and international universities and 4 companies have projects at Nova FoU. The project value for the approved Nova FoU projects where 51 million SEK at the end of year 2012. In cooperation with SKB a new research laboratory at Äspö HRL was taken in use (Figure 7-22) and new research niches in the Äspö HRL tunnel are under construction.

7.6 The Nova FoU steering committee and personnel

The Nova FoU steering committee during 2012 consisted of representatives from SKB, the municipality of Oskarshamn, Nova, KTH and Linnaeus University 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).

Bo Bergbäck, (Professor, Linnaeus University) – since September 2012

Marcus Laaksoharju is the Chief coordinator for Nova FoU, Anna Rockström is the administrator. Sten Göthe was employed for spin-off and business development at the end of year 2012

Figure 7-22. *The new research laboratory at Äspö HRL.*

8 International co-operation

8.1 General

During 2012 ten organisations from eight countries in addition to SKB participated in the cooperation at Äspö HRL. Eight of them; Andra, BMWi, NDA, NUMO, CRIEPI, JAEA, NWMO and Posiva together with SKB formed the Äspö International Joint Committee (IJC), which is responsible for the coordination of the experimental work arising from the international participation.

Several of the participating organisations take part in the two Äspö Task Forces on:

- 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.
- 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 took part in work within the IAEA framework. The 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.

During 2012 SKB was actively involved in the European technology platform IGD-TP (Implementing Geological Disposal of Radioactive Waste Technology Platform) which was launched in November 2009. Up to the end of 2012 SKB held the position of Secretary General providing the Secretariat to the IGD-TP. 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. By the end of 2012 the platform involved eleven waste management organisations and in addition about 90 participants from industry, research organisations, research centres, academia, and technical safety organisations in Europe. IGD-TP related research in the Äspö HRL according to the IGD-TP Deployment Plan has already started with the LUCOEX and DOPAS projects. Work in the Äspö HRL is foreseen to be an increasingly important part of the joint work in the platform during coming years.

NUMO has during 2012 participated in the planning, of a full-scale Multi-Purpose Test (MPT) within the KBS-3H project. In 2013 NUMO will follow the installation of the test equipment. The participation involves one to two persons stationed periodically at the Äspö HRL to get general experience on the planning and operation of actual underground tests.

During 2012 SKB has also excavated some new tunnels (about 100 m) aimed for future use by international parnerts for their own experiments. This work has been funded via the Added Value[1] programme.The tunnels are ready for use from 2013 and onwards. These tunnels could also be used for tests not related to nuclear waste, in which case the cooperation will be handled by NOVA.

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).

[1] The SKB Added Value programme refers to the agreement for funds available for community projects in the two locations of Osthammar and Oskarshamn where SKB is applying for facilities for the system regarding final disposal of spent nuclear fuel. The term Added Value is used as the requirements for a "project" to be considered a part of the added value package is that the "project" is beneficial to both parties – SKB (and its owners) and the community in question.

In this framework, the main interest of Andra's participation in the Äspö activities have been 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 in recent years been involved in three major experiments: Temperature Buffer Test (TBT), Large scale injection test (Lasgit) and Alternative buffer materials (ABM).

8.2.1 Temperature buffer test and task force on engineered barrier systems

Andra has especially been involved in the Temperature Buffer Test conceived during 2002, started beginning 2003, dismantled in 2010 and has produced major expected THM results. Temperature Buffer

Test dismantling gave a large amount of sampled material. Information on the bentonite blocks-mechanical behaviour has been collected, the result from 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 was re-assessed during the first half of 2011. The results of laboratory analysis, reports on the dismantling operations, the THM results and the HMC analysis were available in 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 has not been directly active during 2012.

8.2.3 Alternative buffer materials

Andra has been involved in the Alternative buffer materials project (ABM) at different levels:

- It has provided different clay materials to be put in the different parcels: Callovo-Oxfordianclaystone (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 has supported three laboratories (CEA, G2R and LEM) to conduct chemical and textural analysis of different clay materials after dismantling of the parcels.

Planning of the dismantling of Alternative Buffer Materials experiment is ongoing and Andra will participate in this project during 2013.

8.3 BMWi

In 1995 SKB and the then Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMFT) 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 happened in 2003. 2008 the agreement was extended a further five years, and in 2012 for another year. On behalf of and/or funded by the Bundesministerium für Wirtschaft und Technologie (BMWi) thredd research institutions are participating in experiments and activities related to the Äspö HRL programme: The Federal Institute for Geosciences and Natural Resources (BGR), Hannover, 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, especialy, 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 2012 is described below.

8.3.1 Microbe project

Introduction

The contribution of the Helmholtz-Zentrum Dresden-Rossendorf (HZDR)/Institute of Resource Ecology (IRE) is concentrated 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 project finished in December 2012.

The activities in 2012 were concentrated on (a) interaction of Pu in mixed oxidation states with planktonic cells of *P. fluorescens*, and (b) continuation of experiments characterizing both the growth of *P. fluorescens* biofilms and the effect of the addition of Eu(III) to these biofilms. Selected results of these topics will be reported.

The impact of the Äspö ground water bacterium Pseudomonas fluorescens on the speciation of plutonium

The focus of the work is on the unknown interaction between plutonium in mixed oxidation states (60% Pu(VI) and 18% Pu(IV)-polymers) and cell-suspensions of the Äspö-strain *P. fluorescens*. Accumulation experiments were performed in order to obtain information about the amount of Pu bound by the bacteria. Solvent extraction and UV-vis-NIR absorption spectroscopy were used to determine the speciation of Pu oxidation states.

Since microbes are well known to affect the mobility of actinides, dominant microbial strains from sites destined for future nuclear waste deposition have to be investigated regarding their interaction mechanisms with soluble actinides (Neu et al. 2005, Ohnuki et al. 2010). Pu is one of the hazardous components of nuclear waste (radio- and chemical toxicity). Pu experiments are challenging because it can coexist in several oxidation states in environmental aqueous solutions. The investigated subsurface groundwater strain *P. fluorescens* (CCUG 32456A) has been isolated from the Äspö site, Sweden (Pedersen 1997).

P. fluorescens cells were harvested in the mid-exponential growth phase washed and suspended in 0.9% NaCl solution. The experiments were performed at [dry biomass] of 0.2 $g_{dry\ weight}$/L and pH 6 under N_2 atmosphere at 25°C in 0.1 M $NaClO_4$ solution. $[^{242}Pu]_{initial}$ was varied between 0.2 and 100 mg/L. The ^{242}Pu present in blank (no cells added), supernatant, and washed biomass suspension at pH 0 was analyzed using UVvisNIR spectroscopy, solvent extraction, and liquid scintillation counting (LSC) as described in Moll et al. (2006).

The amount of Pu sorbed by *P. fluorescens* increased with time as shown in Figure 8-1 A. Steady state conditions were reached after approximately 8 days. The data could be successfully fitted to a bi-exponential law. This suggests that at least two different processes occur after adding Pu to the biomass. A higher Pu binding capacity of dead biomass was detected at larger contact times.

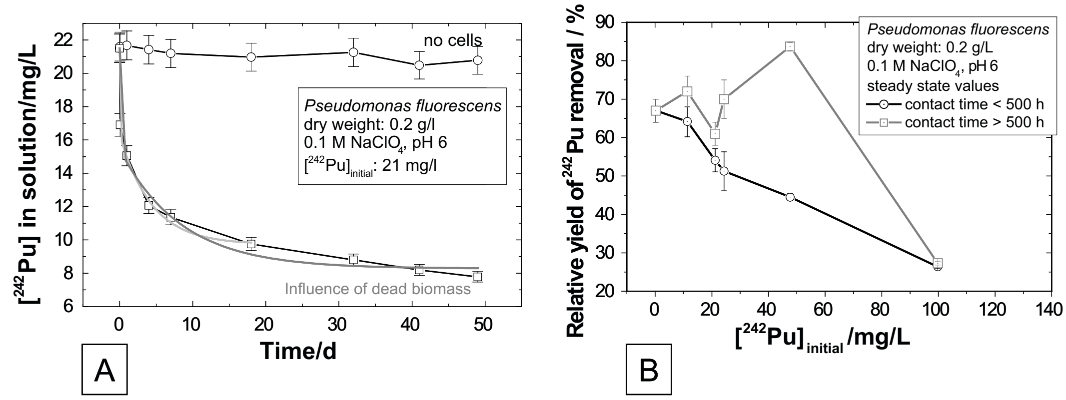


Figure 8-1. *A) Decrease of the ^{242}Pu concentration in solution at $[^{242}Pu]_{initial}$: 21 mg/L and (B) summary of the removed plutonium as a function of $[^{242}Pu]_{initial}$ at pH 6.*

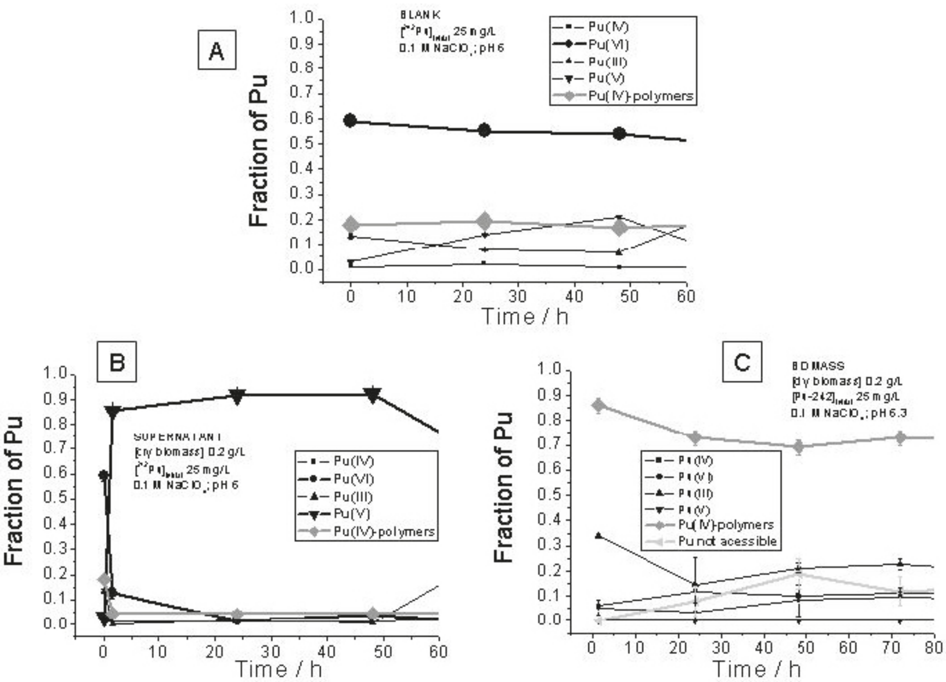


Figure 8-2. *Time dependent ^{242}Pu oxidation state distribution in the samples (a) blank, (b) supernatant, and c) biomass at pH 0 determined by solvent extraction.*

At $[Pu]_{initial}$ 0.2 mg/L 67 % of the initially present Pu was removed by the cells. Whereas at $[Pu]_{initial}$ 100 mg/L the removal efficiency dropped down to 27 % (see Figure 8-1B). Hence we found a strong dependence of the amount of Pu associated with *P. fluorescens* cells on the initial Pu concentration in the test solutions. The time dependent Pu oxidation state distribution depicted in Figure 8-2 demonstrates the strong impact of the Äspö strain *P. fluorescens* on the Pu speciation (Moll et al. 2012)[2]. In the first step, a fast binding of Pu(VI) and Pu(IV)-polymers on the biomass occurred. Approximately 85 % of the initially present Pu(VI) was reduced to Pu(V) due to the activity of the cells within the first 24 h of contact time (no electron donor added). Most of the formed Pu(V) dissolves from the cell envelope back to the aqueous solution due to the weak complexing properties of this plutonium oxidation state. Pu(IV)polymers dominated the Pu oxidation state distribution on the biomass showing the good binding properties of Pu(IV)-polymers on functional groups of the cell envelope. To conclude *P. fluorescens* cells had a strong impact on the Pu speciation.

[2] Moll H, Lütke L, Sachs S, Schmeide K, Bernhard G, 2012. The impact of the Äspö ground water bacterium Pseudomonas fluorescens on the speciation of plutonium. Lecture at the conference Plutonium Futures – The Science 2012, 15.-20.07.2012, Cambridge, UK.

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 electric 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.

In the frame of the project "Retrieval of the Prototype Repository at the Äspö Hard Rock Laboratory" electrodes retrieved from the backfill of Section II and from the buffer are inspected and the reasons for buffer electrode failure are investigated. In addition, water content and resistivity of material samples are measured in order to verify earlier calibration measurements.

The backfill electrodes (Figure 8-3) show clear signs of corrosion, but since no electrode failure in the backfill occurred throughout operation of the backfill array, corrosion does not seem to be an issue.

Two core samples with embedded electrode chains (Figure 8-4) were retrieved from the buffer, one from the center and one close to the deposition hole wall. Many of the buffer electrodes had failed during operation. It was found that the electrodes were nicely coupled to the buffer and showed little corrosion, but all electrodes were disconnected from their cables (Figure 8-5).

The reason for the cable failure is a significant upward swelling of the uppermost buffer blocks in the range of decimeters which was found during the post-test investigations. This elongation could not be taken by the cables. The volume increase of the buffer blocks during swelling was caused by an insufficient stiffness of the tunnel backfill above the buffer, which had not been foreseen.

Figure 8-3. *Electrodes retrieved from the backfill of Section II.*

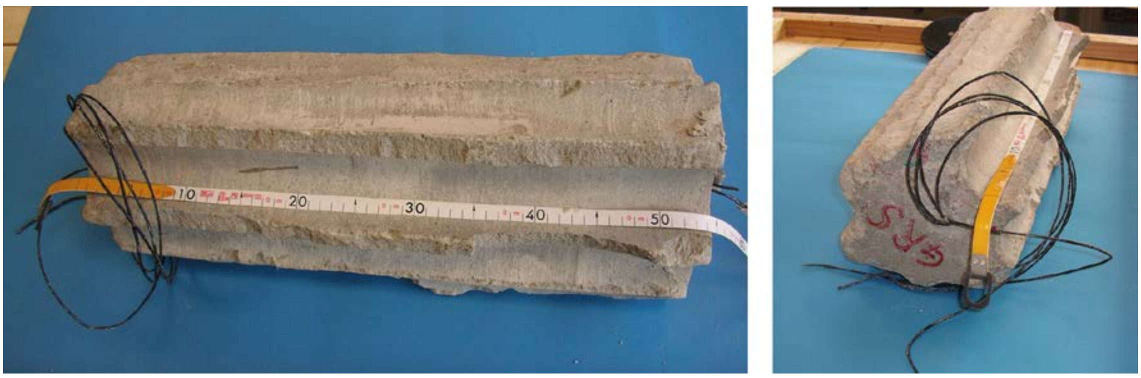


Figure 8-4. *Core section from top central buffer of deposition hole #5.*

***Figure 8-5.** Buffer electrodes.*

Measurement of water content of samples from the buffer cores resulted in values between 21 and 22 wt.% in the center and around 23 wt.% near the deposition hole wall. These values are in good agreement with measurement results achieved by Clay Technology.

Investigations by BGR

In 2012 BGR received four samples of the Prototype repository test (P5+P6). The blocks were sampled and are currently investigated with respect to the mineralogical and chemical alterations including exchangeable cations.

8.3.3 Alternative buffer materials

In 2012 the layer charge density of all materials were characterised with the alkylammonium-method (AAM). In contrast to the chemically based structural formula method to determine the layer charge density, the AAM provides information about the spatial distribution of the permanent charges. For the measurement a sample is split into e.g. 10 portions and each portion is reacted with an n-alkylammoniumcation of different chain lengths (typically n = 6–18). After several reaction and washing steps the basal spacing is measured with XRD and the so called peak migration curve, i.e. the basal spacing depending on the chain length n, is plotted. Particularly the increase of the d-spacing from 15–17 Å which is the mono-bi-layer transition is considered for the calculation of the layer charge density.

In addition to this comprehensive characterisation five samples were investigated which were collected after the heating experiment. All this data was summarized in an internal BGR laboratory report and will be discussed in the frame of the next meeting.

A particularly interesting result was found for sample LOT (MX80) which after the experiment did not expand at all. The initial material showed some expansion but was far from reaching the bi-layer indicating a low layer charge density. The material after the test showed even lower basal spacing and the resulting layer charge density would be even lower than the starting material. This has to be explained based on future investigations on similar materials.

Concerning the Long term test BGR performed no clay laboratory activities in 2012.

8.3.4 Temperature buffer test

The work formerly conducted by DBE TECHNOLOGY GmbH regarding the TBT test is finished.

8.3.5 Large scale gas injection test

BGR's activities within the Lasgit project focused on the investigation of processes and interactions that occur in the experiment, particularly with regard to the behaviour of the engineered barrier system and the influence of the excavation damaged zone (EDZ). Test evaluation and modelling exercises are executed using the finite-element code OpenGeoSys (THMC-code, www.opengeosys.org).

Besides the on-going code development to integrate the simulation of gas transport processes in clay-rich materials, work on the modelling of the Lasgit experiment was continued in 2012. 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 (Figure 8-6). For the simulation of the gas transport processes a gas pressure dependent permeability approach was applied, which was implemented for the simulation of experiments at the Mont Terri rock laboratory. By this means the opening of gas pathways in the bentonite due to increasing gas pressure could be successfully captured. However, the approach reaches its limits when it comes to a sudden decrease of the flow rate due to pathway collapse (Figure 8-7).

Future steps in the modelling of the Lasgit experiment will include the consideration of hydro-mechanical processes, including a deformation dependent permeability approach, and going from an axisymmetric to a quarter-symmetric model.

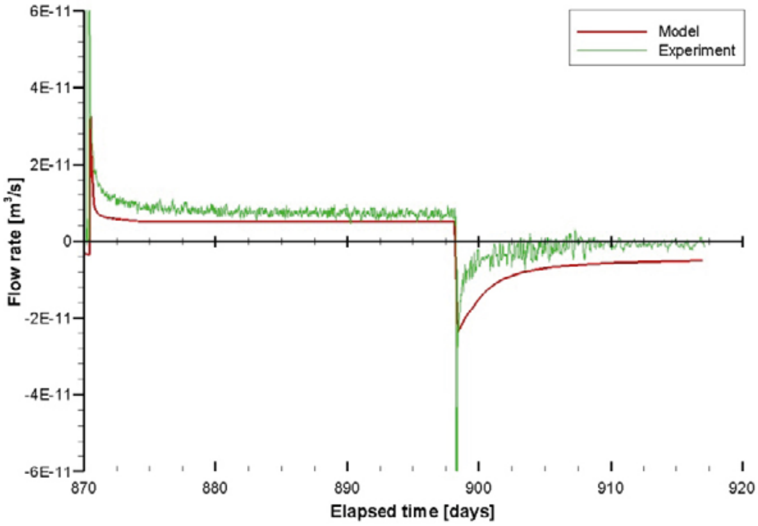


Figure 8-6. *Measured and simulated flow rate through injection filter FL903 during the first hydraulic test of the Lasgit experiment.*

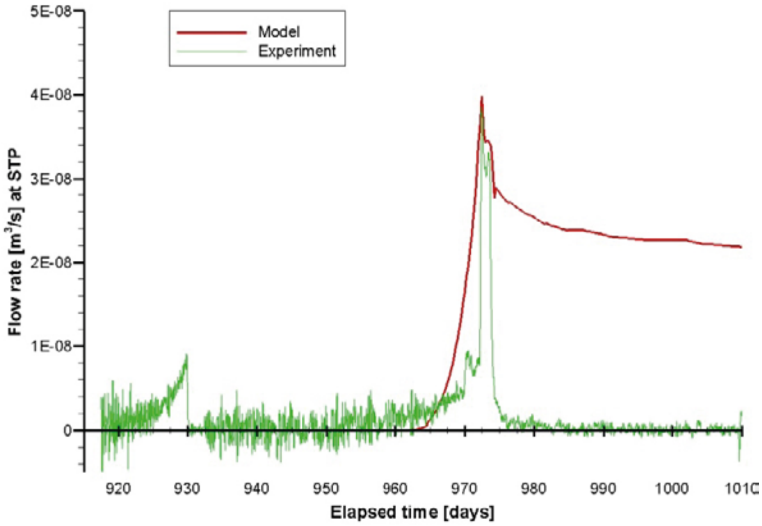


Figure 8-7. *Measured and simulated flow rate through injection filter FL903 during the first gas injection test of the Lasgit experiment.*

8.3.6 Task force on engineered barriers

In 2012, the focus of BGR's activity within the Task Force on Engineered Barrier Systems was on the sensitivity analysis assignment. The objectives of this task are to study the effects of parameter value uncertainties and model simplifications on the results of THM-coupled calculations of engineered barrier systems. BGR was responsible for the preparation of a task descripttion.

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. Results of BGR's calculations were presented at the Task Force meetings in May and November 2012 (see examples in Figures 8-8 and 8-9).

Since the base case of the sensitivity analysis presents a good example to compare the results of different numerical codes, it was decided to use this model as the basis for a code validation. The task description for this code validation was prepared by BGR.

	Parameter		Significant influence on T	Significant influence on H	Significant influence on M
1	Rock intrinsic permeability	$k_{R,i}$	✓	✓	
2	Buffer density at saturation	$\rho_{B,sat}$		✓	✓
3	Buffer intrinsic permeability	$k_{B,i}$		✓	
4	Rock thermal conductivity	λ_R	✓	✓	
5	Buffer tortuosity	τ_B		✓	
6	Rock retention	$P_{R,0}, m_R$		✓	

Figure 8-8 . *Influence of changes in material parameters on the thermal (T), hydraulic (H) and mechanical (M) output quantities.*

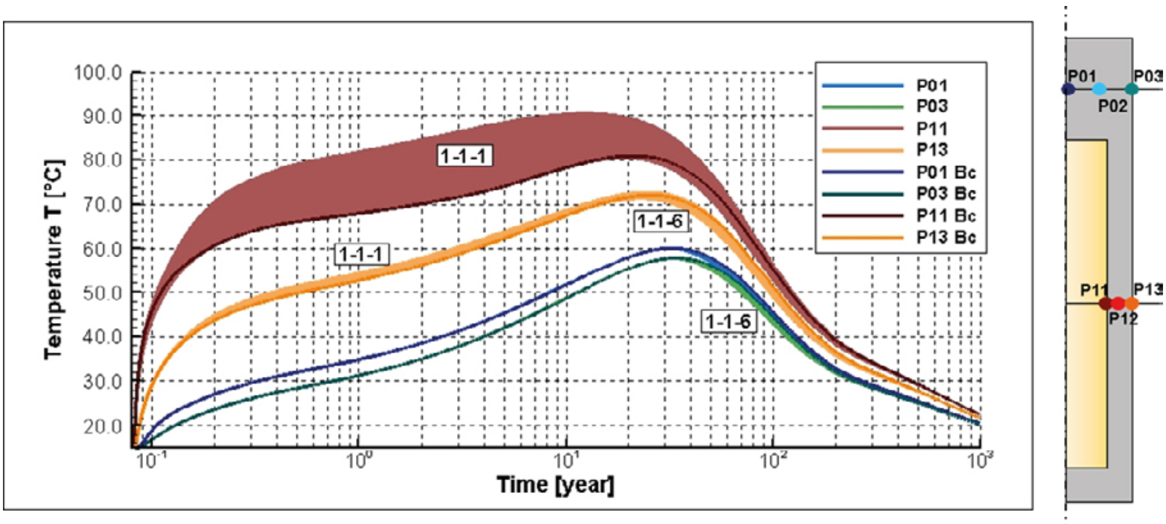


Figure 8-9. *Temperature evolution in four observation points in the buffer for base case model (dark lines) and deviation of results for Case 1-1-1 (decreased rock intrin-sic permeability) and Case 1-1-6 (increased rock intrinsic permeability) (light areas).*

In the frame of EBS-TF GRS's activities were as follows: In Task 8 a re-saturation model has been developed to simulate the bentonite in the BRIE-experiment at the HRL Äspö. The inflow rate calculated with VIPER indicates the water uptake by the bentonite if water was freely available from the host rock. These inflow data were compared with the results for water flow from the matrix and fractures at the BRIE-site that have been obtained with the groundwater flow code d^3f. (see Section 8.3.7).

Even if the comparison is only based on an uncoupled calculation, the results strongly indicate that flow from the fractures can locally be treated as if an infinite amount of water was instantaneously available for the bentonite. In contrast, the matrix does not provide as much water as demanded by the bentonite for a considerable length of time. Data for fluxes and for the amount of water crossing the bentonite-rock interface amount to 23 days and 95 days, respectively, until water supply from the rock equilibrates with the water demand from the bentonite. Therfore, it has to be concluded that the uptake dynamics at the bentonite-matrix contact may indeed differ significantly from the uptake behaviour observed in the laboratory tests.

A sketch of the water content distribution in the buffer after a certain period of time as envisioned by the present results is given in Figure 8-10.

To enable VIPER to cope with such a situation a new boundary condition was derived. However, implementation may take some time.

8.3.7 Task force on groundwater flow and transport of solutes

Groundwater flow model

The groundwater flow model around the TASO-tunnel that had been set up earlier in the project (Figure 8-11) was calibrated in such a way that inflow into the water producing probing boreholes was reproduced. As shown in Figure 8-12, the trend of decreasing pressue in the probing boreholes in the direction of the TASD-tunnel was captured as well. The plot of the velocity field shows the influence of the large fractures on groundwater flow.

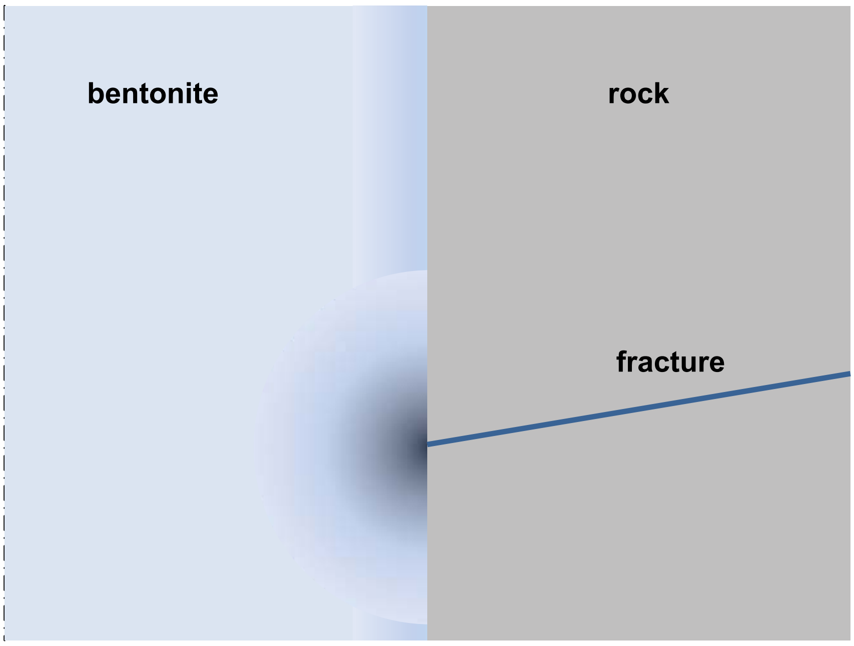


***Figure 8-10.** Water content distribution in the buffer connecting to fractured rock.*

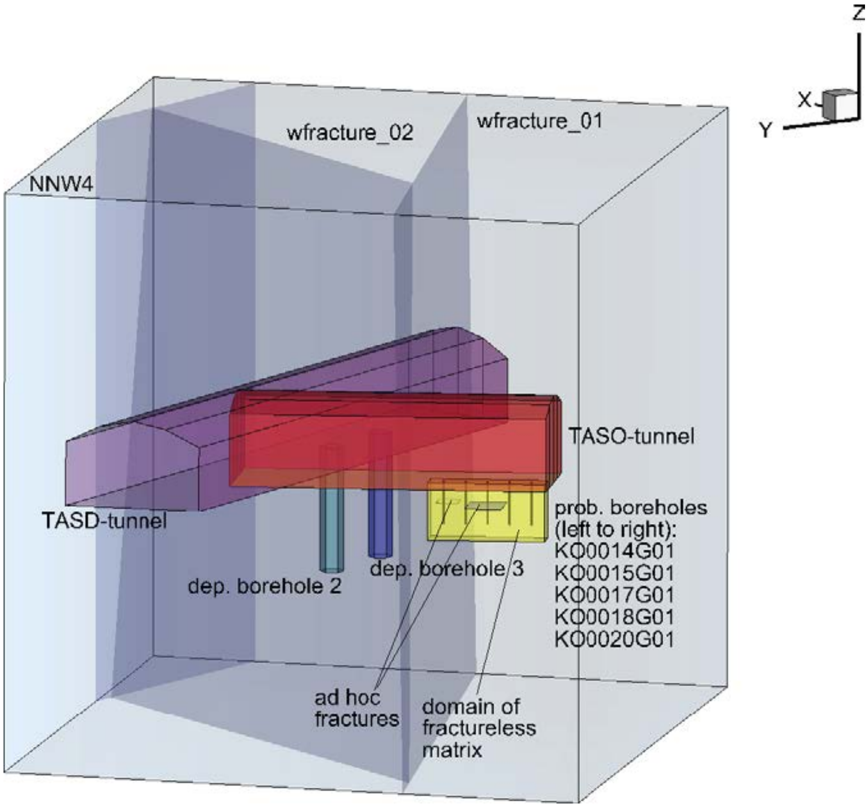


Figure 8-11. *Groundwater flow model for Task 8c.*

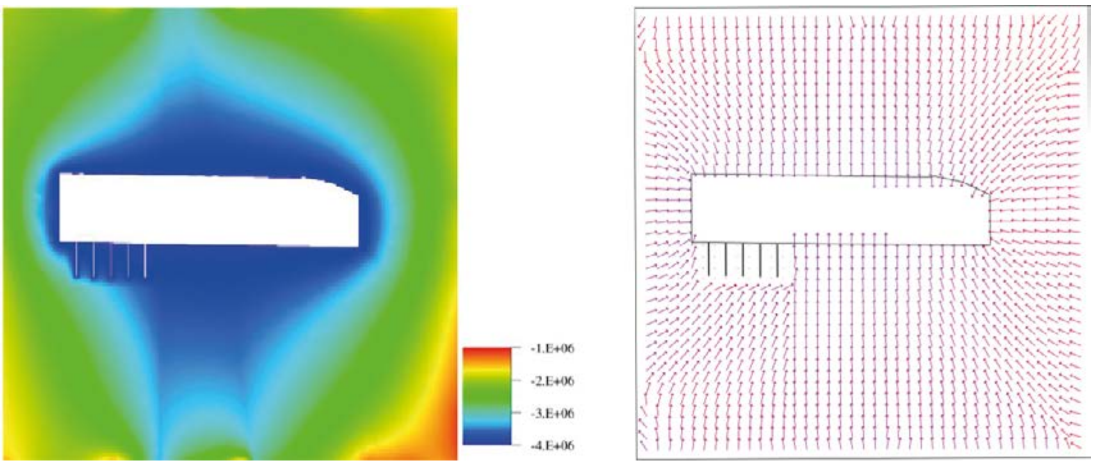


Figure 8-12. *Model results for a vertical cross-section through the TASO-tunnel; left: hydraulic pressure, right: velocity field.*

Considering the total inflow into the TASO-tunnel, it becames apparent that this inflow is dominated by the large fractures, and that the asumend flow rate in the model was too high. A reduction of the fracture permeability value by a factor of 100 was required to comply with an official estimate for the total outflow. There are two possible explanations for this model behavior: because the groundwater flow code d³f requires fracture permeability instead of a transmissivity there might have been errors in the assumptions for the necessary conversion. However, discussions with the Task Force members seem to exclude this interpretation. The other explanation concerns the pressure boundary conditions for the fractures. Since the pressure at the model boundary had to be extracted from a large scale flow model for the whole URL it might be that the local pressure at the fracture boundaries has not been described accurately enough by the extraction procedure. A pressure decrease due to the locally higher permeability in the fracture cannot be explained in this way. It was therefore tried to reduce the hydraulic pressure in the vicinity of the fracture boundaries. This proved to be difficult, though, due to the complex interaction of tabulated data for the pressure at the model boundary and the ad hoc implemented inverse distance weighing for a smooth pressure distribution on the model surface. A satisfying model with modified boundary conditions is still pending.

Additional measured data, both concerning a comparatively low inflow into one of the probing boreholes and the flow rate across the more or less fractureless tunnel wall, were distributed and initiated a rerun of the flow model. However, only minor changes were necessary for this purpose.

Equations of state for granite

Since the water uptake dynamics of bentonite in case of a limited water supply (see Section 8.3.6) has not been investigated yet, GRS prepared an adequate laboratory test studying water flow through a piece of Äspö rock before it reaches the bentonite. To estimate the breakthrough time for water in the rock, which is exclusively driven by capillary pressure, requires equations of state (EOS) for granite. These EOS includes the capillary pressure-saturation relation (CPS) and a relative permeability-saturation relation (RPS). They were compiled from literature (for granite at Äspö, Grimsel and the URL in Canada). Including plausible variants these EOS added up to 13 possible sets that were used in an appropriate numerical model to calculate the breakthrough time for a 4 cm piece of Äspö granite. As an example the results for the data from Grimsel (Finsterle and Pruess 1995) suggested for use in Task 8 are given in Figure 8-13.

Observations and conclusions from the 13 models are:

- A correct formulation of both – CPS and RPS – as well as the related parameters is essential for a meaningful prediction.
- Transfer of EOS between similar materials can be strongly misleading.
- RPS for the liquid states is a particular problem since it is usually not measured directly. It is to be therefore either derived from the CPS (often according to van Genuchten's or Brooks and Corey's relations), or a simple power law is used without theoretical justification.
- The calculated breakthrough times thus varied between 4 and 1,144 hours.

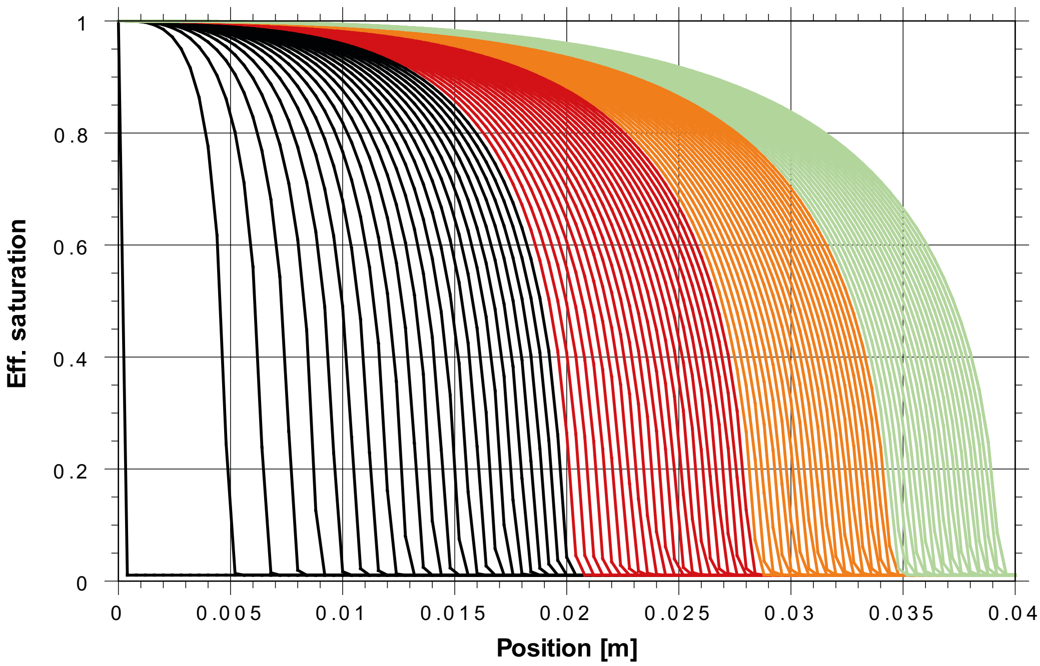


Figure 8-13. *Calculated effective saturation for capillary pressure driven water uptake of a 4 cm piece of granite based on EOS from the Grimsel site; one line per hour and one coulour per day of simulation time.*

There is presently no sound data base for predicting breakthrough time in the envisioned experiment. Surprisingly, there is but little information concerning the EOS for granite, especially at Äspö. As a general rule it has to be concluded that (at least) in the context of unsaturated flow direct measurements on the material in question is preferable over theoretical considerations.

8.4 CRIEPI

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

8.4.1 Task force on modelling groundwater flow and transport of solutes

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 2012, CRIEPI applied FEGM to the modelling work for Task 8c1. TASO tunnel is a primary investigation area of the Bentonite Rock Interaction Experiment (BRIE). In Task 8c1, the inflow to open boreholes is addressed with a focus on being a guide to the management of the BRIE experiment but also to test the modelling tool's ability to predict inflow to deposition holes based on limited information. The modelled domain is a cube 40 meters on a side which incorporates the TASO tunnel (Figure 8-14). Tunnels, three deposition holes, boreholes and surrounding rock mass were considered in the model. The boreholes were modelled as 3 metres deep and with a diameter of 76 millimetres. Three geological structure model fractures and background fractures exist in the surrounding rock mass.

The finite element mesh used for the numerical simulation is shown in Figure 8-15. 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 624,762 nodes, 3,719,920 three-dimensional elements and 8,075 two- dimensional elements. The domain within and near the boreholes was subdivided into smaller elements.

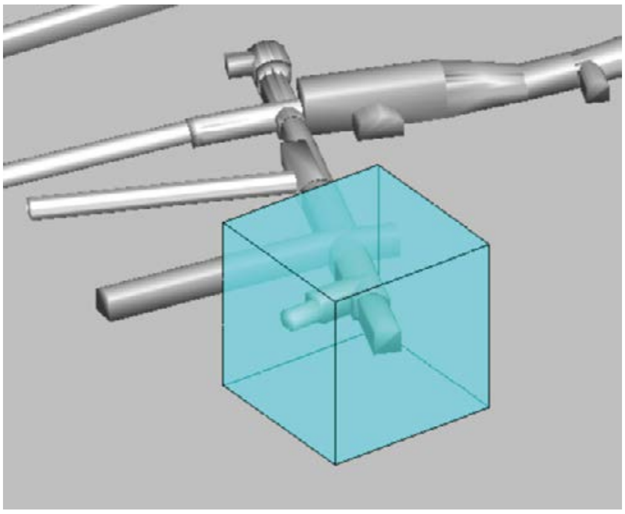
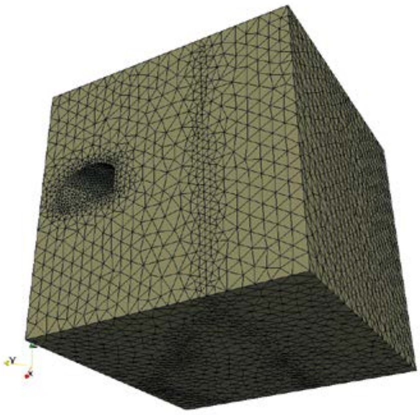
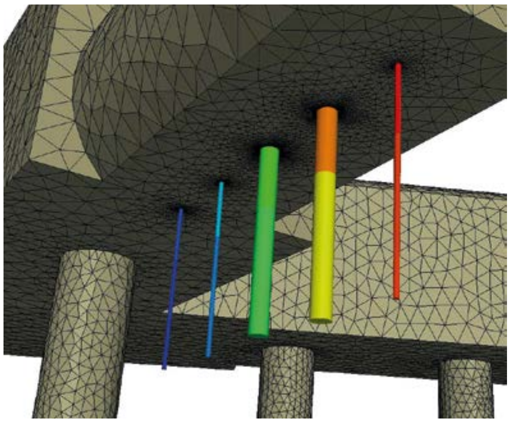


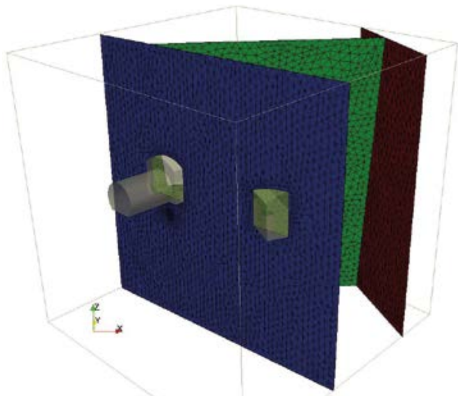
Figure 8-14. *Modelled domain used for Task 8c.*



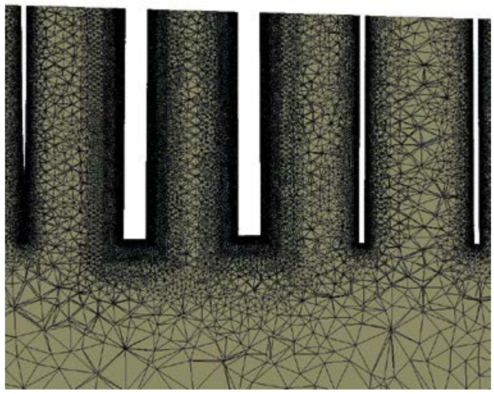
(a) Overall view



(b) Tunnels, deposition holes and boreholes



(c) Geological structure model fractures



(d) Rock mass around the boreholes

Figure 8-15. *Finite element mesh used for Task 8c.*

Background fractures were modelled using the smeared fracture model. In the smeared fracture model, the hydraulic conductivity tensor of an element which a fracture crosses is given by the following equation:

$$\boldsymbol{k}_e = \frac{\boldsymbol{k}_f \cdot V_f + \boldsymbol{k}_m \cdot V_m}{V_e}$$

where $\boldsymbol{k}_e$ the hydraulic conductivity tensor of an element, $\boldsymbol{k}_f$ is the hydraulic conductivity tensor of the fracture, $\boldsymbol{k}_m$ the hydraulic conductivity tensor of the rock matrix, V_e the volume of the element, V_f the volume of the fracture in the element, and V_m the volume of the rock matrix in the element (see. Figure 8-16). The following relationship was assumed between the transmissivity of background fractures, *T*, and the length of the fracture, *L*.

$$T = 7 \times 10^{-11} \times L^{1.7}$$

The following four cases of simulation were conducted.

Case 1: the upper limit of radius of background fractures is 25 m. Skin effect is not considered.

Case 2: the upper limit of radius of background fractures is 5 m. Skin effect is not considered.

Case 3: the upper limit of radius of background fractures is 25 m. Skin effect is considered.

Case 4: the upper limit of radius of background fractures is 5 m. Skin effect is considered.

In Case 3 and Case 4, fracture transmissivity was assumed to decrease to one percent within 2 cm from borehole wall due to skin effect (see. Figure 8-17).

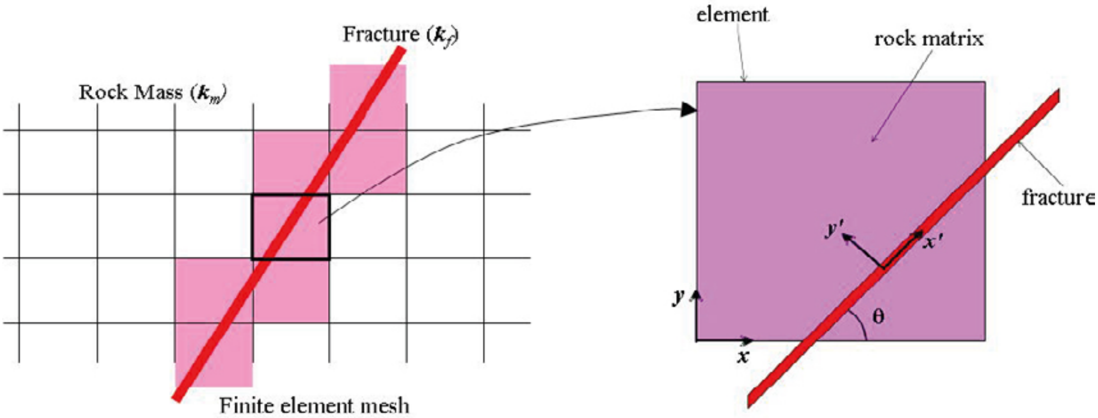


Figure 8-16. *Smeared fracture model.*

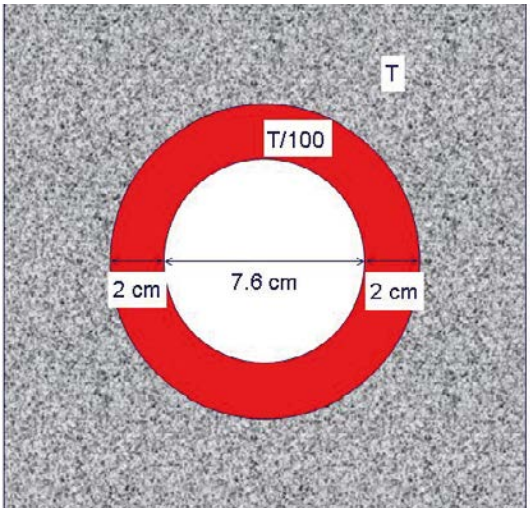


Figure 8-17. *Skin effect introduced in the numerical analysis.*

Figure 8-18 shows the examples of the realizations of the background fractures in Case 1 and Case 2. 5 realizations of the background fractures were generated for each simulation cases. Table 8-1 shows the calculated and measured results of the largest and the second largest inflows to the boreholes. In Case 1, the calculated inflows were 50 times larger than the measured ones. In Case 2 where the upper limit of the background fractures is 5 m, the largest inflows decreased to one-fifth of the ones in Case 1 but are still 11 times larger than the measured ones. In Case 3 and Case 4 where skin effect was considered, the largest inflows decreased to one-fifth of the ones in Case 1 and Case 2, respectively. In Case 4, the largest and the second largest inflows were the halves of the measured ones.

Table 8-1. The largest and the second largest inflows to the boreholes.

Realization no.	Case 1		Case 2		Case 3		Case 4	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
1	43.2	40.1	11.7	3.5	6.5	5.5	1.7	0.5
2	45.9	39.5	3.7	1.3	9.2	8.6	0.5	0.1
3	117.4	15.5	16.0	13.5	26.5	2.2	3.4	1.6
4	46.0	12.3	12.7	12.6	7.0	1.6	2.5	1.6
5	15.1	10.3	11.5	7.4	2.4	1.3	1.9	1.0
Average	53.5	23.5	11.1	7.7	10.3	3.8	2.0	1.0
Measured inflows	1.0	0.5	1.0	0.5	1.0	0.5	1.0	0.5

Unit : ml/min

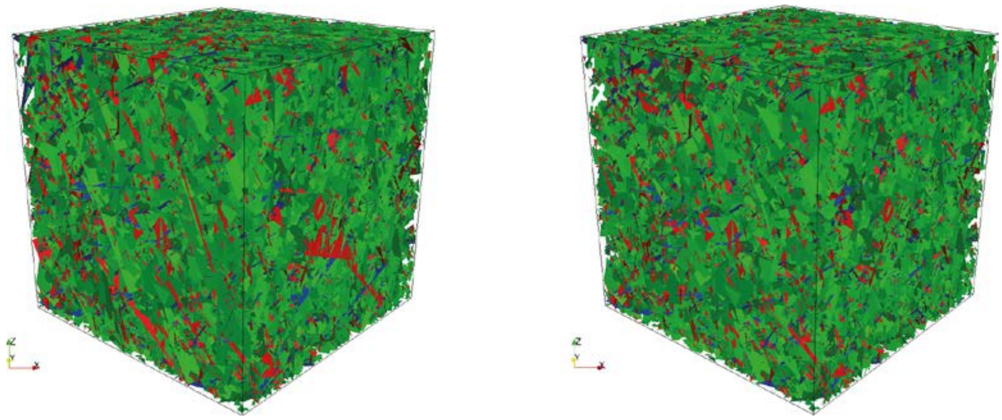


Figure 8-18. *Examples of the generated background fractures.*

8.4.2 Task force on engineered barrier systems

CRIEPI has been developing the thermal-hydrological-mechanical (THM) coupling code "*LOSTUF*" for evaluating the phenomena that will occur around the engineered barrier system.

In 2012, THM benchmark simulation of Prototype Repository (PR) was carried out. There are three suggested tasks in benchmark of Prototype Repository. First is 3D H-modelling of the PR before installation, second is 3D T/H/TH-modeling of the PR after installation, and the third is THM-modelling concerning on deposition hole 6. First and second tasks had been conducted in 2011. CRIEPI conducted the third task of PR, THM axisymmetric modelling.

Figure 8-19 shows the domain and boundary conditions for PR simulation. FE mesh consists of 3,669 nodes and 3,668 elements. At first, the permeability of surrounding rock mass was calibrated. Surrounding rock mass was divided into three regions, which were the regions around the TBM tunnel, around the deposition hole 6 and the outer region. The permeability of outer regions was determined from the results from 3D H simulation before installation. Permeability of the other two regions was determined so that measured water inflow was reproduced in the simulation. Water inflow around the TBM tunnel was converted in consideration with volume difference of the TBM tunnel in 3D and axisymmetric model. The results of the calibration are shown in Figure 8-20.

Figure 8-21 shows the temperature evolution in the R5 block on the mid-height of the canister in deposition hole 6. Numbers in the legend shows the distance from the center axis of the deposition hole (r) in the unit of mm. At r=585 mm, maximum temperature is almost 65 deg. C. Calculated temperature was lower than the measured because the effect of other heaters were not considered. Figure 8-22 shows the suction evolution in the R5 block in deposition hole 6. Saturation was achieved after almost 1,400 days in the R5 block. Figure 8-23 shows the calculated vertical displacement of canister bottom. Canister was once lifted more than 20 mm in 1,000 days, but shrank after 1,000 days. It is considered that the lag of swelling time between upper and bottom bentonite caused this behaviour in the simulation. CRIEPI has plan to update the modelling of PR after measured data at deposition hole 6 is delivered.

As the other work, a series of sensitivity analyses have been started in order to understand which material parameters and boundary conditions have large effects on numerical results.

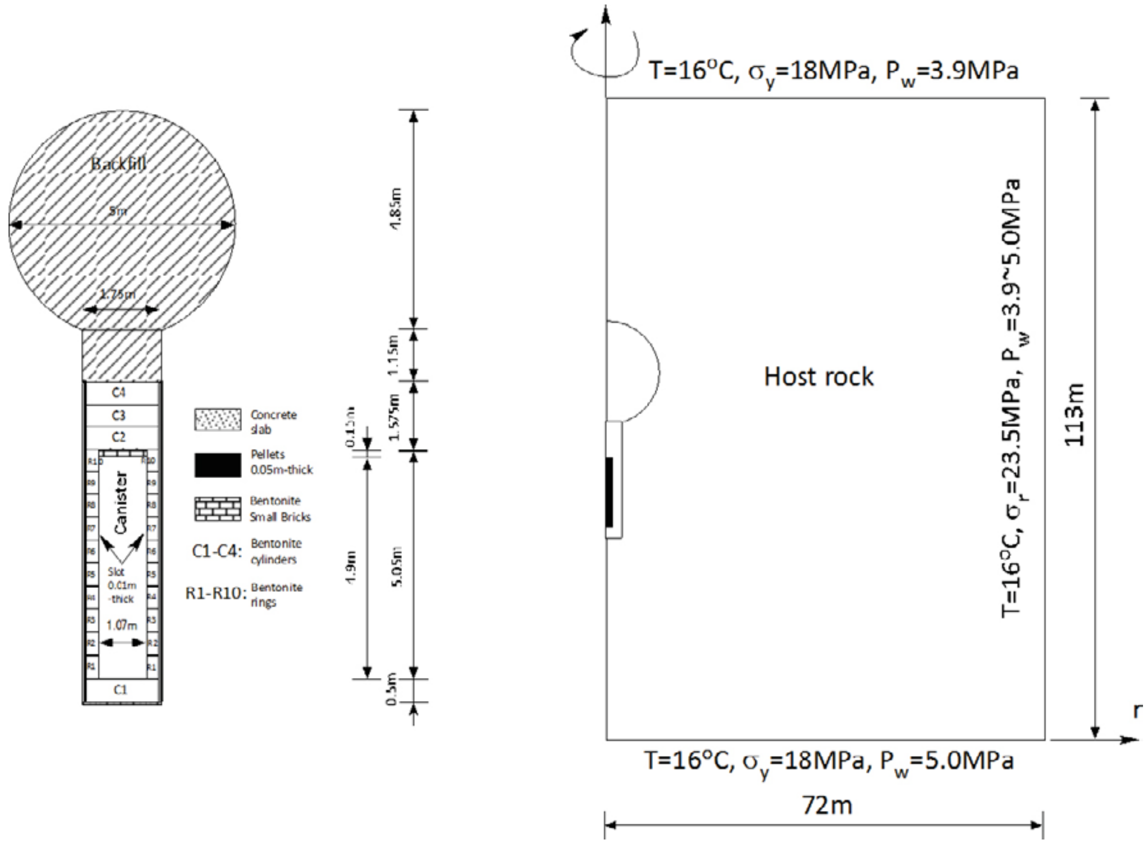


Figure 8-19. *Analytical domain and boundary conditions.*

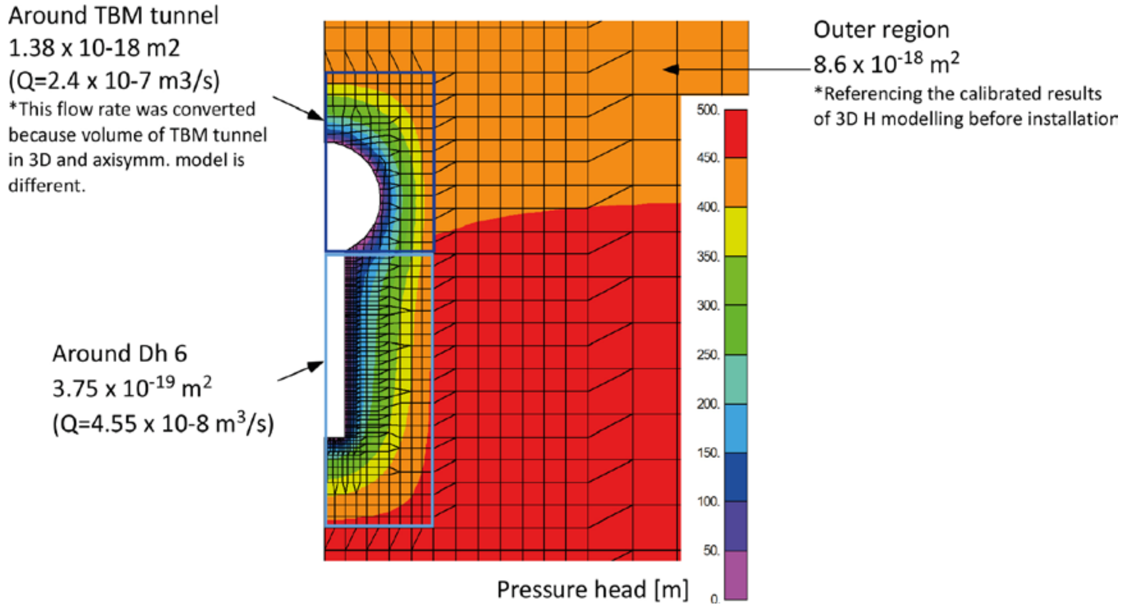


Figure 8-20. *Contour of pressure head and calibrated permeability around deposition hole 6.*

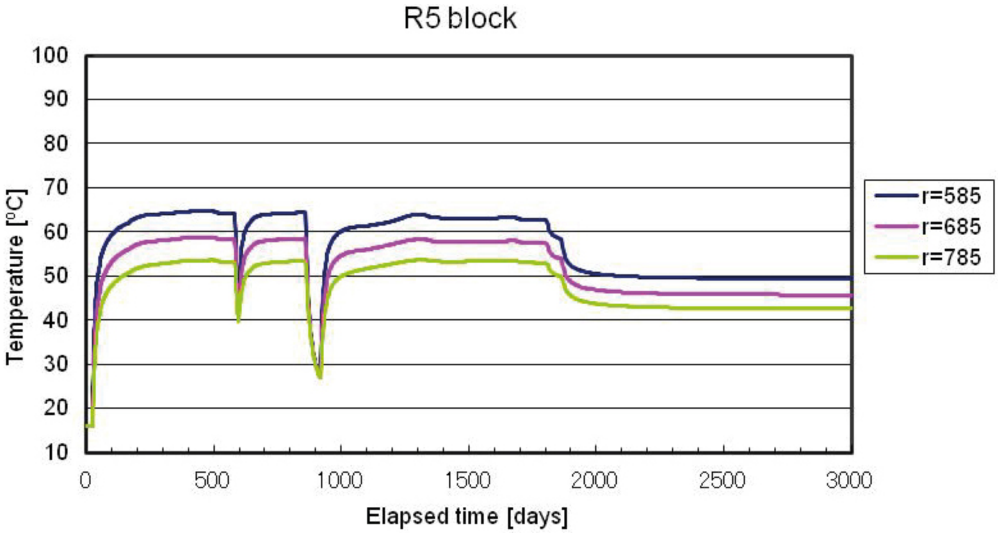


Figure 8-21. Calculated temperature in bentonite on the canister mid-height in deposition hole 6.

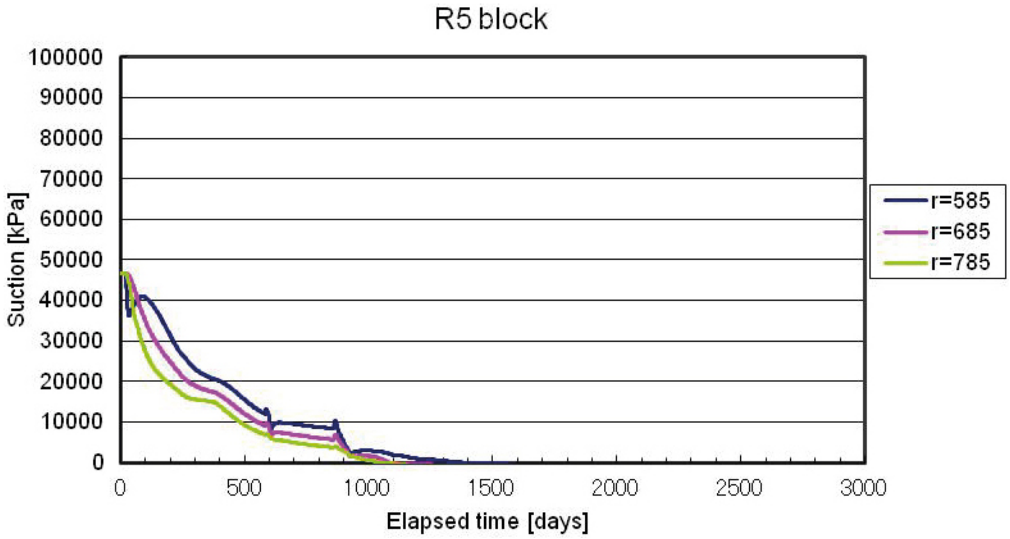


Figure 8-22. Calculated relative humidity in bentonite on the canister mid-height in deposition hole 6.

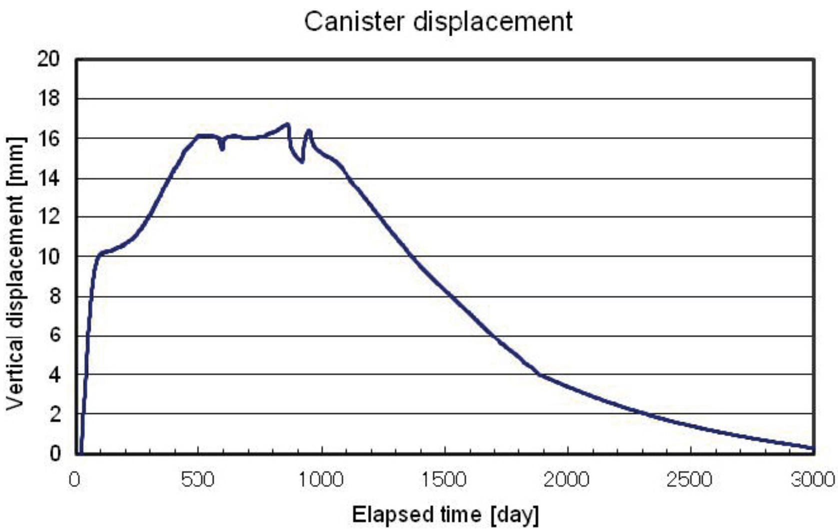


Figure 8-23. Calculated canister displacement in deposition hole 6.

8.5 JAEA – Japan atomic energy agency

The aim of Japan Atomic Energy Agency (JAEA)'s participation in the Äspö HRL programme is to contribute directly to its R&D mission. JAEA's research objectives at Äspö HRL during 2012 include the followings:

- 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 2012 focused on development of modelling capabilities for coupled flow in fractured rock and bentonite, within the context of "Task 8", simulates the *in-situ* experiment, Bentonite Rock Interface Experiment (BRIE) at Äspö Hard Rock Laboratory. JAEA's goal for participation in Task 8 is to improve understanding, characterization procedures, and analysis methodologies for the interface between bentonite and water conducting fractures at the scale of a disposition hole.

During 2012, JAEA also reported on the "Task7" modelling task for groundwater and transport at Onkalo (Olkiluoto, Finland), focusing on the Posiva Flow Fog (PFL) for constraining hydrogeological model at each scale of regional, block and a single fracture.

During 2012, JAEA participated in the Groundwater Flow and Transport of Solutes Task Force meeting at Berlin, Germany, January 17–19, the Task 8 modeling workshop at Äspö Hard Rock Laboratory, Sweden, April 24–25, and the Groundwater Flow and Transport of Solutes Task Force meeting at Lund, November 27–29.

Task 8 – Modelling the Bentonite Rock Interaction Experiment

The overall objective of Task 8 is to enhance understanding and modelling capabilities for the hydraulic interaction between the rock and water unsaturated bentonite at the scale of individual deposition hole scales and at the scale of a deposition tunnel. Task 8 is coordinated with the BRIE *in-situ* experiment, which provides data and geometry for the task.

During 2012, JAEA focused primarily on Task 8C, which requires modelling of the BRIE *in-situ* experiment site and the TASO tunnel, within a 40 m × 40 m × 40 m block region. The BRIE experiment includes five probe holes drilled at TASO tunnel floor, and two enlarged boreholes intended to represented canister emplacement holes. At each probe hole, the inflow rate and head distribution were measured. These measured values are used to support conditioning and sensitivity studies. Task 8C modelling will predict the pressure distribution, inflow distribution to the enlarged boreholes, and water movement within bentonite blocks emplaced in those holes should be predicted.

In this section, JAEA's modelling procedure for Task 8C is summarised. JAEA has assumed that discrete fracture network (DFN) flow dominates groundwater flow around disposal holes, and dual-permeability effects of the rock matrix provides additional pore water supply to the bentonite emplaced in two enlarged boreholes. Figure 8-24 summarizes the modelling concept developed for fractured rock and bentonite. To model these processes, JAEA uses the FracMan/MAFIC (Dershowitz et al. 2012, Miller et al. 2001) discrete fracture network (DFN) groundwater flow and transport codes, and the Thames (Chijimatsu et al. 2000) code which can simulate the coupled thermal, hydraulic and mechanical behaviour in bentonite. This approach could provides a more accurate description of the interaction of groundwater flow and flow within bentonite, because it recognizes both of the heterogeneous groundwater flow caused by the discrete geometry of fractures and water movement behaviour in unsaturated bentonite. However, this approach requires coupling between two distinct codes. JAEA has therefore developed two utility programs to provide an interface between the DFN and bentonite flow processes: “mtot” (Mafic to Thames) and “ttom” (Thames to Mafic).

The implementation of “mtot” and “ttom” for Task 8C included the following features:

1. Calculation of FracMan fractures into Thames’s cylindrical coordinate system.
2. Identification of the elements and nodes in bentonite column models corresponding to the location of fracture traces.
3. Transfer of information about the groundwater flow rate along the fracture traces on the surface of the emplacement holes to the regularly gridded bentonite column model.
4. Coordination of time steps between FracMan/MAFIC and Thames, using a single varying time step (“duration variable”) for both codes.
5. Setting a damping factor to moderate high flux from fractures to bentonite in “mtot”. This flux is the Neumann boundary condition on the bentonite column model in Thames, representing the infiltration rate from fractures calculated in FracMan/MAFIC. This damping factor was determined by examination of the maximum infiltration rate based on Darcy’s law.
6. Setting a damping factor to moderate high head values from bentonite to fractures in “ttom”. This head is the Dirichlet boundary condition on the borehole wall of FracMan/MAFIC model. This damping factor was specified as a maximum head of 10 meters, based on sensitivity studies.

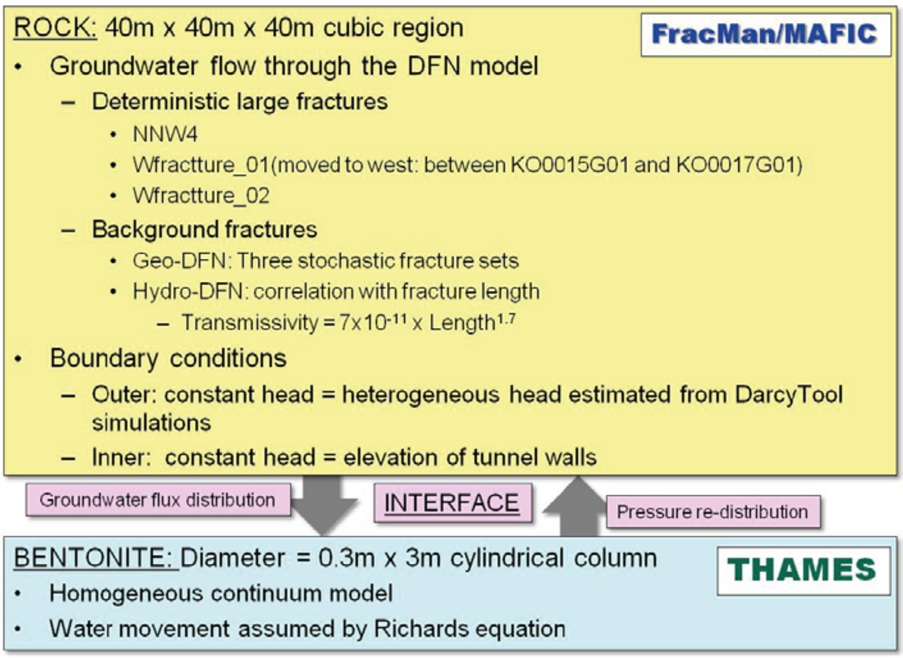


Figure 8-24. *Conceptual illustration of coupling between FracMan/MAFIC and Thames codes simulation.*

The Task 8C base case model implemented by JAEA in shown in Figure 8-25 and Figure 8-26. This model includes deterministically defined fault zone models (see Figure 8-25) and stochastically defined background fractures (see Figure 8-26), based on the parameterisation included in task specification. This represents a combined hydrostructural model of identified large conductive structures, and a "geo-DFN" of geologically identified structures. An empirical correlation between fracture size and transmissivity, including a ± one order of magnitude variability was assumed to estimate a "hydro-DFN" model which is hydrogeological fracture network model of background fractures from the geo-DFN.

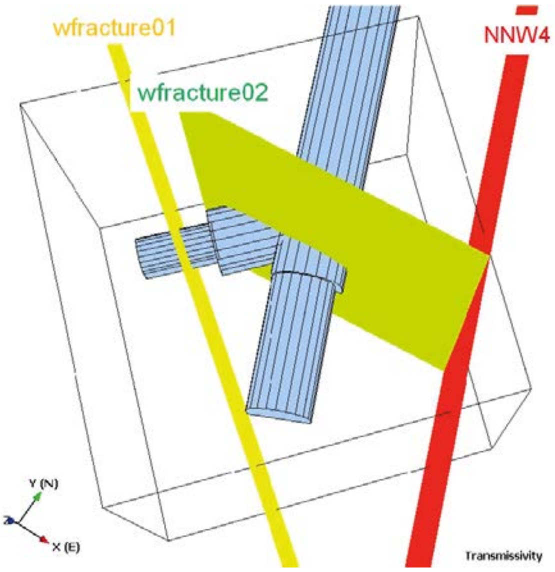


Figure 8-25. *Layout of deterministically defined fault zones.*

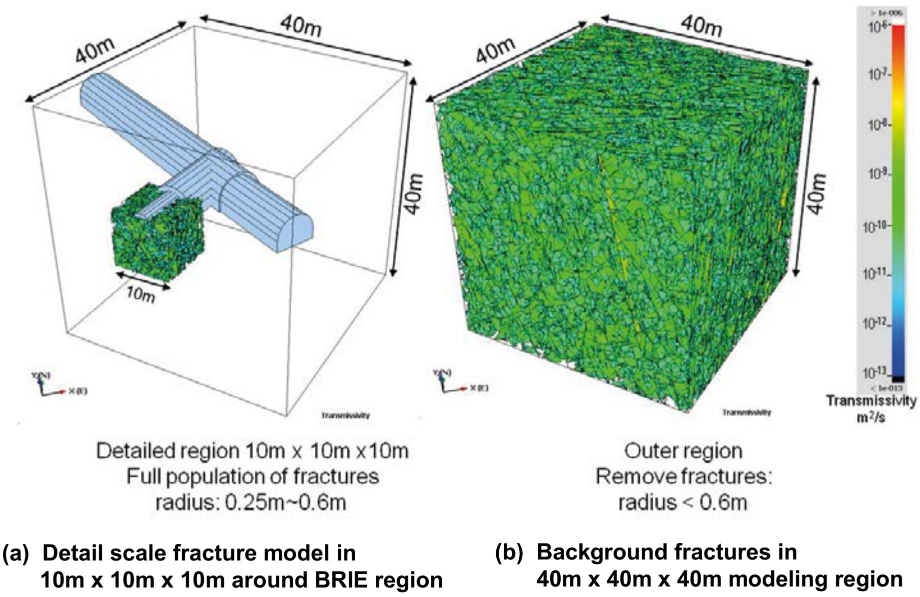


Figure 8-26. *An example of the stochastically defined DFN model.*

DFN modelling generally assumes that only a very small proportion of features included in a geo-DFN have sufficient transmissivity to be included in a hydro-DFN. However, the Task 8 geo-DFN specification does not identify the "water-conducting" fractures which should be included in a hydro-DFN. In addition, for Task 8C, there is a concern that low permeability fractures which would not normally be included in a hydro-DFN might be sufficiently permeable to provide some water for bentonite resaturation. Therefore, the hydro-DFN was implemented using the full volumetric fracture intensity P_{32} specified in the geo-DFN. However, for computational efficiency, beyond the detailed 10 m × 10 m × 10 m model region fractures smaller than 0.6 m were omitted from flow simulations.

Five stochastic realizations of the hydro-DFN were generated using FracMan/MAFIC For flow simulations, the outer boundary of the 40 m × 40 m × 40 m model domain were assigned constant head values estimated by interpolating head values calculated by the larger scale of numerical model simulation provided by the task specification. At the tunnel walls, head was specified as the elevation of the wall (i.e., atmospheric pressure). At the five probe boreholes conducted in BRIE, two sets of head assumptions were run. To calculate inflow to water filled probe boreholes, the head values of the probe boreholes were assigned at a head corresponding to the elevation of TASO tunnel floor (–417 m). To calculate inflow to the two enlarged boreholes (diameter 30 cm); the head was specified as the elevation of the borehole walls (i.e., atmospheric pressure).

The Task 8C hydro-DFN model was calibrated using the inflow rate and pressure measurements provided in the task specification. Simulation results for five stochastic realizations are shown in Figure 8-27. Black solid symbols indicate base case realizations and red open circles indicate measured results. The stochastic realizations show significant variability. However, this base case model consistently produces inflows to the five probe-holes which are significantly higher than the measured values.

Two approaches were implemented to better match measured probe-hole inflows:

1. Scaling of fracture transmissivity by factors of 1/10, 1/50, and 1/100. This is consistent with the uncertainty and variability in the generic fracture transmissivity ~ size correlation assumed for this task.
2. Conditioning fractures intersecting the five probe-holes using measured fracture (geo-) data.

Figure 8-28 presents results for a simulation case using calibration approach 1), with a factor 1/50 reduction in the fracture transmissivity. This case significantly reduces the flow rate to the five boreholes. Figure 8-28 also shows results of the sensitivity study for outer boundary assumptions. Constant head boundary conditions without skin can be considered as an un-realistic unlimited water reservoir. To mitigate this, a low permeability skin (1/10 of original transmissivity at 1 m thickness region at outer edge) was added in this sensitivity study. The low permeable skin assumption also reduces the flow rate to the boreholes and head values along the boreholes. The Task 8C specification also includes a homogeneous head of –50 m on the periphery of the model as an alternative case. A weak sensitivity to increase the flow rate to the boreholes is shown in the homogeneous outer boundary case, caused by relatively high head values than the base case at the northwest side.

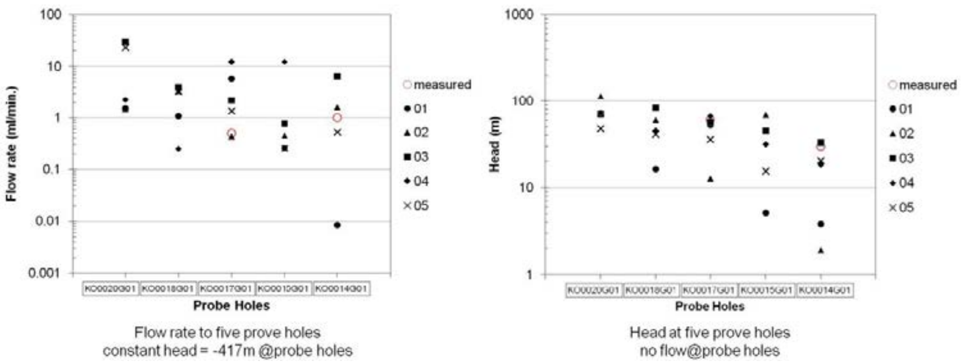


Figure 8-27. Simulated flow rate and head at five probe holes (solid symbols), comparison with measured values (red open circle).

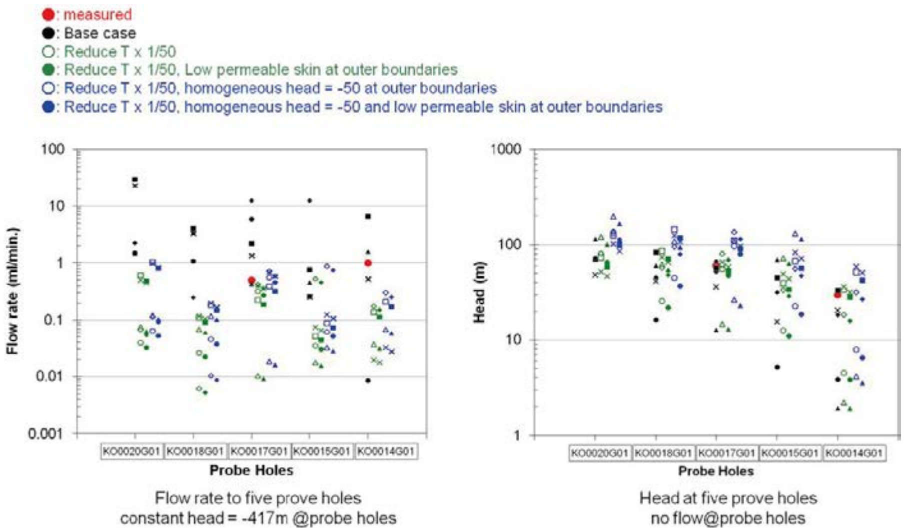


Figure 8-28. Sensitivity study results by changing transmissivity and boundary conditions.

The simulation carried out by conditioning water conducting features (WCF) to geologic fractures, calibration approach 2), assumed that fractures characterized as "Broken/Open" and "Calcite" might correspond to potential WCF. The location and orientation of these potential WCF are shown in Figure 8-29. Because the data provided are described independently at each borehole and no data for connecting fractures (geologically) is provided, the size of constrained fractures can be estimated by assuming that their extent is limited to the spacing of five boreholes array, such that no two boreholes are directly connected. Figure 8-30 describes the procedure of fracture conditioning:

a) remove stochastic background fractures which do not match identified geo-DFN based WCF, and

b) add WCF the locations of mapped fractures, using stochastic fracture parameter values.

Figure 8-31 shows an example of simulation results for the calibrated hydro-DFN model, showing the heterogeneous inflow distribution to the enlarged borehole, 17 and 18. These flow distributions are used as initial condition for simulating resaturation process in emplaced bentonite.

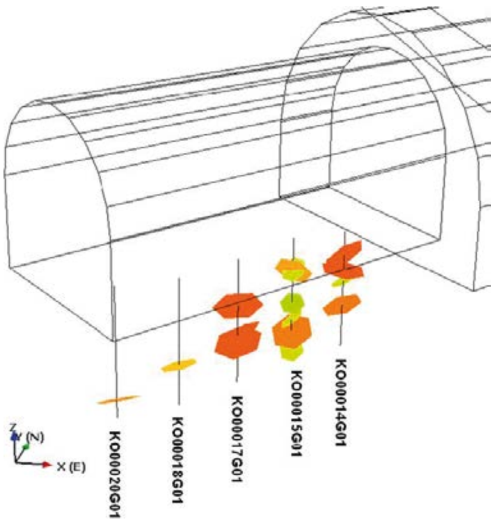


Figure 8-29. Location and orientation of potential WCF from geological information.

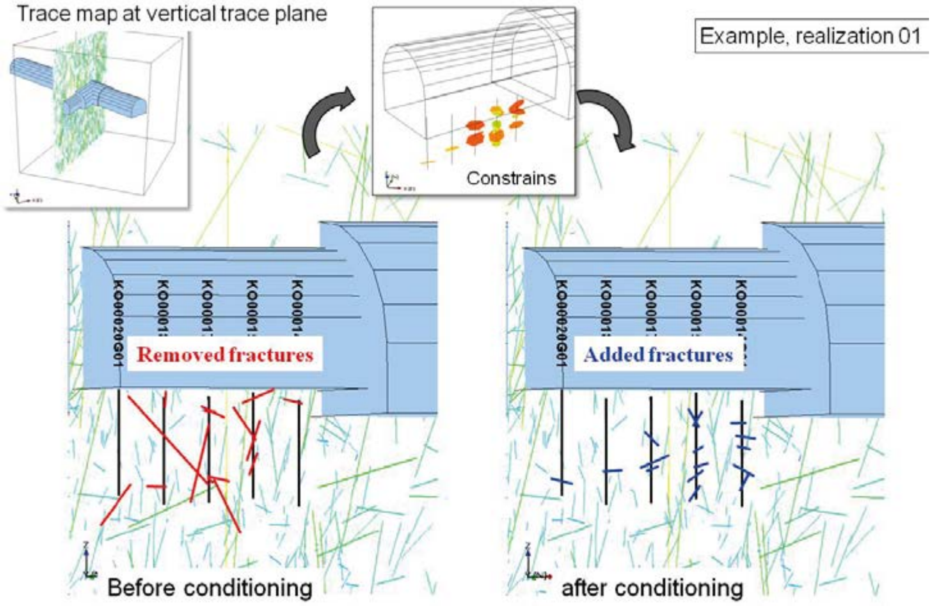


Figure 8-30. Procedure of "conditioning" of the potential WCF location and orientation intersecting five probe holes.

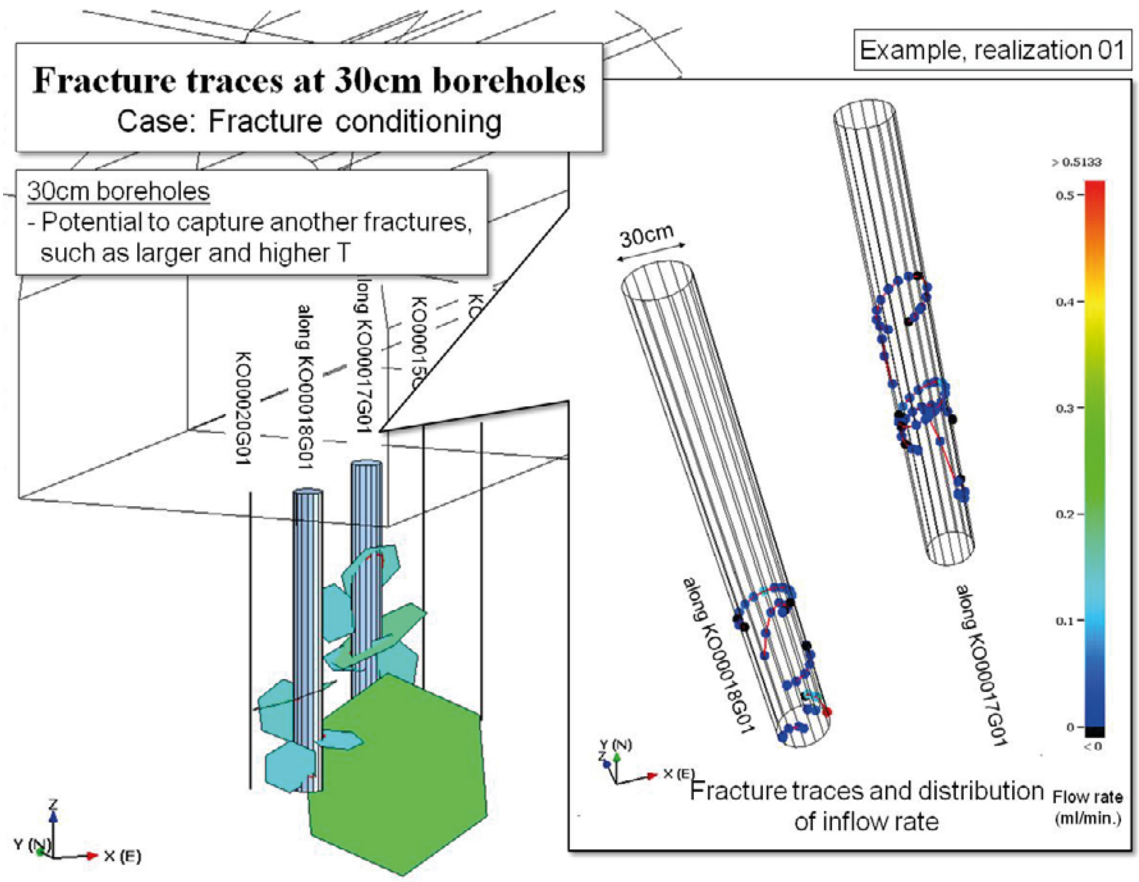


Figure 8-31. Example of flow simulation of calibrated hydro-DFN model, groundwater flow rate distributed at the wall of enlarged borehole.

Water movement in compacted bentonite is assumed to be described by Richards equation (Bear 1972). Key parameters for implementation of Richards equation describe the hydraulic conductivity characteristic curve for saturated and unsaturated flow in terms of pressure (tension) and relative permeability. Table 8-2 provides the Richards equation parameters used for preliminary simulations, based on the Task 8C specification. Figure 8-32 shows the applied retention curve and relative permeability curve.

The coupling simulation between heterogeneous groundwater flow through hydro-DFN model by MAFIC and water movement by Richards Equation by Thames were performed. Figure 8-32 shows an example of the evolution of bentonite saturation as simulated by coupling between FracMan/MAFIC and Thames. The upper and lower figures show evolutions of saturation distribution in bentonite column in hole 17 and hole 18, respectively. The left five columns present saturation evolutions in the vertical section crossing centre line of the holes, at each elapsed time, 1day, 0.1 years, 0.5 years, 1 year and 10 years. The right side circles are the saturation distribution at horizontal section on the middle height of the bentonite column, at each elapsed time, 1 day, 0.1 years and 0.5 years. The heterogeneous water movement caused by the fracture flow from rock can be recognised. In hole 17, the water is infiltrated from the middle height of the column, and the saturated area are extending from the middle height part to both lower and upper parts. In hole 18, the infiltration is from the lower part of the column and the saturated area expanding from lower part to the upper part. For these example cases, both columns could be fully saturated until ten years.

8.5.2 Alternative buffer materials

FESEM observation/EDS analysis and EPMA analysis on the bentonite material (Kunigel V1) retrieved from parcel 1 were reported in the Annual report 2011 (SKB 2012a). In the EPMA analysis, iron was identified in the color altered part of Kunigel V1 block adjacent to the iron heater. In this report, alteration of smectite in the color altered part of Kunigel V1 block was investigated by humidity controlled X-ray diffraction analysis, elemental mapping analysis by EPMA, SEM observation/EDS analysis, TEM observation/EDS analysis and AFM analysis.

Table 8-2. Parameters applied for MX80 bentonite column.

Parameter	unit	value
Dry density	kg/m³	1,560
Particle density	kg/m³	2,780
Saturated density	kg/m³	2,000
Void ratio	–	0.78
Porosity	–	0.438
Initial liquid saturation	%	35.6
Initial water content	%	10
Hydraulic conductivity	m/s	6.4×10^{-14}

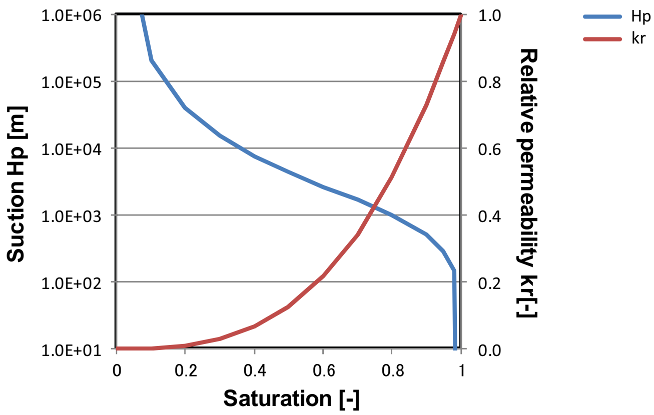


Figure 8-32. Retention curve and Relative permeability applied for MX80.

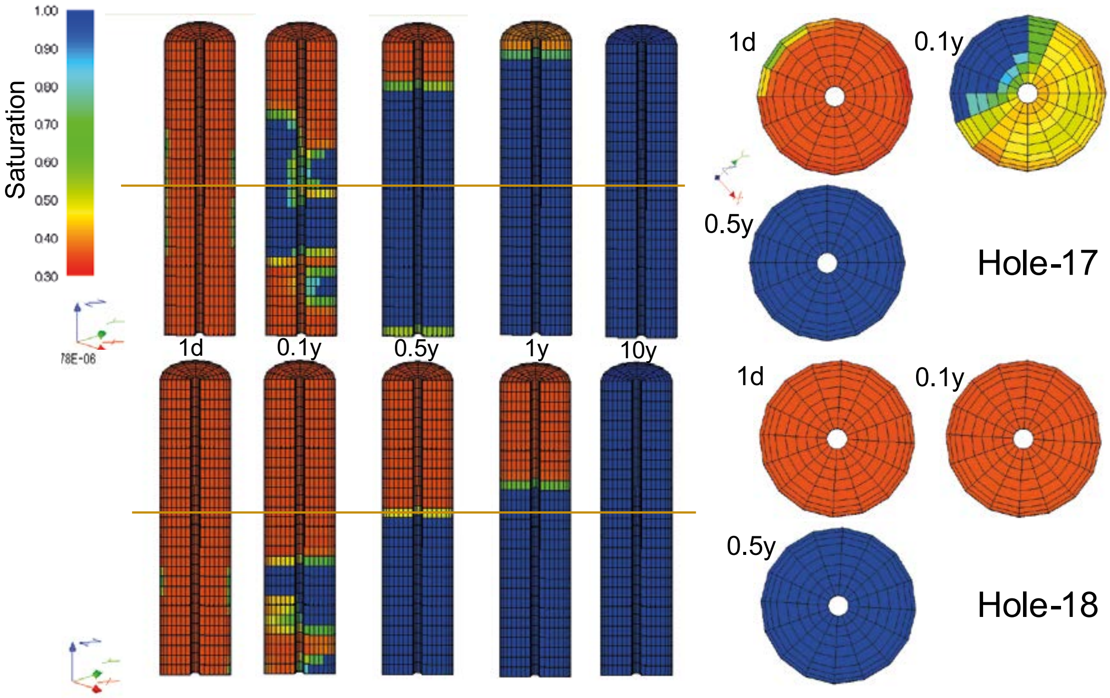


Figure 8-33. *Example of bentonite saturation evolution from coupled FracMan/MAFIC and Thames simulations.*

The variation of basal specing depending on relative humidity was observed by X-ray diffraction in order to investigate the exchange of Na^{+} in the interlayer of smectite from to Fe^{2+} or Fe^{3+}. The bentonite samples were obtained at the distances of 5, 10 and 75 mm from the interface between iron heater and bentonite block. The humidity was controlled from 0% to 100% in the analysis. The basal spacing of smectite was measured at every 10% humidity. Figure 8-34 shows the variations of basal specing with changing relative humidity. The basal spacings of smectite in the bentontie sample at 5 mm from heater were larger than those in the other bentonite samples at lower than 30% of relative humidity as shown in the figure on the left. The variation of basal spacing is known to depend on the kind and valency of cation in the interlayer of smectite, e.g. Sato et al. (1992). The figure on the right shows the variations of basal spacing of Fe-type (Kozaki et al. personal communication), Ca-type and Na-type (Sato et al. 1992) smectite together with those of the bentonite samples. The basal spacing variation of smectite in the bentonite sample at 5 mm from heater was similar to that of Fe-type smectite, suggesting that Na^{+} in the interlayer of smectite was exchanged to Fe^{2+}. The basal spacing variations of smectite in the bentonite samples at 10 and 75 mm from heater were a little different from that of Na-type smectite. The interlayer cation in these samples might be also exchanged partly to Fe^{2+}.

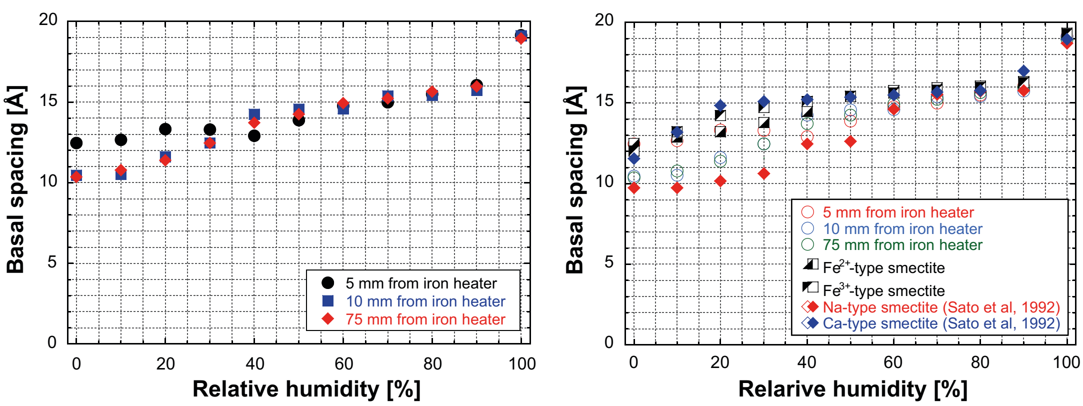


Figure 8-34. *Variations of basal specing with changing relative humidity in the bentontie samples at the distances of 5, 10 and 75 mm from the interface between iron heater and bentonite block.*

Figure 8-35(b), (c) and (d) shows the results of elemental mapping analyses of Si, Fe, Mg, Al, Ca and Na by EPMA on the bentonite block at point #1shown in Figure 8-35(a), where the bentonite block contacted with the iron heater, and at point #2 and #3 apart from the iron heater, respectively. The area containing high concentrations of Fe and Ca, which is shown in red or yellow in the image, were identified in the bentonite block at point #1. The area containing high concentration of Fe distributed uniformly in this bentonite block, while Ca was concentrated on the interface between the iron heater and the bentonite block. The concentrations of Si, Mg and Al were partly lower on the image at point #1. The concentration of Na at point #1 was almost the same as those at points #2 and #3. The decrease of Na concentration was not observed, although X-ray diffraction analysis with humidity control suggested the alteration of Na-type smectite to Fe-type. This increase of Fe concentration observed by EPMA elemental mapping analysis was considered to be due to the existence of minerals containing Fe, which was formed by the precipitation of Fe migrating from the iron heater.

SEM observation/EDS analysis was conducted on the bentonite block at point #1, where the area containing high concentration of Ca was identified on the interface between the iron heater and the bentonite block. The precipitation of calcite was observed in this area by SEM observation/EDS analysis.

HRTEM (High Resolution Transmission Electron Microscopy) observation/EDS analysis was carried out on the bentonite block at point #1 in order to analyze the minerals formed by the alteration of smectite with a high degree of identification accuracy. Figure 8-36 shows the result of TEM observation/EDS analysis on the bentonite block. A mineral which forms aggregate with folded edges was observed at the upper-right corner on the bottom-left image. This structure is typical of chrysotile, which is in the serpentine group of phyllosilicate. EDS analysis indicates that Fe content of this mineral was around 30%. This Fe-rich mineral was considered to be formed by the alteration of smectite in the bentonite block.

AFM (Atomic Force Microscope) analysis was conducted to measure the thickness of unit layer of clay mineral in the bentonite block. The unit layer thickness of clay mineral was found to be around 1.26 nm by AFM analysis, which is roughly equivalent to that of smectite.

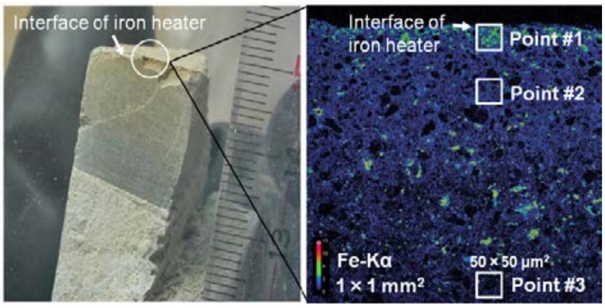


Figure 8-35(a). *Photograph and EPMA mapping image of Fe on bentonite block. Points #1 to #3 are the positions where elemental mapping analyses were conducted by EPMA.*

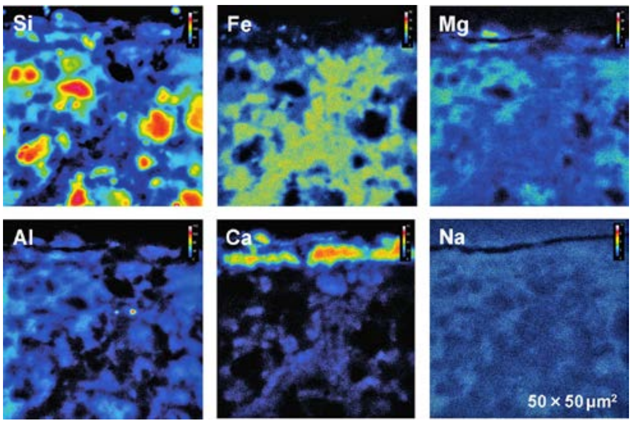


Figure 8-35(b). *Images of elemental mapping analyses of Si, Fe, Mg, Al, Ca and Na by EPMA on the bentonite block at point #1.*

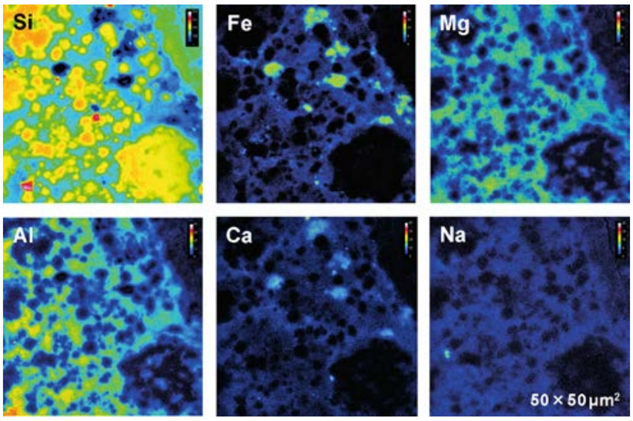


***Figure 8-35(c).** Images of elemental mapping analyses of Si, Fe, Mg, Al, Ca and Na by EPMA on the bentonite block at point #2.*

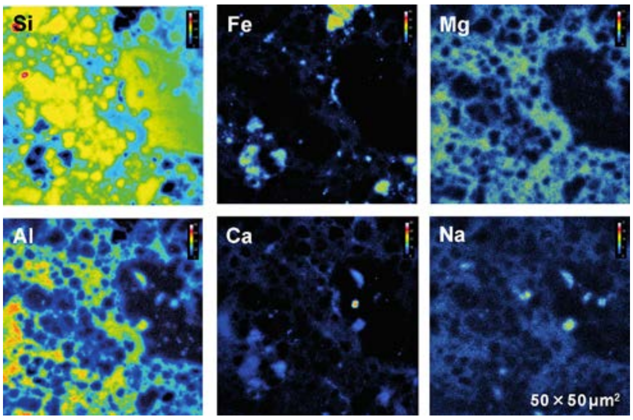
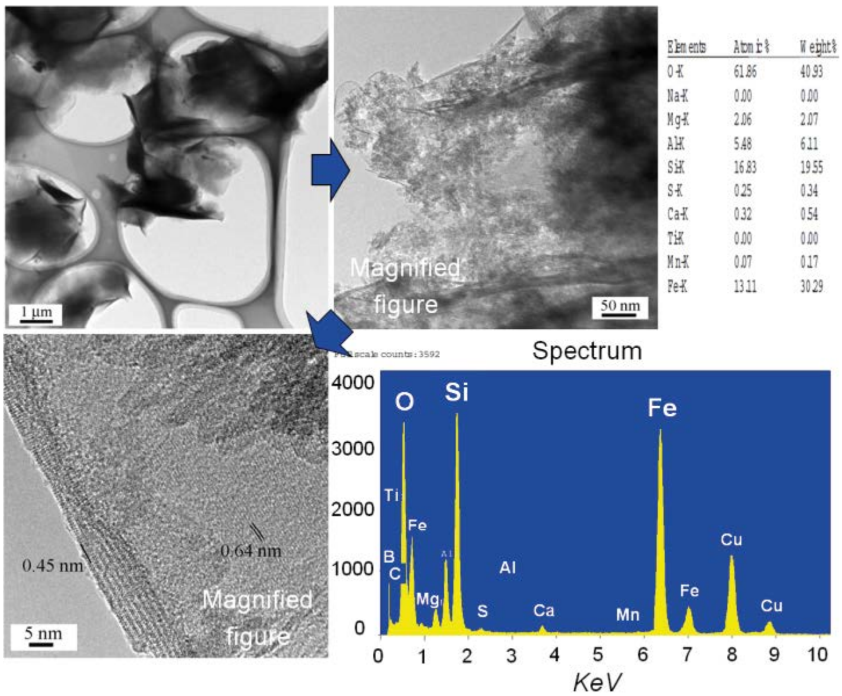


***Figure 8-35(d).** Images of elemental mapping analyses of Si, Fe, Mg, Al, Ca and Na by EPMA on the bentonite block at point #3.*



Elements	Atomic%	Weight%
O-K	61.86	40.93
Na-K	0.00	0.00
Mg-K	2.06	2.07
Al-K	5.48	6.11
Si-K	16.83	19.55
S-K	0.25	0.34
Ca-K	0.32	0.54
Ti-K	0.00	0.00
Mn-K	0.07	0.17
Fe-K	13.11	30.29

***Figure 8-36.** Results of TEM observation/EDS analysis on the bentonite block at point #1.*

Consequently mineralogical alteration of smectite was scarcely observed by the analyses on the bentonite material (Kunigel V1) retrieved from parcel 1. The Fe-rich mineral formed by the alteration of smectite, which belongs to the group of serpentine, was identified at the interface between the iron heater and the bentonite block. However, this mineral was detected only by HRTEM observation with a high degree of identification accuracy, indicating that the amount of this mineral was quite low. Although the mineralogical change of smectite was, thus, scarcely detected, the possibility of cation exchange in the interlayer of smectite from Na^+ to Fe^{2+} was suggested from the analyses.

These analyses were partly funded by the Ministry of Economy, Trade and Industry (METI) of Japan (JAEA 2012).

8.6 NWMO

In 2012, the Nuclear Waste Management Organization (NWMO) effort under the Äspö Project Agreement was supported by Geofirma Engineering. The results of this work are briefly described below.

8.6.1 Large scale gas injection test

NWMO is providing modelling support for the Large Scale Gas Injection Test (LASGIT) using the TOUGH2 code modified with pressure-dependent permeability and capillary pressure to simulate microfracturing of the bentonite buffer surrounding the container. In 2012, several modifications in the gas model were recommended, particularly modifications to the pressure-dependent permeability and capillary pressure functions to improve the ability of the model to simulate a distinct pathway, and inclusion of a heterogeneous stress boundary and stress-dependent permeability to simulate a gas pathway not immediately adjacent to the injection port. Simulations are being conducted on Gas Test 3 (conducted in 2010), which hydraulic data indicates is fully saturated. Gas Test 3 data are complex, with strong responses at the canister-bentonite interface as illustrated in Figure 8-37.

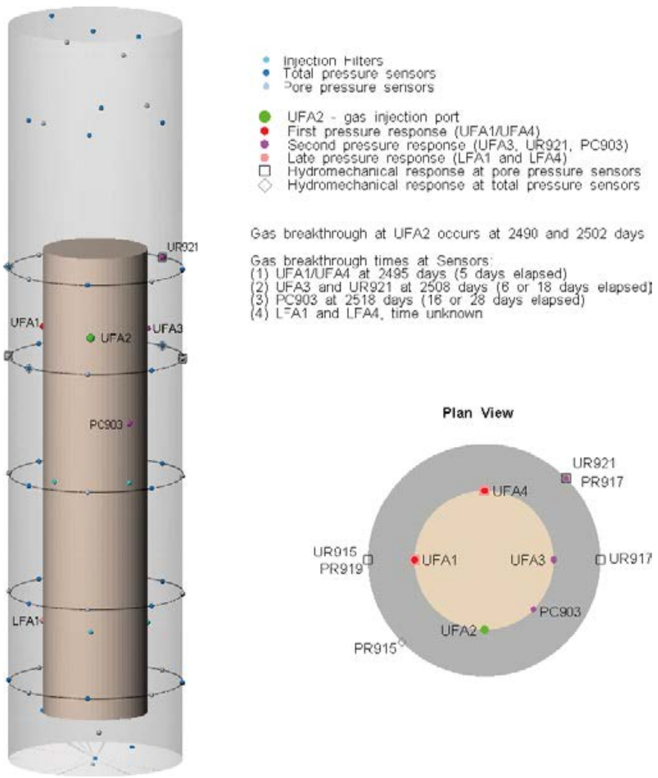


Figure 8-37. SKB LASGIT Gas Test 3 (2010 Gas Injection Tests) Showing Locations of Gas Injection (UFA2) in the Bentonite Buffer and Gas Breakthrough.

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 and the co-operation has been organised in four areas divided to the:

- Safety and licensing.
- Underground characterisation, design and construction.
- Design, development and demonstration of the engineered barrier system (Clay line and Canister Line).
- Assessment of long-term safety and system performance.

The focus of the co-operation is to plan and implement the research and development activities related to the KBS-3 disposal concept. Part of the activities is performed within Äspö facility and/or within ONKALO underground rock characterisation facility. The implementation and construction of the underground rock characterisation facility ONKALO at Olkiluoto in Finland give possibilities to co-operate within the research and development of underground construction technology. The first demonstration tunnels and holes produced with similar specifications as for deposition tunnels and deposition holes has been excavated and bored during 2011–2012 and the EBS testing can be initiated within coming years also in ONKALO. Posiva's co-operation in Äspö is divided between Äspö HRL activities within Engineered Barriers and more generic work that can lead to demonstrations in Äspö HRL or in ONKALO URCF. Posiva also contributes to several of the research projects within Natural Barriers.

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. The current project phase "KBS-3H System Design, 2011–2016" has initiated studies that were identified in the previous project phase as important issues. The preparations including planning and procurement of drift components has been ongoing during 2012 to start the full-scale demonstration called MPT (Multi Purpose Test) at Äspö. The operational phase of MPT, which belongs to the international LucoeX project (2011–2014) supported by Euratom, will be started during 2013. Part of MPT preparations the upgrading (both hardware and software) of the deposition machine has been ongoing. MPT demonstration has been in the focus point of the entire 3H project due to its importance for the 3H concept. Posiva has participated e.g. in the review work of the plans regarding MPT preparations.

Posiva's contribution has included e.g.

- Buffer swelling laboratory tests related buffer extrusion from a Supercontainer.
- Instrumentation plan for Multi Purpose Test (MPT).
- Production line reports "Underground construction Design, Construction and Initial State of the KBS-3H Underground Openings" and "Buffer and Filling Components were started during 2012".
- Ti studies 2012–2014 programme was started in order to investigate bentonite buffer and its interaction with titanium shell materials in long-term. The focus is on chemical processes, which may adversely affect the safety functions of the buffer. The work builds on the previous work on titanium-bentonite interaction.

Posiva's Construction License Application was submitted end 2012 and a topical report on KBS-3H (Description of KBS-3H Design Variant, POSIVA report 2012-50) was appended to it.

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 2012 according to the plans agreed in steering committee meetings by continuing hydration and gas release tests. 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.

8.7.4 Alternative buffer materials

Posiva's contribution has been attending project meetings.

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

Äspö Task Force Task 8 was launched in 2010 with the aim at increasing knowledge of the interaction between the bentonite buffer and host rock, and, in particular, the flow of groundwater from bedrock fractures into the buffer and its ensuing saturation. The temporal and spatial evolution of groundwater pressure and flow in the rock matrix and fractures in the neighborhood of a deposition hole, and the saturation of the bentonite in the deposition hole is modelled. In addition, the groundwater flow through the interface between the bentonite buffer and host rock is assessed.

In Task 8a the saturation of bentonite was modelled with the TOUGH2 and COMSOL Multiphysics computer programs in the axially symmetric case which considered a block of the host rock and part of a deposition tunnel. In Task 8b, in turn, the saturation of bentonite and evolution of groundwater flow was modelled in simplified three-dimensional site geometry of Äspö HRL. Work in 2012 concentrated on Task 8c in which a three-dimensional model for the groundwater flow and bentonite saturation in the BRIE experiment in Äspö HRL was developed. Initially the model parameters were matched to observed inflow rates and water pressures in experimental holes. The observations can be captured by the model with different parameter configurations, thereby several fittings were made. After the fitting, model predictions of the saturation of the bentonite installed in an experimental hole were presented based on different parameter choices.

The conceptual model of Task 8c, progress and results were presented to Äspö Task Force meeting in Berlin in January, Oskarshamn in April (including a presentation on the numerical solution of the saturation model), and Lund in November in 2012. In addition, a memorandum on the modelling work to the date was prepared in spring 2012.

8.7.6 Task force on engineered barrier systems

During the year 2012 Posiva participated to the following EBS Task Force activities:

- dismantling of the Prototype Repository modelling activities related to the T-H and H behaviour and the progress of the work has been presented in the Montpellier clay conference, and
- modelling of Task 8 (BRIE).

Work within bentonite homogenisation, sensitivity analyses for rock-buffer-canister-system and the chemistry group benchmark cases were continued.

8.7.7 Prototype repository

Posiva participates in the project on the dismantling of the outer section of the Prototype repository during 2012. Posivas main activities are to contribute to the modelling work and laboratory analyses related to behaviour 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 optimisation 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 and Posiva need improved knowledge on plugging and sealing of deposition tunnels in crystalline rock. The stated reference design (which justifies the license applications for the final repositories in Sweden and Finland) needs to be proven to fulfil the requirements and it must be demonstrated that plugs can be implemented on an industrial scale. Both organisations test in a full scale at Äspö HRL (Sweden) and at ONKALO (Finland) the construction and performance of the plug in relation to current design criteria for KBS-3V plugs. Both experiments are partly supported by Euratom and are implemented within DOPAS Project. Posiva has participated to the construction of the full-scale DOMPLU plug experiment performed at Äspö during 2012 by participating to the meetings and collecting the information to be used in joint evaluation of Experiments. Posiva's full scale POPLU plug experiment receives valuable information from the experiences gained in the full-scale demonstration done at Äspö.

8.8 KAERI

Since 2007 KAERI has joined to the Äspö Task Force on Modeling of Groundwater Flow and Transport of Solutes. Although SKB Task 8 was launched at 2010, KAERI have joined it late at 2012. Task 8 consists of subtask 8A, 8B, 8C, 8D and 8E. At 2012, KAERI conducted the Task 8A and a part of 8B as a member of the Äspö Task Force.

8.8.1 Task force on modelling of groundwater flow

The objective of Taks 8A is to enhance understanding on the hydraulic interaction between the bentonite and near-field rock with regard to groundwater ingression and identify the effects of a rock joint on the hydraulic behaviors of bentonite buffer. As for scoping calculation of Task 8, 1D axi-symmetric problem was solved using TOUGH2 code and compared with the simulation results from the Code_Bright model and the analytical solution (Crank 1975, pp 71–81) as follows.

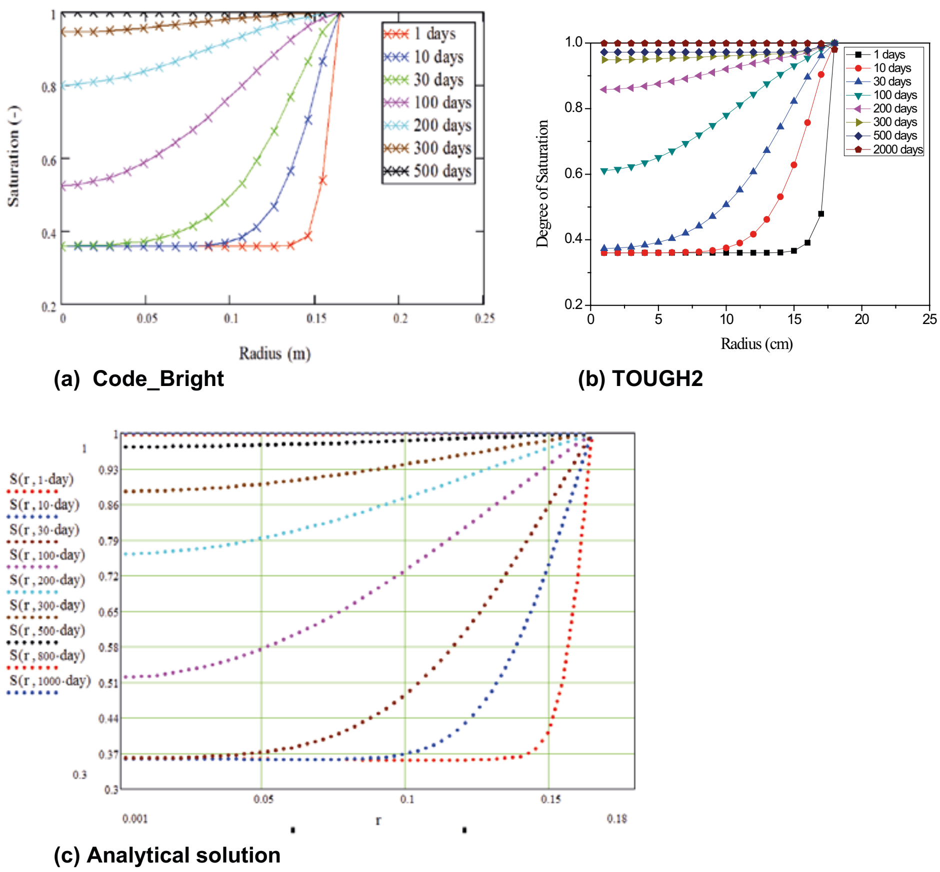


Figure 8-38. Radial distribution of liquid saturation in a 1D axi-symmetry model.

The time required for the full saturation of bentontie buffer is approximately 300 days, which is almost same in all the other cases. In addition, the hydraulic behaviors of bentonite buffer focusing on the interactions between bentonite and a rock mass with a joint were investigated using TOUGH2 code as part of a sub-mission of Task 8a. The effects of a rock joint and high capillary pressure of bentonite on the re-saturation properties and pressure distribution in a buffer were identified and successfully incorporated in the TOUGH2 code.

The variations of pressure generated around a tunnel are presented in Figure 8-39 and Figure 8-40 and the degree of saturation around the bentonite buffer is also shown in Figure 8-41. In case of an intact rock, it takes about 25 years for the full saturation of bentonite. While, in a jointed rock, the full saturation of bentonite requires about 2 years and 10 years at the bentonite position contacted with rock joint and the top position, respectively. Consequently, it was found that the speed of re-saturation in bentonite surrounded by a rock mass with a joint is 2.5 to 12 times faster than that in a condition without a rock joint, while the degree of saturation in the lower part of the buffer material is generally higher than in the upper part in both the cases of with and without a joint.

The KAERI will further simulate to develop more reliable prediction modeling technique focusing on the hydraulic interaction between the bentonite backfill material and near-field host rock. In 2013, Task 8C, and 8D will be studied based on the Task 8A and 8B.

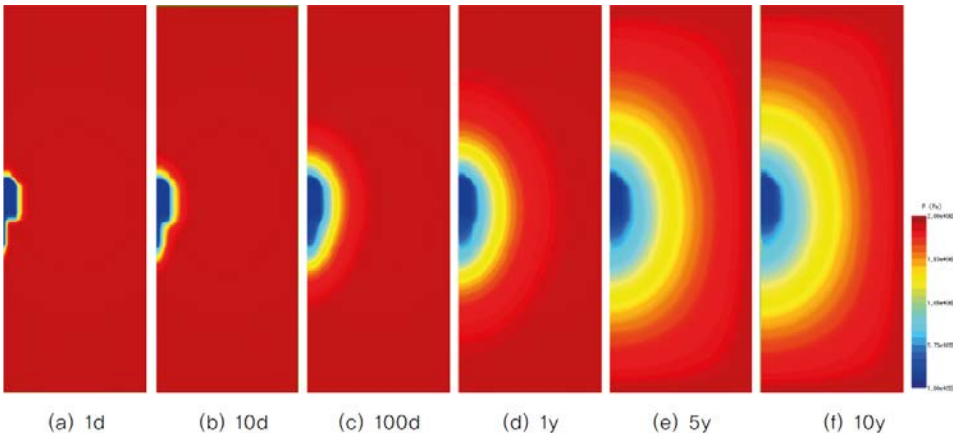


Figure 8-39. *Water pressure distribution around the tunnel with time (intact rock).*

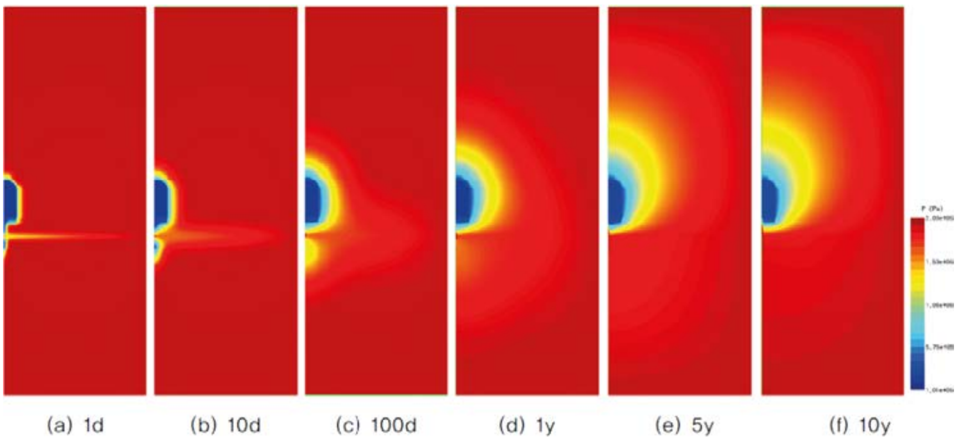


Figure 8-40. *Water pressure distribution around the tunnel with time (jointed rock).*

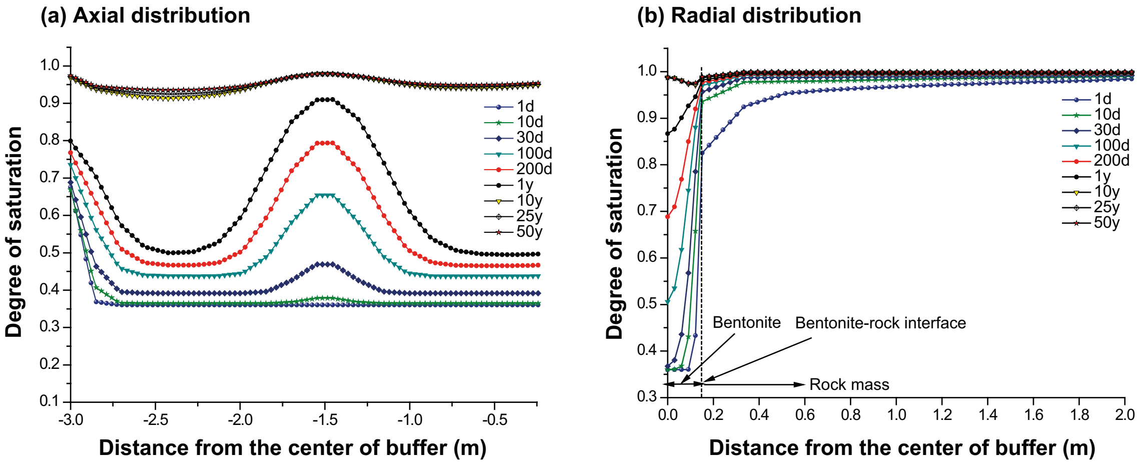


Figure 8-41. *Degree of saturation in the bentonite buffer (at 1.5 m of a bentonite in a jointed rock).*

8.9 Nagra

8.9.1 Task force on engineered barriers systems

Nagra participates actively in both the THM- and the C-Group, of the Task Force. A modeling 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. The status of Nagra's THM-related modeling activities was presented in the context of the Task Force Meetings in Berlin (May 22–24, 2012) and Lund (November 27–29). A final task report was elaborated on the sensitivity analyses, which has been submitted for publication in a peer reviewed journal (Engineering Geology).

8.9.2 Alternative buffer materials

During this year Nagra and co-workers participated at the annual Alternative Buffer Materials (ABM) meeting in Malmö. Different groups are involved in the investigation of the ABM samples and the results were presented during that meeting.

8.9.3 Prototype repository

Nagra joined the annual meeting in Olkiluoto (4–5 June 2012).

8.10 Rawra

The task concentrated on setting erosion rates of bentonite from the Rokle deposit. The chemical composition of compacted bentonite pore water was defined using various types of bentonite, two input values of porosity and two types of groundwater. The ratio of solid and liquid phases was identified as the most affecting parameter. Hydrochemical data acquisition from depth about 500 m was proved to be the major aim for following stages of research. For flow rates 1.12×10–5–2.48×10–4 m/s and aperture of the fracture 0.15–2 mm, the erosion rate was estimated to be 0.4–30.2 $kg/m^2/yr$.

8.10.1 Task Force on engineered barrier systems

TUL team work concentrated on the modelling of water inflow from rock to bentonite, for the BRIE experiment conditions and for the Prototype Repository. They have evaluated 3D models of BRIE boreholes with real positions of the fractures, by means of non-linear diffusion model for water flow based on the retention-curve data. In addition to the defined benchmark problem, they also calculated stress and deformation resulting from bentonite saturation, with contact problem at the bentonite/rock interface (a gap). For the Prototype Repository, they processed the geometry of the fracture network and tunnel/borehole positions and compared with the drawing schemes of the fracture positions at the tunnel walls. This will be a basis for coming simulation of the water inflow.

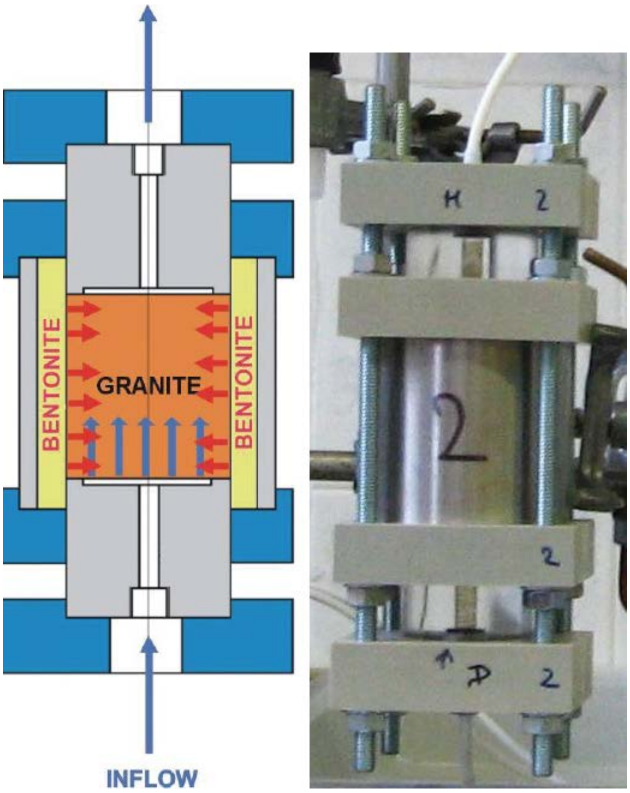


***Figure 8-42.** The measurement equipment.*

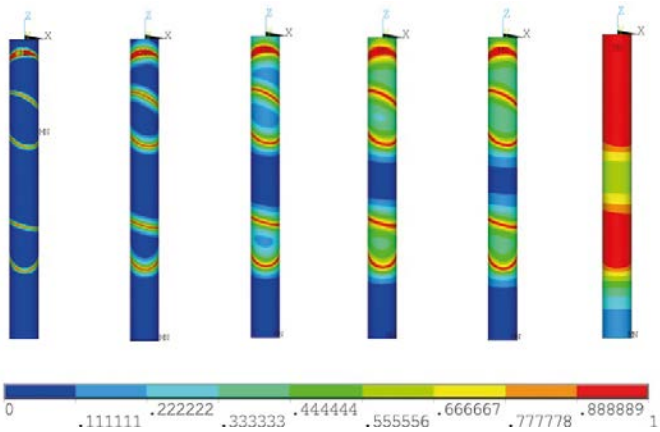


***Figure 8-43.** Distribution of water saturation in the borehole KO0017G01, for a sequence of times.*

8.11 NDA

The Nuclear Decommissioning Authority (NDA) of the United Kingdom has had long standing involvement in experiments conducted at Aspo HRL. In March 2012, NDA signed an agreement with SKB International AB to further increase access to scientific and technical information and results from experiments run by SKB at Aspo HRL. This is designed to support an increase in active NDA involvement and facilitate a research step-change from a predominately laboratory scale R&D programme to one consisting of large-scale demonstration experiments.

NDA is currently a member of the EBS taskforce, LASGIT experiment, and Prototype Repository.

8.11.1 Task force on engineered barrier systems

The Äspö Engineered Barrier System Task Force offers a unique opportunity to develop methodologies, software and modelling approaches to develop understanding of bentonite saturation and coupled, THMC processes. NDA, through its contractor AMEC, is actively involved in this project with emphasis on Task 8, a collaborative research project between the Groundwater Flow and Transport of Solutes (GWTS) Task Force and EBS Task Force, designed to produce:

- a scientific understanding of the exchange of water between the bentonite and sparsely fractured rock,
- improvements to the predictions for the wetting of the buffer, and
- improvements to the characterisation methods of canister boreholes.

Modelling tasks are identified as part of the Task Force to enable the development of understanding of relevant THMC processes. One of these tasks, which consists of modelling the Buffer Rock Interaction Experiment (BRIE), has demonstrated the significant potential of the combination of CONNECTFLOW, TOUGH2 and FLAC software to simulate the swelling of bentonite through 2011/12 EBS Task Force modelling activities. This has principally involved the modelling of the BRIE experiment using four specific fracture parameters (orientation, intensity, size, and transmissivity) and focussed on two aspects, namely:

- 8C1: Predictions of groundwater inflow to a series of five open boreholes in the TASO tunnel.
- 8C2: Predictions of the hydration of unsaturated bentonite subsequently emplaced within these five boreholes.

The modelling of the BRIE experiment has demonstrated the feasibility of simulating the rock bentonite interface using a physically realistic approach. This approach allows the heterogeneity of the fractured rock to be modelled explicitly. This work has revealed significant differences to the homogeneous assumptions commonly made to estimate the resaturation of the bentonite, and has demonstrated that a significantly longer period of time is potentially needed for complete resaturation of the bentonite in fractured rock.

Future modelling tasks will allow a direct comparison between the various software tools used in the Task Force. This is especially important in an area in which there is significant complexity, arising from the THMC couplings. The ability to compare, verify and ultimately validate models of these complex processes is essential. This will allow models for real engineering decisions in the UK to be used with confidence. In addition, the development of understanding of cation and anion diffusion in compacted bentonite will allow more complex applications relevant to EBS performance to be tested appropriately. It is intended that such studies will provide future recommendations on the approach and appropriate level of detail for representation of EBS transport in performance assessment calculations.

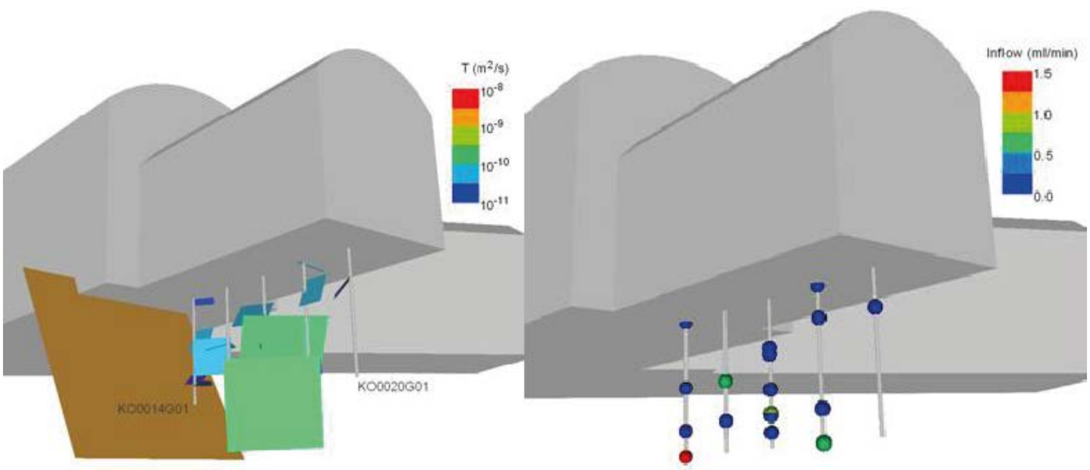


Figure 8-44. *Realisation 2 of the stochastic fracture network illustrating (a) the local fracture tessellates coloured by transmissivity, and (b) inflows to boreholes KO0020G01 through KO0014G01.*

8.11.2 Large scale gas injection test

The British Geological Survey (BGS) was commissioned by NDA as part of the international collaborative Lasgit project, in order to perform a series of diagnostic tests on preserved samples of compact bentonite supplied through SKB by Clay Technology AB.

Each test history comprises a series of component stages designed to elicit or test specific material responses. In test Mx80-A particular emphasis was placed on examining the processes and mechanisms governing initial gas penetration of the clay. Specific objectives are to better understand (i) the minimum pressure gas will become mobile and enter the clay, (ii) how much interstitial water, if any, is displaced as a direct consequence of gas flow either through visco-capillary processes or compression of the surrounding clay matrix and (iii) what is the nature of the observed coupling between gas flow, gas pressure, total stress and porewater pressure, and the impact this has on gas permeability. Test Mx80-A has predominantly focussed on issues (i) and (ii) and this phase of testing remains ongoing.

8.11.3 Prototype repository

NDA are members of the Prototype Repository. Going forward, NDA will look to take a more active role in sample analysis in support of the project team, with particular emphasis on the development of technologies to investigate bentonite behaviour.

9 Literature

9.1 References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

Alonso M C, García Calvo J L, Walker C, Naito M, Pettersson S, Puigdomenech I, Cuñado M A, Vuorio M, Weber H, Ueda H, Fujisaki K, 2012. Development of an accurate pH measurement methodology for the pore fluids of low pH cementitious materials. SKB R-12-02, Svensk Kärnbränslehantering AB.

André M, Neretnieks I, Malmström M E, 2008. Measuring sorption coefficients and BET surface areas on intact drillcore and crushed granite samples. Radiochimica Acta 96, 673–677.

André M, Malmström M E, Neretnieks I, 2009. Specific surface area determinations on intact drillcores and evaluation of extrapolation methods for rock matrix surfaces. Journal of Contaminant Hydrology 110, 1–8.

Barcena I, Garcia-Sineriz J- L, 2001. Äspö Hard Rock Laboratory. Prototype Repository. System for canister displacement tracking. SKB IPR-02-06, Svensk Kärnbränslehantering AB.

Barrett E P, Joyner L G, Halenda P P, 1951. The determination of pore volume and area distributions in porous substances. I. Computations from nitrogen isotherms. Journal of the American Chemical Society 73, 373–380.

Bear J, 1972. Dynamics of fluids in porous media. New York: Elsevier.

Berglund J, Curtis P, Eliasson T, Olsson T, Starzec P, Tullborg E-L, 2003. Äspö Hard Rock Laboratory. Update of the geological model 2002. SKB IPR-03-34, Svensk Kärnbränslehantering AB.

Bodén A, Pettersson S, 2011. Development of rock bolt grout and shotcrete for rock support and corrosion of steel in low-pH cementitious materials. SKB R-11-08, Svensk Kärnbränslehantering AB.

Bond A E, Hoch A R, Jones G D, Tomczyk A J, Wiggin R M, Worraker W J, 1997. Assessment of a spent fuel disposal canister. Assessment studies for a copper canister with cast steel inner component. SKB TR 97-19, Svensk Kärnbränslehantering AB.

Bono N, Röshoff K, 2003. Äspö Hard Rock Laboratory. Prototype Repository. Instrumentation for stress, strain and displacement measurements in rock. SKB IPR-03-19, Svensk Kärnbränslehantering AB.

Byegård J, Cvetkovic V, Drake H, Hakami E, Hjerne C, Nordqvist R, Tullborg E-L, Winberg A, 2012. TRUE-1 completion. Final report. SKB TR-12-11, Svensk Kärnbränslehantering AB.

Börgesson L, Sandén T, 2003. Äspö Hard Rock Laboratory. Prototype Repository. Instrumentation of buffer and backfill in Section II. SKB IPR-03-21, Svensk Kärnbränslehantering AB.

Chijimatsu M, Fujita T, Kobayashi A, Nakano M, 2000. Experiment and validation of numerical simulation of coupled thermal, hydraulic and mechanical behaviour in the engineered buffer materials. International Journal for Numerical and Analytical Methods in Geomechanics 24, 403–424.

Christiansen B C, 2004. Äspö Hard Rock Laboratory. A transformational, structural and natural occurrence study of green rust. SKB IPR-06-24, Svensk Kärnbränslehantering AB.

Collin M, Börgesson L, 2001. Äspö Hard Rock Laboratory. Prototype Repository. Instrumentation of buffer and backfill for measuring THM processes. SKB IPR-02-03, Svensk Kärnbränslehantering AB.

Crank J, 1975. The mathematics of diffusion. 2nd ed. Oxford: Clarendon.

Dershowitz W, Lee G, Josephson N, 2012. FracMan interactive discrete feature data analysis, geometric modeling, and exploration simulation. User documentation version 7. Redmond, WA: Golder Associates Inc.

Destouni G, Jaramillo F, Prieto C, 2013. Hydroclimatic shifts driven by human water use for food and energy production. Nature Climate Change 3, 213–217.

Dideriksen K, Stipp S L S, 2005. Äspö Hard Rock Laboratory. Iron oxides in fractures at Äspö. A feasibility study to test the possibility of finding a geothermometer or a palaeo-redox indicator. SKB IPR-06-09, Svensk Kärnbränslehantering AB.

Dideriksen K, Christiansen B C, Baker J A, Frandsen C, Balic-Zunic T, Tullborg E -L, Mørup S, Stipp S L S, 2007. Fe-oxide fracture fillings as a palæo-redox indicator: Structure, crystal form and Fe isotope composition. Chemical Geology 244, 330–343.

Dideriksen K, Christiansen B C, Frandsen C, Balic-Zunic T, Mørup S, Stipp S L S, 2010. Palaeo-redox boundaries in fractured granite. Geochmica et Cosmochmica Acta 74, 2866–2880.

Dubois I E, 2011. Specific surface area of some minerals commonly found in granite. Lic. thesis. KTH Royal Institute of Technology, Stockholm. (TRITA-IM 2011:32)

Dubois I E, Holgersson S, Allard S, Malmström M E, 2009. Dependency of the particle size on the BET surface area for some minerals composing granitic material. In Proceedings of the 4th Asian Pacific Symposium on RadioChemistry (APSORC '09), Napa, CA, 29 November – 4 December 2009.

Dubois I E, Holgersson S, Allard S, Malmström M E, 2011. Dependency of BET surface area on particle size for some granitic minerals. Proceedings in Radiochemistry 1.75–82.

Eriksson S, 2007. Äspö Hard Rock Laboratory. Prototype Repository. Analysis of micro-organisms, gases and water chemistry in buffer and backfill 2004–2007. SKB IPR-08-01, Svensk Kärnbränslehantering AB.

Farquhar J, Johnston D T, Wing B A, Habicht K S, Canfield D E, Airieau S, Thiemens M H, 2003. Multiple sulphur isotopic interpretations of biosynthetic pathways: implications for biological signatures in the sulphur isotope record. Geobiology 1, 27–36.

Finsterle S, Pruess K, 1995. Solving the estimation-identification problem in two-phase flow modeling. Water Resources Research 31, 913–924.

Goudarzi R, Åkesson M, Nilsson U, 2010. Temperature buffer test. Sensors data report (Period 030326–100301) Report No: 13. SKB P-12-03, Svensk Kärnbränslehantering AB.

Hakami E, Johansson M, Byegård J, Drake H, Tullborg E-L, 2013. Analysis of core material from the TRUE-1 site. Fracture mineralogy, fracture pore volume geometry and Cs sorption. TRUE-1 Completion. SKB P-11-28, Svensk Kärnbränslehantering AB.

Hakami H, 2003. Äspö Hard Rock Laboratory. Update of the rock mechanical model 2002. SKB IPR-03-37, Svensk Kärnbränslehantering AB.

Hallbeck L, 2009. Evaluating hydrochemical data from shallow groundwater in Laxemar from a microbiological perspective. SKB R-09-02, Svensk Kärnbränslehantering AB.

Hallbeck L, Edlund J, Eriksson L, 2012. Microbial analyses of groundwater and surfaces during the retrieval of experiment 3, A04, in MINICAN. SKB P-12-01, Svensk Kärnbränslehantering AB.

Harrström J, Andersson P, 2010. Prototype Repository. Tracer dilution tests during operation phase, test campaign 3. SKB IPR-10-17, Svensk Kärnbränslehantering AB.

Heikkinen E, Kantia P, Lehtimäki T, Silvast M, Wiljanen B, 2010. EDZ assessments in various geological environments using GPR method. Posiva Working Report 2010-04, Posiva Oy, Finland.

Hökmark H, Börgesson L, Hernelind J, 2005. Äspö Hard Rock Laboratory. Temperature buffer test. Scoping design calculations. SKB IPR-05-07, Svensk Kärnbränslehantering AB.

Hökmark H, Ledesma A, Lassabatere T, Fälth B, Börgesson L, Robinet J C, Sellali N, Sémété P, 2007. Modelling heat and moisture transport in the ANDRA/SKB temperature buffer test. Physics and Chemistry of the Earth, Parts A/B/C 32, 753–766.

JAEA, 2012. Report of "The project for assessment methodology development of chemical effects on geological disposal system in H23", METI, Japan, 172–178. (In Japanese.)

Johannesson L-E, 2010. Temperature Buffer Test. Measurements of water content and density of the excavated buffer material. SKB P-12-05, Svensk Kärnbränslehantering AB.

Johannesson L-E, Sandén T, Åkesson M, Bárcena I, García-Siñeriz J L, 2010. Temperature Buffer Test. Installation of buffer, heaters and instruments in the deposition hole. SKB P-12-02, Svensk Kärnbränslehantering AB.

Johnston D T, Farquhar J, Wing B A, Kaufman A J, Canfield D E, Habicht K S, 2005. Multiple sulfur isotope fractionations in biological systems: A case study with sulfate reducers and sulfur disproportionators. American Journal of Science 305, 645–660.

Johnston D T, Farquhar J, Canfield D E, 2007. Sulfur isotope insights into microbial sulfate reduction: when microbes meet models. Geochimica et Cosmochimica Acta 71, 3929–3947.

Kruschwitz S, Yaramanci U, 2004. Detection and characterization of the disturbed rock zone in claystone with the complex resistivity method. Journal of Applied Geophysics 57, 63–79.

Laaksoharju M, Gurban I, 2003. Äspö Hard Rock Laboratory. Update of the hydrogeochemical model 2002. SKB IPR-03-36, Svensk Kärnbränslehantering AB.

Lydmark S, 2010. Äspö Hard Rock Laboratory. Prototype Repository. Analysis of micro-organisms, gases and water chemistry in buffer and backfill, 2009. SKB IPR-10-04, Svensk Kärnbränslehantering AB.

Malm R, 2012. Low-pH concrete plug for sealing the KBS-3V deposition tunnels. SKB R-11-04, Svensk Kärnbränslehantering AB

Mathurin F A, Åström M E, Laaksoharju M, Kalinowski B E, Tullborg E-L, 2012a. Effect of tunnel excavation on source and mixing of groundwater in a coastal granitoidic fracture network. Environmental Science & Technology 46, 12779–12786.

Mathurin F A, Kalinowski B E, Åström M, Laaksoharju M, 2012b. Classification of groundwater from a coastal granitoidic fracture network. Goldschmidt Conference Abstracts 2012. Mineralogical Magazine 75, 2079.

Mattsson H, 2011. 2D and 3D modelling of magnetic and resistivity data from Äspö. SKB P-11-19, Svensk Kärnbränslehantering AB.

Miller I, Lee G, Dershowitz W, 2001. MAFIC, Matrix/fracture interaction code with head and solute transport. User documentation, version 2.0. Redmond, WA: Golder Associates Inc..

Moll H, Merroun M L, Hennig C, Rossberg A, Selenska-Pobell S, Bernhard G, 2006. The interaction of *Desulfovibrio äspöensis* DSM 10631^{T} with plutonium. Radiochimica Acta 94, 815–824.

Neu M P, Icopini G A, Boukhalfa H, 2005. Plutonium speciation affected by environmental bacteria. Radiochimica Acta 93, 705–714.

Nicollin F, Gibert D, Lesparre N, Nussbaum C, 2010. Anisotropy of electrical conductivity of the excavation damaged zone in the Mont Terri Underground Rock Laboratory. Geophysical Journal International 181, 303–320.

Nordqvist R, Byegård J, Hjerne C, 2012. Complementary tracer tests – SWIW, CEC and multi-hole reciprocal cross flow tests at the TRUE-1 site. TRUE-1 Continuation project. TRUE-1 Completion. SKB P-11-27, Svensk Kärnbränslehantering AB.

Ohnuki T, Kozai N, Sakamoto F, Ozaki T, Nankawa T, Suzuki Y, Francis A J, 2010. Association of actinides with microorganisms and clay: implications for radionuclide migration from waste-repository sites. Geomicrobiology Journal 27, 225–230.

Pedersen K, 1997. Microbial life in deep granitic rock. FEMS Microbiology Reviews 20, 399–414.

Posiva, 2012. Description of KBS-3H design variant. Posiva 2012-50, Posiva Oy, Finland.

Puigdomenech I, Sandén T, 2001. Äspö Hard Rock Laboratory. Prototype Repository. Instrumentation for gas and water sampling in buffer and backfill. Tunnel Section I. SKB IPR-01-62, Svensk Kärnbränslehantering AB.

Rhén I, Forsmark T, Magnusson J, Alm P, 2003. Äspö Hard Rock Laboratory. Prototype Repository. Hydrogeological, hydrochemical, hydromechanical and temperature measurements in boreholes during the operation phase of the prototype repository tunnel section II. SKB IPR-03-22, Svensk Kärnbränslehantering AB.

Rosdahl A, Pedersen K, Hallbeck L, Wallin B, 2011. Investigation of sulphide in core drilled boreholes KLX06, KAS03 and KAS09 at Laxemar and Äspö. Chemical-, microbiological- and dissolved gas data from groundwater in four borehole sections. SKB P-10-18, Svensk Kärnbränslehantering AB.

Rothfuchs T, Hartwig L, Komischke M, Miehe R, Wieczorek K, 2003. Äspö Hard Rock Laboratory. Prototype Repository. Instrumentation for resistivity measurements in buffer backfill and rock in Section II. SKB IPR-03-48, Svensk Kärnbränslehantering, AB.

Sato T, Watanabe T, Otsuka R, 1992. Effects of layer charge, charge location, and energy change on expansion properties of dioctahedral smectites. Clays and Clay Minerals 40, 103–113.

Sigurdsson O, Hjerne C, 2012. Overcoring of resin-impregnated boreholes KXTT3 and KXTT4 at the TRUE-1 site. TRUE-1 completion. SKB P-11-21, Svensk Kärnbränslehantering AB.

Silvast M, Wiljanen B, 2008. ONKALO EDZ-measurements using ground penetrating radar (GPR) method. Posiva Working Report 2008-58, Posiva Oy, Finland.

SKB, 2001. Forsknings-, utvecklings- och demonstrationsprogram för ett KBS-3-förvar med horisontell deponering. SKB R-01-55, Svensk Kärnbränslehantering AB.

SKB, 2010a. Design, production and initial state of the backfill and plug in deposition tunnels. SKB TR-10-16, Svensk Kärnbränslehantering AB.

SKB, 2010b. RD&D Programme 2010. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste. SKB TR-10-63, Svensk Kärnbränslehantering AB.

SKB, 2012a. Äspö Hard Rock Laboratory. Annual report 2011. SKB TR-12-03, Svensk Kärnbränslehantering AB.

SKB, 2012b. KBS-3H complementary studies, 2008–2010. SKB TR-12-01, Svensk Kärnbränslehantering AB.

Skovbjerg L L, 2005. Äspö Hard Rock Laboratory. Reduction of hexavalent chromium by green rust sulphate: determination of end product and reduction mechanism. SKB IPR-06-25, Svensk Kärnbränslehantering AB.

Smart N R, Rance A P, 2009. Miniature canister corrosion experiment – results of operations to May 2008. SKB TR-09-20, Svensk Kärnbränslehantering AB.

Smart N R, Rance A P, Fennell P A H, 2006. Expansion due to the anaerobic corrosion of iron. SKB TR-06-41, Svensk Kärnbränslehantering AB.

Smart N, Rance A, Reddy B, Fennell P, Winsley R, 2012a. Analysis of SKB MiniCan. Experiment 3. SKB TR-12-09, Svensk Kärnbränslehantering AB.

Smart N, Reddy B, Rance A, 2012b. Miniature Canister (MiniCan). Corrosion experiment progress report 4 for 2008–2011. SKB P-12-13, Svensk Kärnbränslehantering AB.

Smellie J A T, Waber H N, Frape S K, 2003. Matrix fluid chemistry experiment. Final report. SKB TR-03-18, Svensk Kärnbränslehantering AB.

Svensson D, Dueck A, Olsson S, Sandén T, Lydmark S, Jägevall S, Pedersen K, Hansen S, 2011. Alternative buffer material. Status of the ongoing laboratory investigation of reference materials and test package 1. SKB TR-11-06, Svensk Kärnbränslehantering AB

Tullborg E-L, Larson S Å, 2006. Porosity in crystalline rocks – A matter of scale. Engineering Geology 84, 75–83.

Tulborg E-L, Smellie J, Nilsson A-C, Gimeno M J, Auqué L F, Brüchert V, Molinero J, 2010. SR-Site – sulphide content in the groundwater at Forsmark. SKB TR-10-39, Svensk Kärnbränslehantering AB.

Vidstrand P, 2003. Äspö Hard Rock Laboratory. Update of the hydrogeological model 2002. SKB IPR-03-35, Svensk Kärnbränslehantering AB.

Vogt C, Lagerblad B, Wallin K, Baldy F, Jonasson J-E, 2009. Low pH self compacting concrete for deposition tunnel plugs. SKB R-09-07, Svensk Kärnbränslehantering AB

Waber H N, Smellie J A T, 2008. Characterisation of pore water in crystalline rocks. Applied Geochemistry 23, 1834–1861.

Zerkle A L, Farquhar J, Johnston D T, Cox R P, Canfield DE, 2009. Fractionation of multiple sulfur isotopes during phototrophic oxidation of sulfide and elemental sulfur by a green sulfur bacterium. Geochimica et Cosmochimica Acta 73 (2), 291–306.

Åkesson M (ed), 2006a. Äspö Hard Rock Laboratory. Temperature Buffer Test. Evaluation modeling – Field test. SKB-IPR-06-10, Svensk Kärnbränslehantering AB.

Åkesson M (ed), 2006b. Äspö Hard Rock Laboratory. Temperature Buffer Test. Evaluation modelling – Mock-up test. SKB IPR-06-11, Svensk Kärnbränslehantering AB.

Åkesson M (ed), 2008. Äspö Hard Rock Laboratory. Temperature Buffer Test. Evaluation modeling. TBT_3 Mock-up test. SKB IPR-08-09, Svensk Kärnbränslehantering AB.

Åkesson M, 2010. Temperature Buffer Test. Dismantling operation. SKB P-12-04, Svensk Kärnbränslehantering AB.

Åkesson M, 2012. Temperature Buffer Test. Final report. SKB TR-12-04, Svensk Kärnbränslehantering AB.

Åkesson M, Jacinto A C, Gatabin C, Sanchez M, Ledesma A, 2009. Bentonite THM behaviour at high temperatures: experimental and numerical analysis. Géotechnique 59, 307–318.

Åkesson M, Olsson S, Dueck A, Nilsson U, Karnland O, Kiviranta L, Kumpulainen S, Lindén J, 2012a. Temperature Buffer Test. Hydro-mechanical and chemical/mineralogical characterizations. SKB P-12-06, Svensk Kärnbränslehantering AB.

Åkesson M, Malmberg D, Börgesson L, Hernelind J, Ledesma A, Jacinto A, 2012b. Temperature Buffer Test. Final THM modelling. SKB P-12-07, Svensk Kärnbränslehantering AB.

9.2 List of papers and articles published 2012

Andersson I, Petersson M, Jarsjö J, 2012. Impact of the European Water Framework Directive on local-level water management: case study Oxunda Catchment, Sweden. Land Use Policy 29, 73–82.

Balfor B, Hammer M, Mörtberg U, Larsson M, Quin A, 2012. The role of strategic environmental assessment in the implementation of the Water Framework Directive: example from Sweden. 2nd International Association for Hydro-Environment Enegineering and Research Europe Conference, Munich, 27–29 June 2012.

Berger T, Peltola P, Drake H, Åström M, 2012. Impact of a fluorine-rich granite intrusion on levels and distribution of fluoride in a small boreal catchment. Aquatic Geochemistry 18, 77–94.

Cvetkovic V, 2012. A general memory function for modeling mass transfer in groundwater transport. Water Resources Research 48, W04528. doi:10.1029/2011WR011657

Cvetkovic V, Frampton A, 2012. Solute transport and retention in three-dimensional fracture networks. Water Resources Research 48, W02509. doi:10.1029/2011WR011086

Cvetkovic V, Carstens C, Selroos J-O, Destouni G, 2012. Water and solute transport along hydrological pathways. Water Resources Research 48, W06537. doi:10.1029/2011WR011367

Dohrmann R, Genske D, Karnland O, Kaufhold S, Kiviranta L, Olsson S, Plötze M, Sandén T, Sellin P, Svensson D, Valter M, 2012a. Interlaboratory CEC and exchangeable cation study of bentonite buffer materials: I. Cu(II)-triethylenetetramine method. Clays and Clay Minerals 60, 162–175.

Dohrmann R, Genske D, Karnland O, Kaufhold S, Kiviranta L, Olsson S, Plötze M, Sandén T, Sellin P, Svensson D, Valter M, 2012b. Interlaboratory CEC and exchangeable cation study of bentonite buffer materials: II. Alternative methods. Clays and Clay Minerals 60, 176–185.

Drake H, Tullborg E-L, Hogmalm K J, Åström M E, 2012. Trace metal distribution and isotope variations in low-temperature calcite and groundwater in granitoid fractures down to 1 km depth. Geochimica et Cosmochimica Acta 84, 217–238.

Gren I-M, Destouni G, 2012. Does divergence of nutrient load measurements matter for successful mitigation of marine eutrophication? Ambio 41, 151–160.

Hallbeck L, Pedersen K, 2012. Culture-dependent comparison of microbial diversity in deep granitic groundwater from two sites considered for a Swedish final repository of spent nuclear fuel. FEMS Microbioly Ecology 81, 66–77.

Holton D, Baxter S, Hoch A R, 2012. Modelling coupled processes in bentonite: recent results from the UK's contribution to the Äspö EBS Task Force. Mineralogical Magazine 76, 3033–3043.

Jarsjö J, Asokan S M, Prieto C, Bring A, Destouni G. 2012. Hydrological responses to climate change conditioned by historic alterations of land-use and water-use. Hydrology and Earth System Sciences 16, 1335–1347.

Kim J-S, Cho W-J, Lee K-S, Choi H-J, Cho G-C, 2012. Numerical simulation for variations of water saturation in bentonite buffer under the effect of a rock joint using the TOUGH2 code. Journal of Korean Tunnelling and Underground Space Association 14, 575–593. (in Korean.)

Koussis A D, Mazi K, Destouni G, 2012. Analytical single-potential, sharp-interface solutions for regional seawater intrusion in sloping unconfined coastal aquifers, with pumping and recharge. Journal of Hydrology 416–417, 1–11.

Lütke L, Moll H, Bernhard G, 2012. Insights on the uranium(VI) speciation with *Pseudomonas fluorescens* on a molecular level. Dalton Transactions 41, 13370–13378.

Novak J, 2012. The Prototype Repository test: thermal model verification. In Topping B H V (ed). Proceedings of the Eighth International Conference on Engineering Computational Technology. Stirlingshire, UK: Civil-Comp Press, Paper 105. doi:10.4203/ccp.100.105

Rautioaho E, Kristensson O, Koskinen K, 2012. Modeling the Prototype Repository project. Sensitivity analysis of thermo-hydraulic behavior. Abstract in Clays in Natural and Engineered Barriers for radioactive Waste Confinement. GM/NM/17. Montpellier, 22–26 October 2012.

Škarydová I, Hokr M, 2012. Local inflow to bentonite - solution with simple diffusion/swelling model. Poster at the Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Book of Abstracts, 692–693.

Törnqvist R, Jarsjö J, 2012. Water savings through improved irrigation techniques: basin-scale quantification in semi-arid environments. Water Resources Management 26, 949–962.

Åström M E, Österholm P, Gustafsson J P, Nystrand M, Peltola P, Nordmyr L, Boman A, 2012. Attenuation of rare earth elements in a boreal estuary. Geochimica et Cosmochimica Acta 96, 105–119.