Technical Report
TR-15-10
October 2015

Äspö Hard Rock Laboratory
Annual Report 2014

SVENSK KÄRNBRÄNSLEHANTERING AB

SWEDISH NUCLEAR FUEL
AND WASTE MANAGEMENT CO

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

SVENSK KÄRNBRÄNSLEHANTERING

ISSN 1404-0344
SKB TR-15-10
ID 1466418
October 2015

Äspö Hard Rock Laboratory

Annual Report 2014

Svensk Kärnbränslehantering AB

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 main access 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 2014 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. Studies are performed in both laboratory and field experiments, as well as by modelling work. The activities aim to provide basic geoscientific data to the experiments and to ensure high quality of experiments and measurements related to geosciences.

The project *Rock Characterisation System* (RoCS II) is concentrated on finding or constructing a new system for geological underground mapping. Photogrammetry based on digital photography and/or laser scanning are parts of that system. The software in the system was used for the first time as a professional mapping tool in the project "Expansion of Äspö HRL 2011–2012".

The aim of project *DETUM-1 Large Fractures experiment* experiment is to further develop strategies and integrated investigation and modelling methodology for the identification and characterization of geological structures. The Large fractures experiment investigations include geological mapping, hydraulic testing and geophysical investigations using boreholes and tunnels.

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.

The aim of the *Integrated Sulphide* project is to collect all studies and investigations undertaken by Posiva and SKB to gain knowledge and collect data on processes that may affect either the concentration of sulphide or the sulphide production rates. The project covers both the geosphere and the buffer-backfill systems. Also overall modelling of sulphide both in the near field and in the geosphere are included in the project.

Important goals of the activities at Äspö HRL are the evaluation of the usefulness and reliability of different models and the development and testing of methods to determine parameter values required as input to the models. An important part of this work is performed in the *Task Force on Modelling of Groundwater Flow and Transport of Solutes*. During 2014, the modelling work within Task 7 was completed, and the focus has been on reporting, and optional publishing. The Task 8 work mainly contained modelling of BRIE with different levels of detailed data.

The *BRIE* project is subdivided into two main parts: Part I describing the selection and characterisation of a test site and two central boreholes and Part II handling the installation and extraction of

the bentonite buffer. *BRIE* has couplings to Task 8 of the *Task Force on Modelling of Groundwater Flow and Transport of Solutes* 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.

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 was finalised during 2013. The reporting of the retrieval of the outer section started during 2013 and was finalized at the beginning of 2014. The monitoring of the inner section will be continued at least until 2020.

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 was retrieved in April 2013. The time of retrieval for parcel #3 is not decided. 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.

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 KBS-3H and KBS-3V (reference concept for both SKB and Posiva), 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. Two main activities 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 MPT was installed during the end of 2013 and has been monitored during 2014. Sensor data indicate that the buffer is starting to saturate, but still being in an early stage of development.

The aim of the *Large Scale Gas Injection Test* (Lasgit) 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. During 2014 (day 3,255 – day 3,620) the test programme of Lasgit concentrated on the characterisation of the bentonite buffer and the study of homogenisation.

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. The main acitivity for 2012 was the report on the analysis of the retrieved miniature canister #3. In that report specimens for evaluation of stress corrosion cracking (SCC) of copper were examined by optical microscopy. During 2013 these specimens were examined further using scanning electron microscopy (SEM) and energy dispersive x-ray analysis (EDX). Neither optical, nor SEM/EDX analysis revealed any signs of SCC in the copper samples. Further metallographic examination has been made during 2014 and will be published during 2015.

In the project *Concrete and Clay* the aim of the project is to increase our understanding of the processes related to degradation of low and intermediate level waste in a concrete matrix, the degradation of the concrete itself through reactions with the groundwater and the interactions between the concrete/groundwater and adjacent materials such as bentonite and the surrounding host rock. During the time period 2010–2014 a total of 9 packages comprising concrete cylinders or bentonite blocks each containing different types of waste form materials will be deposited at different locations in the Äspö HRL. The four concrete specimens were prepared and deposited during 2010 and 2011. During 2014 the bentonite specimens comprising 150 bentonite blocks in 5 different packages have been prepared and installed in TAS06. In each bentonite block (Ø 270 mm and height 100 mm) 4 different material specimens have been placed.

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. During 2013, three rock bolts, two horizontally and one vertically emplaced, have been over-cored and investigated. The investigation covered both the condition of the low-pH concrete and the corrosion behaviour of the bolts after almost five years of in situ exposure. Six concrete blocks containing three steel bars each, were also investigated during 2013 following the corrosion experiment. The results of these investigations have been published during 2014.

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. The Task Force is divided into two groups, one dealing with the original THM issues and one group concentrating on geochemical issues. Two Task Force meetings have been held during 2014; one in Tokyo on May 20–22 and one in Berkely on November 9–12. The latter meeting was a joint meeting with the *Task Force on modelling of groundwater flow and transport of solutes*.

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 and with reasonable efficiency. The main achievement during 2014 has been the performance of a full scale backfill installation test with prototype equipment underground at Äspö HRL, testing the designed system in full scale.

The project *System Design of Dome Plug for Deposition Tunnels* aims to ensure that the reference design 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 experiment tunnel (TAS01) was excavated and the accurate plug location was determined. The installation of the inner parts of the plug began in late 2012 and was completed in the beginning of 2013. On March 13th 2013, the casting of the concrete dome took place. The monitoring of the Domplu experiment started in September 2013 (month 0) when the bentonite seal had been artificially wetted by flooding of the filter during the summer. The experiment will be under continued observation until 2016. 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.

Several projects are ongoing with focus on *System design of buffer*. During 2014 the activities at Äspö HRL for buffer design for KBS3-V concerned controlled atmosphere as an alternative buffer protection system. Several activities performed in 2013 have also been reported during 2014.

The project *Tunnel Production* is a technology development project with aim to establish methods and concepts for excavation of deposition tunnels in the planned Final Repository for Spent Nuclear Fuel. This includes rock excavation methods, grouting and concepts for rock reinforcement. In total five rectangular slots was excavated in the floor and wall of the two new experimental tunnels TASN and TAS04 during November 2014. The slots were located through control of charging data, visible blasting half pipes in the contour and GPR-reflectors. Mapping was conducted in two steps in which both blast induced and geological fractures were documented.

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 for Spent Nuclear Fuel. 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, including the Deposition Machine, equipment for backfilling and equipment for buffer emplacement. A Mission Control System and a Transport system for buffer and backfill materials are also developed.

Äspö facility

The Äspö facility comprises both the Äspö Hard Rock Laboratory and the Bentonite Laboratory. The main goal for the operation of the Äspö facility is to provide a facility which is safe for everybody working in, or visiting it, and for the environment. This includes preventative and remedial maintenance in order to ensure that all systems such as drainage, electrical power, ventilation, alarm and communications are available in the underground laboratory at all times.

In *the Bentonite Laboratory* different methods and techniques for installation of pellets and blocks in deposition tunnels are tested, and work on buffer and backfill is performed. During 2014, approximately 50 tonnes of bentonite was mixed, most of it used by the projects *Alternative Buffer Protections* and *Concrete & Clay*. During 2014 a press for extruded pellets was bought, which will during 2015 produce pellets for several experiments at Äspö HRL.

As a part of the needed infrastructure, a *Material science laboratory* has been constructed at Äspö, with focus on material chemistry of bentonite issues and competence development. The key focus areas are long term safety related research and development of methods for quality control of the bentonite buffer and backfill materials.

The operation of the facility during 2014 has been functioning very well, with a very high degree of availability. During 2014 a new fire alarm system was installed both above ground and in the Äspö tunnel. The tunnel has also been scanned during 2014 to provide a three-dimensional documentation of the tunnel geometries.

The main goal for the unit *Communication Oskarshamn* is to create public acceptance for SKB, which is done in co-operation with other departments at SKB. During 2014, 4,943 people visited the Äspö HRL and with the visitors at Clab and the Canister Laboratory included it resulted in a total of 7,379 people. The total number of visitors to SKB's facilities in both Oskarshamn and Forsmark was 10,086 people. The unit also arranged a number of events and lectures during 2014.

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 2014 nine organisations from seven countries in addition to SKB participated in the cooperation at Äspö HRL. Three of them; BMWi, RWM and NUMO formed together with SKB 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:

a) modelling of Groundwater Flow and Transport of Solutes, which is a forum for cooperation in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock, and

b) THMC modelling of Engineered Barrier Systems, which is a forum for code development on THMC processes taking place in a bentonite buffer and gas migration through a buffer.

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

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 2014.

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.

Projektet *Rock Characterisation System* (RoCS II) syftar till att finna eller konstruera ett nytt system för geologisk kartering under jord. Fotogrammetri baserad på digitalt fotografi och/eller laserscanning ingår som del i detta system. Systemets programvara, som SKB låtit utveckla, användes för första gången som ett professionellt karteringsverktyg i projektet Utbyggnad av Äspölaboratoriet 2011–2012.

I projektet *DETUM-1* genomförs experiment inom *Stora Sprickor* för att vidareutveckla strategier och integrera metoder för undersökning och modellering för indentifiering och karakterisering av geologiska strukturer. Large fractures-experimentundersökningarna inkluderar geologisk kartläggning, hydraulisk testning och geofysiska undersökningar i borrhål och tunnlar.

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.

Målet med det *Intergrerade Sulfidprojektet* är att samla alla studier och undersökningar som genomförs av Posiva och SKB för att öka kunskaper och insamla data för processer som kan påverka sulfidkoncentration eller sulfidproduktionshastighet. Projektet täcker både geosfär och buffer backfill-system. Även övergripande modellering av sulfid både i närfält och geosfären är inkluderade i projektet.

Aktiviteterna vid Äspölaboratoriet omfattar projekt med syfte att utvärdera användbarhet och tillförlitlighet hos olika beräkningsmodeller. I arbetet ingår även att utveckla och prova metoder för att bestämma parametervärden som krävs som indata till modellerna. En viktig del av detta arbete genomförs i ett internationellt samarbetsprojekt ”*Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes*”. Under 2014 har modelleringsarbetet inom Task 7 slutförts, och fokus har legat vid rapportering och publicering. Arbetet med Task 8 har mest inneburit modellering av *BRIE* med data i olika detaljnivå.

BRIE-projektet är indelat i två huvudaktiviteter: Del 1 beskriver val och karakterisering av experimentplats och Del 2 omfattar installation och brytning av bentonitprover. *BRIE* 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 KBS-3-systemets funktion. 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 KBS-3-systemet 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. Den yttre sektionen bröts och kapslarna återtogs under 2011. Laboratoriestudier av tagna prover inleddes 2011 och avslutades 2013. Rapporteringen av återtaget av den yttre sektionen inleddes under 2013 och färdigställdes i början av 2014. Moniteringen av den inre sektionen kommer fortsätta till minst år 2020.

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 togs upp i april 2013. Tidpunkten för upptag av paket #3 är ännu inte fastställd. Tre nya testpaket installerades i november 2012. Tre nya lertyper inkluderades; Asha NW BFL-L, Saponite och en kinesisk bentonit – GMZ. Friedland, Callovo Oxfordian och specialburar med korn av MX-80 togs bort. Alla tre paket har artificiell bevätning.

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. Fasen täcker samtliga delar av KBS-3 metoden men fokuserar på KBS-3H specifika frågor. Två större aktiviteter initierades under 2011; ett systemtest (Multi Purpose Test, som även är del i EU-projektet LucoeX, vars finansiering stöds från Euratoms Seventh Framework Programme FP7/2007–2013) och konstruktion och förberedelser av en ny KBS-3H drift på –410 m nivå. Systemtestet installerades under 2013 och har övervakats under 2014. Sensordata indikerar att bufferten har börjat vattenmättas, men är fortfarande i en tidig utvecklingsfas.

Syftet med ett *Gasinjekteringsförsök i stor skala* (Lasgit) är att studera gastransport i ett fullstort deponeringshål (KBS-3). Installationsfasen med deponering av kapsel och buffert avslutades under 2005. Vatten tillförs bufferten på artificiell väg och utvecklingen av vattenmättnadsgraden i bufferten mäts kontinuerligt. Under 2008 avslutades de preliminära hydrauliska testerna och gasinjekteringstesterna. Under 2014 fokuserade testprogrammet på karakteriseringen av bentonitbuffert och homogeniseringsstudier.

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 från 2012 var en rapport på analysen av experiment tre, och under 2013 analyserades proverna vidare med flera olika metoder. Ytterligare metallografiska undersökningar har genomförts under 2014, och kommer att publiceras under 2015.

I *"Betong- och lerprojektet"* är syftet att öka förståelsen för processer i samband med nedbrytning av låg- och medelaktivt avfall i en betongmatris, nedbrytning av betongen självt genom reaktioner med grundvattnet och växelverkan mellan betong, mark och angränsande material som bentonit och den omgivande berggrunden. Fyra betong prover installerades under 2010 och 2011. Under 2014 har fem bentonitprover bestående av 150 bentonitblock fördelade i 5 paket, förberetts och installerats i TAS06.

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. Under 2013 har tre bergbultar, två horisontellt placerade och en vertikalt placerad, överborrats och undersökts. Undersökningen omfattade både låg pH-betongen och bultarnas korrosionsbeteende efter nästan fem års exponering i fält. Sex stycken betongblock innehållande tre stålstänger vardera har också undersökts under 2013. Resultaten från dessa undersökningar har publicerats under 2014.

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-grupp som behandlar geokemiska processer i ingenjörsbarriärer. Två Task Force-möten har ägt rum under 2014; ett i Tokyo under 20–22 maj och ett i Berkley under 9–12 november. Det senare var ett gemensamt möte med *Task Force on Modelling of Groundwater Flow and Transport of Solutes.*

Huvudmålet med projektet *Systemdesign av Återfyllnad för Deponeringstunnlar* är att säkerställa att vald metod för återfyllnad fungerar med önskad effektivitet. Huvudaktiviteten under 2014 har varit genomförandet av ett försök med backfillinstallation med prototyputrustning i full skala, i Äspötunneln.

Projektet *Systemdesign av Valvplugg för Deponeringstunnlar* syftar till att säkerställa att referensutformningen av KBS-3V deponeringstunnel och plugg fungerar som tänkt. Genom att testa designen i fullskala ska det visas att metoden för pluggning av en deponeringstunnel är genomförbar och kontrollerbar. Under 2012 producerades tunnelplats för test och lämpligt plugg-läge fastställdes. Installationen av pluggens inre delar påbörjades i slutet av 2012 och stod färdig i början av 2013. Gjutningen av betongkupolen genomfördes den 13 mars 2013. Efter att betongtätningen hade bevätts artificiellt under sommaren inleddes övervakningsfasen av testet som fortsätter till 2016. Testet är del i EU-projektet DOPAS, som erhållit finansiering från Euratoms Seventh Framework Programme FP7/2007–2013.

Flera projekt pågår med fokus på *Systemkonstruktion av buffert*. Under 2014 har aktiviteterna vid Äspö kretsat kring tester av kontrollerad atmosfär som system för buffertskydd. Flera aktiviteter utförda under 2013 har också rapporterats under 2014.

Projektet *Tunnelproduktion* är ett teknikutvecklingsprojekt med syfte att etablera metoder och koncept för tunnelproduktion för deponeringstunlar i det planerade slutförvaret. Detta inkluderar metoder för berguttag, injektering och koncept för bergförstärkning. Under november 2014 sågades totalt 5 rektangulära slitsar ut i golv och väggar i de två nya experimenttunnlarna TASN och TAS04. Kartläggning genomfördes i två steg, i vilka både spränginducerade- och geologiska sprickor dokumenterades.

Maskin- 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 system, 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 maskin- och systemteknik pågår, bland annat deponeringsmaskin för vertikal deponering av kapsel, utrustning för återfyllnad och utrustning för buffertplacering. Ett Mission Control System och ett Transportsystem för buffert och återfyllnadsmaterial utvecklas även.

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. Huvudmålet för driften av Äspöanläggningen är att garantera säkerheten för alla som arbetar i eller besöker anläggningen samt att driva anläggningen på ett miljömässigt korrekt sätt. Detta inkluderar förebyggande och avhjälpande underhåll för att se till att alla system som dränering , elkraft , ventilation , larm och kommunikation alltid fungerar.

I *Bentonitlaboratoriet* provas olika metoder och tekniker för installation av pelletar och block i deponeringstunnlar och studier av erosion av buffert och återfyllningsmaterial utförs. Under 2014 har ca 50 ton bentonit blandats i Bentonitlaboratoriet, det mesta för användning i projekten *Alternative Buffer Protections* och *Concrete & Clay*. Under 2014 köptes även en press för tillverkning av extruderade bentonitpelletar, vilken under 2015 kommer att producera pelletar till flera försök på Äspö.

Under året har ett nytt *Laboratorium för Materialstudier* byggts och tagits i bruk på Äspö, med fokus på materialkemi för bentonitfrågor och kompetensutveckling. De största fokusområdena är metodutveckling för kvalitetskontroll av bentonit som ska användas som buffert och fyllnadsmaterial.

Driften av anläggningen under 2014 har fungerat mycket bra med en mycket hög tillgänglighet. Under 2014 har ett nytt brandlarm installerats ovan och under jord på Äspö. Äspötunneln har scannats för att skapa en tredimensionell dokumentation av underjordsanläggningen.

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 2014 besöktes Äspölaboratoriet av 4 943 personer. Enheten arrangerade ett flertal evenemang och seminarier under året.

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 nio organisationer från sju länder deltagit i det internationella samarbetet vid Äspölaboratoriet under 2013. Tre av dem; BMWi, RWM och NUMO utgör tillsammans med SKB "Äspö International Joint Committee" vilken ansvarar för att koordinera det experimentella arbetet som uppkommer från det internationella deltagandet. Flera av de deltagande organisationerna medverkar i de två Äspö Task Force-grupperna.

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 for Spent Nuclear Fuel 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 main access 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.

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

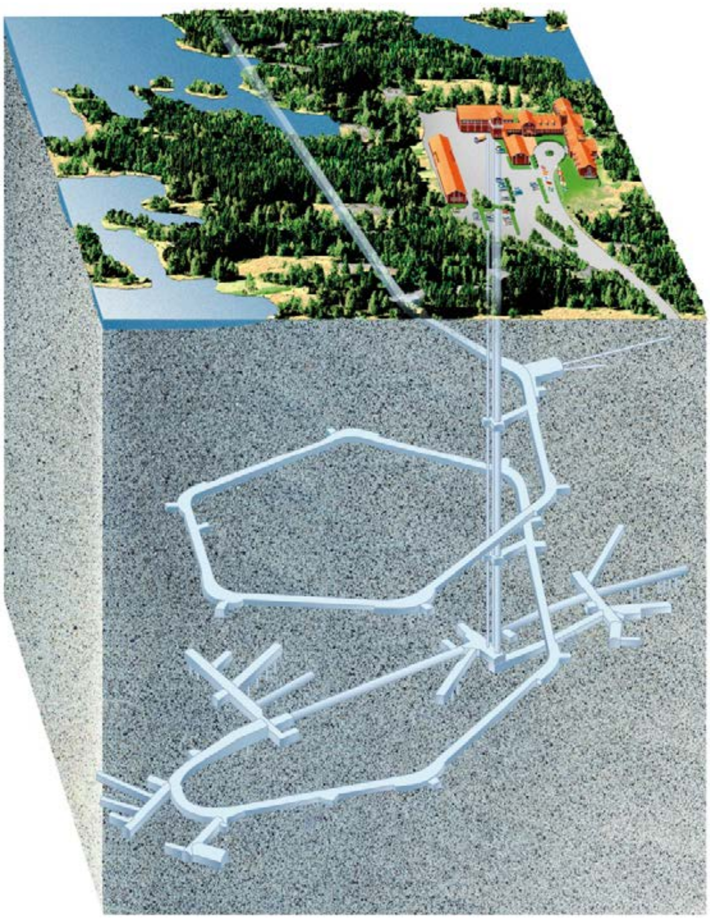


Figure 1-1. Overview of the Äspö HRL facilities, including the new areas produced in the tunnel expansion, and the Simpevarp peninsula.

During the Pre-Investigation phase, 1986–1990, extensive field studies were made to provide a basis 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 2014–2019 is described in SKB's RD&D-Programme 2013 (SKB 2013).

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 for Spent Nuclear Fuel 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 finalised, 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 for Spent Nuclear Fuel'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. Studies on buffer and backfill materials are performed at the laboratory to complement the studies performed in the underground research laboratory.

As a part of the needed infrastructure, a Material science laboratory was constructed at Äspö during 2013, with focus on material chemistry of bentonite issues and competence development. The key focus areas are long term safety related research and development of methods for quality control of the bentonite buffer and backfill materials.

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 unit's development activities.

1.3 Organisation

The research, technical development and safety assessment work is organised into the Technology department, in order to facilitate co-ordination between the different activities. The Technology department comprises 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 and Safety Assessment 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 unit in Oskarshamn.

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 for Spent Nuclear Fuel 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 for Spent Nuclear Fuel.
- *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 Characterisation 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 2014 nine organisations from seven countries in addition to SKB participated in the cooperation at Äspö HRL. Three of them; BMWi, RWM and NUMO formed together with SKB 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:

a) Modelling of Groundwater Flow and Transport of Solutes, which is a forum for cooperation in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock and

b) THMC modelling of Engineered Barrier Systems, which is a forum for code development on THMC processes taking place in a bentonite buffer and gas migration through a buffer.

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

For more information on the international participation in Äspö HRL, see Chapter 8.

1.5 Allocation of experiment sites

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

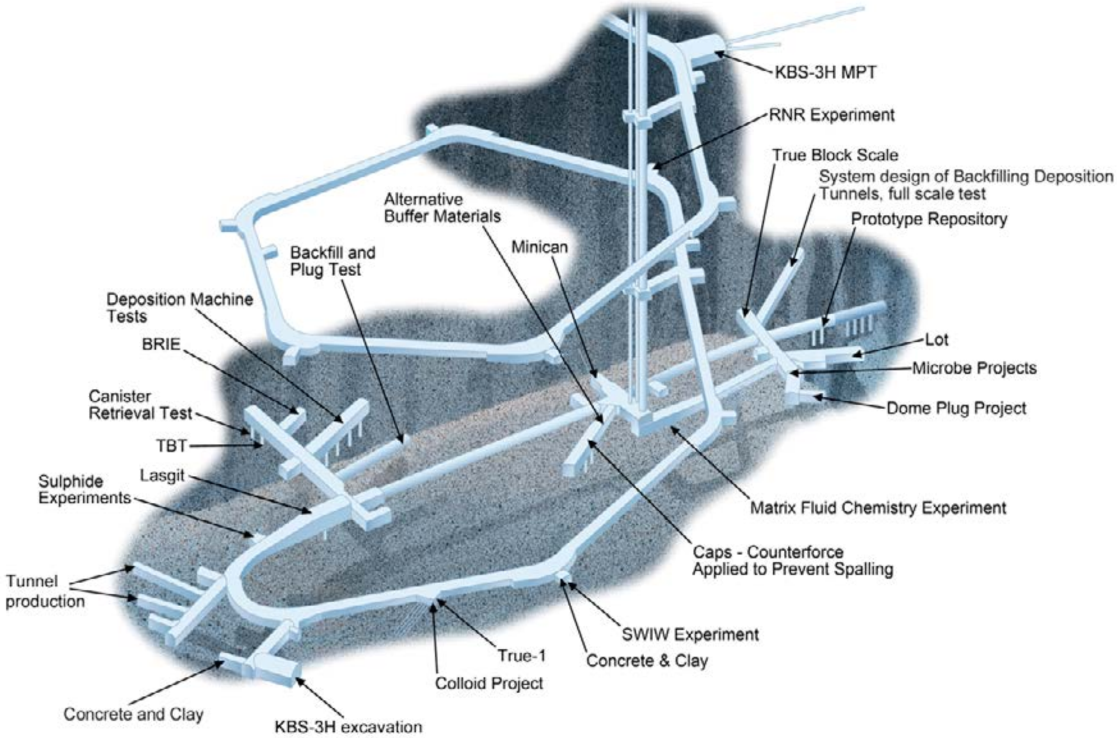


Figure 1-2. Allocation of experiment sites from –220 m to –460 m level.

1.6 Reporting

Äspö HRL is an important part of SKB's RD&D Programme. The plans for research and development of technique during the period 2014–2019 are presented in SKB's RD&D-Programme 2013 (SKB 2013). 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 2014.

Project information is published in SKB's report series' (TR-, R- and 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 (SDTD-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 2014 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 which were stipulated early in connection to construction of the Äspö HRL;

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.

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 for Spent Nuclear Fuel 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 methods for investigations of rockmass properties.

2.2 Geology

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

2.2.1 Geological mapping and modelling

Background

All new rock surfaces which are exposed after tunnel excavation and all drill cores which are collected are characterised at Äspö HRL. This is done in order to increase the understanding of the geometries and properties of rocks and structures, which is subsequently used for up-dating of the 3D model.

Objectives

During and after every tunnel has been excavated mapping of the tunnel surfaces will be performed with e.g. RoCS-mapping. As well major structures, such as Full Perimeter Intersections (FPI's), and wet areas/structures will be documented (Figure 2-1).

Experimental concept

Through different experiments and projects undertaken in the tunnel, additional data is collected and understanding is gained for the local experimental volume. As such this local knowledge constitutes a building block for integration in the larger scale site descriptive volume. With new experiments new local models are providing input to the gradual updating and refining of the site descriptive model.

The inclusion of data collected from various experiments and the adoption of the modelling procedures developed during the Site Investigations at Oskarshamn and Östhammar are implemented. The intention is to develop the site descriptive model (SDM) into a dynamic working tool suitable with short turn over times for predictions in support of the experiments in the laboratory as well as to test the geological, hydrogeological and hydrochemical models in order to improve the conceptual understanding of the disciplines (Figure 2-2).

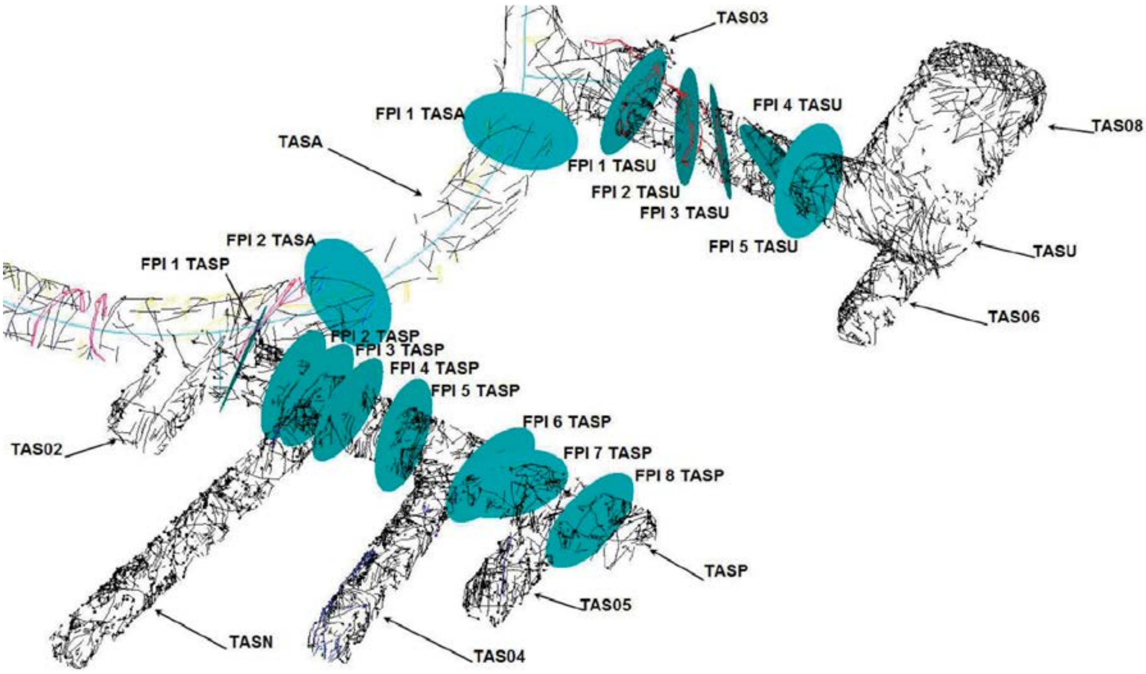


Figure 2-1. *Mapped fracures with RoCS supplemented by mapping of Full Perimeter Intersections (FPI's).*

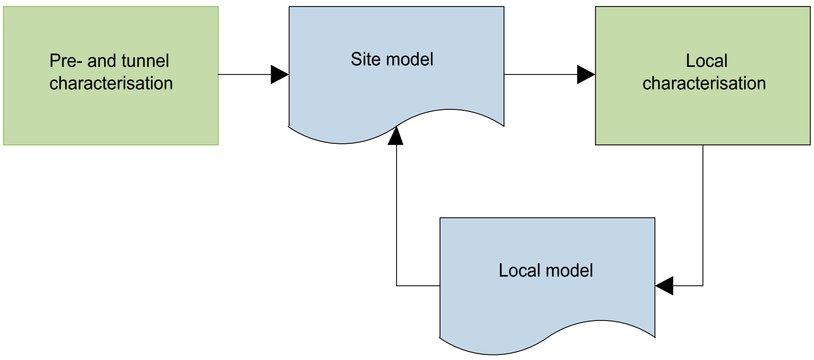


Figure 2-2. *Evolution of local- and site descriptive model.*

2.2.2 RoCS – II – method development of a new technique for underground surveying

Background

The 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 for the construction of a Final Repository for Spent Nuclear Fuel. The system developed by SKB rely on digital data collection and digital photos which is included in this system. The software in the system, developed by SKB, was used for the first time in the project "Expansion of Äspö HRL 2011–2012".

Experimental concept

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 for Spent Nuclear Fuel.

Results

The RoCS system was implemented in the Äspö HRL Expansion Project. For each round (drilling, blasting and hauling) digital fotogrammetry and digital photos were taken to make it possible to create a 3D-model of the newly excavated section.

The geological mapping of walls and roof took place after a tunnel/drift had been completed (Figures 2-3 and 2-4). Mapping data was delivered to the Sicada database after each mapping session.

Using the RoCS-system in the Äspö HRL Expansion Project gave the opportunity to make test under industrial conditions. RoCS have resently been applied on the platform Windows 7. Suggestions for improvements of the mapping system were given to the RoCS.

The advantage is that data can be used for e.g. modelling purposes almost immediately, as soon as the data have been checked and approved (Figure 2-3).

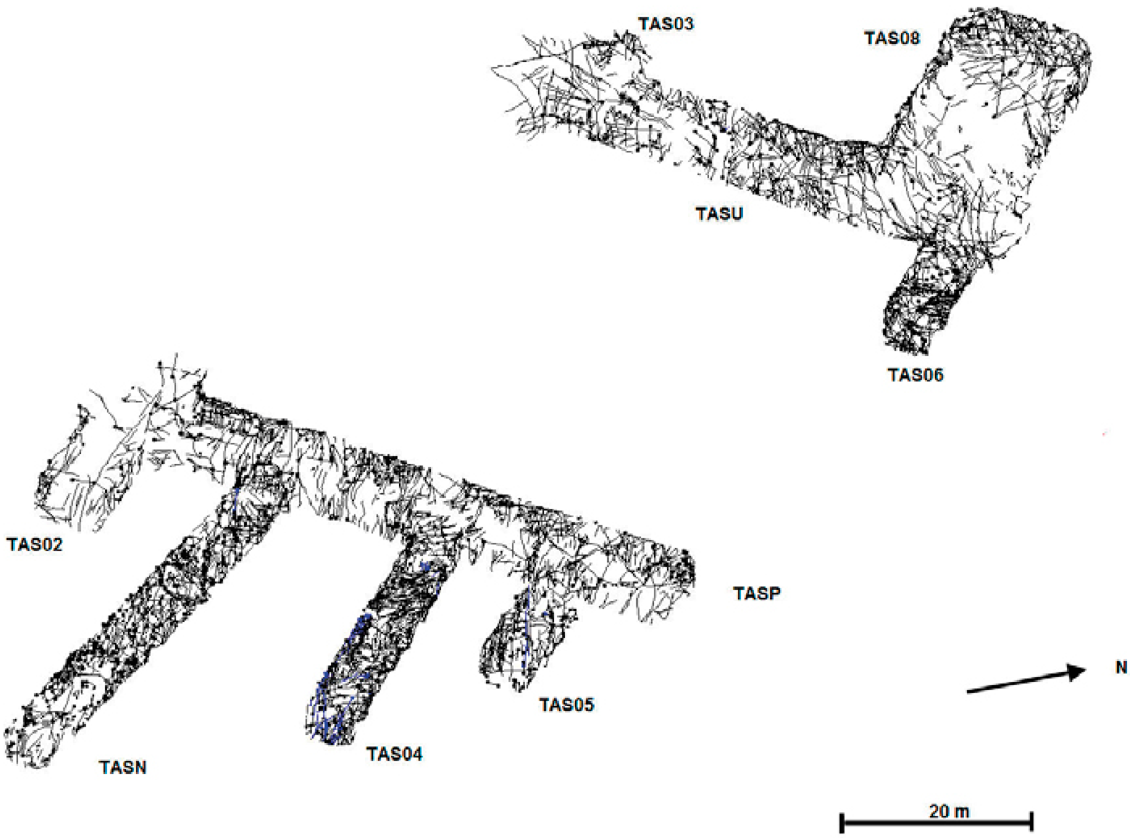


Figure 2-3. *Mapped and then RVS-modelled fractures in the tunnels of the expansion of Äspö HRL project.*

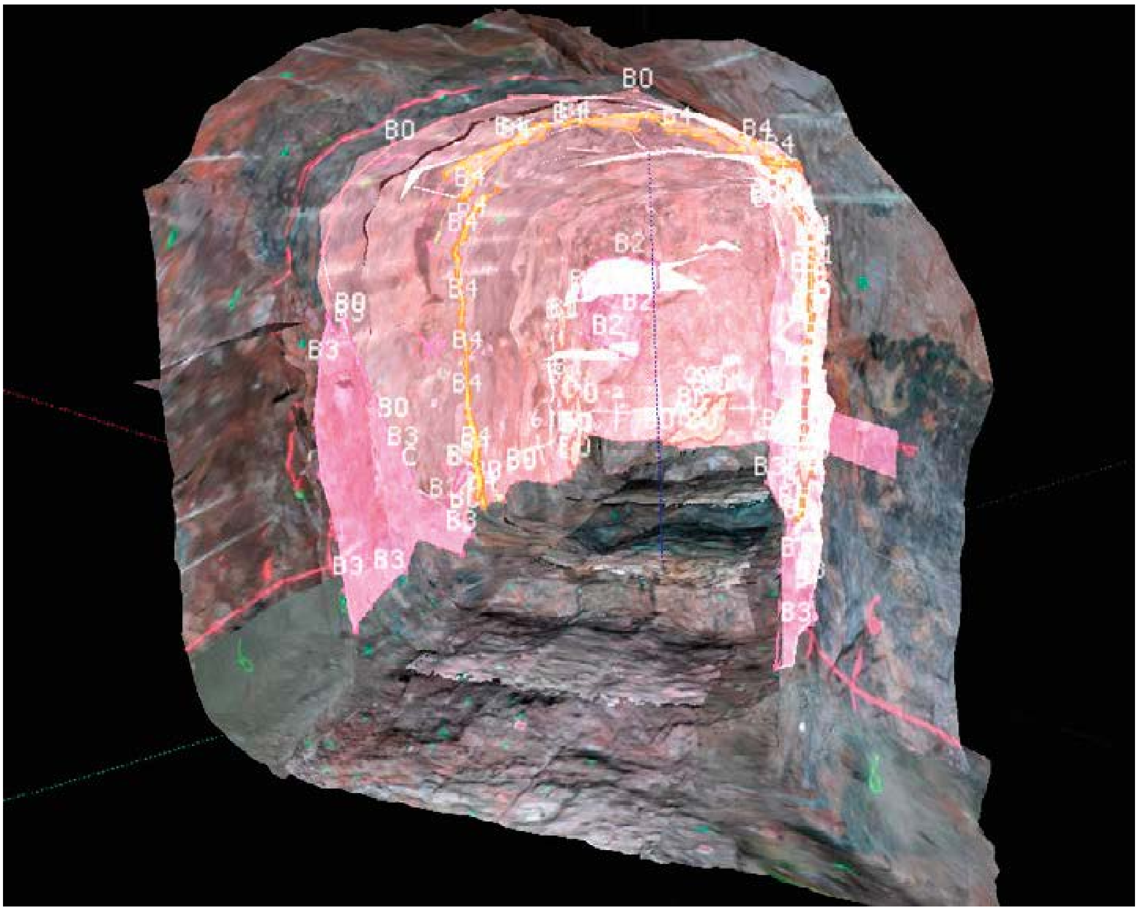


Figure 2-4. Print out from the computer screen showing mapped rock types in pinkish and yellowish colours, the TAS05-tunnel.

2.3 Hydrogeology

Background

An understanding of the hydrogeological framework, i.e. geometries, processes and parameters, is often a requirement from the different experiments undertaken in the Äspö HRL tunnel. This understanding has developed over time with a first descriptive model produced 1997 and a second one in 2002.

Through the different experiments and projects undertaken in the tunnel, additional data is collected and understanding is gained for the local experimental volume. As such this local knowledge constitutes a building block for integration in the larger scale site descriptive volume. With new experiments new locals model are providing input to the gradual updating and refining of the site descriptive model.

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 with short turn over times for predictions in support of the experiments in the laboratory as well as to test hydrogeological hypotheses in order to improve the conceptual understanding.

Objectives

The major aims of the hydrogeological activities are to:

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

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

Hydrogeological resources were to a major extent provided to the Large fracture project for hydrogeological characterisation, modelling and forecasting. To a lesser degree also in support of on-going and up-coming experiments.

Experimental and project related results are reported separately in project dedicated chapters.

2.3.1 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. A staged approach of monitoring has been adopted according to Figure 2-5 (Morosini 2013). Monitoring initiated as part of the pre-investigation for the site selection process. Upon completed characterisation boreholes were retained for long term monitoring in support of establishing a baseline. The monitoring system is also utilised for characterisation during construction and to develop site descriptive models.

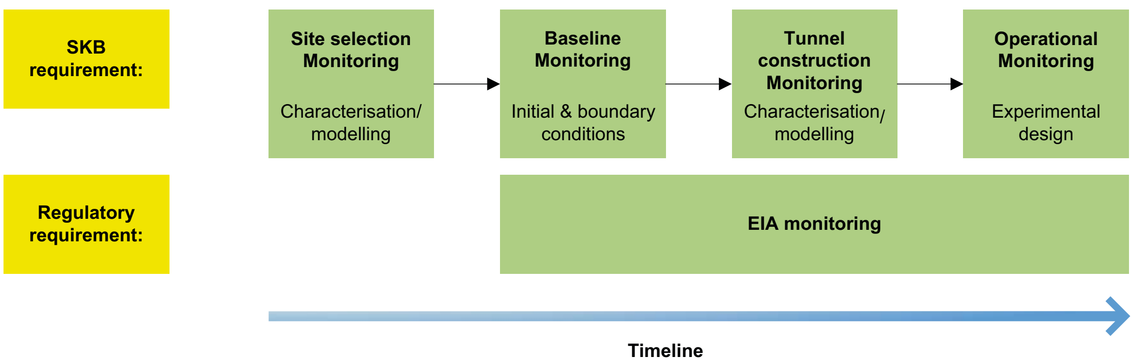


Figure 2-5. *The staged approach of monitoring at Äspö.*

During its operational phase the laboratory houses a number of different research experiments which are conducted simultaneously at different locations throughout the tunnelsystem. The monitoring system is critical for these several experiments for various reasons. In conjuction with the site descriptive model it provides:

- means to select an appropriate experimental site,
- initial and boundary conditions for the experiment,
- direct data to experiments,
- means to minimize hydraulic disturbances between experiments.

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.

Objectives

The purpose with monitoring is to:

- Provide base data for tunneldrainage processes and impact on its surrounding.
- Establish and follow up a baseline of the groundwater head and groundwater flow situations.
- Provide information about the hydraulic boundary conditions for the experiments and modelling in the Äspö HRL.
- Provide data to various groundwater flow and transport modelling exercises, including the comparison of predicted head with actual head.

Experimental concept

The monitoring system is relies on a relatively large number (1,500) of measuring points of various hydrogeological variables.

Water level and groundwater pressure constitute the bulk of the data collection where we at present record from about 400 locations mostly from the tunnel. For longterm monitoring boreholes are instrumented with up to ten pressure sections where water samples may be taken or tracers injected/circulated. The tunnel drainage is monitored through V-notch weirs at 29 locations of which water salinity is also measured at 22 stations. Hydrological monitoring of flow and salinity is performed in two streams and one meteorological station is recording wind, radiation, precipitation, pressure and humidity. Surface hydrological and soil aquifers monitoring were initiated during the site investigation in Oskarshamn. Some of these monitoring stations were later incorporated to the Äspö HRL monitoring system.

Results

The monitoring system is continuously maintained and data collected. 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 in their planning and execution and for the tunnel activites.

For example, the monitoring system was instrumental to detect, quantify and remedy a leaky casing grout which caused sub-normal formations pressure. This was achieved through a combination of flow balance calculations and customised measurements of borehole and tunnel monitoring which pin-pointed the leak to 2.55 m borehole length amounting to 5.5 L/min causing the formation pressure to decrease 127 kPa/month, Figure 2-6 (left). It was remedied by placing a packer sealing the leak from the inner part of the borehole causing formation pressure to rise and tunnel inflow to decrease, Figure 2-6 (right).

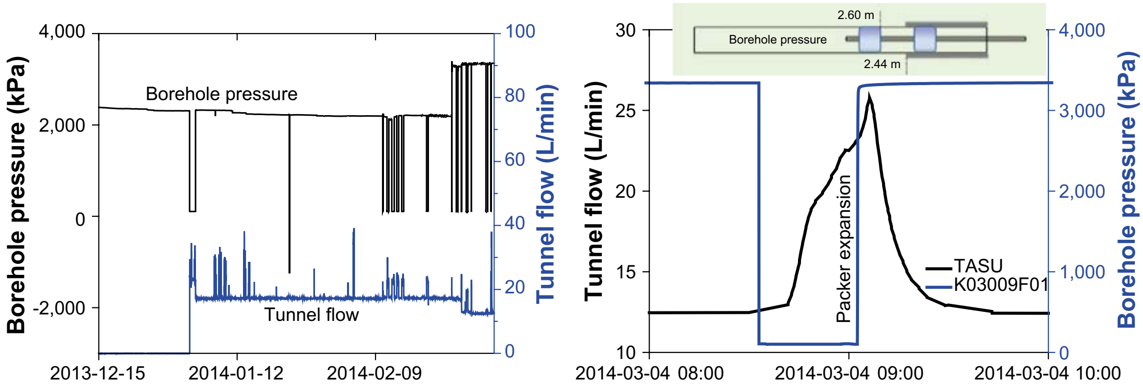


***Figure 2-6.** Monitoring results of tunnel flow and borehole pressure measurements.*

The process of upgrading the hydro monitoring system software to 64 bit windows operating system have continued and is in its final stage. Launch is however planned for 2015. The upgrade also comprise a switch to a database platform, enhanced access to the system through the world wide web and additional functionality for system administrators as well as for end users. The system to be phased out was commissioned in 1997; it has been and still is working reliably and well.

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

In support of the site for the coming Final Repository for Spent Nuclear Fuel, a transfer of knowledge and know-how from Äspö Hard Rock Laboratory to Forsmark Site administration on all aspects of hydrogeological monitoring was implemented. This is sustained on a structured and recurrent basis comprising technical, organisational and Q/A & Q/C issues.

2.4 Geochemistry

Background

Two small projects has been in focus; rare earth element sampling with DGT (Diffusive Gradient in Thin-film) and on-line measurements of the parameters pH, EC, Eh, O2, redox and temperature on groundwater. All analytical data are quality assured and stored in SKB database to provide background information for modelling.

Objectives

The major objectives within the geochemical work are to:

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

Results

The second phase of the DGT (Diffusive Gradient in Thin-film) sampling for trace elements in deep groundwaters has been completed performed with results from different boreholes in the Äspö tunnel. The description of the method has been published in a scientific publication in 2014. A second publication with all data and results will be published during 2015.

On-line measurements of the parameters pH, EC, Eh, O_2, redox and temperature on groundwater in the tunnel has been tested during 2013–2014. Preliminary result shows that the system is performing well and can be operated with a remote control over the local Internet. More tests will be performed during 2015.

2.4.1 Hydrogeochemical monitoring program

Background

The hydrogeochemical monitoring program includes a range of sampling points in Äspö HRL, surface waters, near surface waters, and in core- and percussion boreholes. The sampling campaigns are designed as biannual or monthly depending on what type of water. Analyses take place at Äspö chemical laboratory as well as in external laboratories.

The current sampling is tailored to provide basic information for the ongoing SKB scientific programme and experiments in the tunnel at Äspö as well as for continuous improvement of the site model. It is also to provide data for external organizations such as Nova FoU.

Objectives

The monitoring program is designed to provide information to determine where, within the rock mass, the hydrogeochemical changes are taking place and at what time stationary conditions are established. Its aim is to create time series and opportunity to detect/exclude the influence of the surface waters chemical composition caused by SKB's own activity.

Results

During 2014 two groundwater sampling campaigns have been made in Äspö HRL, one completed in May and the other in November. Surface waters and nears surface waters is performed six times a year. Core- and percussion boreholes were not sampled during 2014.

2.5 DETUM-1 Large Fractures

Background

The Large fractures experiments is one part of DETUM-1 handling the SKB investigation program for the Final Repository for Spent Nuclear Fuel (see SKB 2010). The aim of the investigation program is to provide a basis for adaptation of the repository to site-specific conditions in order to meet the design criterias in the light of long-term safety considerations. Furthermore, investigations should provide input for engineering decisions, such as grouting and reinforcement. They are also performed to update site models, which will in turn form the basis for long-term safety assessments.

According to the KBS-3 method, the canister and the bentonite should be placed in 1.75 m diameter deposition holes drilled to a depth of approximately 8 meters in the floor of the deposition tunnels. The important geoscientific issue treated in the Large fractures experiment is the location of fractures and deformation zones with shearing potential, as they are not allowed at a canister position. With regard to size of the fracture, a canister should not be localized where an intersecting fracture has a diameter exceeding approximately 200 m (e.g. Fälth 2015).

Objectives

The aim of the Large fractures experiment is to further develop strategies and integrated investigation and modelling methodology for the identification and characterization of geological structures. The objective is to ensure that the *size* determination can be based to a greater extent on real properties and to a lesser extent on criterias related to the existence of a full perimeter fracture–tunnel intersection (FPC) or an extended criteria (EFPC) relating to large fractures subparallel to but not intersecting the deposition tunnels.

Experimental concept

The Large fractures experiment investigations include geological mapping, hydraulic testing and geophysical investigations using boreholes and tunnels (e.g. groundpenetrating radar, seismics, resistivity and mise à la masse). This is followed by an integrated interpretation aiming at an increased confidence in the location, orientation and size of the larger fractures and deformation zones. The experiment is related to the different steps included in the SKB investigation program for the repository (SKB 2010) with focus on investigations from deposition tunnels (Measurement Campaign 1, MC1) and probe holes for deposition tunnels (Measurement Campaign 2, MC2), see Figure 2-7.

Results

Confidence in the location and size of the deformation zones in the area of the Large fractures experiment varies but has increased in the area between the tunnels following the geophysical measurements performed during MC1 and the ongoing integrated interpretation, For example, DZ1 and DZ4 were identified, see Figure 2-8 and Fransson et al. (2014), and the presence of a new zone referred to as DZ9 will be further investigated during MC2.

Grouting of fractures intersecting one of the investigation boreholes (K03009F01, Figure 2-7) of the Large fractures experiment was designed based on field data and a decrease in flow from over 200 l/min to less than 1 l/min was achieved. Key aspects were penetrability (the ability of the grout to enter the fracture), grout penetration and erosion due to a high gradient. Grouting of the borehole was performed successfully. The magnitude of the transmissivity of the fracture/deformation zone that was grouted indicates a large fracture size. This is also indicated by the ongoing integrated interpretation (geology, hydrogeology and geophysics).

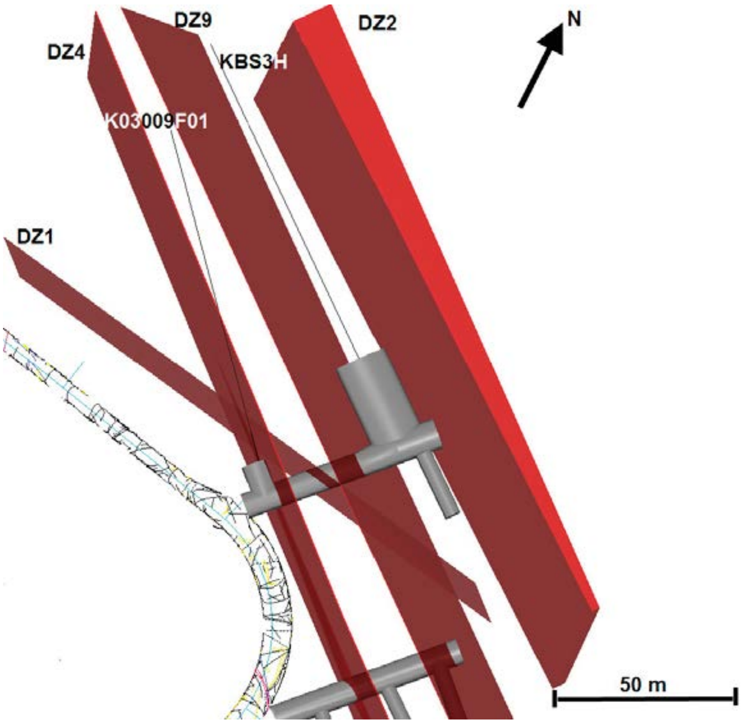


Figure 2-7. *The focus in Measurement Campaign 1 is on the volume between two short tunnels (lower part of the drawing). The focus in Measurement Campaign 2 is on the volume between two boreholes (upper part of drawing). Included in the figure are a number of preliminary (in terms of location and size) deformation zones.*

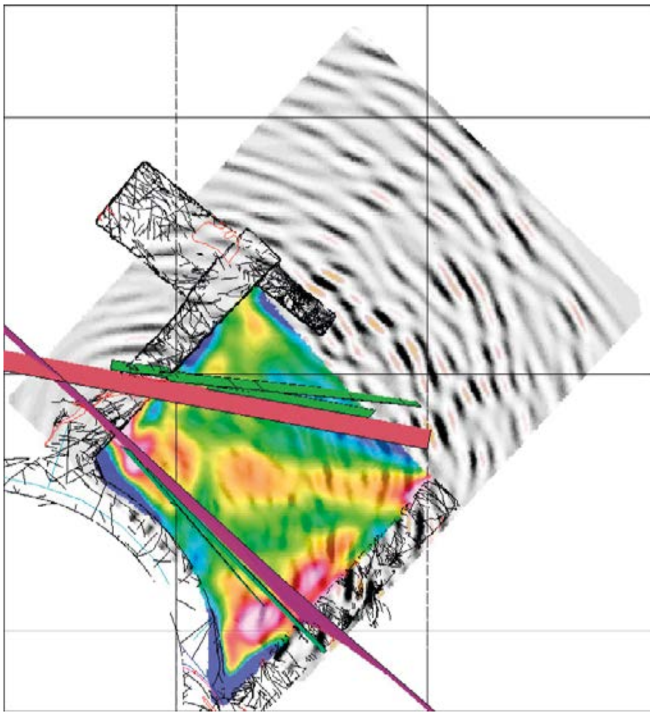


Figure 2-8. *Example from the geophysical investigations in Measurement Campaign 1: Seismics (preliminary results). Migrated 3D reflection profile together with P-wave velocity tomogram and preliminary interpretations of deformation zones DZ1 and DZ4 (magenta) and interpreted reflectors corresponding with DZ:s (green). The velocity range in tomogram is 5,500 m/s (blue) to 5,850 m/s (red).*

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 The Integrated Sulphide Project

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 and Pedersen 2008, 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 utilise 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. This was the background to the previous Sulphide project, but as many questions remaind the Intergrated sulphide project was initiated. It is a collaboration project between Posiva and SKB and consists of seven subprojects all with the purpose to answer questions related to sulphide levels a Final Repository for Spent Nuclear Fuel.

The project is divided into three working packages (WP) with their respective leaders. The three main activities (Work Packages) and the sub activities are:

WP1 – Sulphide concentrations and processes in the geosphere

Sub activity 1: Artefacts and/or natural sulphide production processes in boreholes

Sub activity 2: Transport and origin of gases that can be used by SRB

Sub activity 3: Microbial release of Fe(III) from rock minerals

WP2 – Sulphide concentrations and processes in bentonite

Sub activity 1: Solubility of sulphides originally present in the buffer materials

Sub activity 2: Threshold buffer density

Sub activity 3: FATSU

WP3 – Integration with the safety case

Sub activity 1: Modelling

Objectives

The aim of this project is to collect all studies and investigations undertaken by Posiva and SKB to gain knowledge and collect data on processes that may affect either the concentration of sulphide or the sulphide production rates. The project covers both the geosphere and the buffer-backfill systems. Also overall modelling of sulphide both in the near field and in the geosphere are included in the project.

The project shall be conducted and financed as a collaboration between Posiva and SKB with a common project plan.

Experimental concept

WP1: the geosphere

The goals are:

1. To understand the processes controlling sulphide production in deep groundwaters by:
   a. Determining if any material from borehole instrumentations provides energy sources for SRB (sulphate reducing bacteria), for example by releasing organic components tothe groundwater in the borehole section. Investigating the possible release of hydrogen from metal parts used in the borehole installations (packers). Galvanic metal corrosion may produce hydrogen as well as acting as a source of metal ions in the water.
   b. Monitoring high sulphide boreholes with respect to chemistry, microbes and gases at Olkiluoto (Posiva share results with SKB).
2. To understand transport processes that involve hydrogen and other gases that can be used by SRB, can be achieved by:
   a. Development of sampling techniques (is done within the project DETUM) for analyses of gases including stable isotopes.
   b. Obtaining more gas data (concentration in groundwater and isotope signatures) from Forsmark, Äspö HRL and ONKALO will be collected using more sensible analytical methods. Studies on the origin and flow of groundwater gaseous components, to aid understanding the fate of hydrogen and any other gases that may be used by SRB.
   c. Analysing the gas concentration in bedrock and studying its diffusion using a new technique, called Dry boreholes. A new borehole will be drilled, packed off and filled with nitrogen gas. The gas concentration will then be monitored first on a weekly basis and then on a monthly basis.
3. To study the microbial release of Fe(III) from rock minerals and fracture infillings (and bentonite), as a potential source of dissolved Fe(II) to limit sulphide concentration by the precipitation of Fe(II)-sulphide.

WP2: the buffer and backfill

The purpose of this subactivity is to give an increased process understanding and a more quality assured data for the PSAR safety assessment. The expected outcomes are:

1. A verification that sulphide minerals originally present in the backfill will have no effect on canister corrosion due to low solubility.
2. Confirmation of the minimum dry density or swelling pressure of the bentonite where microbially mediated sulphate reduction can occur.
4. Understanding of what additional factors will affect microbially mediated sulphate reduction and transport in the near field.

WP3: integration with the safety case

The target is to obtain tools, to be used in safety assessments, which evaluate as realistically as possible the fluxes of sulphide to waste packages (i.e., copper canisters or steel) in repositories forspent fuel or long-lived low and intermediate radioactive waste.

Results

The first results vill be reported during 2015.

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

Background

The work within SKB (earlier called 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. Relevant experiments are utilised as topics for the modelling tasks, and the modelling can in turn potentially support the design, performance, and interpretation of the experiments.

The modeling tasks so far, 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 (final reporting ongoing).

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

Task 9: Modelling of the field experiments REPRO and LTDE-SD (planning phase).

Objectives

The SKB 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 for Spent Nuclear Fuel 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 is focusing 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.

The main objective of Task 9, modelling of the field experiments REPRO and LTDE-SD, is to increase the realism in solute transport modelling.The task was in the planning phase during 2014.

Results

During 2014, the modelling work within Task 7 was completed, and the focus is on reporting, and optional publishing. The Task 8 work mainly contained modelling of BRIE with different levels of detailed data. The BRIE project 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 31st international Task Force meeting was held in Daejeon, South Korea, in April. The presentations were mainly addressing modelling results on sub-tasks 8D (modelling of BRIE with more and updated data) and 8E (modelling of the Prototype experiment). 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 was proposed that Task 9 will be a combination of modelling LTDE-SD and Posiva's experiment REPRO.

A workshop for mainly Task 8 was held in September where modelling approaches and plans for the future modelling were presented and discussed. The venue took place at Arlanda.

Minutes of both venues (TF meeting 31 and workshop) have been distributed to the Task Force together with presentation material. The description and the status of the specific modelling subtasks within Task 7 and 8 are given in Table 3-1.

The 32nd international Task Force meeting was held in Berkeley, USA, in December. The meeting was partly a combined meeting with EBS TF, and partly a stand-alone TF GWFTS meeting. The presentations were mainly addressing updated modelling results on sub-tasks 8D and 8E. Again, a review session on Task 8 was held. The planning of Task 9 was presented, and discussed.

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. (Reporting ongoing).
7C	Here focus is on deposition hole scale issues, resolving geomechanics, buffers, and hydraulic views of fractures. (Reporting ongoing).
8	Interaction between engineered and natural barriers
8A	Initial scoping calculation (reported as presentation files)
8B	Scoping calculation (simplified reports)
8C	Final results (presented at Task Force meeting 32)
8D	Updated results (presented at Task Force meeting 32)
8E	Updated results (presented at Task Force meeting 32)

3.4 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 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:

- An increased scientific understanding of the exchange of water across the bentonite-rock interface.
- Better predictions of the wetting of the bentonite buffer.
- Better characterisation methods of the deposition holes.

Experimental concept

The experiment is subdivided into two main parts: Part I describing the selection and characterisation of a test site and two central boreholes and Part II handling the installation and extraction of the bentonite buffer. The characterisation will result in a deterministic description of the fracture network at a small scale (≈ 10 m). Focus is on the most important water-bearing fractures. The experiment and the site is further described in Fransson et al. (2012, 2014) and Holton et al. (2012). Results related to the experiment is found in Dessirier et al. (2014) and Åkesson et al. (2014).

Results

Following selection and characterisation of the test site in the TASO-tunnel, two 300 mm boreholes (Hole 17 and Hole 18) were drilled and investigated. Along each of the two boreholes one section with a fracture and one section with intact rock matrix were selected for monitoring. Bentonite was installed in September 2012 and relative humidity, total pressure and pore pressure were monitored in the sections of interest. Pore pressure (hydraulic head) was also monitored in boreholes in rock close to the ones with bentonite. The monitoring of sensors data from the bentonite in Hole 17 was terminated in November 2013, whereas the corresponding monitoring of Hole 18 continued to February 2014.

The bentonite parcel in Hole 17 was dismantled, sampled and analyzed during November and December 2013, and the same was made for Hole 18 in February-March 2014. The dismantling operation followed a procedure of stitch-drilling of a Ø 700 mm rock pillar which was cut in the lower end through wire sawing. Due to fractures intersecting the pillar, the parcels and rock blocks were partly lifted separately.

The bentonite was partitioned, sampled and analyzed with respect to water content and density. Figure 3-1 presents a comparison of water content plots (blue high water content and orange low) for five different orientations with markings on bentonite parcel surface for Hole 18 (lowermost meter). Further, Figure 3-2 shows a mosaic of photos of the entire bentonite parcel and the rock cores from the 300 mm cored borehole. Three rock blocks formerly being part of the borehole wall and that had been in contact with the bentonite during the experiment was used for laboratory investigations of rock matrix hydraulic conductivity and for measurement of relative humidity profiles from the borehole wall into the rock.

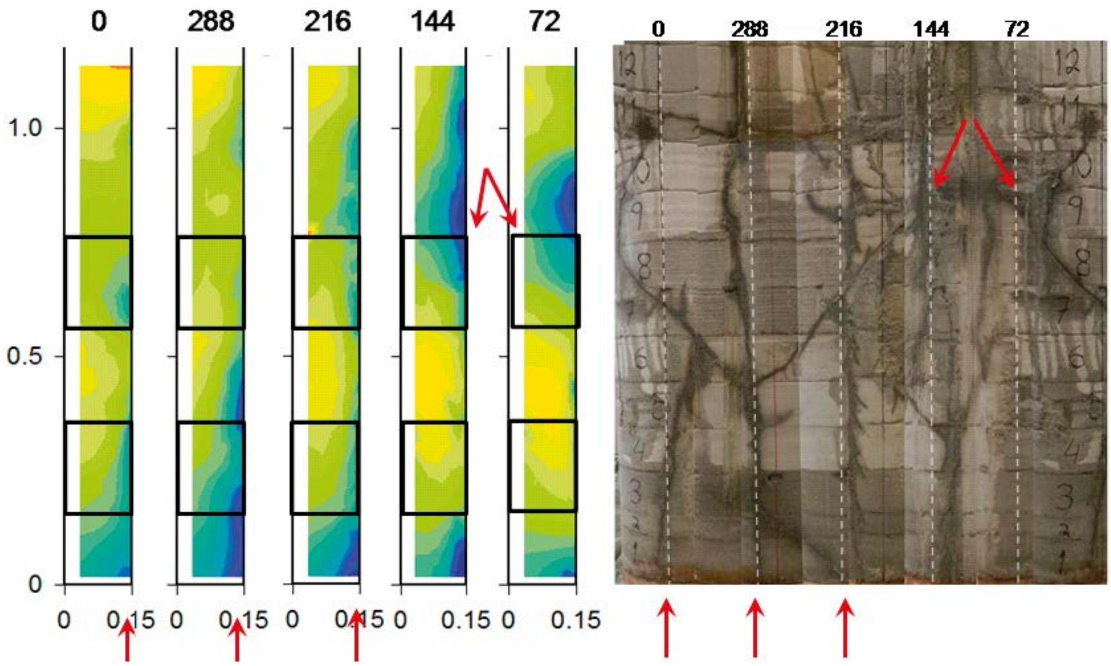


***Figure 3-1.** Comparison of water content plots (blue high water content and orange low) for five different orientations with markings on parcel surface for Hole 18 (the lowermost meter).*

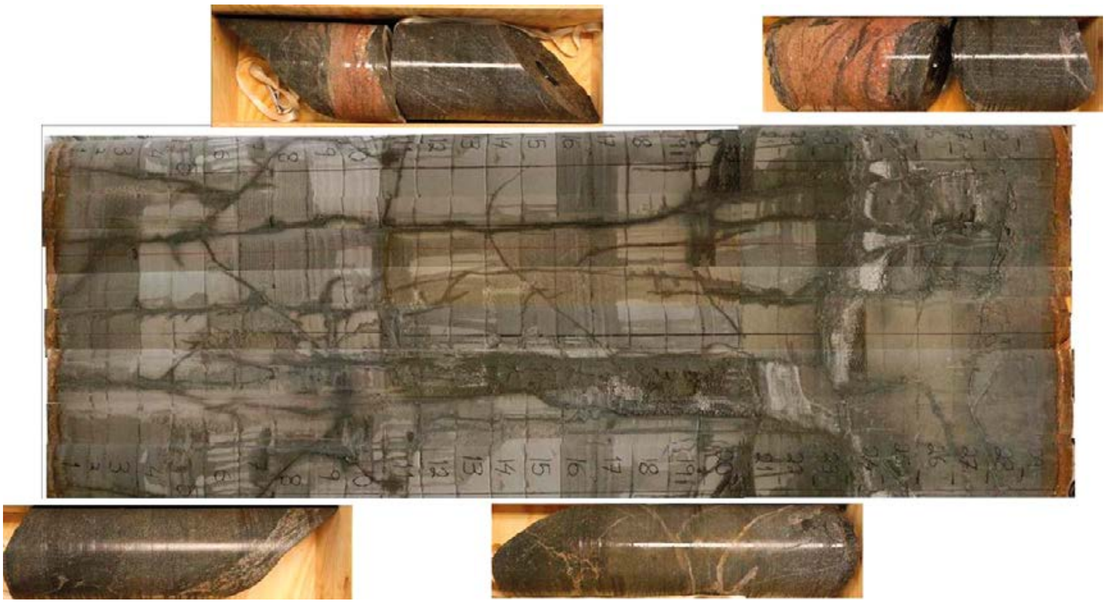


***Figure 3-2.** Comparison of some fractures in rock core and traces on bentonite for Hole 18. The core is broken by the main water-bearing fracture.*

4 Engineered barriers

4.1 General

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 are in line with what is adressed in SKB's RD&D programme.

During 2014 following experiments and projects within the Engineered Barriers were conducted:

- Prototype Repository.
- Alternative Buffer Materials.
- KBS-3 method with Horizontal Emplacement.
- Large Scale Gas Injection Test.
- In Situ Corrosion Testing of Miniature Canisters.
- 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.
- System design of buffer.
- Tunnel production.

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 and was finalized at the end of 2013, was made in cooperation with Posiva. Furthermore, the following organisations were participating and financing the work with the dismantling; NWMO (Canada), ANDRA (France), BMWi (Germany), NDA (United Kingdom), NAGRA (Switzerland) and NUMO (Japan). The reporting of the retrieval of the outer section stared during 2013 and was finalized at the beginning of 2014. The monitoring of the inner section will continue until at least 2020.

Objectives

The main objectives for the Prototype Repository are to:

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

Experimental concept

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

Instrumentation is used to monitor processes and evolution of properties in canister, buffer, backfill and near-field rock. Examples of processes that are studied include:

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

The outer test section was 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 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. Problems with the heaters in canister 3 were observed during 2013 and the power was reduced to about 500 W.

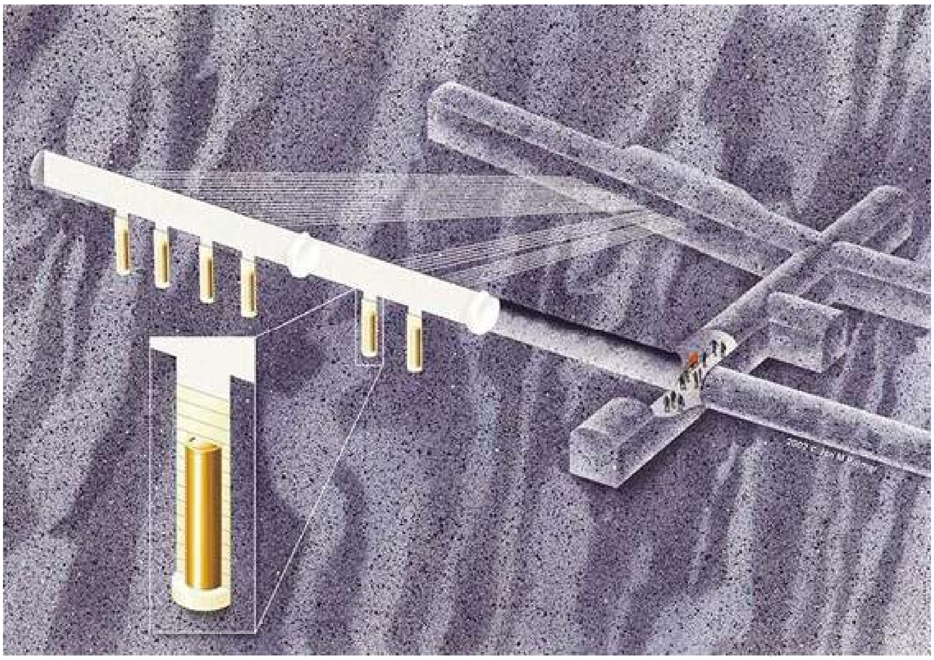


Figure 4-1. *Schematic view of the layout of the Prototype Repository (not to scale).*

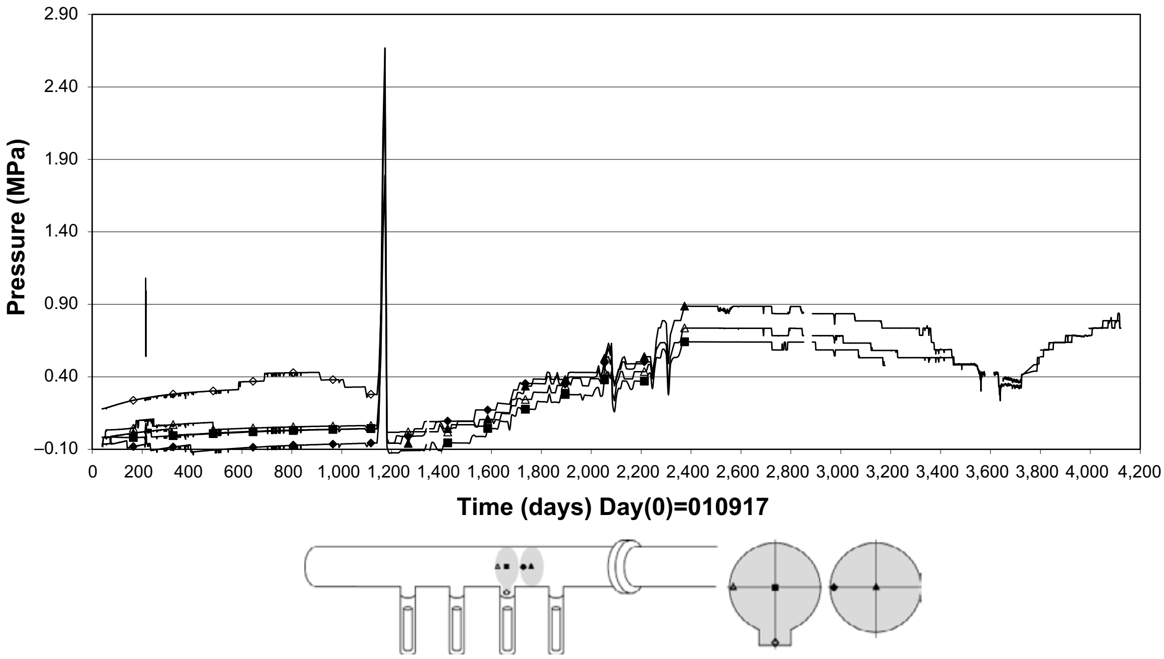


Figure 4-2. *Examples of measured total pressure in the backfill around deposition hole 3 (17th September 2001 to 1st January 2013) (Goudarzi 2014).*

Measurements in rock, backfill and buffer

Altogether more than 1,000 transducers were installed in the rock, buffer and backfill (Collin and Börgesson 2001, Börgesson and Sandén 2002, Rhén et al. 2003). The transducers measure the temperature, the pore pressure and the total pressure in different part of the test area. The water saturation process is recorded by measuring the relative humidity in the pore system of the backfill and the buffer, which can be converted to total suction.

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

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

A large programme for measuring the water pressure in the rock close to the tunnel is also ongoing (Rhén et al. 2003). The measurements are made in boreholes which are divided into sections with packers. In connection with this work a new packer was developed that is not dependent of an external pressure to seal off a borehole section. The sealing is made by highly compacted bentonite with rubber coverage. Tests for measuring the hydraulic conductivity of the rock are also made with the use of the drilled holes (Harrström and Andersson 2010). 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 2008). 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 aim of the retrival of the outer section of the Prototype Repository was in particular to capture the following processes and phenomena:

- Temperature evolution in canister, buffer, backfill and rock.
- Copper corrosion.
- Hydraulic conductivity and hydraulic head of the near-field rock.
- Stresses and displacements in the near-field rock.
- Coupled hydraulic and stress regimes in the rock.

- Wetting of buffer and backfill.
- Evolution of pore pressure in buffer, backfill and rock.
- Evolution of swelling pressure and displacement in buffer and backfill.
- Deformation and displacement of canisters.
- Gas accumulation and composition in the buffer and backfill.
- Chemical composition of the backfill and buffer pore waters and the water in the near-field rock.
- Salt accumulation in the buffer.
- Mineral alteration in the buffer.
- Bacterial growth and migration in the buffer.
- Cellulose alteration in high pH environment.
- Strains and deformations in plug during curing.

The planning of the retrieval of the outer section of the Prototype Repository started during 2010 and the actual fieldwork started during the 2011.The retrieval of the outer section of the test included the following items:

Dismantling of the outer plug: The technique used for demolishing the plug was to first core drill trough the outer part of the plug towards the retaining wall in a cross like pattern. After the drilling the plug was mechanical demolished with the use of a hydraulic hammer.

Excavation of the backfill: The excavation of the backfill was made in inclined layers with a backhoe loader. On every 2 meter the excavation stopped and samples were taken for determinations of the water content and density of the backfill material. Several installed sensors were also retrieved for future tests and validation.

Excavation of the buffer in the two deposition holes: The main objectives of the excavation of the buffer was beside to empty the deposition hole also to get samples for determining the density and water content and for other laboratory investigations of the bentonites. The excavation was made by first making several core drillings from the upper surface of each buffer block and then remove the rest of the buffer. Several installed sensors were also retrieved for future tests and validation.

The field work is described in detail in Johannesson and Hagman (2013).

The results from the determinations of the water content and density of the backfill and buffer were made as quickly as possible after the samples were taken (Johannesson 2014a). The results from the determination of the density and water content of the backfill material show that it is fully saturated. The results from the measurements of the water content and density of the buffer in the two deposition holes show that the buffer was not fully saturated in all parts and a variation in density and water content both within the two deposition holes and between them. The analyses indicate that the water content was depending on the location of the water baring fractures inside the deposition holes, see Figure 4-3.

The laboratory examinations of the taken samples started during 2011 and was finalised during 2013. This work included:

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

The hydromechanical and chemical characterisations of the buffer and backfill are described in detail in Olsson et al. (2013) while the microbical investigations are described in Arlinger et al. (2013).

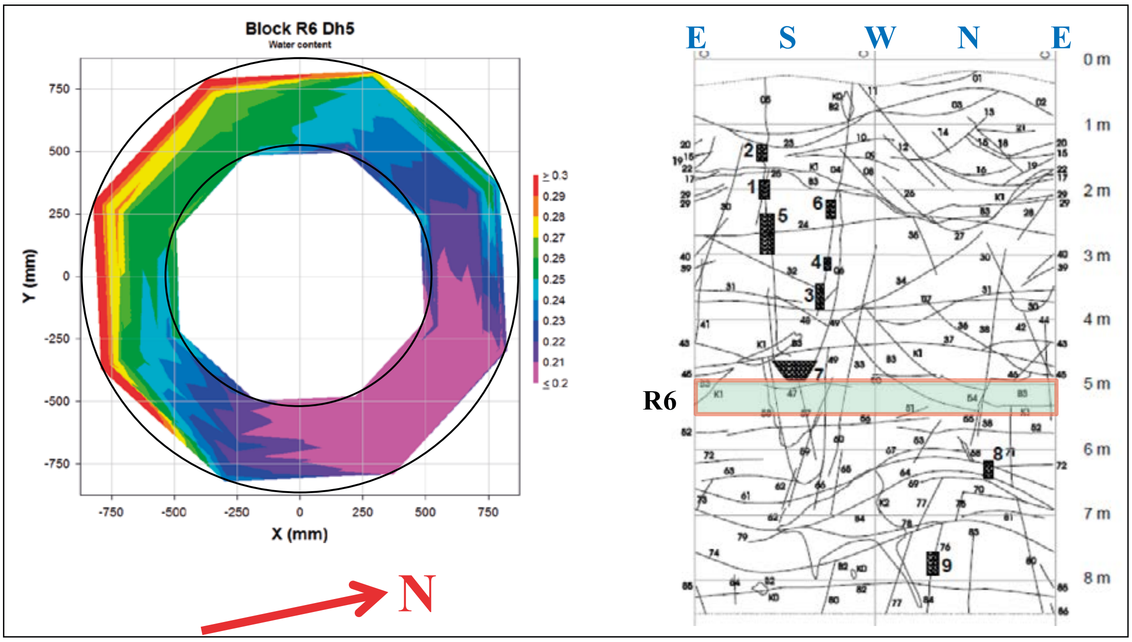


Figure 4-3. Contour plots of the water content of block R6 in deposition hole 5 together with the observed fractures on the wall of the deposition hole (Johannesson 2014a).

The examination of the canisters (involves investigations of samples taken of the canister surface, detailed deformation-measuring of the canister which was made at the Canister Laboratory in Oskarshamn and examination of the cables and heaters installed in the canister. This work was finalized during 2013. The investigation showed damages on the cables caused by the heating and the swelling pressure from the buffer. Furthermore, water had entered one of the canister (canister no 6). This has probably caused the failure of the heating elements at the running of the test. The deformation measuring indicated small changes in the shape of the canisters.

57 sensors from the buffer and backfill have been retrieved at the excavation of the backfill and buffer and 35 of them have been validated with good quality with equipment which have been constructed and manufactured within subproject five, see Figure 4-4. This work is described in detail in Nilsson (2014).

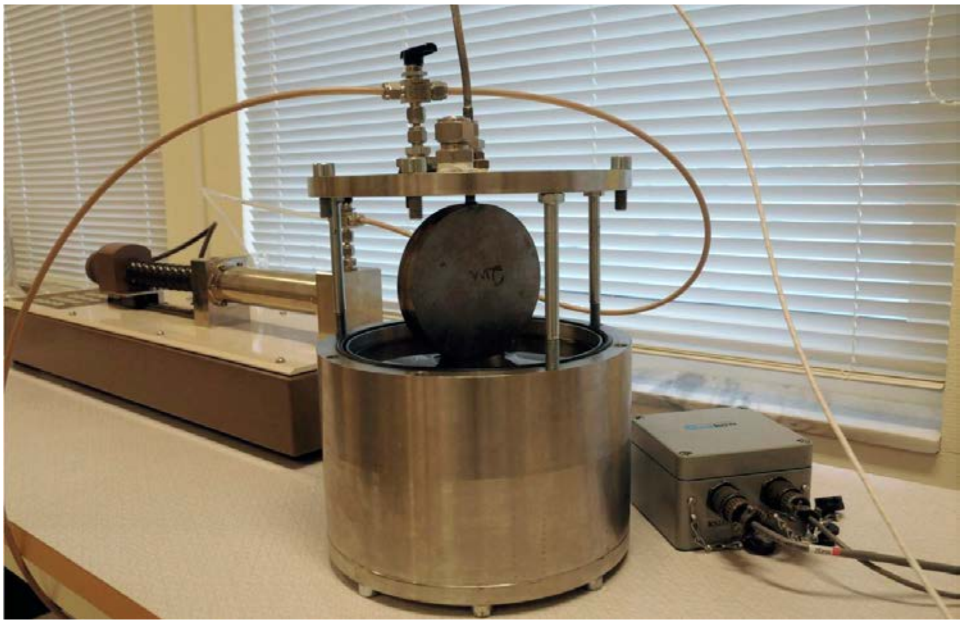


Figure 4-4. Test cell with a total pressure sensor before immersion into water (Nilsson 2014).

The modelling work of the Prototype Repository (subproject three) involves thermal, mechanical and hydro mechanical analyses of the rock, backfill and buffer. A stepwise solution strategy, including three steps, had been proposed for the task in which models at different scales and level of detail were used for solving the problem. Most of the modelling work was made within EBS-TF project, see Section 4.9.

Furthermore, rock examination, numerical thermo-mechanical modeling of the rock mass surrounding the Prototype Repository has been performed (Lönnqvist and Hökmark 2013). The objectives of the modeling were:

- to compare model results with mechanical measurements made in the rock,
- to assess the potential for spalling in the walls of the deposition hole walls,
- to assess the stability and normal stress variations of selected fracture planes intersecting the repository openings,
- to study the impact of a simplistic fracture network on stresses around the deposition holes.

Because of the poor performance of the rock mechanical instruments, no rigorous quantitative validation of the *in situ* stress model or the material model was possible .The modeling shows that rock mass appears to have responded to excavation and heating largely as an elastic continuum. 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 located in the most stress-disturbed regions near the regions close to the 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. 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 2006 (ABM, consisting of three test parcels, ABM1-3) and in November 2012 (ABM45).

Results

In ABM1 minor traces of trioctahedral clays were observed, as well as an increased Fe(II)/Fe-total ratio associcated with oxygen sensitive phases (Svensson and Hansen 2013). In ABM2 plenty of various precipitates have been observed (e.g. anhydrite, calcite, aragonite) as well as various corrosion products (hematite, goehite and magnetite; Svensson 2013). More interestingly, much higher content of trioctahedral smectite was found in samples from the ABM2 experiment compared to ABM1 and TBT (Svensson 2013). One sample was taken by scraping corrosion products directly from the heater at Febex block number 9. This sample was found to be composed of a mixture of magnetite from the corrosion, the original bentonite (Figure 4-5) and what was identified to be a newly formed trioctahedral smectite, an iron rich saponite. The elemental composition was calculated by subtracting the quantity of the identified phases from the X-ray diffraction (XRD) results from the elemental data. Complementary analysis was performed by consecutive thermal heating followed by XRD analysis and Infrared spectroscopy. The level of formation is currently not expected to have any significant impact on the buffer performance. In experiments with copper (e.g. LOT, Prototype, CRT), no trioctahedral smectites have been observed.

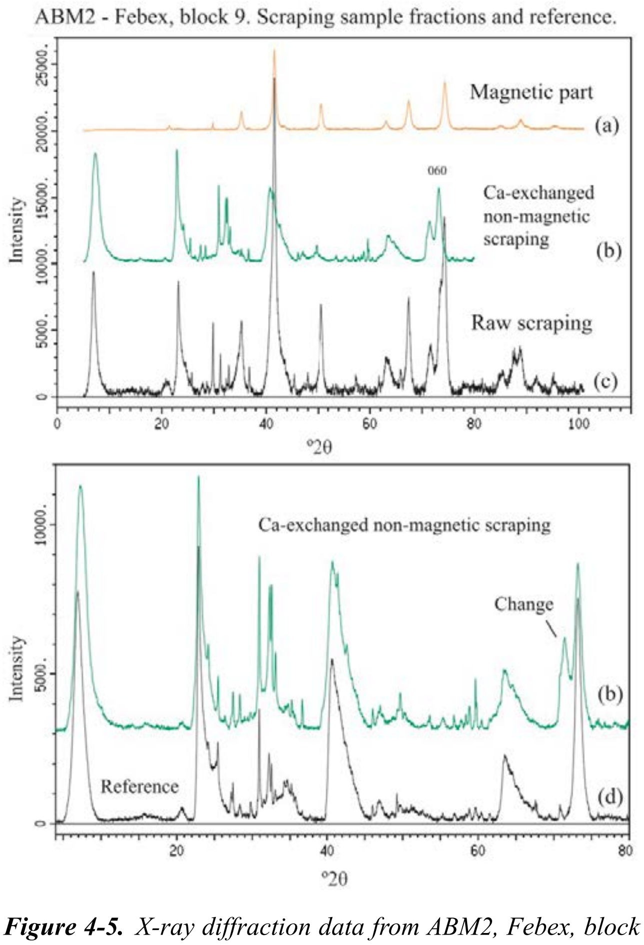


Figure 4-5. X-ray diffraction data from ABM2, Febex, block 9 showing saponite formation. a) Magnetic fraction of scraping sample (magnetite), b) Ca-exchanged non-magnetic fraction of scraping sample, c) raw scraping sample, d) reference Febex bentonite. λ = 1.789 Å. (Svensson 2013)

4.4 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 needed. Examples of positive effects are:

- Less environmental impact during construction.
- Reduced disturbance on the rock mass during construction and operation due to the mechanical excavating method instead of the drill and blast used in KBS-3V.
- 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 4-6 and Figure 4-7, and a controlled and efficient saturation process.

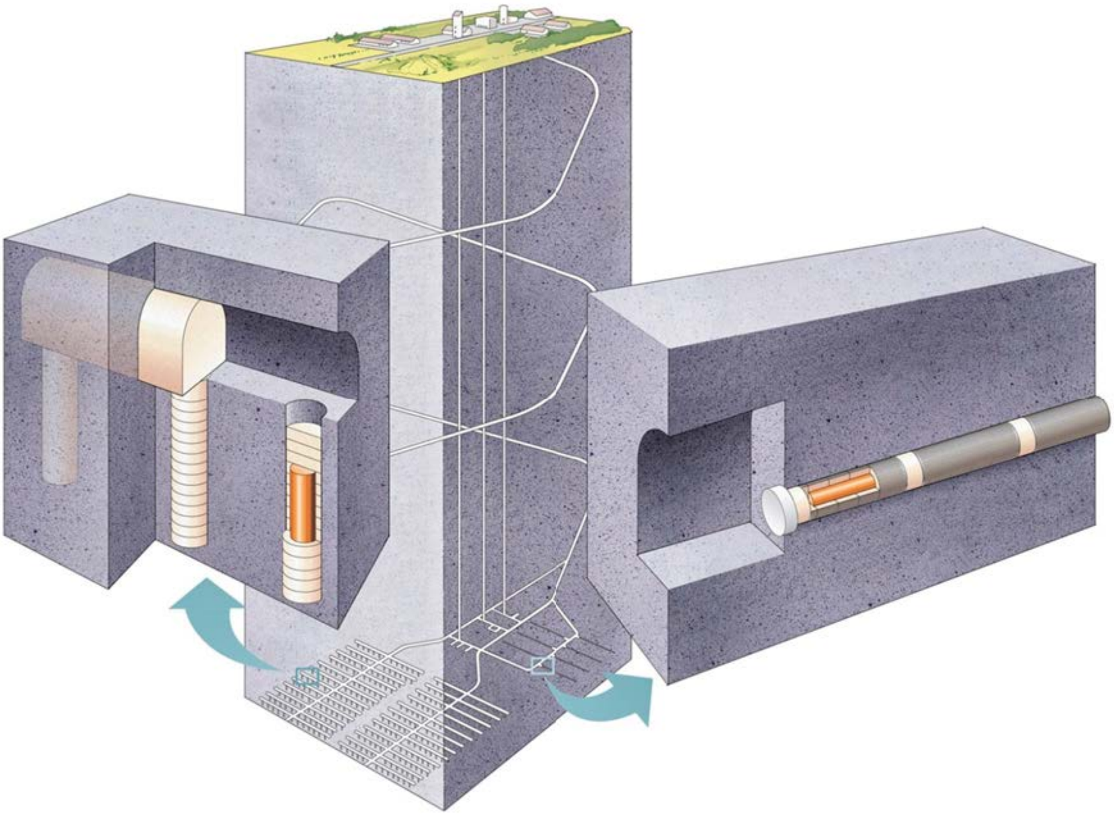


Figure 4-6. *Schematic drawing of the KBS-3V reference design (left) and KBS-3H (right).*

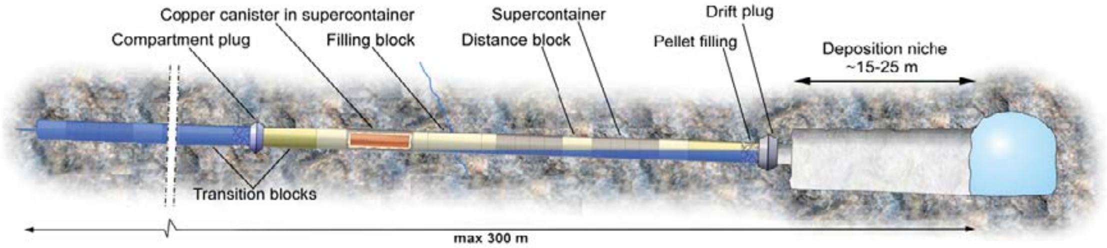


***Figure 4-7.** KBS-3H reference design DAWE with its main components; the plugs with their transition zones, the Supercontainers, and the distance and filling blocks. The illustration shows an ongoing artificial water filling procedure of the second compartment.*

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 (SKB 2012). 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.

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 final goal of the KBS-3H System Design phase is to bring KBS-3H design and system understanding to such a level that a PSAR can be prepared and that a subsequent comparison between KBS-3V and KBS-3H is made possible. 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 long term safety evaluation. The safety evaluation will be done for Olkiluoto. The work for Olkiluoto is deemed to provide results that will indicate if KBS-3H is also applicable to Forsmark. This work will be based on earlier safety assessment work and will make use of Posiva's safety case "TURVA-2012" for KBS-3V (produced by SAFCA) for Olkiluoto and SR-Site for Forsmark. 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 at the Äspö HRL and at Posivas Underground research facility ONKALO. The work is part of the Demonstration sub-project focusing on verifying the functionality of equipment, methods and components developed within the KBS-3H project. The sub-project consists of two main activities at the Äspö HRL; the Multi Purpose Test (MPT) at the –220 m level, and the excavation and preparation of a new KBS-3H drift at the –410 m level. The MPT is also part of the EU-project LucoeX, which receives funding from the European Atomic Energy Community's (Euratom) Seventh Framework Programme. The sub-project also includes an activity at ONKALO, the drilling of a 300 m steered core pilot hole.

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 4-8. It is installed at the –220 m level which implies that the hydraulic boundary conditions differ from those foreseen at a typical repository depth.

The test itself was installed by the end of 2013 according to the DAWE reference design in a 20 m long section in the innermost part of the 95 m long full face drift DA1619A02 (d=1.85 m).

The MPT has been set up with 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 has provided important experiences from working in full-scale at ambient *in situ* conditions, although not fully representative of typical repository depth. It has also enabled the recognition of potential implementation issues related to the DAWE design such as the Supercontainer being designed with blocks of two different water contents.

Excavation and preparation of a KBS-3H drift

A new full scale KBS-3H test site is being planned at the –410 m level of the Äspö HRL, and hence being more representative of a 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 100 m length scale, including fulfilment of defined geometrical requirements. This includes:
  - test and verification of deviation measurement equipment in the surface based deviation facility at the Äspö HRL,
  - assessment of transferability of results and experiences between sites.
- Reaming of pilot borehole for the KBS-3H experimental drift to full-size drift diameter (1.850 m diameter) over a 100 m length scale.
- Application and performance at repository depth of KBS-3H groundwater control techniques:
  - Prediction and comparison 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.
  - Post-grouting of the drift using the Mega-Packer (Eriksson and Lindström 2008).

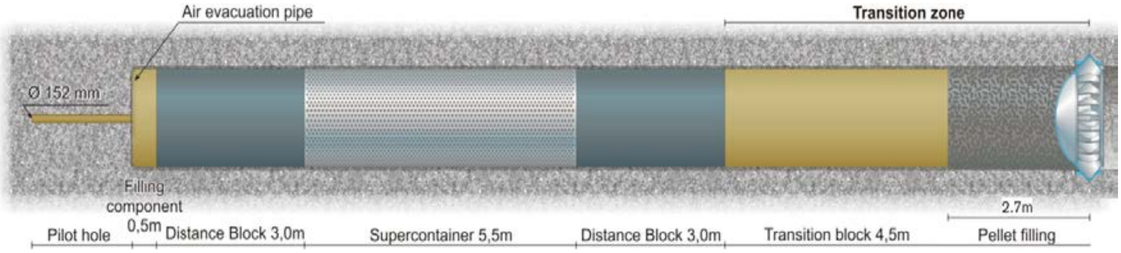


Figure 4-8. *Schematic illustration of the MPT layout. The length of the pellets filling has been increased from 1.3 m to 2.7 m; this is for practical reasons related to cabling and the manual installation. The KBS-3H reference design still has a 1.3 m long pellets section inside the plugs.*

Results

Results of the previous project phase, Complementary studies of horizontal emplacement, are reported in SKB (2012). The KBS-3H System Design phase is based on the outcome presented in this report.

The Multi Purpose Test (MPT)

The MPT has been monitored during 2014 and sensor data indicate that the buffer is starting to saturate, but still being in an early stage of development. The sensors with cables are transmitting data while there have been problems with the wireless sensors, their transmission failed stepwise during the first months after installation. The failure is unfortunate, but the system was novel for the KBS-3H application and redundant sensors with wires are in place.

A small leakage in the steel plug was remediated by re-welding early 2014 after which no further leakages have been noted.

Two reports covering the MPT have been recently prepared, one concerning the manufacturing of buffer (Johannesson 2014b) and one concerning the deposition machine development work (Ojala and von Numers 2015).

A report covering the MPT drift preparations, assembly and installation and an initial data report is planned to be published during 2015.

Excavation and preparation of a KBS-3H drift, pilot hole drilling

This is the main KBS-3H activity at Äspö during 2014 and it is thus presented in more detail.

A new KBS-3H niche has earlier been developed as part of the Äspö expansion at the –410 m level. The DETUM project carried out a 100 cored drilling, borehole K03009F01, in 2013 where the KBS-3H project participated in the performed tests of steered drilling. Experiences from this drilling and earlier drilling operations were employed in a steered core drilling activity in the KBS-3H niche in 2014.

A full scale deposition drift is planned to be located in the niche and the cored borehole is intended to be used as a pilot for the reaming.

Alignment of the casing has been identified as being of highest importance for a geometrically accurate drilling and new equipment was developed for this purpose, Figure 4-9. It works by aligning a drilling machine for the casing with high accuracy and thus drilling a casing hole with accurate direction.

The equipment has only been tested once so far, in conjunction with the drilling of K08028F01, but a high accuracy of 1.94° inclination (originally aiming at 2.0°) was achieved for the casing hole.

In addition to the efforts towards an accurate casing alignment several measures were taken in order to cater for a high precision steered drilling operation:

- A rigid platform was used.
- A powerful drill rig, Sandvik type DE140, was used in order to enable steering while maintaining torque on the drill bit.
- An AC Corac N3/50 core barrel with split inner tube of stainless steel constituting a triple tube wireline system with a core dimension slightly exceeding 50 mm was used. With a normal wireline core barrel, it is common to experience a steady deviation caused by drilling parameters, equipment wear and/or structures in the geological formation. To reduce these effects a specially devised stable core barrel using shorter outer tube sections, multiple reamers and a top stabilizer was built and used.
- To reduce the risk of an operator error during the steered drilling a reducer valve was installed on the control panel preventing the flush water pressure to be less than 30 bars when steering. At that pressure the steering equipment is locked in correct orientation during the steered drilling period.
- The deviation measurement tools used were selected based on proven accuracy in the Äspö deviation measurement facility. Both a gyro and a magnetic tool were used.
- A steering strategy was developed to manage decisions regarding steering towards fulfilling the KBS-3H requirements.

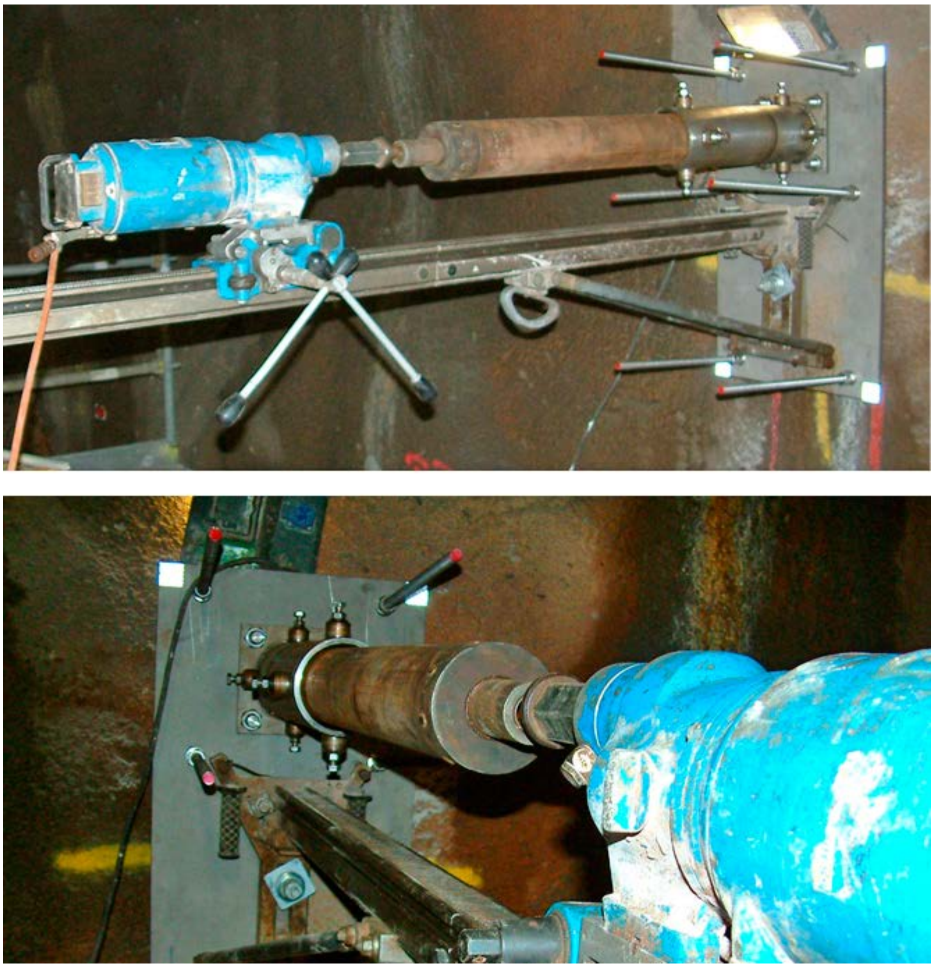


Figure 4-9. Aligning equipment developed by the KBS-3H project for drilling casing holes with high accuracy.

The drilling of the borehole, designated K08028F01, was carried out 1st to 12th of June 2014. Drillcon Core AB was contracted to drill the borehole and Devico Sweden AB provided the directional equipment and expertise. It was planned for 100 m but the borehole was terminated at 94 m due to intersection of extensive red staining and foliation, most likely associated with a spaly or a parallel structure to the dominant Äspö shear zone (EW01). The argument for termination was that large groundwater inflows would influence characterisation work and could require grouting of the pilot hole, an action the project prefered to avoid given the planned Mega Packer tests planned in the drift.

During drilling of the first 64 m, the direction of the borehole was measured multiple times both with the gyro and the magnetic tool. Its direction was controlled a few times by adjusting the position and sequence of the reamers on the core barrel, which gave some directional control of the borehole trajectory both in the vertical and the horizontal planes.

After 64 m the borehole was surveyed approximately 25 times and was still kept within the KBS-3H requirements. However, the borehole had started to show a deviation to the right that prompted the first steering action. The DeviDrill directional core barrel was prepared with a low offset angle and directed to the left over a drilling length of 1.2 m. The effect of the steered drilling was as expected with the borehole turning left, however along with a slightly larger upward inclination, but still within the requirements.

To improve the accuracy of the borehole further, a second short 1.2 m correction was initiated at 73 m depth. It was directed slightly down to the left to guide the borehole towards the theoretical bulls-eye. It worked out as the rise in inclination was supressed and azimuth continued to trend to the left.

When assessing the deviation of the borehole, based on the final measurement with the gyro in and out, it is well within the KBS-3H requirement. For inclination it deviates less than 3 mm/6 m and for azimuth less than 4 mm/6 m which is well within the ±10 mm/6 m of the KBS-3H requirement.

The borehole is also well within the KBS-3H requirements with regards to max/min inclination and sideways deviation.When the (x,y,z)-coordinates were calculated, the deviation from the theoretical point of the hole at 92 m (max length with gyro) was 3.5 cm (in terms of space vector).

Characterisation of K08028F01

The characterization of the borehole includes; Ramac borehole radar, BIPS and OPTV optical televiewer imaging, Boremap logging of the drillcore, Posiva difference flow logging (PFL), borehole geophysics and reciprocal interference tests between K08028F01 and the neighbouring K03009F01 cored borehole.

The borehole has subsequently been subjected to a geoscientific borehole interpretation (SHI-GS) involving geology, geophysics and hydrogeology aiming at identifying rock units and potential deformation zones in the borehole.

The dominant rock types observed in the borehole are Ävrö granodiorite, fine-medium grained granite and fine-grained Diorite-gabbro in total making up c. 95% of the borehole length. Subordinate rock types include pegmatite and porphyritic Äspö diorite. The SHI-GS identified five potential deformation zones, of which the innermost (DZ5) was attributed high confidence of existence, Figure 4-10. Borehole radar reflectors are associated with DZ1, DZ2 and DZ5.

The PFL investigations indicated three principal flowing fractures in borehole K08028F01 with a total inflow of approximately 1.5 l/min. This stands in contrast to the results from neighbouring borehole K03009F01 that indicates a large number of conductive structures.

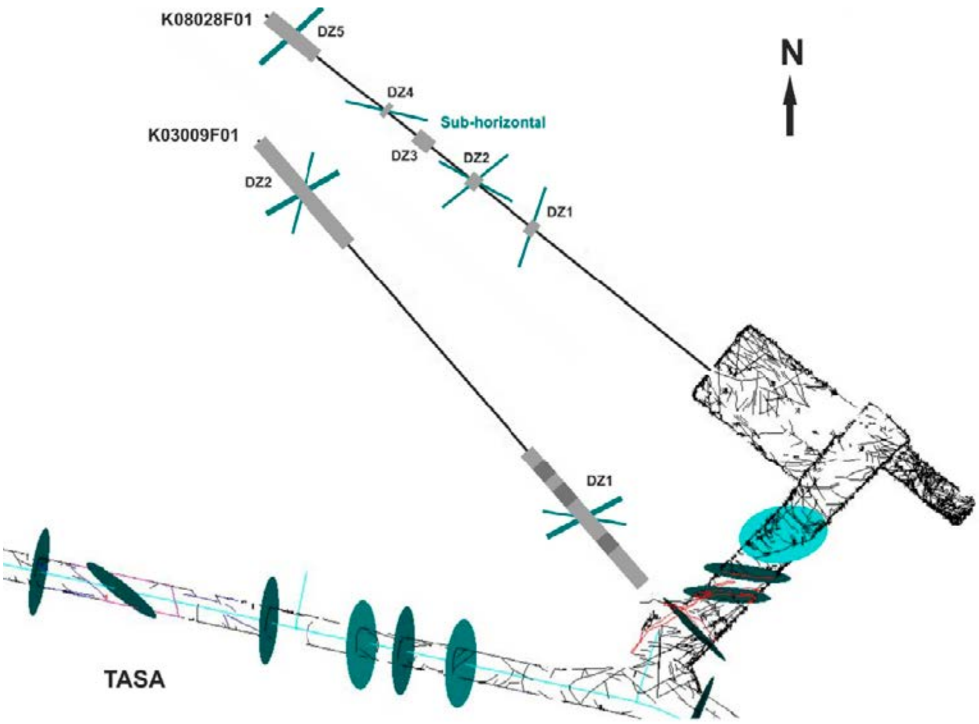


Figure 4-10. *Mapping of potential deformation zones (DZX) in borehole K08028F01 and the neighbouring K03009F01, with associated principal fracture orientations. It should be noted that the identification of DZs in K03009F01 was done with low resolution whereas the resolution in K08028F01 is better tuned for identification of large (critical) fractures.*

Subsequent to single-hole investigations multipacker systems, optimized to the situation in the two boreholes, were installed in both boreholes. In all, boreholes K03009F01 and K08028F01 were equipped with 10 and 9 test sections, respectively. In total, 9 constant rate pumping tests were performed employing the SKB HWIC test regulation equipment, of which four were conducted in K08028F01. The evaluation of the tests involved calculation of different response indices, transient evaluation of observation sections and steady state and transient evaluations of pump sections. Evaluated transmissivities of the pumping sections in K08028F01 vary between c. $2 \cdot 10^{-9}$ and $2 \cdot 10^{-8}$ m^2/s.

Future drilling activities

The successful drilling of a 94 m borehole within the KBS-3H requirements will be followed by a 300 m steered core drilling for KBS-3H at ONKALO. A similar methodology will be implemented which will allow the KBS-3H project to assess the transferability of results and experiences between sites.

Borehole K08028F01 at Äspö is also suitable for a future stepwise reaming to a full scale KBS-3H drift which will allow for an assessment of the capabilities to predict the hydraulic conditions in a drift based on measurements in the pilot borehole. It should also allow for future studies of post-grouting using the Mega-Packer at groundwater conditions similar to that of a repositiory.

4.5 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.

Knowledge pertaining to the movement of gas in initially water saturated buffer bentonite is largely based on small-scale laboratory studies. While significant improvements in our understanding of the gas-buffer system have taken place, laboratory work 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. Additionally, a full-scale experiment designed to identify gas pathway formation is suited to study the hydration of the bentonite buffer over a 10+ year time-scale.

The experiment has been in continuous operation since February 2005 (Cuss et al. 2010). 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 and involved a gas injection test throughout 2013. In 2014, the focus of the experiment was to determine the hydraulic properties of the bentonite buffer at all measurable locations by means of two-stage hydraulic head tests.

Objectives

The aim of 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.
- Provide data on the hydration of a full-scale KBS-3 system.

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 4-11). A deposition hole, 8.5 m deep and 1.8m in diameter, was drilled into the gallery floor. A full-scale KBS-3 canister (without heater) has been emplaced in the hole. Thirteen circular filters of varying dimensions are located on the surface of the canister to provide point sources for the injection of gas to mimic canister defects. Pre-compacted bentonite blocks with high initial water saturation have been installed in the deposition hole. The hole has been capped by a conical concrete plug retained by a reinforced steel lid capable of withstanding over 5,000 tonnes of force.

In the field laboratory instruments continually monitor variations in 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.

Lasgit has consisted of four operational phases; the installation phase, the hydration phase, the gas injection phase, the homogenisation 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.

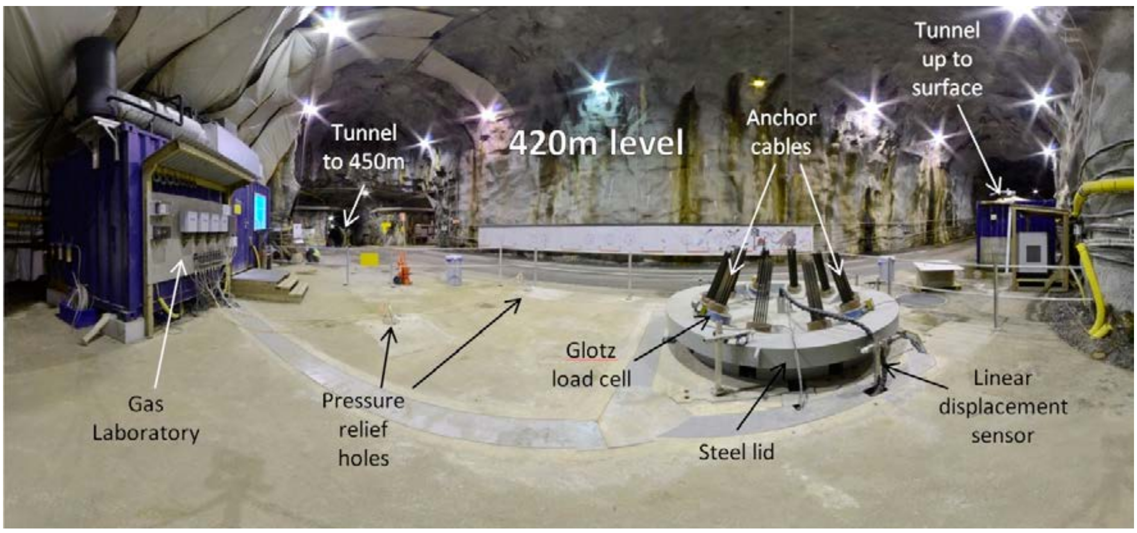


Figure 4-11. *The Large Scale Gas Injection Test at the –420 m level in Äspö HRL.*

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

Results

During 2014 (day 3,255 – day 3,620) the test programme of Lasgit concentrated on the characterisation of the bentonite buffer and the study of homogenisation. Following the completion of the gas injection test performed in 2013, the system was modified in order to study the water uptake of the buffer. The four syringe pumps have been arranged so that one each studies the artificial hydration mats, the lower canister filters, the mid-plane canister filters and the upper canister filters.

Two-stage hydraulic constant head tests were conducted in eleven of the thirteen canister filters in order to determine the hydration state of the buffer at these locations. Figure 4-12 shows an example of the two stage test for filter FU909. Filter FL903, the filter used for the gas injection test, was not tested, neither was filter FU912; the latter of these filters has not been artificially hydrated at all during testing and has been left so that predictions of the hydration state at this location can be compared with that measured later in the test history.

The two-stage hydraulic constant head tests offer a snap-shot measurement of the hydration state, which can be compared with the previously determined hydraulic data. These data will be published as a peer reviewed paper in 2015. During testing, filter FL902 was found to be problematic. Higher than expected flow rates were observed and on isolating the testing syringe pump the pore pressure was seen to drop rapidly. Examination of the laboratory during the annual calibration and service in January 2015 showed that no leak could be identified in the lab; this sugests that the buffer at FL902 had become conductive. Final decommissioning of the canister at the end of Lasgit will determine whether the filter itself has been leaking into the canister or if conductive channels have been formed in the buffer.

Filter FL903 was used to perform a gas injection experiment in 2013. During 2014 this filter was isolated and the pressure was monitored during pressure decay. Pressure reduced from 5.8 MPa to 4.9 MPa during 2014. This filter will continue to be isolated in order to determine the capiliary threshold pressure at this location.

Figure 4-13 shows the complete history of the Lasgit experiment and shows that stress is continuing to increase in the deposition hole. Pore pressure within the bentonite buffer is now increasing and should equilibrate with the pore water within the host rock within 3 to 5 years. The reduction in pore pressure of the host rock as a result of draw-down from the tunnel excavation has appeared to have reached a plateau.

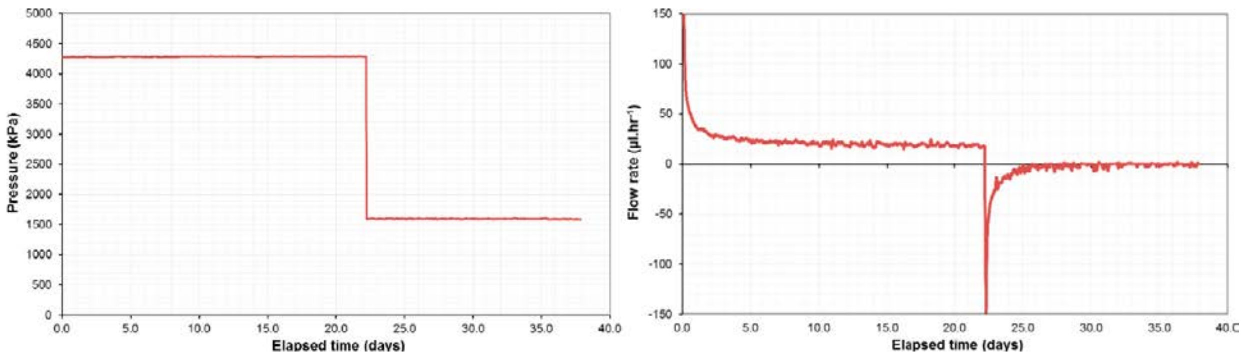


Figure 4-12. *Results for two-stage hydraulic constand head test conducted in upper canister filter FU909. Pore pressure imposed in the filter is shown on the left, with the resultant flow shown on the right. These data are used to determine permeability and storage of the buffer.*

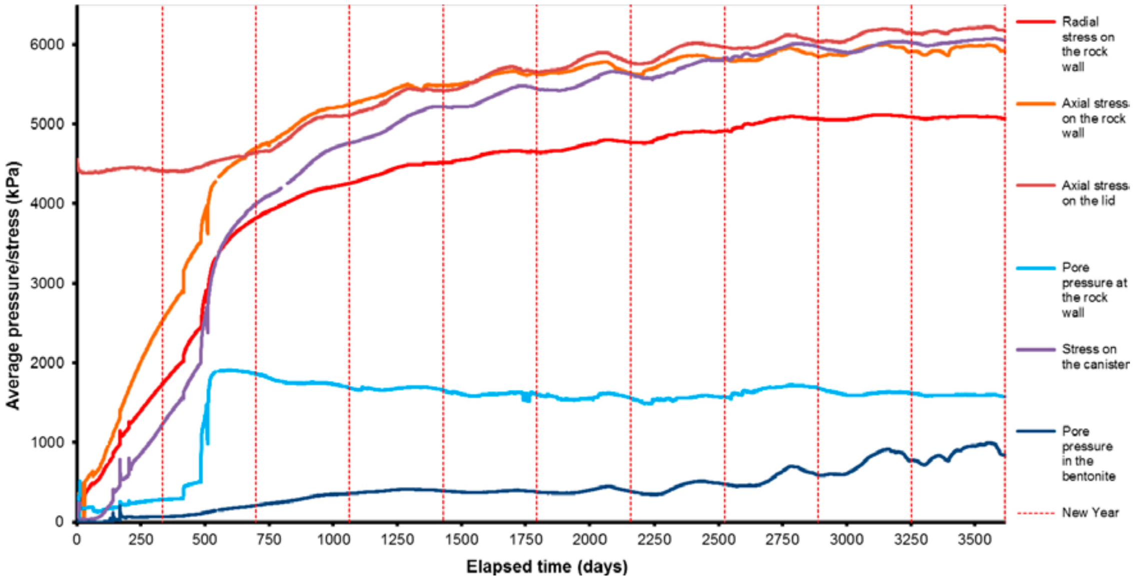


Figure 4-13. *Average pore water pressure and stress readings during the complete 10-year history of Lasgit. As can be seen pore water pressure readings at the deposition hole wall has been decaying since day 500 due to the draw-down of the Äspö HRL due to pumping of the galleries. It can be clearly seen that stress, axial force and radial stress at the rock wall all continue to increase as the buffer matures. The pore pressure within the bentonite buffer continues to increase and should equilibrate with the local pore water pressure within 3 to 5 years.*

4.6 In situ corrosion testing of miniature canisters

Background

The post-failure evolution of the environment inside a copper canister with a cast iron insert is important for the assessement of 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).

Five miniature copper-cast iron canisters have been exposed to the groundwater flow in boreholes in the Äspö HRL since late 2006. In order to model failure, defects were introduced into the outer copper shell, making it possible to investigate the evolution of corrosion inside the canisters. Corrosion will take place under saline, eventually oxygen-free and reducing conditions in the presence of the microbial flora in the Äspö groundwater; such conditions are very difficult to create and maintain for longer periods of time in the laboratory. Consequently, the MiniCan experiment will be valuable for understanding the microbiological influences on canister corrosion and degradation, as well as for the understanding the development of the environment inside the canister after penetration of the outer copper shell.

Objectives

The main objectives of the experiment are; 1) to provide information about how the environment inside a copper-cast iron canister would evolve if failure of the outer copper shell were to occur, and 2) how microbiological influences affect canister corrosion and degradation. 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?
- 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?
- How does the microbial flora of the deep ground water influence the development of canister corrosion?

Experimental concept

In late 2006, five miniature copper-cast iron canisters were mounted at a depth of 450 m in the Äspö HRL (Smart and Rance 2009). 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.

The canisters are mounted in electrically insulated support cages (Figure 4-14), 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 effect of direct groundwater flow on the corrosion behaviour.

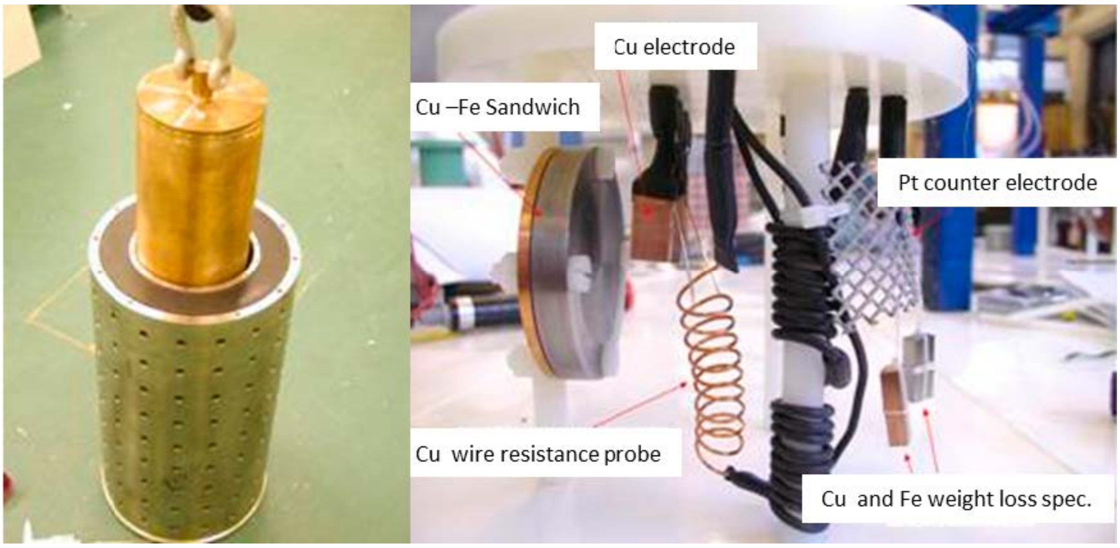


Figure 4-14. Model canister being lowered into support cage containing bentonite pellets in annulus (left). Test electrodes inside support cage around model canister experiments (right).

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 detectany 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 groundwater to the canisters. The experiments are continuously monitored to measure the following parameters:

- Corrosion potential of the model canister, cast iron and copper.
- Electrochemical potential of gold, platinum and a mixed metal oxide Eh probe.
- Corrosion rate of cast iron and copper, using linear polarisation resistance (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.

Water samples are taken regularely from the support cages as weel as from the boreholes 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 was the report on the analysis of the retrieved experiment 3 (Smart et al. 2012). In that report U-bend- and wedge open loaded specimens for evaluation of stress corrosion cracking (SCC) of copper were examined by optical microscopy. During 2013 these specimens were examined further using scanning electron microscopy (SEM) and energy dispersive x-ray analysis (EDX). Neither optical, nor SEM/EDX analysis revealed any signs of SCC in the copper samples (Smart et al. 2013). Further metallographic examination has been made during 2014 and will be published during 2015.

In October 2013, the retrieval and post-test analysis of experiment 3 was presented at the 5th International Workshop on Long-Term Prediction of Corrosion Damage in Nuclear Waste Systems in Asahikawa, Japan. A paper based on the presentation and discussion at the conference was published during 2014 (Smart et al. 2014).

4.7 Concrete and Clay

Background

The project Concrete and Clay was initiated with the aim of increasing the understanding of processes that may occur in SKB's repositories for low- and intermediate level waste; the Final Repository for Short-lived Radioactive Waste (SFR), and the future Final Repository for Long-lived Radioactive Waste, SFL.

In SFR which was taken into operation more than 25 years ago, concrete and other cement based materials are extensively used in the engineered barrier system, either alone or in combination with bentonite as in the Silo.

For SFL which is currently planned to be taken into operation in the year 2045 the SFL concept study suggested that the core components as well as the PWR reactor pressure vessels from the nuclear power plants should be disposed of in a rock vault in which the engineered barrier system is based on the use of concrete alone. The legacy waste currently stored at the Studsvik site and which comprises a complex mixture of different materials and nuclides was suggested to be disposed of in a rock vault in which large amounts of bentonite clay is used in the engineered barrier system.

In these repositories interactions will take place between the materials in the engineered barriers, the different waste form materials, the ground water itself as well as species dissolved in the ground water.

These interactions will cause changes in the physical and chemical properties of the barrier materials as well as a degradation of the waste leading to the formation of species that may further affect the properties of the materials in the engineered barriers.

Objectives

The objective of this project is to increase the understanding of the processes described above.Three main fields of interest have been identified:

- Decomposition of different waste form materials and transport of the degradation products in a cement based matrix.
- Mineral alterations in the concrete itself and at the interface between concrete and different types of bentonite in the presence of degradation products.
- Transport of degradation products in bentonite under natural conditions and mineral alterations in the bentonite.

Experimental concept

During the time period 2010–2014 a total of 9 packages comprising concrete cylinders or bentonite blocks each containing different types of waste form materials have been deposited at different locations in the Äspö HRL.

The concrete specimens which were prepared and deposited during 2010 and 2011 are cylinder shaped with a diameter of 300 mm and a length of one meter. A total of 12 concrete cylinders in four packages were deposited in two Ø 350 mm holes in each of NASA0507A and NASA2861A respectively. The slit between the concrete specimens and the rock wall in the hole was filled with sand. The experiments were finally sealed with sand, and bentonite and closed with a concrete lid.

During 2014 the bentonite specimens comprising 150 bentonite blocks in 5 different packages have been prepared and installed in TAS06. In each bentonite block (Ø 270 mm and height 100 mm) 4 different material specimens have been placed. The specimens were manufactured from ordinary cement and low-pH cement or the same type of bentonite as the block itself and contain either a metallic powder or a metal salt of a material representative for low- and intermediate level waste.

As a complement to the experiments described above, different waste form materials have also been placed in steel containers filled with a mixture of Äspö ground water and hardened and crushed cement paste under a nitrogen atmosphere to mimic the oxygen free conditions in the bedrock. The objective of these specimens is to serve as a guide for the decision on when to retrieve the specimens from the bedrock. Samples of the water can be retrieved and analysed at regular intervals in order to detect the presence of waste form degradation products. The steel containers were transferred from the cement laboratory at Ringhals NPP during 2013 and are currently stored in NASA2861A. About half of the containers are stored under ambient temperature and the remaining at about 50°C in heated water.

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

Installation of the experiments

During 2010 and 2011 a total of 12 concrete cylinders containing different waste form materials were prepared and deposited in two holes in each of NASA0507A and NASA2861A respectively.

During 2014 the bentonite experiments were prepared and installed in TAS06. A total of 150 bentonite blocks were manufactured from MX-80, Asha, Febex and Ibeco RWC. In each bentonite block 4 holes were drilled in which the different specimens were emplaced, Figure 4-15. The specimen cylinders were manufactured from standard cement and low-pH cement respectively and each contain a metal powder or a powder of a metal salt representative of the low- and intermediate level waste. Specimens were also manufactured from solid rods of steel and stainless steel.

The bentonite blocks were then stacked on top of each other inside a cage made of titanium, Figure 4-16, after which the entire deposition package was placed in a protective cover and transported to the experimental site for emplacement in the deposition holes, Figure 4-17. Finally the experiments were sealed with sand and bentonite and closed with a concrete lid, Figure 4-18.

Due to the very low water flow in the fracture system in TAS06 it was decided to install a system for artificial saturation of the bentonite blocks. The design of this system was inspired by the design of the system used for saturation of the experiments in the project Alternative Buffer Material, ABM, described by Eng et al. (2007).

The system comprises a pressurised tank, a system of valves, plastic tubes and perforated titanium tubes attached to the titanium cages for distributing the water in the sand bed between the bentonite blocks and the bedrock in the deposition hole. The tank (approximate volume of about 150 dm^3) was filled with Äspö ground water and pressurized to an absolute pressure of about 1.2 atm. by means of nitrogen gas.

An installation report is currently being compiled and will be published during 2015.

Analyses of the water in the steel containers

During 2014 the first samples from the steel containers have been analysed. This study was aimed at investigating the possible presence of colloids in the steel cylinders containing bitumen and other types of organic materials such as ion exchange resins and cellulose with the main focus being on bitumen which had been stored at 50°C for 3 ½ years. The number of colloids which was analysed by means of Photon Cross-Correlation Spectroscopy (PCCS) was found to be very low and on the same level as ordinary drinking water in all cylinders. It was thus concluded that no colloid formation had occurred during the first 3 ½ years of storage. The cylinders have all now been restored to Äspö and future analyses will be perfomed.

Figure 4-15. Final preparation of a bentonite block. Left image shows how the block has been given its final shape with slits made to fit with the titanium cage and holes drilled for the small sample cylinders. In the centre image a cement cylinder has been placed in the small hole and the right image finally shows how the holes have all been filled with bentonite powder of the same type as the bentonite block itself.

Figure 4-16. *The lower part of three of the titanium cage used in the large scale bentonite experiments.*

Figure 4-17. *Lowering the bentonite package into the deposition hole.*

Figure 4-18. Installation completed and system for artificial saturation of the experiments connected.

4.8 Low pH-programme

Background

The purpose of the Low-pH programme is to develope cementitious low-pH 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 in construction of plugs for the deposition tunnels. The low-pH concrete, B200, developed within this programme (Vogt et al. 2009) has been used for construction of a full size plug for sealing of a deposition tunnel during 2013. A monolite was also cast in the same low-pH concrete and with the same time, to be able to investigate long term properties of this material. A new project which aims to widen the recipes for cementitious low-pH materials started at 2014. Developed recipes in this project will be tested at Äspö HRL during 2016–2017.

Objectives

The purpose of the programme is to develop cementitious low-pH materials which can be used in the Final Repository for Spent Nuclear Fuel.

Experimental concept

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

During 2009 field tests also started on corrosion behaviour of steel in low-pH concrete. 24 samples were prepared and placed in an open container in a niche at Äspö HRL. Each specimen contained three steel bars, Figure 4-19 and Figure 4-20. Each steel bar, with a diameter of 20 mm and a length of 200 mm, was carefully cleaned and weighed with a accuracy of a thousandth gram. The specimens were then placed for field exposure in an open container in niche NASA2715 at the Äspö HRL, Figure 4-21. The development of the rock bolt grout and shotcrete for rock support and the results of corrosion tests after one year of exposure are reported in a SKB report (Bodén and Pettersson 2011).

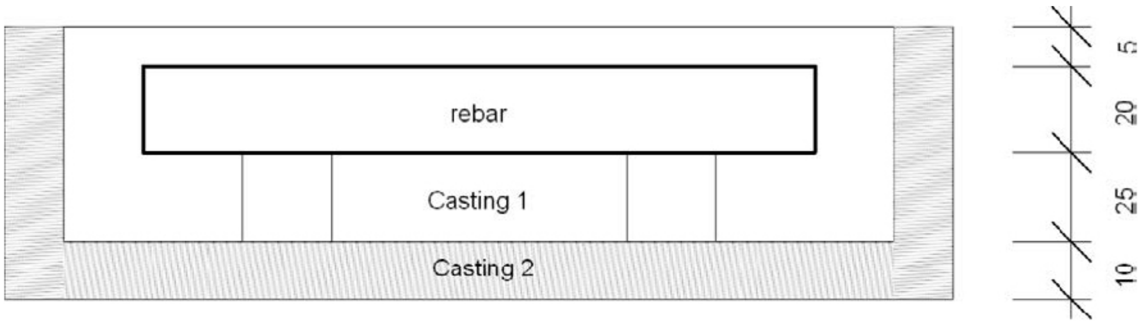


Figure 4-19. *Specimen's dimentions (mm).*

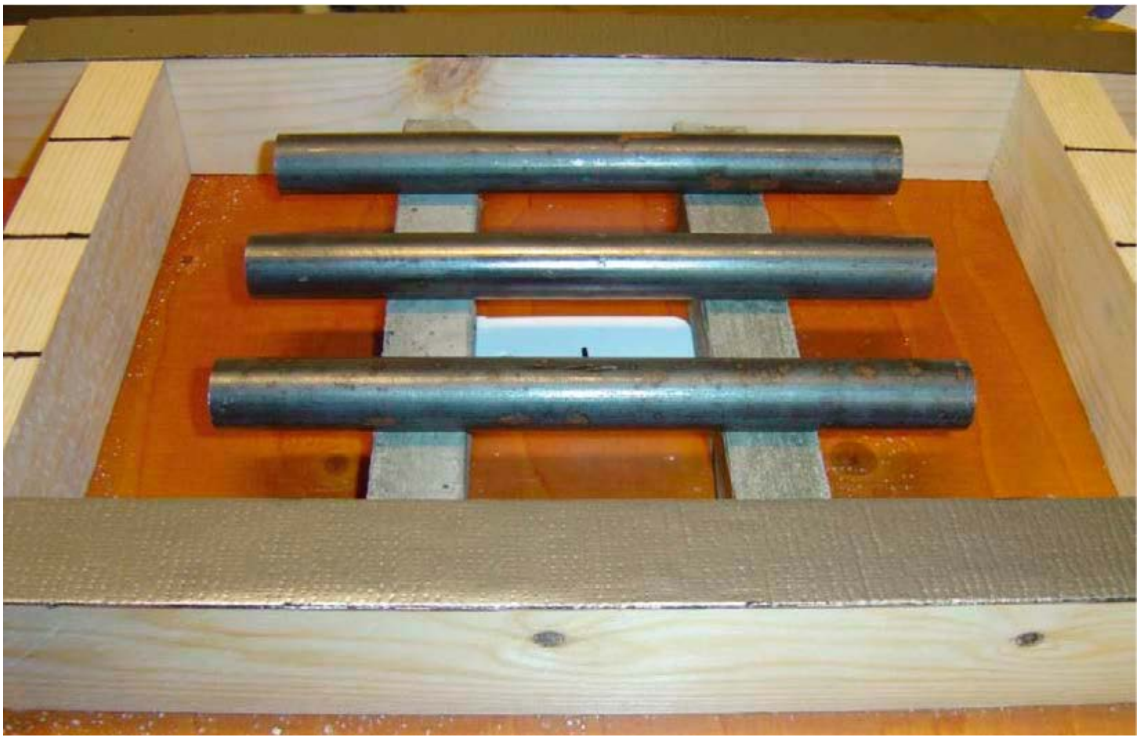


Figure 4-20. *Mould and steel bars on support before casting.*

Figure 4-21. *Container in Äspö HRL with corrosion tests samples.*

A monolite has been cast using the same low-pH concrete as in the Domplu-test (system design of dome plug for deposition tunnels, see Section 4.11) and in the same area as the plug, Figure 4-22. The programme will follow the evolution of the low-pH concrete and changes in material properties by taking core samples from the monolite, during three years and even further if it shows to be of advantage for better understanding of these materials.

Results

During 2013, three rock bolts, two horizontally and one vertically emplaced, were over-cored and investigated. Over-coring the vertically emplaced bolts showed to be extremely demanding and time consuming. Therefore it was decided to settle with over-coring for only one of the vertical bolts. The investigation covered both the condition of the low-pH concrete and the corrosion behaviour of the bolts after almost five years exposure at the field. Six concrete blocks containing three steel bars each, were also investigated during 2013 following the corrosion experiment. Corrosion behaviour of the steel bars in low-pH concrete and conventional concrete, both in presence of chlorides and without chlorides has been investigated and compared. The results of these investigations have been published in a SKB report (Aghili 2014). Due to the results of this investigation it was decided to extend the time schedule for the experiment. The next investigation will be done at 2018 and the date for the last investigation will be settled with respect to the results from the investigation at 2018.

Concrete cores have been taken from the monolite, casted with the same material as the Domplu, after 28 days, 90 days, 120 days and 180 days hardening in the Äspö HRL. These cores have been investigated with regard to their strength. Even the modulus of elasticity has been determined in some cases. The results have been published in a SKB report (Mathern and Magnusson 2015). The testing programme has continued with investigations after one year of exposure which will be reported in the Domplu project. Thereafter the low-pH programme will continue to take out cores and investigate them with 2 and 3 years of exposure. The exposure and investigations may continue even for a longer period of time, if the results are jugded to be of interest.

Figure 4-22. *Monolite in low-pH concrete.*

4.9 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 summarised 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), NDA (England) and DOE/UFC (USA). All together 10–15 modelling teams are participating 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 (Clay Technology).
3. Ca/Na-exchange in montmorillonite (Clay Technology).
4. Core infiltration test on material from parcel A2 in the LOT-experiment (UniBern).
5. Anion of selected anions through compacted bentonite (ÚJV Rez).

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 2014; one in Tokyo on May 20–22 and one in Berkely on November 9–12. The latter meeting was a joint meeting with the *Task Force on modelling of groundwater flow and transport of solutes*. For information about performed work within the different tasks by the international organisations, see Chapter 8.

THM

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,

4–6 teams are working with this task. An additional phase 2 of this task has been added. It implies code validation with well defined tasks and parameter values. SKB has contributed to this phase with Code Bright models and Comsol models.

Task 8: hydraulic interaction rock/bentonite

This task focuses on the hydraulic interaction between the rock and the bentonite and is a joint task with the groundwater 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 been finalised during 2014. The project is described in more detail in Chapter 3. Six modelling teams have been working with this task and presented the status of the work. SKB team 1 has given the following status report:

The primary goal of the modelling was to predict the hydration in the two boreholes (Hole 17 and 18) in the BRIE experiment, by modelling the natural wetting of the bentonite from the host rock. The models were constructed using characterisation data from the field, which consisted of: 1) open borehole inflow mapping (based on nappy measurements) in hole 17, 2) open borehole inflow into the lower part of hole 18, and 3) the position of the boreholes and their depth within the ÄSPÖ HRL. Furthermore, a DFN model describing the fracture network around the BRIE site was provided. However, as the models described here were solved using the finite-element program Code_Bright, such a fracture network could not be implemented, and a simplified approach was used. The host rock was considered to be a homogeneous material with high water conductivity everywhere except just around the boreholes, where the fractures identified from the field characterisation were included. These intersected a low-conductivity material, which was used to represent the rock matrix. An illustration of the large scale (left panel) and borehole scale (right panel) geometry is shown in Figure 4-23.

The models presented here were constructed and executed when the field experiment was ongoing, and hence before it was dismantled. Thus, data from the RH sensors emplaced in the bentonite from approximately the first 100 days were used to calibrate the models. Furthermore, at the time of writing the field experiment has been dismantled and the bentonite parcels analysed. In the results shown

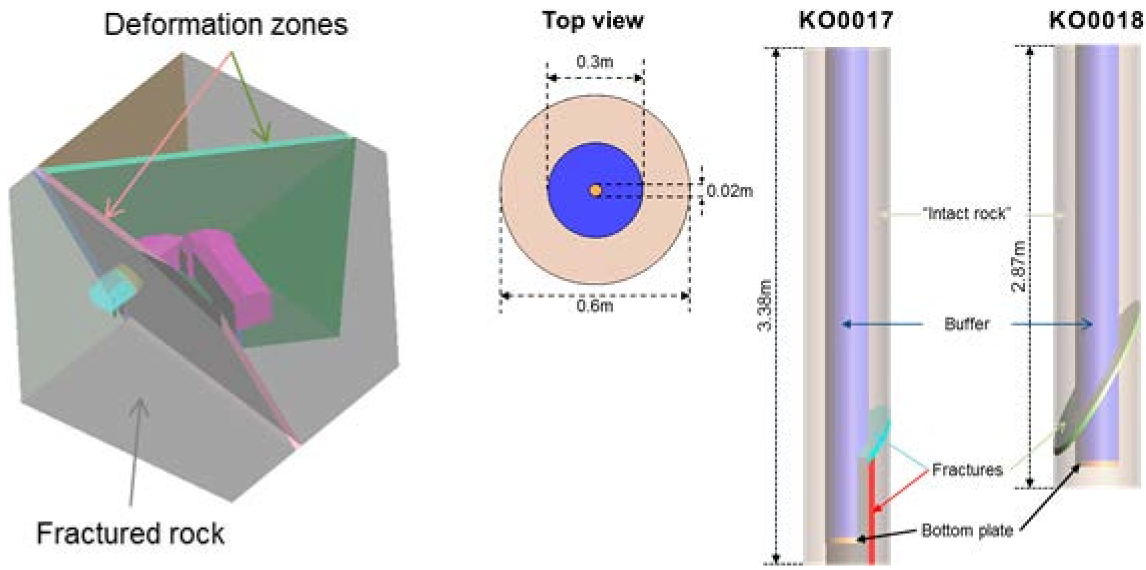


***Figure 4-23.** Illustration of the large-scale geometry (left panel) and the borehole geometry (right panel) used to simulate the BRIE field experiment.*

in Figure 4-24, the modelled data is therefore shown together with the experimentally measured RH data. After the excavation and dismantling operation it was also realised that the position and orientation of the fractures relative to the instruments was slightly different compared to what had been previously thought. In the results shown in Figure 4-24 this has been accounted for by changing the coordinates of the evaluated RH evolutions. The results from the model of hole 17 shown in the left panel of Figure 4-24, while the results from the model of hole 18 is shown in the right panel. Here solid lines represent model data and dashed lines identify experimental data.

Comparing the modelled and experimental data shows that the models are able to reproduce the evolution in both hole 17 & 18 rather well, even though they are constructed using a rather coarse treatment of the surrounding rock on the large scale. Some discrepancies do, however remain, in particular in hole 18. This is, as shown by dismantling data, most likely caused by wetting from several small fractures, which were not included in the model.

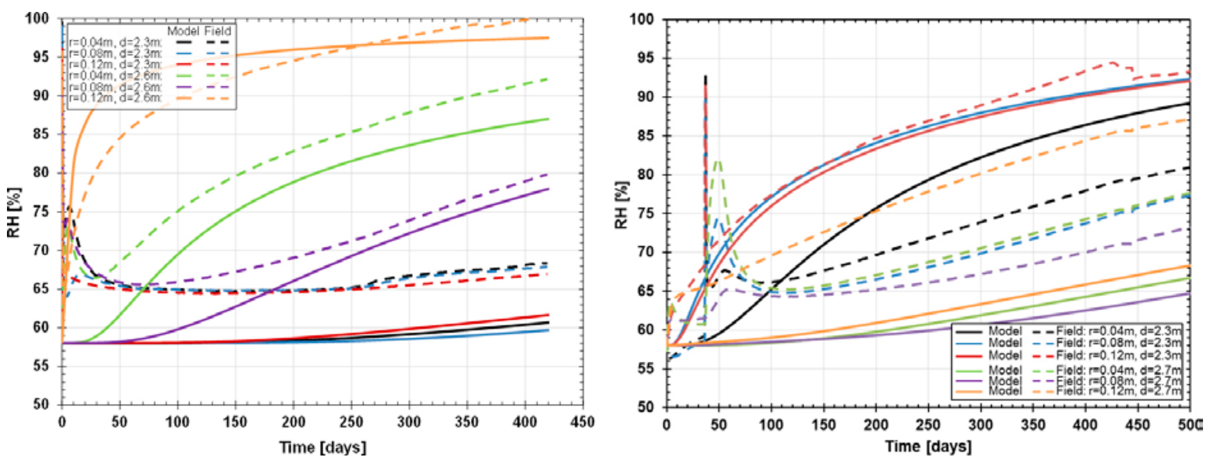


***Figure 4-24.** RH evolution as seen in the model (solid lines) and in the field (dashed lines) in the deposition borehole 17 (left panel) and borehole 18 (right panel). It should be noted that both holes were temporarily flooded with water during the early stage of the experiment. This increased the RH at the sensor positions; an effect which is not included in the models.*

An important result of the modelling is that the models which best reproduce the experimental RH-data has very small matrix flow. That is, almost all the water enters the bentonite via the modelled fractures. As the agreement between model and experimental data is very good for hole 17, this strongly suggests that at least in that borehole, the volume of water which may have entered the bentonite from the rock matrix was insignificant compared to that which came in via fractures. In borehole 18 the picture is not as clear, as the model data does not agree as well with experimental data; however, if matrix flow was present, its contribution to the overall wetting still appears small compared to the water which entered via the fracture(s).

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 involves two subtasks. In subtask 1 a number of laboratory swelling tests that have been made are modelled and used for checking/calibrating the mechanical model. In subtask 2 a laboratory scale test that simulates bentonite lost in a deposition hole was started two years ago and is still running and could be preceded by predictive modelling, which was also done by the SKB group.

During 2014 the modelling groups have continued the modelling and in the autumn reports of subtask 1 was delivered by four modelling groups.

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. Three steps for solution strategy have been proposed:

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.

Eight modeling teams are working with this task. Most of them have finished step 1 and are working with the following steps.

Geochemistry

Two meetings were held during 2014, one in Tokyo and one in Berkeley (US), in which modelling results, laborartory results and conceptual considerations were presented.

The basic part of the work concerns modelling of a set of four previously defined Benchmark experiments; Benchmark 1 concerns chloride diffusion at different salt gradients in Na- and Ca-bentonite, Benchmark 2 concerns gypsum dissolution and Na/Ca diffusion in Na- and Ca-bentonite, Benchmark 3 concerns Na-to-Ca and Ca-to-Na ion exchange and diffusive transport and swelling pressures, Benchmark 4 concerns multi-component advective-diffusive transport in a column experiment at constant confining pressure. A fifth benchmark was added at the Tokyo meeting, and concerns diffusion of anions (Cl, Se, I) through compacted bentonite (B57, treated Rokle).

Urs Mäder launched the Tokyo meeting with an introduction concerning the five Benchmarks.

Eva Hofmanova presented the experimental results from the new Benchmark five, followed by Radek Cervinka who presented new modelling results from the benchmarks. Magnus Hedström showed results from MD simulations dealing with ion equilibrium in compacted montmorillonite. Ola Karnland showed experimental results and theory for what was interpreted to be chemical reactions in montmorillonite interlayers at high pH conditions. Tsutomo Sato also dealt with high pH interation with bentonite and presented observations by X-ray Computed Tomography and results from geochemical modelling. The purpose of modelling was discussed by Martin Birgersson, who effectively demonstrated the futility of just reproducing laboratory results without assessing e.g. model complexity and number of fitting paramters. Magnus Hedström presented work concerning network forces in smectite gels investigated by their thermoreversible behaviour. Finally, Urs Mäder presented the outcome of "C-Workshop" at Uni Bern 2013.

At the meeting in Berkeley Urs Mäder made an introduction to chemistry session including an overview of issues. Mingliang Xie showed an update on MIN3P-THCm Simulations of EBS TF-C Compacted Bentonite Diffusion Experiments. Eva Hofmanová presented experimental work on Pertechnetate and perchlorate diffusion through compacted bentonite and made a comparison with Benchmark 5. Martin Birgersson showed the results from modeling of Benchmark 5 by use of the code previously developed by himself. Peter Alt-Epping showed the main outcome of the reactive transport modelling of chemical processes in the bentonite backfill at Olkiluoto. Atomistic level views of clay-water interfaces was presented by Ian Bourg. Ola Karnland denounce the nomenclature problems in the "Letter to Nature" by R. Couture, and presented experimental results concerning swelling pressure and hydraulic conductivity response on Na/Ca exchange in compacted bentonite. Martin Birgersson commented the STUK-TR 10 document, which was brought up in the previous meeting. Finally there was a discussion of Chemistry Session led by Urs Mäder with special respect to future activities/ bench marks, code comparison in the C session.

4.10 System design of backfilling of deposition tunnels

Background

The KBS-3V Final Repository for Spent Nuclear Fuel consists of deposition tunnels with copper canisters containing spent nuclear 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 the rock wall is filled with pellets. The project *System design of backfill* has been completed during 2014. The work has consisted of investigations, calculations, laboratory tests and full-scale tests underground at Äspö HRL.

Objectives

The project objective was 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

Since 2010, work has been done on system design, optimisation of pellets, development of the production processes for bentonite components, and design and construction of prototype equipment for installation of backfill blocks and pellets. The main achievement during 2014 has been the performance of a full scale backfill installation test with prototype equipment underground at Äspö HRL, testing the designed system in full scale.

Results

In the test, 12 meters of the TASS-tunnel, situated at a level of –450 meters, was filled with backfill blocks and pellets. An installation robot was placed on a platform. Temporary guide rails were placed on the blasted tunnel floor so that the robot platform could be operated and moved easily during the test. A wheel loader was used to move the platform along the guide rails, as the installation proceeded.

The control system was operated in semi-automatic mode, in which the control system suggested the next task to be run rather than running it automatically. The robot was operated and monitored from a container placed 100 meters from the installation site. A dome camera was used to give visual feedback from the installation to the operator. Logistics regarding the moving bentonite components was handled manually in the absence of a sufficient transport system.

The test was performed around the clock for nine days. Six people worked at each shift. In total, 1,684 blocks weighing about 225 kg each, were installed. 72,000 kg pellets were installed in the gap between the tunnel wall and the block stack by using shotcrete equipment. The total mass of pellets, including that which was placed on the tunnel floor, was 84,500 kg.

The main goal with the project was to ensure that the selected method for installation of backfill, and control of the installation, works as intended and with reasonable efficiency. The test was regarded as successful in showing that the installation method and control of the installation works. However, further work is needed to develop the installation concept and to make it more efficient. The project results has been published during 2015 (Arvidsson et al. 2015).

A new project has been started to complete the system design phase of the barriers buffer and backfill of the Final Repository for Spent Nuclear Fuel.

Figure 4-25. *A photo of KUKA KR 1000 L750 Titan, the prototype robot for installation of backfill.*

Figure 4-26. Installation robot operating in the TASS-tunnel.

Figure 4-27. Robot platform with block feeding system and installation robot.

Figure 4-28. The full-scale backfill installation is completed at Äspö HRL. 84.5 tons of pellets and 380 tons of blocks were installed in 12 m of tunnel.

4.11 System design of plug of deposition tunnel

Background

The reference conceptual design of a KBS-3V deposition tunnel end plug consists of an arched concrete dome, a bentonite seal, a filter zone and material delimiters between each layer. 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.

In the Final Repository for Spent Nuclear Fuel, plugs will be made of low-pH concrete instead of conventional concrete. The reason for this is to avoid the negative effects that alkaline 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 if possible. However, reassessment of the system during testing has reduced the applied water pressure to 4 MPa due to experimentally related water escape problems, as later presented in section Results below. A load case with a water pressure equal to 4 MPa is also a more realistic case for groundwater pressure in the repository. At the end of the measurements, i.e. just before dismantling the Domplu, the plan is still to perform a load test with up to 10 MPa of total pressure.

Data freeze for a functional evaluation of the first years' operation of Domplu was done on September 30, 2014. Monitoring will then continue until October 2016 and is reported separately.

Experimental concept

The experimental site for the Domplu-test is located at Äspö HRL –450 m level, where realistic hydro-geological conditions for a repository 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 displacements of the bentonite seal, filter and the backfill zone.

As stated above, a key objective is to monitor the water leak through the plug over time (about 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 cover) just downstream of the concrete dome and directed by gravity to a pendent scale for on-line registration of effluent water. The experiment is pressurised artificially with water in the backfill behind the plug, see Figure 4-29. The experimental set-up and pressurisation by water is targeted to reflect the conditions expected in the Final Repository for Spent Nuclear Fuel.

Results

In 2012, a suitable plug location was determined by core drilling and high pressure water injection tests (10 MPa) in a 30 meter long pilot hole. The test-tunnel (TAS01) was then excavated to 14 meters length by using drill and blast methods, with a modified blast sequence to ensure a discontinuous Excavation Damaged Zone (EDZ). The contour boreholes were thus blasted in a separate round.

The tunnel dimensions correspond to the reference design of SKB's deposition tunnels, which are 4.8 meters high by 4.2 meters wide, for a cross sectional area of 18.9 m^2.

The plug slot area was excavated to obtain smooth surfaces using the wire sawing technique in an octagonal shape, almost 9 meters in diameter. The wire sawing method is assumed to minimise risk of continuous EDZ and it provides as well smooth rock surfaces for the concrete dome. The performance and results of wire sawing are presented by Grahm and Karlzén (2015). In Figure 4-30, a model composed of data from the 16 laser scanned slot surfaces has been incorporated in the laser scanned model of experiment tunnel TAS01. The remaining half-pipe boreholes as seen in Figure 4-30 were filled by mortar before casting of the dome.

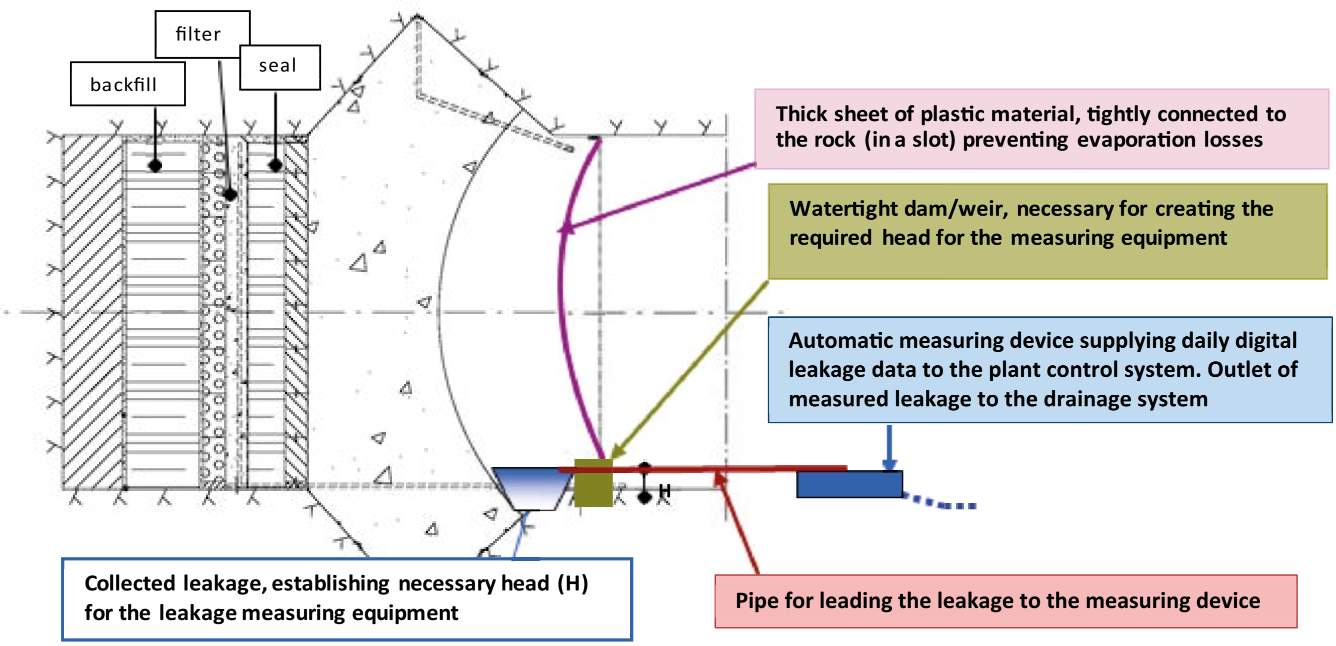


***Figure 4-29.** Layout of the full-scale experimental set-up Domplu.*

Figure 4-30. *Illustrative model structured of data from laser scanning of TAS01 as well as of the excavated slot abutment (seen from above).*

The installation of the inner plug components began in late 2012 and was completed in the beginning of 2013 see Figure 4-31 and Figure 4-32. Domplu was designed with 45 sensors in the backfill and seal layer and another 56 sensors within the concrete dome. The sensors in the backfill and seal layers are fed through pipes in the rock to the adjacent tunnel, a distance of about 21 meters. Sensors within the concrete are fed out the front face of the concrete dome. The properties being measured by the array of sensors include temperature, relative humidity, strain, displacement, pore pressure and total pressure. All data results are summarised and evaluated in SKB (2015).

On March 13, 2013 the casting of the concrete dome took place (Figure 4-33). The use of the B200 concrete was successful for the 94 m^3 structure. About 100 days later, to await the early concrete shrinkage, contact grouting was performed over three sections of the dome to close any gaps in the concrete – rock interface.

The monitoring of Domplu started in September 2013 (month 0) when the bentonite seal had been artificially wetted by controlled flooding of the filter during the summer. When the drainage valves to the filter were closed, pressurisation of the experiment began by the natural groundwater inflow, corresponding to about 100 kPa per week (month 1–2). From December 2013 (month 3), the pressurisation system is operational, pumping in water for a faster pressure increase rate of about 250 kPa per week.

When exceeding a water pressure just over 3 MPa (≈30 bar), two experimental related water escapes were observed; One water escape via the cable bundle from sensors within the concrete dome and one water escape in a rock fracture 14 metres in front of the plug. The flow rate of the two water escapes was subsequently measured manually, supplementing the on-line recording of leakage past the plug collected in the weir, see Figure 4-35.

***Figure 4-31.** 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.*

***Figure 4-32.** Installation of concrete delimiters, bentonite seal, macadam filter and sensors.*

Figure 4-33. *Concrete is pumped in behind the formwork for casting of the concrete dome structure.*

Figure 4-34. *The hardened concrete dome structure after removal of formwork. The steel beams in front of the dome are used for displacement sensors.*

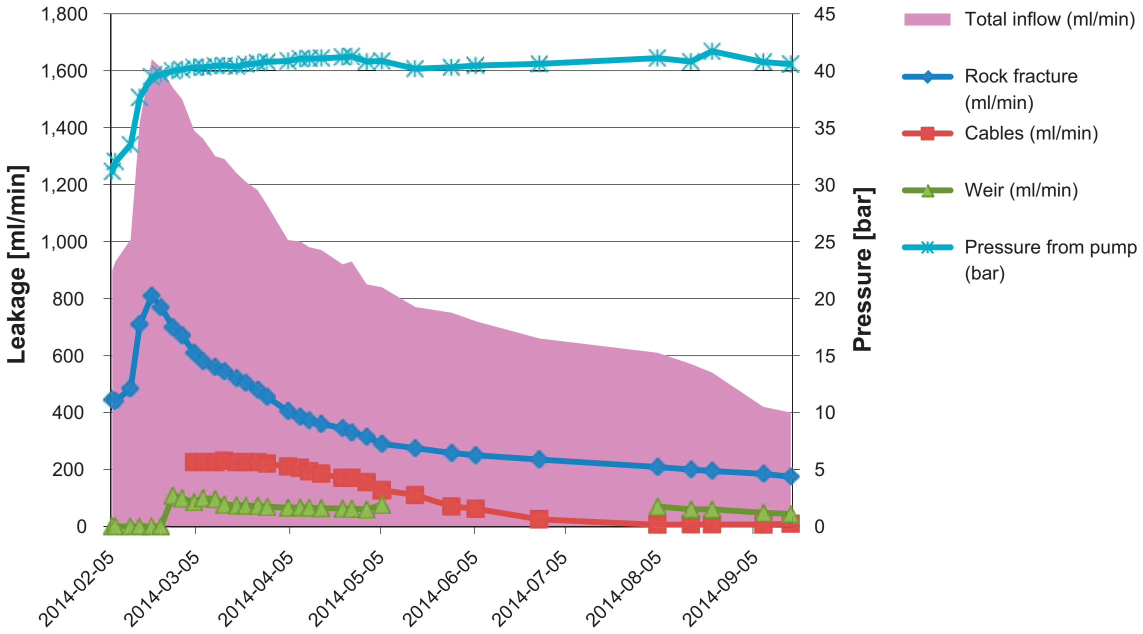


Figure 4-35. *Measurements of leakage together with total water injection flow needed to keep the water pressure stable near at 4 MPa (about 40 bar).*

As seen in Figure 4-35, initially about 1,600 ml/min injection water was needed to keep the 4.0 MPa water pressure in the filter. After eight months of plug system operation, just about 400 ml/min was needed to maintain the same pressure. This is probably due to effects of the swelling bentonite clay as well as of mineralogical clogging of fractures.

All data from monitoring of Domplu including comparisons with numerical analyses are presented and evaluated in SKB (2015). A brief summary of results is given below.

Since February 2014 (month 5), the water pressure has been fixed at about 4.0 MPa and the leakage rate collected from the weir during the follow up until the first data freeze September 30 (month 12) has been steadily reduced. On September 30, 2014, the recorded leakage rate was about 2.6 litres per hour (44 ml/min). This is well below the ambition level of a leakage rate past the deposition tunnel plug below 0.1 l/min. Moreover, based on the appearance of the measured leakage it is believed to decrease further since the swelling pressure of bentonite seal will continue increasing for a couple of years. The trend of the leakage rate based on data from on-line recording is shown by Figure 4-36.

The monitored swelling pressure (total pressure minus pore pressure) in the bentonite sealing has increased slowly with time as expected. On September 30, 2014, the swelling pressure was between 100 and 700 kPa. A fully watertight function of the seal is expected from about 500 kPa of swelling pressure.

Domplu monitoring of the concrete dome showed that tensile stresses were induced in the dome as the heat from the hydration reduced. These stresses are high enough to have forced the concrete dome to at least partially release from the rock, but may also to have caused cracks in the concrete dome. Based on the evaluation of the measurements, it can be concluded that the dome did not release fully, instead it had some restraint. This conclusion is based on the following observations:

- High tensile stresses occur in the concrete dome during the first three months, which could cause cracking in the concrete dome.
- The obtained thermal pre-stress is lower than what would have been obtained if it had released from the rock (about 53% of the theoretical value).
- The relative displacements between concrete and rock was significantly lower than the expected displacements that would occur if it released.

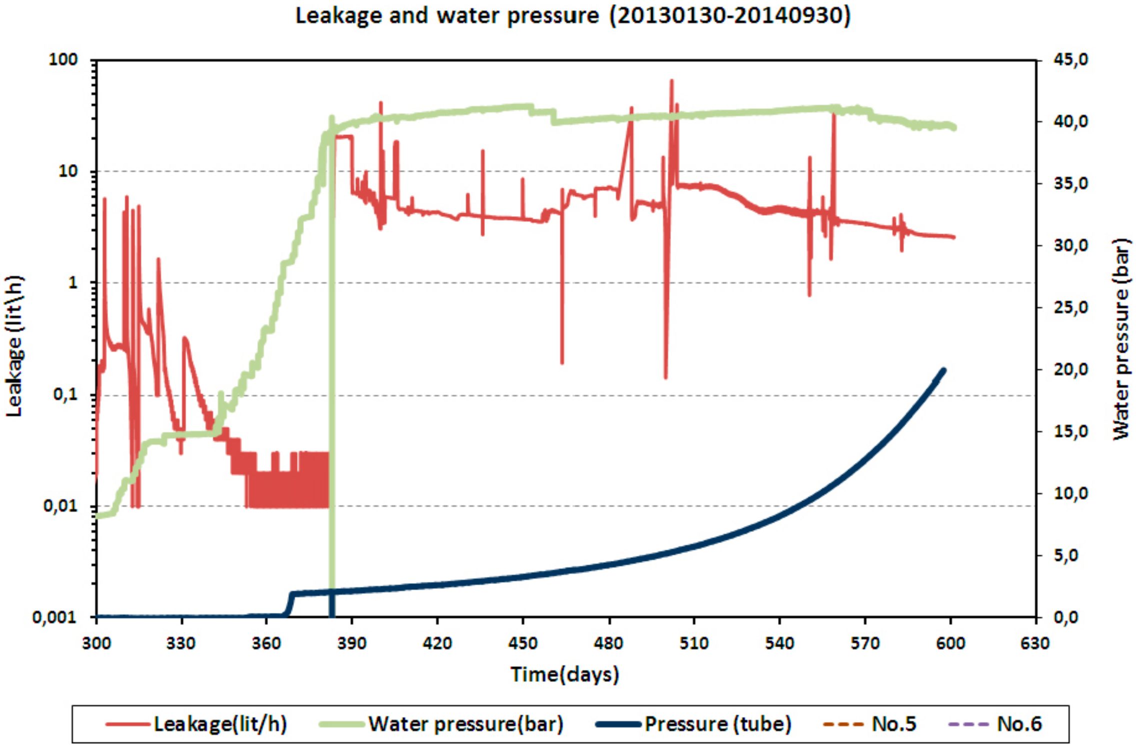


Figure 4-36. *Measured leakage from the weir and the applied water pressure.*

One of the main outcomes from the full-scale test was also to demonstrate feasibility of a dome plug construction. This includes practical aspects of logistics, concrete mixing and transports as well as arranging of parallel construction activities in a tunnel system. In SKB (2015) a full review of the plug installation is given.

The results presented in SKB (2015) also show that almost all installed sensors in the concrete dome have worked successfully and captured the behaviour from a few hours after casting up to the point of contact grouting the concrete dome, which occurred about 100 days after casting. However, after this, several of the sensors have failed. Most of the sensors failed due to the increasing water pressure, since none of these sensors were designed to withstand the water pressure. A similar situation is also present for the sensors installed in the bentonite sections. These sensors were all known in advance to be subjected to high water pressures and therefore these were all designed to withstand a water pressure of at least 10 MPa. However, some of the sensors in the bentonite sections have also failed during the full-scale test.

The Domplu experiment will be under continued observation and monitoring until October 2016.

DOPAS (Full scale Demonstration of Plugs and Seals)

The Domplu test is part of the EU-project DOPAS, which receives funding from the European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2011–2013, under Grant Agreement No. 323273 for the DOPAS project. 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.

4.12 System design of buffer

Background

Several activities within the system design of buffer were performed during 2013, as previously described in SKB (2014). During 2014 much of this work has been reported, in the following SKB reports;

- Buffer protection for the installation phase. Design and testing. (Nyblad et al. 2014).
- Modelling of bentonite block compaction. (Börgesson and Hernelind 2014).
- Basic engineering of buffer production system. (Eriksson 2014).
- Tests and simulations of THM processes relevant for the buffer installation. (Johannesson et al. 2014).

During 2014 the activities at Äspö HRL for buffer design for KBS3-V concerned controlled atmosphere as an alternative buffer protection system. This is reported in this section.

In the current reference design all the buffer is installed in a deposition tunnel before backfilling of the tunnel is started. This means that the buffer could be standing for up to three month in the deposition hole before backfill is installed above the buffer. During this period the buffer needs to be protected from drying and wetting because this could make the buffer crack and if chunks from the buffer block would fall into the outer gap it would be a problem to install the pellets surrounding the buffer. In some cases the buffer could also start to heave which would reduce the density of the buffer.

In the current reference design the buffer is protected by a buffer protection which consists of a rubber sheet installed in the deposition hole until the backfill is installed. However, tests done (Johannesson et al. 2014) has shown that the buffer protection do not work as well as intended. Therefore an investigation was started to see if there were any alternatives, other than the buffer protection sheet, that could protect the buffer during the installation time. One possible method was to control the relative humidity in the deposition hole and thereby stop the buffer from drying or wetting.

Objectives

The objective with the test is to find out if the method with controlling the environment in the deposition hole is a feasible method for protecting the buffer. The data will also be used to help further development of the method if it is considered to work well and for improving and verifying modelling done of the system.

Experimental concept

To simulate as realistic situation as possible the test was done in a deposition hole in Äspö HRL to get the thermal conditions correct a canister with a heater was used. The power of the heater was set to 1,700 Watts during the test. This is important because even small temperature differences can give a relative big change in relative humidity.

To simplify the assembly and disassembly of the test it was decided to use dummy buffer block of concrete since they do not crack due to water uptake or drying.

The dehumidified air was led down to the bottom of the deposition hole with the help of six tubes located in the gap between the buffer and the rock wall. The six inlet tubes can be seen in Figure 4-37. Before the test started, three extra outlet tubes and extra fan was added to improve the air flow through the system.

The dehumidifier was set to keep the relative humidity in the bottom of the deposition hole to 75%. This value was chosen because it is close to the relative humidity were the buffer blocks are in equilibrium with its surroundings. Temperature and relative humidity sensors were used to monitor how the test evolves with time. Placement of sensors is shown in Figure 4-38.

Figure 4-37. Lid on top of deposition hole. Inlet pipes are blue, out let pipes are green and dehumidifier is orange.

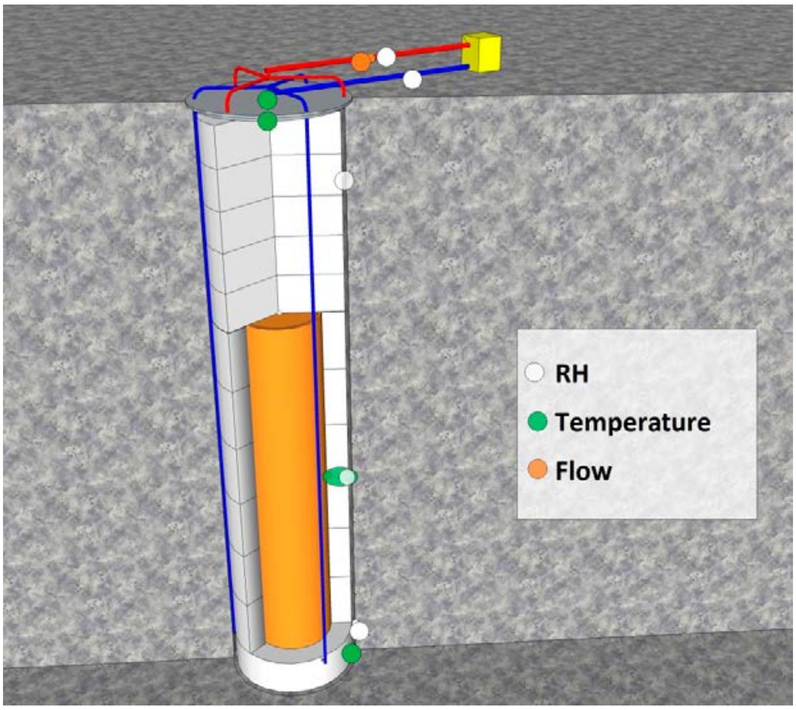


Figure 4-38. Test setup and sensor placement, note that more inlet and outlet pipes were added to increase flow.

Results

The test has been modelled to get a better understanding of what is happening in the deposition hole. The modelling shows good agreement with experimental values.

From the experimental data and modelling the following conclusion could be made:

- The method works reasonably well first six meters from the bottom of the deposition hole as long as the flow of air though the system is high. However a relatively big axial temperature gradient is still present which could cause problems.
- The top 3–4 blocks would probably need some extra form of protection due to the temperature being lower in this area and therefore the relative humidity is high.
- The method is very sensitive to eccentric placement of the buffer stack which could require individual control of each inlet pipe. This will make the system complex.

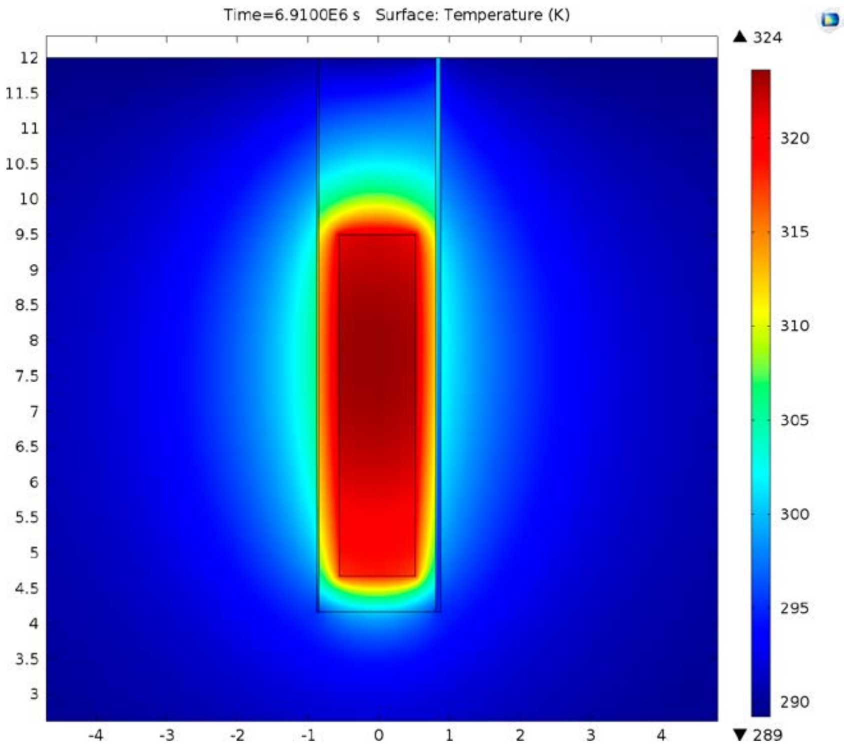


Figure 4-39. *Modelled temperature in the rock, buffer stack and canister at the time when the test was finished.*

4.13 Tunnel production

Background

Tunnel Production is a technology develop project with aim to establish methods and concepts for excavation of deposition tunnels in the planned Final Repository for Spent Nuclear Fuel. This includes rock excavation methods, grouting and concepts for rock reinforcement.

As a part of the tunnel production project, SKB and Forcit Sweden AB have started a joint project to study blast induced fractures from string emulsion. The project is partly financed by the Swedish Rock Engineering Research Foundation, BeFo.

The Äspö HRL was expanded in 2012 in order to create room for additional experiment sites in the facility. New tunnel were excavated on the –410 and – 450 m levels. The new tunnels were excavated using pump emulsion explosives (Kemitti 810) and charging was conducted using a Forcit charging unit model 201 with a hose feeder for the string charged hole types.

The well documented tunnels are well suited to study blast damage from string emulsion as much effort was invested in the control program for follow up and documentation of the excavation works. Documentation of the blasting works included extensive follow up on drilling and charging precision for each hole with aid from field notes and logger data, see Ittner et al. (2014) and Ittner and Christiansson (2014).

In total five rectangular slots was excavated in the floor and wall of the two new experimental tunnels TASN and TAS04 during November 2014. The slots were located through control of charging data, visible blasting half pipes in the contour and GPR-reflectors. Mapping was conducted in two steps in which both blast induced and geological fractures were documented.

Objectives

The purpose was to study blast induced fractures from controlled string emulsion and to correlate the results to charge concentrations, evaluated from the charging and drilling logs. The data set could be used to update the blast damage tables for string emulsion used in the industry today. This will be an important design tool for SKB in order to predict, control and understand the influence of the excavation method on the rock mass.

Experimental concept

In total 5 slots were excavated in the experimental tunnels TASN and TAS04. Sawing was conducted with a starting blade combined with blades Ø 1,200 mm and Ø 1,600 mm in order to reach a maximum theoretical depth of 70 cm. Figure 4-40 depicts ongoing work with excavation of a slot in the floor of TAS04.

Two separate mappings were conducted, where direct blast induced, natural and fractures influenced by the excavation were mapped. Direct blast induced fractures were defined as fractures originating from the blasting half pipes. Figure 4-41 depicts mapping of direct blast induced fractures.

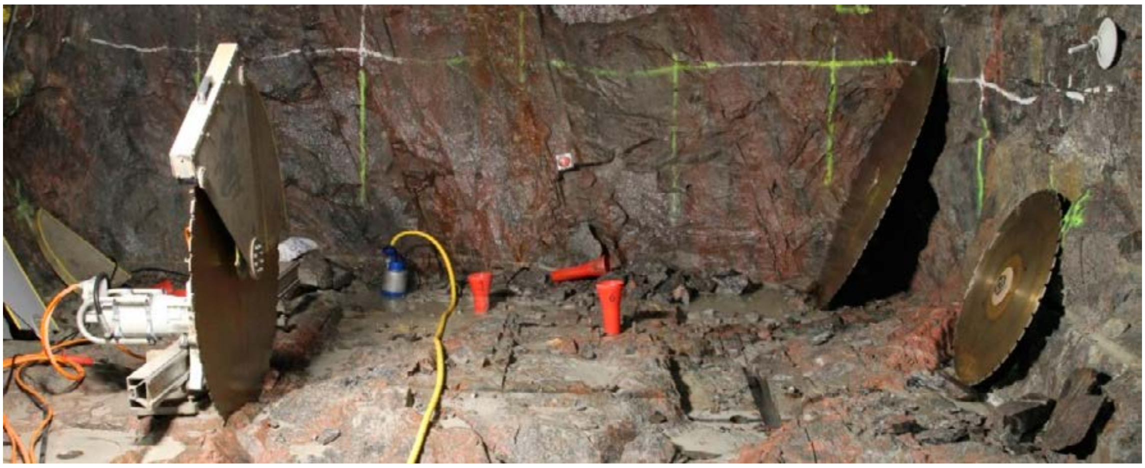


Figure 4-40. *Ongoing sawing work in the floor of TAS04, section 34 m.*

Figure 4-41. *Mapping of blast induced fractures in TAS04 and TASN.*

Results

Contour and floor holes were charged with concentration 0.35 and 0.5 kg/m respectively. The results from mapping of the slots shows a longest blast induced fracture of 24.5 cm for the 0.35 kg/m charge and 24.1 cm for the 0.5 kg/m charged holes.

By combining the charging log and sequence with hole length registration from the drill log, charge concentrations could be calculated and associated to individual holes. Mapping of direct blast induced fractures was associated to charge concentrations for each hole with a visible blasting half pipe in the slots.

Blast induced fractures are generally oriented towards the nearest blast hole and as a result the mapped fracture length is not necessary the same as the extension of blast damage from the tunnel contour into the rock. Figure 4-42 shows some results from the project: The length of the longest direct blast induced fracture, originating from a blasting half pipe, in the slots together with calculated charge concentration q (kg/m). Generally, there is a large spread in the results with few fractures longer than 20 cm.

A full project report will be published by BeFo in 2015 and a continuation of the blast damage project is in the planning for the late autumn 2015 or spring 2016. The continuation is planned to include excavation of a short tunnel with blast design adopted to study the effect on the rock mass from larger charge concentrations. The test is planned to use a newly developed charging unit by Forcit Sweden AB.

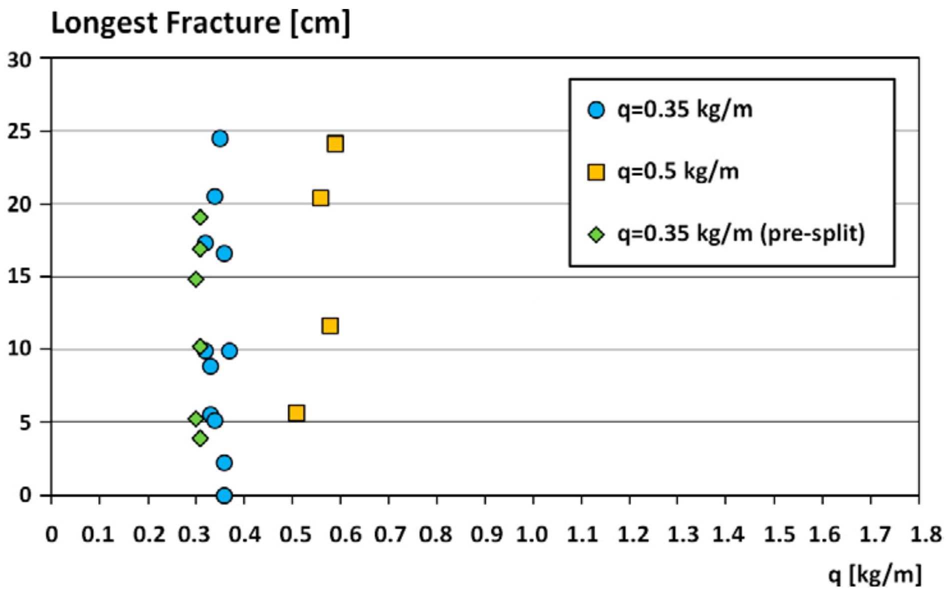


Figure 4-42. *The longest blast induced fracture [cm] plotted against the charge concentration, q. The study included a round excavated by pre-splitting.*

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 for Spent Nuclear Fuel. 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.

Assessment has been made of when the production of machines must begin and when they need to be completed, as well as whether production of prototypes is necessary. The number of objects and affiliated information are 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 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 for Spent Nuclear Fuel is developed. Also systems for navigation and positioning in tunnels are developed. The decision to develop a Mission Control System establishes a working method for the repository that facilitates the use of automated vehicles.

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

Background

Preparatory work has been made during 2010 and formally the project started in October 2010.

Experimental concept

The MCS offers graphical user interface for an operator to monitor and control the production.

Traffic control is responsible for moving the machines at the production area. It takes care of intersections and also the traffic flow inside the tunnels. It decides when machines are allowed to move and also slows down or stops machines if needed.

The Production control reads in production orders from MES (Manufacturing execution system, software that controls production). It generates missions from the production orders and reports results back to MES.

The Area control functions as a user interface for the Area control system (ACS). It shows the area statuses to the user, and allows the user to give commands to the ACS.

The MCS collects alarms from all the machines and reports them to the operator. The operator is able to acknowledge the alarms. The MCS also monitors the safety areas of the machines and slows down or stops them is they go too close to each other.

The development and testing of the systems is synchronised with the development of the machines and equipment.

Results

Integration tests were performed in five test campaigns during 2014. Work is ongoing with compiling results and reporting. The overall result was that the system works as planned, allowing the deposition machine to be sent to perform autonomus depositions.

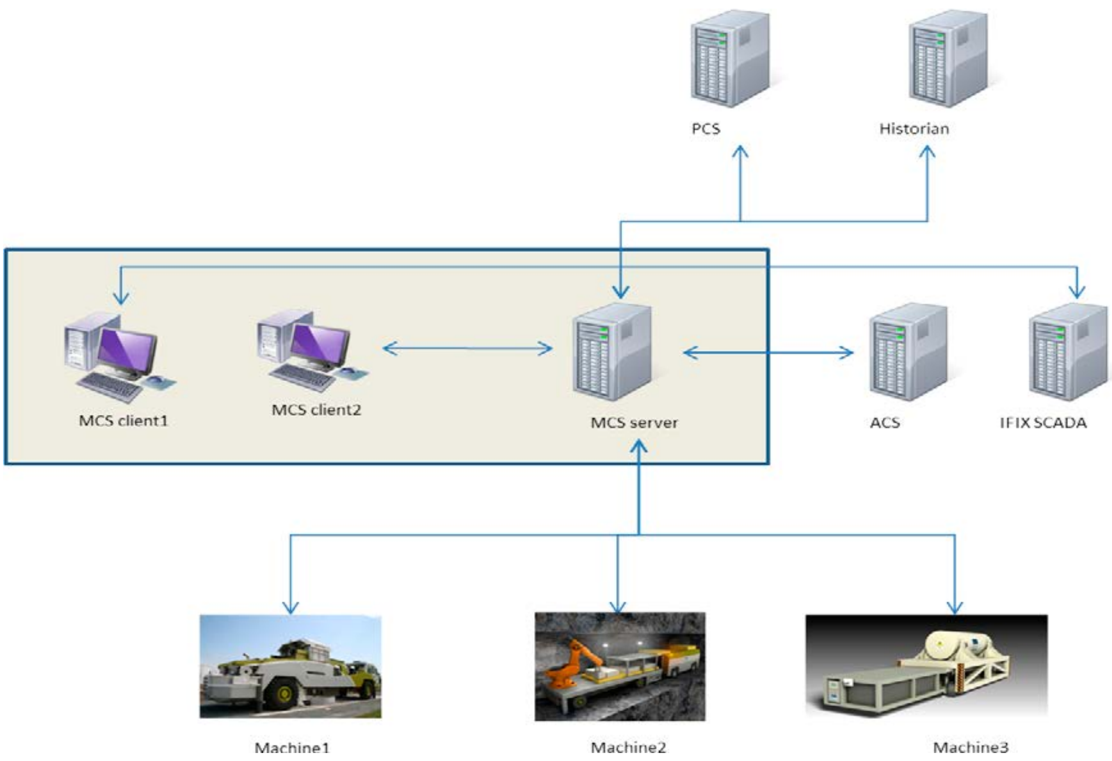


Figure 5-2. *Mission Control System overview.*

5.2.2 Transport system for buffer and backfill material

Objectives

A concept for an autonomous and remotely operated transport system for buffer and backfill material from the production premises to the deposition tunnels.

Background

Bentonite blocks, rings and pellets are used for filling the deposition tunnels after the nuclear waste has been inserted into the vertical deposition holes. The transport system is responsible for transporting bentonite blocks, rings and pellets from the warehouses above ground to the elevator and from elevator to the underground warehouses and finally from underground warehouses to the deposition tunnel where it is to be installed by the buffer handling equipment or the backfill machine. A pallet truck is used for moving the bentonite blocks between the warehouse and elevator above ground. Another pallet truck moves the pallets underground from warehouse to the backfill machine. (Figure 5-3).

Experimental concept

The different parts of the transport system are developed and tested together, and synchronised with the adjacent installation equipment for buffer and backfill.

Results

Testing of the system, with the available machines; the deposition machine, the MPT and the backfill machine, has been performed during 2014.

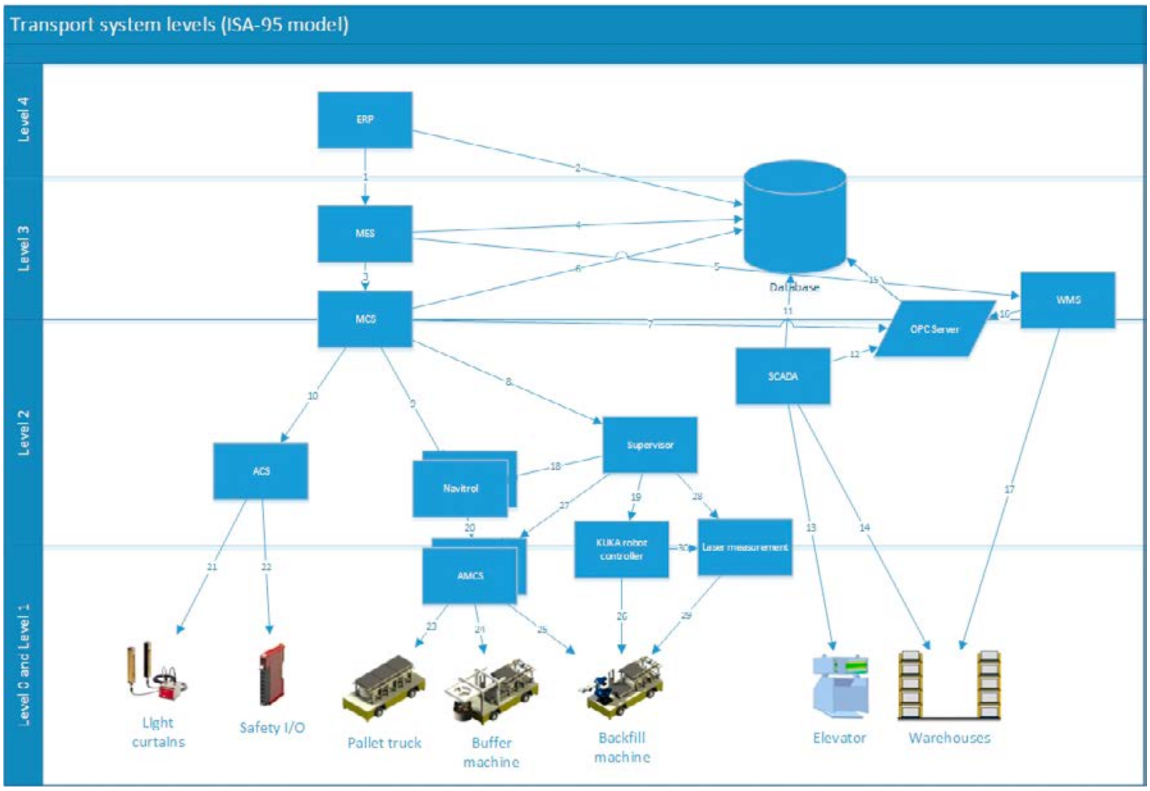


Figure 5-3. *Transport system levels and subsystems.*

5.2.3 Equipment for backfilling

Background

After deposition of canisters in the future Final Repository for Spent Nuclear Fuel, 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 Section 4-10).

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 repository.

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 2014 the following activities have taken place:

- Software for robot and platform was further developed.
- The system's integration with Mission Control System continued.
- The system was a major component in the Åskar underground test of backfill installation during 2014, see Section 4.10.

Figure 5-4. *A robot mouted on an automated mobile platform, for installation of backfill blocks and pellets. On the platform feeding units for material are also mounted.*

5.2.4 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 5-5).

Objectives

The aim of this project is to develop concepts for machines, equipment, methods and systems for control and positioning that is capable of installing buffer blocks and pellets in the deposition hole with the required degree of precision, and without causing damage to the canister or the buffer.

Experimental concept

A total concept for buffer emplacement, blocks and pellets, is developed.

Results

During 2014, 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 was carried out, and prototypes were constructed. Testing of the prototypes is ongoing.

5.2.5 Multipurpose vehicle

Background

There will be frequent heavy load transports in the ramp down to the Final Repository for Spent Nuclear Fuel. To have these transports executed, a Multi Purpose Vehicle (MPV) for heavy transports was ordered in November 2010 and delivered in August 2011.

Objectives

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

Experimental concept

The MPV was manufactured in Italy, and weigh 31 tonnes. The 24 wheels are placed in pairs, and each wheel pair can be controlled and rotated 120 degrees in each direction, making it easy to maneuver in the tunnel.

Results

This vehicle was used for heavy load transports in the ramp att Äspö HRL during 2014.

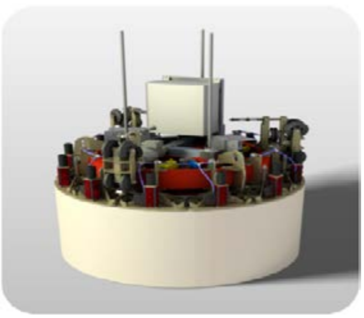


Figure 5-5. *Lifting tool for buffer emplacement.*

Figure 5-6. Ramp Vehicle carrying the modified ATB.

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 experiment conditions and to simulate different environments.

During 2011–2012 new tunnels and experiment sites were constructed. In total about 300 m new tunnel meters were excavated.

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 and Safety Assessment 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 unit in Oskarshamn.

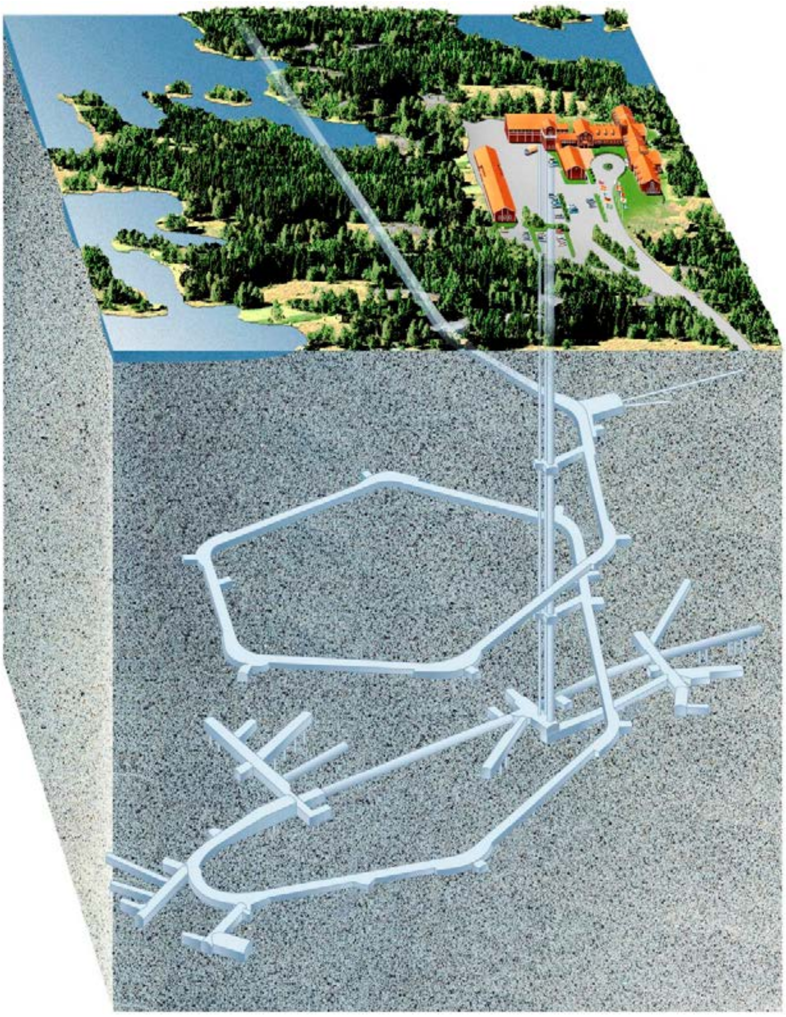


Figure 6-1. *The Äspö HRL tunnel system below the island of Äspö.*

The organisation of the Repository Technology (TD) unit is described in Chapter 1.3 in this report.

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

6.2 Bentonite Laboratory

Background and objectives

Before building a final repository, further studies of the behaviour of the buffer and backfill materials under different installation conditions are required. SKB has constructed 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 deposition holes 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.

Other equipment in the laboratory includes an Eirich bentonite mixer with a load capacity of 1,000 kg to allow mixing of bentonite with desired water ratio. During 2014, approximately 50 tonnes of bentonite was mixed, most of it used by the projects Alternative Buffer Protections (see Section 4.12) and Concrete & Clay (see Section 4.7).

During 2014 a press for fabrication of extruded pellets was bought, which will during 2015 produce pellets for several experiments at Äspö HRL.

Experimental concept

Several projects have had tests and activities performed in the Bentonite Laboratory during 2013. These include testing and fine tuning of robot equipment for backfilling (see Section 4.10), Test and simulations of THM processes relevant for buffer installation (see Section 4.12.3) and Test of buffer protection system (see Section 4.12.4).

6.3 Material Science Laboratory

Background

There are remaining challenges regarding the bentonite buffer and backfill materials when it comes to research related to long term safety assessment, as well as industrial scale quality control of central safety parameters. As a part of the needed infrastructure, a material science laboratory has been constructed at Äspö, with focus on material chemistry of bentonite issues and competence development. The key focus areas are long term safety related research and development of methods for quality control of the bentonite buffer and backfill materials.

Objectives

The quality control development is conducted within the Material Science project with the goal of method documents describing the laboratory measurements of key parameters such as montmorillonite content, organic carbon, total sulphur content, hydraulic conductivity and swelling pressure. The long term stability of various bentonites is studied within the Alternative Buffer Material (ABM) project conducted within the Research and Safety Assessment line work. The second ABM-package (ABM2) was excavated in April 2013 and already in October 2013 results based on internal work at Äspö were presented at the Clay Minerals Society conference in Urbana-Champaign, USA, with a high acceptance of the quality of the work. Beside of the key areas, various more or less related works in different fields is conducted with the purpose of competence development and problem solving in other projects or areas of SKB.

Results

A number of methods and equipments have been implemented and developed. Wet chemical methods such as cation exchange capacity (CEC) and exchangeable cations (EC) have been implemented. Equipments implemented during 2013 are X-ray diffraction (XRD) for the determination of crystalline solids, X-ray fluorescence (XRF) spectroscopy for elemental compositon, Fourier Transformed IR (FT IR) spectroscopy for detailed analysis of the clay mineral structure and amorphous material, and UV/Vis for the CEC method. A μ-Raman equipment has been installed as a complement for analysis of corrosion products, accessory minerals and precipitates all with a very high spatial resolution in a non destructive manner. Swelling pressure and hydraulic conductivity measurements are in the construction phase. An example of the kind of results one can obtain by combining high resolution polarisation microscopy with μ-RAMAN can be seen in Figure 6-2, were hematite was identified as minor red sections within a 50 μm small particle inside of the bentonite clay. In 2015 to 2016 a number of ABM2-profiles will be analysed using this combination as a complement to the other more traditional clay techniques.

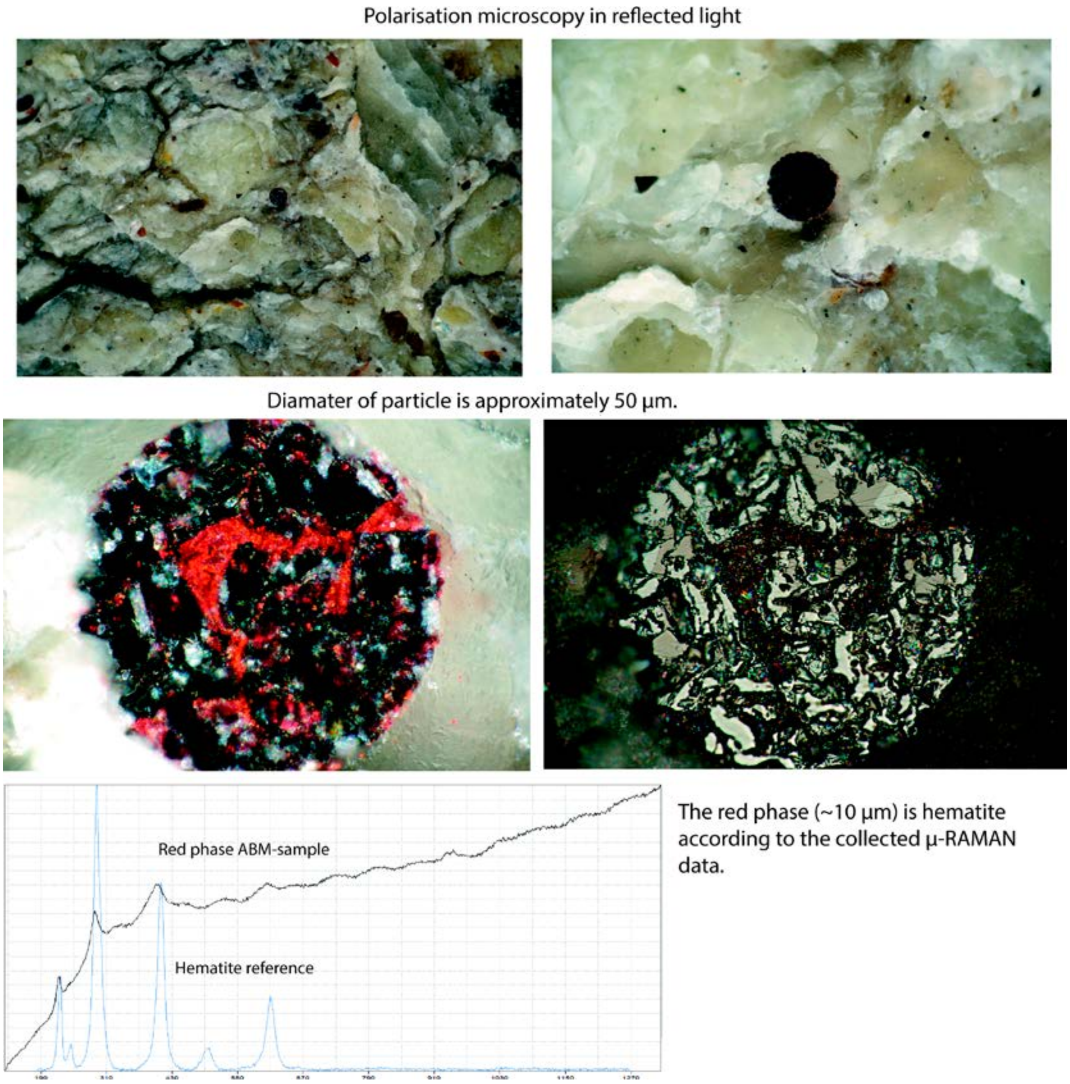


Figure 6-2. *Example of how polarisation microscopy with reflected light can be combined with the μ-RAMAN technique. The bentonite sample comes from the ABM2 experiment (MX-80, block 8). The round particle is seen at different magnifications and also different polarisations of the reflected light. The collected μ-RAMAN data identified the red phase as hematite.*

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 preventative and remedial maintenance in order to ensure that all systems such as drainage, electrical power, ventilation, alarm and communications are available in the underground laboratory at all times.

Results

The facility has had a stable operation during 2014, with almost 100% accessibility. During the winter of 2013 and spring of 2014, Siemens has installed a new fire alarm system above and below ground at Äspö. The old fire alarm only detected in public areas, making up 5–10% of the entire surface. The detection was also needed to be shut off in case of work that genererated dust, smoke or steam. With the new system, 100% of the surface is detected. During the installation, tests have been performed with transports, welding, rock work, etc. In these works, no shutdowns of the fire alarm system have been necessary.

This work included installation and integration of the new system in all buildings in the Simpevarp peninsula and at Äspö that belong to the Äspö HRL. All control of the entire system can be performed through a PC-based program.

The underground facility has been scanned during 2014 to provide a three-dimensional documentation of the tunnel, as well as to provide geometries that can be used to investigate conditions for e.g. bulky transports in the tunnel. The underground facility has also has added geodetical triangulation points. Older and still useful triangulation points have been re-measured.

The scanning and fixing of triangulation points have been performed by Tyréns. Several members of the facility operations unit have been actively participating in the field work led by experts from Tyréns.

Tyréns have also performed an independent fixing of the triangulation points along the Äspö HRL facility for testing borehole deviation equipment, which was completed in 2013 and consist of an above ground 300 m long pipe representing a curved borehole in the rock. The facility is used to quality assure curvature measurement equipment and testing proceedures.

Figure 6-3. *Control panel for the new fire alarm system in the Äspö HRL.*

6.5 Communication Oskarshamn

General

SKB operates three main facilities in the municipality of Oskarshamn: Äspö HRL, the 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 unit takes care of and organises visits for foreign guests every year. The visits from other countries mostly have the nature of technical visits, but there are also questions regarding societal consensus. The information unit has a special booking team 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, press release matters locally and to carry out internal as well as external communication at the facilities.

During 2014, one person retired and at the end of the year Communication Oskarshamn consisted of 10 persons.

Special events and activities

During 2014, 4,943 people visited the Äspö HRL and with the visitors at Clab and the Canister Laboratory included it resulted in a total of 7,379 people. The total number of visitors to SKB's facilities in both Oskarshamn and Forsmark was 10,086 people. The visitors represented the general public, teachers, students, professionals, politicians, journalists and visitors from foreign countries. The total number of foreign visitors to the Äspö HRL was 482. The special summer arrangement "Urberg 500" was arranged during six weeks and 923 persons took the opportunity to visit the underground laboratory. Tours for the general public also took place some Saturdays during the year.

During 2014 the unit's school information officer went to schools and high schools within the municipality of Oskarshamn to inform about SKB's work. About 25 female students from the scientific program at the high school in Oskarshamn participated 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 subject area otherwise highly dominated by men. Furthermore, the school information officer was part of "Innovation Camp" for freshman students at the high school, arranged by Ung Företagsamhet (Young Enterprise) and Youngster, a national arena for young politicians.

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.

The unit was a part of the national event Geologins Dag (The Geological Day) which in 2014 was part of Skog- och Miljödagen (The Forest and Environment Day) arranged in the Misterhult area. At this occasion, Äspö Miljöforskningsstiftelse handed out prizes to two persons that have contributed to increase the public knowledge and awareness about the Baltic Sea and fish preservation. The unit was also a part of the local events Framtidsdagarna (Future Days) and Turista Hemma (Tourist at home).

In June, the unit arranged guided tours in the exhibition on the transportation vessel m/s Sigrid, when she visited the harbor of Oskarshamn for one day.

Every year the unit arrange lectures with different themes related to SKB's work or to the area. During autumn, SKB held a well attended lecture in Oskarshamn about information preservation. The unit also arranged "An evening with technique" in cooperation with the local experimental laboratory, Xperiment.

On the 15th of November, about 95 competitors participated in "the Äspö Running Competition".

During 2014, 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. The unit is also involved in a number of other communication tasks.

Figure 6-4. *In March, H.R.H Crown Princess Victoria visited Clab.*

Figure 6-5. *In June, SKB’s new transportation vessel m/s Sigrid visited the harbour of Oskarshamn with an exhibition about SKB onboard. More than 600 people come on board to see and learn more.*

7 Open research and technical development platform, Nova FoU

7.1 General – Marcus Laaksoharju

The aim is to describe the major progress during the year 2014 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 and the organisation.

7.2 The Nova FoU mission – Marcus Laaksoharju

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 also open for more general research. Nova FoU (R&D) 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 (Äspö-HRL)
- Bentonite Laboratory at Äspö
- Canister Laboratory in Oskarshamn
- Site Investigation Oskarshamn (Laxemar)

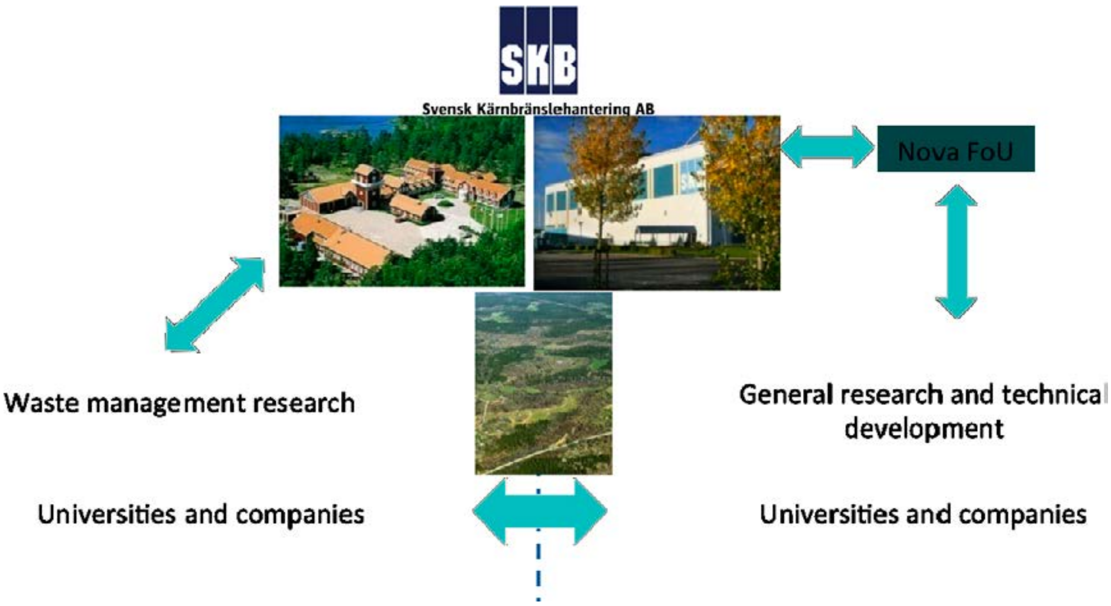


Figure 7-1. Nova FoU provides access to the SKB facilities and data for universities and companies for general research and technical development. The nuclear waste management research is handled by SKB.

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 Nova FoU research platform and the above research infrastructure can be e.g. used for:

- Environmental projects.
- Infrastructure projects.
- Energy projects such as excess heat and geothermal research.
- Technical development.
- Education projects and demonstration of technologies.

Nova FoU supports new and innovative research, for example environmental research, where the extensive SKB data set from geological, hydrogeological, hydrogeochemical and ecological investigations and modelling can be used (Figure 7-2).

The research infrastructure and data can be used for e.g. the following research and technical development:

- 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.
- 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.
- Development of rock characterisation methods for tunnel construction, and technology to be used underground.

During year 2014 about 100 researchers where using the Nova FoU research platform for various environmental and technical development projects. The annual research volume (more than 30 scientific publications per year) equals a middle size Swedish university. The highlight during year 2014 was the international summer course in "Elements of the Back-end of the nuclear fuel cycle: Geological Storage of Nuclear Spent Fuel" (http://www.novaoskarshamn.se/) held in June in Oskarshamn. Further planning and workshop to establish the National Geosphere Laboratory (NGL, http://www.geospherelab.se/) was held in Novermber in Oskarshamn. Establishing the largest infrastructure project for underground construction in Sweden, the TRUST (http://www.trust-geoinfra.se/) project at Nova FoU. Futher details are described in the next chapter.

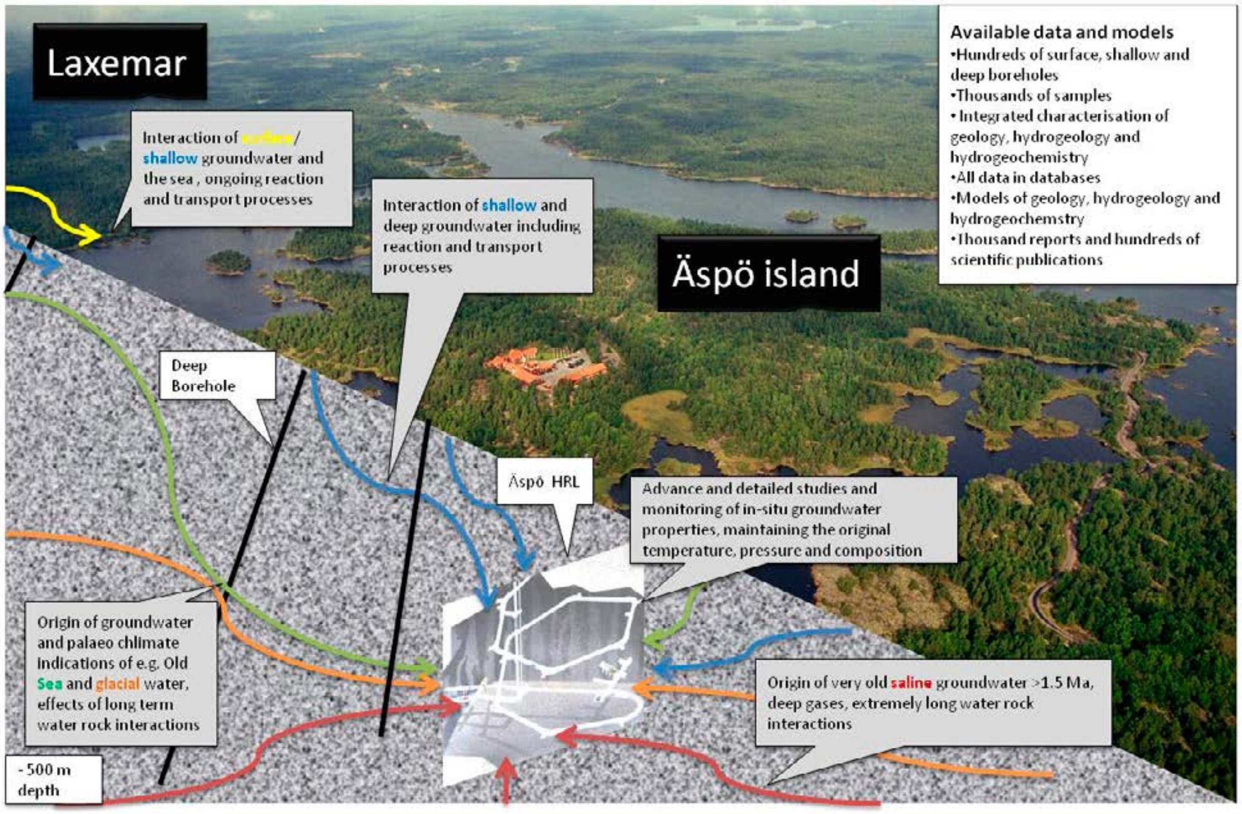


***Figure 7-2.** The Äspö and Laxemar areas have been studied in terms of geology, hydrogeology, hydrogeochemistry and ecology. This information can be used for a number of purposes, for example to describe the water cycle and hydrogeochemical processes in 3D.*

7.3 The status of the Nova FoU projects

In this chapter the research leaders having projects at the Nova FoU research platform are describing the work in progress.

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 (=rare earth elements) in fracture minerals (primarily calcites) and groundwaters in Proterozoic bedrock.

Status of the project – completed

The project is completed. The results are presented in two papers published in scientific journals.

The two manuscripts discuss the sources, distribution, abundance and fractionation of lanthanoids and yttrium in regolith and fracture groundwater (Figure 7-3) and in low-temperature calcite (Figure 7-4) in fractures in the upper kilometer of granitoids in Laxmar and Forsmark. In the regolith groundwater, the lanthanoid concentrations are considerably higher and differently fractionated than in the fracture groundwater, in particular in Laxemar where the regolith groundwaters have relatively low pH. In the calcite, the lanthanoid concentrations decrease weakly with depth (Figure 7-5) and show relatively flat patterns in the c>>a crystals and a smooth decrease across the series for the other crystal habits (Figure 7-6).

Figure 7-3. *Sampling of fracture groundwater for characterization of dissolved concentrations of lanthanoids. Photo: Tobias Berger.*

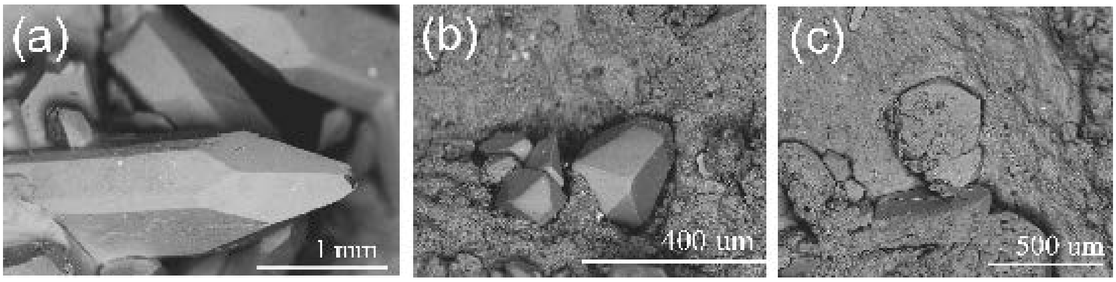


Figure 7-4. *Back-scattered SEM-images of calcite crystals with (a) c-axis >>a-axes ("c>>a" crystals), (b) c-axis ≈ or > a-axes ("c≈/>a" crystals) and (c) c-axis<a-axes ("c<a" crystals).*

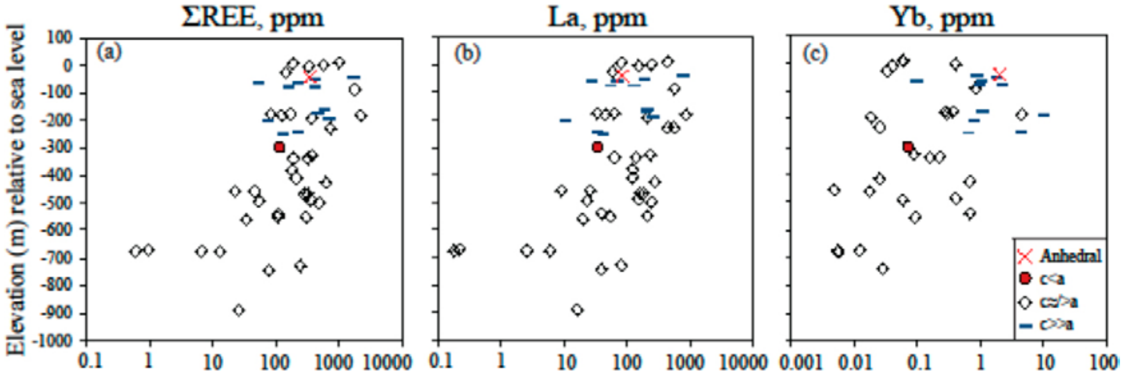


__Figure 7-5.__ Concentrations of ΣREE (=lanthanoids) and selected REEs (La, Yb) in calcite plotted versus the depth at which the specimens were collected. Specimens below detection limit are not included (n_{Yb} = 11).

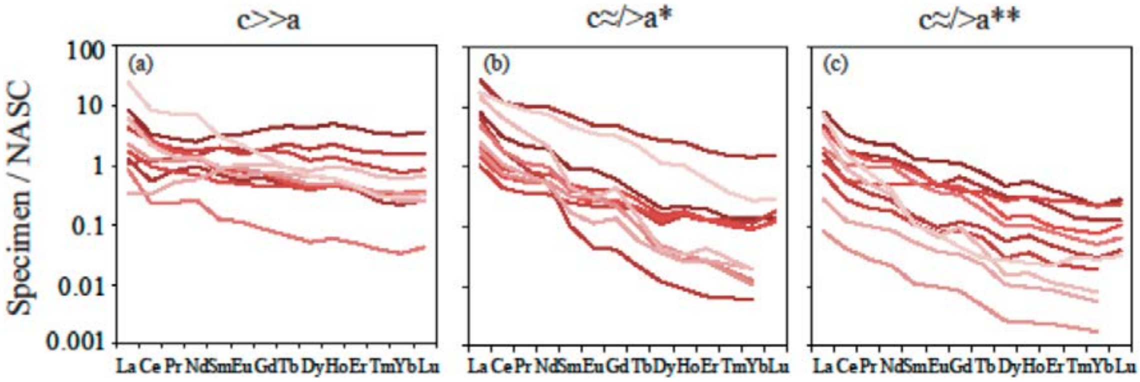


__Figure 7-6.__ REE concentrations in calcite normalized by the North American Shale Composite ("NASC"). Specimens with more than 4 REEs below the detection limit are omitted for clarity. (*) c≈/>a crystals above –260 m; (**) c≈/>a crystals below –260 m. All c>>a are from above –260 m. Different colors (shading) were used in order to distinguish the individual specimens more clearly and thus make the graphs easier to read.

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 have 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 lanthanoid 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 in the bedrock surrounding foreseen nuclear waste repositories.

Future perspectives

This project has provided a strong basis for further studies into lanthanoid behaviour in deep settings. An example of this is on-going studies at the Äspö HRL focusing on lanthanoid uptake by passive samplers (diffusive gradients in thin film), which builds on the two papers presented in this report. It is also possible for nuclear-waste organisations like SKB and Posiva to utilize and further develop the results presented here, in order to aid the assessment of radionuclide retention and transport in bedrock fractures. Finally, forthcoming NGL (National Gesophere Laboratory) research can utilize the results to define lanthanoid pathways and cycles in near-coastal settings.

7.3.2 Fluorine in surface and groundwaters (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 7-7), (2) characterise and model fluoride abundance, transport and speciation in streams in the Laxemar-Äspö area, and (3) characterise fluoride abundance and sources in shallow (soil) and deep (bedrock) groundwaters of the Laxemar-Äspö area. A project focusing on fluoride exposure from wells in Kalmar County has also been carried out (see below).

Status of the project

In April a study was published in Environment International dealing with abundance of fluoride in private wells in Kalmar County and different approaches of assessing the risks of an excessive fluoride intake among children (Augustsson and Berger 2014). The paper was presented at the XXXIInd Conference of the International Society for Fluoride Research in Chiang Mai, Thailand in December. Another study focusing on aluminium speciation in fluoride-rich stream waters was submitted to a scientific geochemical journal in September and is currently undergoing revision after receiving

Figure 7-7. *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).*

comments from reviewers. We discuss the role of fluoride in the release and speciation of aluminium in boreal stream waters. For this, we have utilised Sicada-data from three catchments in the Laxemar area in combination with a geochemical equilibrium model. Currently, a manuscript is in progress focusing on fluoride hydrogeochemistry in the shallow and deep groundwater environments of Laxemar-Äspö.

Spin-off

The spin-off effects from this project will be increased knowledge on fluorine abundance and transport in surface and ground waters 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 groundwaters, 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. Also, the study published in Environment International highlights how risk characterization of fluoride is affected by the basis of comparison, that total fluoride exposure may be overlooked when only focusing on one pathway (e.g. drinking water) and the importance of considering variability in all relevant pathways. Such knowledge can be of importance in areas where fluorosis is abundant and the need of identifying relevant sources and exposure levels is crucial. The findings may also lead to spin-off effects of economical value related to the addressed issues.

7.3.3 Hydrogeochemical investigation and modelling (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 (Figure 7-8). 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. The first stage of this project was focused 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. The knowledge gained from the characterisation of the mixing process via modelling has now been used in order to investigate and better understand the variability of the natural concentration of some trace elements in groundwater.

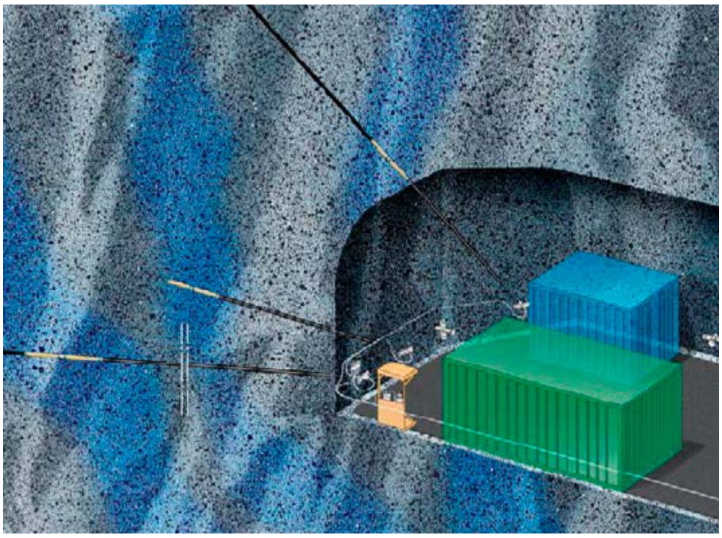


Figure: 7-8. *Boreholes drilled from the tunnel wall of the Äspö HRL, intersecting and enclosing water-bearing fractures. The borehole equipment allows the DGT sampling to be performed in situ under the naturally prevalent conditions in the fractures. Figure adapted from Pedersen (2013).*

Status of the project

For the reporting period, major attention on natural concentration of dissolved caesium, yttrium and rare earth elements (REEs), which are trace elements widely studied in environmental sciences and the field of radioactive waste disposal since these elements are good analogues of certain nuclides composing the spent nuclear fuel.

In the framework of dissolved concentration of Cs (Äspö, Laxemar), the major results of this study were published (Mathurin et al. 2014a) and presented at the NGL Annual Scientific Meeting 2014 in Oskarshamn.

In the framework of the dissolved concentration of yttrium and REEs (YREE) in groundwater (Laxemar and Forsmark), the influence of (i) the groundwater origin, (ii) mixing process and (iii) the groundwater composition via YREE aqueous speciation modelling including sorption to colloidal humic substances were thoroughly investigated and published (Mathurin et al. 2014b). In continuation of the gained experience on the REE behaviour in fracture groundwater, collaborations with other researchers were developed during the reported period:

1. The role of carbonate complexes on REE uptake in low-temperature calcite in the fractured crystalline bedrock (Laxemar) was studied and published (Maskenskaya et al. 2015).
2. The Ce anomaly features in facture coatings and groundwater (Laxemar) were investigated.
3. The modelling of REEs in groundwater at the Äspö HRL was under developement. This work will allow a better understanding (1) of the characterization of REEs obtained via diffusive gradient thin-film (DGT) sampling method under in situ high-Pressure and low-redox conditions (Alakangas et al. 2014) and (2) of the partition coefficient reported between modern groundwater and low temperature calcite precipitated on the equipment of borehole sections with known high sulfide production.

Spin-off

The findings of this study are relevant in term of technical/societal challenges that constitute nuclear-fuel waste repositories. The retention properties of the host rock comprise one of the safety functions as the bedrock composes one (the natural) barrier in a multi-protective barrier system, which must remain intact to isolate the nuclear wastes from the biosphere for at least 100,000 years. The YREE mobility/retention reported in the published and ongoing studies are relevant for scenario of actinide (radionuclide) mobility/retention in the bedrock fractures from the Final Repository for Spent Nuclear Fuel (400–600 m) depth to the surface.

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 by advective transport 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 and comparisons between fluid and mineral chemistry (trace elements and isotopes) can reveal processes on a very local scale in the fractures.

Status of the project

Investigation has been focused to calcite (Figure 7-9) and pyrite 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 minerals and the groundwater, especially regarding the uptake of trace elements and isotopic fractionation. It therefore adds to the knowledge of trace element partition coefficients in calcite in natural granite systems – an understudied topic and to the knowledge of past and present activity of microbes, such as sulphate-reducing bacteria (SRB) and about anaerobic oxidation of methane. These studies are collaborations between Linnaeus University other universities and laboratories, including University of Gothenburg, Scottish Universities Environmental Research Centre (SUERC), UK and Museum of Natural History, Stockholm, Sweden (in particular the NordSIM lab), Universtiy of Göttingen, Germany, and have been published in *Geochimica et Cosmochimica Acta* (one 2013 paper) and *Applied Geochemistry* (one paper published 2014) and some collaborative articles with othe Nova project leaders (Frederic Mathurin, Olga Maskenskaya).

Two studies are currently under revision in high impact journals (January 2015). Other parts of the project are in progress and include e.g.:

- 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.
- Iron isotopes in SRB-related pyrite.

Spin-off

The project will lead to publications of several scientific papers on fracture minerals and their input to the understanding of past and present redox conditions in the bedrock, groundwater-mineral interactions, biological activity in bedrock fractures, stability of groundwater systems in Proterozoic rocks etc.

The results can be used as a reference and starting point for other detailed fracture mineralogical investigations and have a direct influence on the understanding of the long term stability and variability of groundwater chemistry at a site, as well as of hydrological and redox 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.

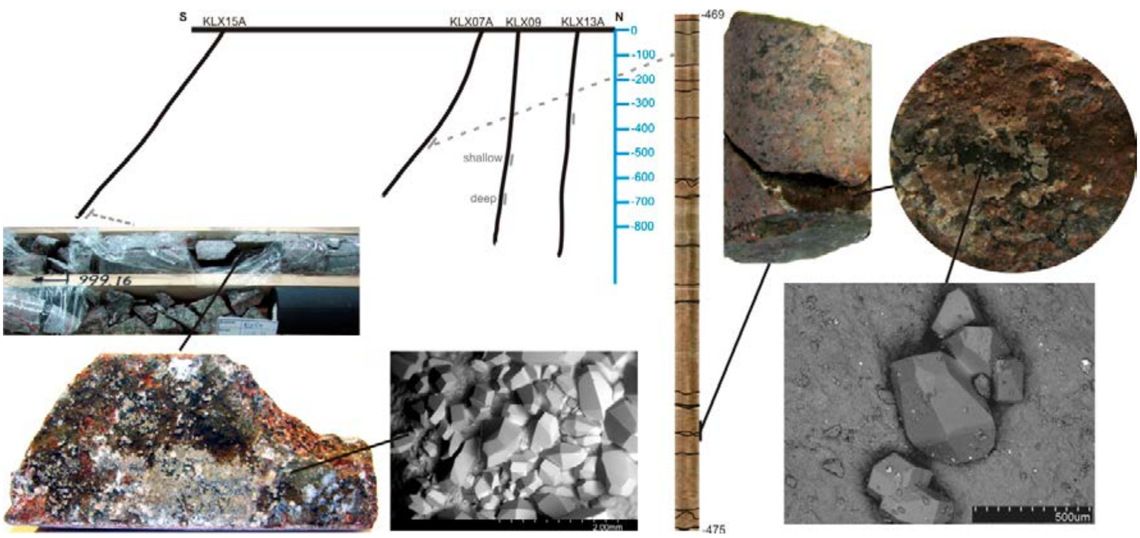


Figure 7-9. *SEM-images of calcite crystals from open fractures, with photographs of fracture surfaces in drill core samples in different borehole sections shown.*

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.

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

Aim of the project

The aim of the project is to characterize geochemistry of secondary minerals precipitated through the last 1.5 billion years that were emplaced in the crystalline bedrocks, the Laxemar area. The overall aim was to define the sources, uptake and fractionation of rare earth elements (REEs) in calcite, and few other cogenetic minerals (fluorite, Ca/Al silicates), precipitated through the geological history under conditions ranging from hydrothermal to low temperature.

Status of the project

The project is completed and the results are presented in two peer-reviewed articles published in scientific journals, and in a PhD thesis (see literature list bellow).

In the manuscript we present and discuss the sources, distribution, abundance and fractionation of REEs mainly in calcite and other minerals (fluorite, Ca/Al silicates) that precipitates in fractures in the upper kilometer of granitoids. Our findings show that that there is no easy and straightforward control of REE abundance and fractionation in calcite and other minerals in fractures and veins in crystalline bedrock settings. For example, the REE features in calcite vary extensively within sub-generations of single vein-precipitating events, on micro scale in transects and across individual veins, and unsystematically over the geological history characterised by successively decreasing temperatures of mineral formation. Although the REE content in, and release from, the crystalline bedrock can have an influence on REE distribution in calcite and other minerals, it is of overall minor importance within a given bedrock domain. The main advantage of determining REEs in secondary minerals in fractures and veins in crystalline rock is therefore, as revealed in this work, to assess the character and evolution of the conditions (including features of the paleofluids) during confined mineral-precipitating events.

Spin-off

Spin-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, paleo and recent hydrothermal fluids, and could be used as a reference.

7.3.6 Fe(II) biomineralisation and La enrichment during oxidation of fracture groundwater (Changxun Yu, Linnaeus University)

Aim of the project

The aims are to gain new insights into the molecular mechanisms underlying i) Ni accumulation in four Fe-rich microbial mats haverested from two flow-reactor experiments at sites 1327B and 2156B, and ii) an extreme La-enrichment (about 1,000 fold compared to other REEs) in a layer of bacteriogenic iron oxides covering granitic surfaces, in the Äspö Hard Rock Laboratory.

Status of the project

To achieve the first aim, the distributions of protein, polysaccharides, ferrihydrite, and Ni in a selected region (Figure 7-10a) of the ultrasectioned specimen of the 9-month old microbial mats at site 1327B have been mapped by Scanning transmission X-ray microscopy on beamline 10ID-1 at the Canadian Light Source (Figure 7-10b-d) in October, 2014. The major findings are: i) polysaccharides and protein, the major components of EPS that form the stalks, are well mapped and discerned from the minerals,

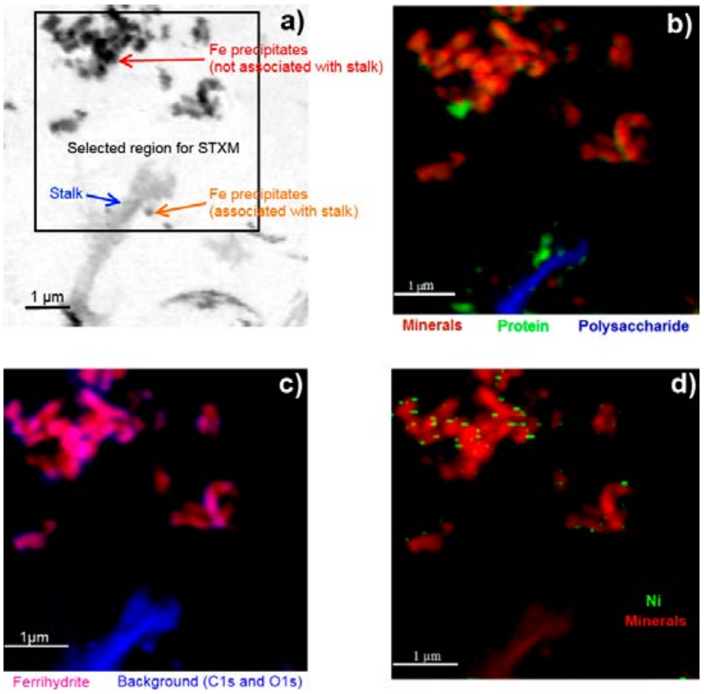


Figure 7-10. *a) Selected region for STXM, and distribution maps of b) protein, polysaccharide and minerals, c) ferrihydride, and d) Ni.*

which are mainly ferrihydrite (Figure 7-10b,c); and ii) vven though Ni was preferentially sequestered by the microbial mats as compared to inorganic Fe oxyhydroxides, it is not associated with stalks, but exclusively sitting at the surfaces of ferrihydrites that are not associated with the stalks (at least in the ultrathin section; Figure 7-10d).

In 2015, smilar speciation maps of protein, polysaccharides, ferrihydrite, and Ni for the other microbial mats and inorganical Fe oxyhydroxides will be collected at Canadian Light Source. In addition, a proposal will be submitted to Advance Photo Source for investigating the chemical associations of La with other mineral phases in the La-enriched layer by combining mirco- X-ray fluorescence, micro-X-ray diffraction, micro-X-ray absorption spectroscopy.

Spin-off

The preferential enrichment of Ni by bacteriogenic 2-line ferrihydrites may point to a potential utility of Ni as microbial biosignatures. Another spin-off effect is that, assuming a biogenic origin for a least part of the Precambrian banded iron formations, the accumulation of Ni by the bacteriogenic 2-line ferrihydrites suggests that Ni concentrations in the Archean oceans may have been even lower than previously calculated based on chemically synthesized Fe oxyhydroxides.

7.3.7 Exposure to arsenic, lead and cadmium via drinking water consumption near contaminated glassworks sites (Anna Augustsson, Linnaeus University)

Aim of the project

The aim of the project is to characterize the exposure of arsenic (As), lead (Pb) and cadmium (Cd) via intake of local groundwater for residents living around contaminated glassworks sites in Småland, and to assess the risk of exceeding tolerable daily intakes from this exposure pathway. Previous site investigations have shown high concentrations of these these metal(loid)s in surface soils and groundwater at the glassworks properties, hence motivating studies of exposure and risks for those of the residents that use private wells. This Nova FoU project is conducted parallell to studies of exposure via other exposure pathways; for example via intake of homegrown vegetables or wild mushrooms and berries, and they are linked to an extensive epidemiological study.

Status of the project

All sampling and analytical work was completed in the summer of 2014. Water samples from 57 households were collected and the metal content was analyzed with ICP-SFMS. Other main chemical parameters were also determined with standard methods: pH, alkalinity, conductivity, permanganate index, and concentrations of calcium, magnesium, sodium, potassium, and fluoride. The concentrations of As, Pb and Cd were determined for unfiltered water samples, which were assessed to give a more conservative estimate of concentrations representative of drinking water than filtered samples.

The results show that concentrations of As, Pb and Cd are well below drinking water criteria in most samples; only three Pb and one As analysis were above these limits. What these results indicate, is that metals that leach from glass waste and can be detected in groundwater around landfill areas, are effectively immobilized as the groundwater flows towards areas where the pollution level of the surrounding solid phase decreases. There is thus reason to focus further efforts toward understanding these sorption mechanisms, in order to take them into account in future risk assessments.

The project is now in the process of compiling two manuscripts for submission during 2015; one focusing on the health risks following water consumption, and how the methods used to assess the risk is critical, and one focusing on the geochemical controls of metal retention in the unsaturated zone.

Spin-off

In addition to relevant regional research being tied to Nova FoU and NGL, the project provides knowledge about how metal contaminated point sources may impact groundwater resources, and how the risks following consumption of water from private wells can be assessed in a way that increases the useability of the risk assessment as a descision tool. This is relevant also for risk assessments of other kinds of metal contaminated sites, around which drinking water is extracted.

7.3.8 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, as well as in the Sea.

Status of the project

During 2012, transport pathways from land to the sea were studied for the Forsmark area using DarcyTools simulations; the simulations were interpreted by the Lagrangian theoretical framework for travel times along pathways. New and important insight was gained about the water residence time distribution, in particular the effects of fast and slow pathways.

During 2013, relatively little resources from the project were used due to different circumstances, among others parental leave. Part of the Nova project resources was used for the analyses of transport pathways from land to sea in a broader context of catchments as well as groundwater in the Forsmark region.

During 2014 very little resources were used from the Nova FoU project mainly in completing an important report by Dargahi and Cvetkovic (2014). However a major boost for the Nova FoU project was the successful application for a new and closely related FORMAS project "The Baltic Sea Region System: Water changes across scales and subsystems over the forthcoming 30-year horizon" (BALSYS) in collaboration with the Stockholm University. The BALSYS project will be co-developed with the continuation of the Nova project during 2015–2017.

The BALSYS project will build on synthesising existing knowledge as well as on generating new knowledge primarily on integrating processes from local to regional scales. The general scientific question of the project is formulated as follows:

How should scaling in space and time be handled, such that water changes are well understood and quantified from local scales of coastal catchments, through archipelagos, to the large scale of the entire sea and its whole drainage basin, under global climate change?

The specific questions are related to the Grand Challenges formulated in recently launched Baltic Earth research program (http://www.baltex-research.eu/) and have been formulated as follows:

- How will human impacts and hydro-climatic change propagate through the Baltic Sea Region System?
- How will biogeochemical fluxes and feedbacks between land water and seawater change?
- How will the above and other climate-environmental changes affect sea salinity dynamics?
- How will sea level dynamics change and affect coastal freshwater?

The above questions can be answered only by an integration of the different subsystem processes.

Appart form the Baltic Sea scale analysis, the focus of the BALSYS – Nova studies will be on down-scaling and analysing local scale flow and transport processes. On the one hand, these analyses will consider biogeochemical processes of which *eutrophication* is the most important one. On the other hand, the focus will be on *contaminant transport* from point sources, such as are present in the Oskarshamns harbour.

As an interesting case study, we shall consider the Oskarhamn harbour and simulate the transport of pollutants that are present in the sedment. The bathymetry scales for the analysis are shown in Figure 7-11. During 2015, we plan to complete the hydrodynamic and contaminant transport simulatons at these three resolutions and demonstrate the potential spreading of contaminants from the harbour along the Swedish coast. This analysis will be particularly interesting since drudging measures are to be implemented in the Oskarshamns harbour.

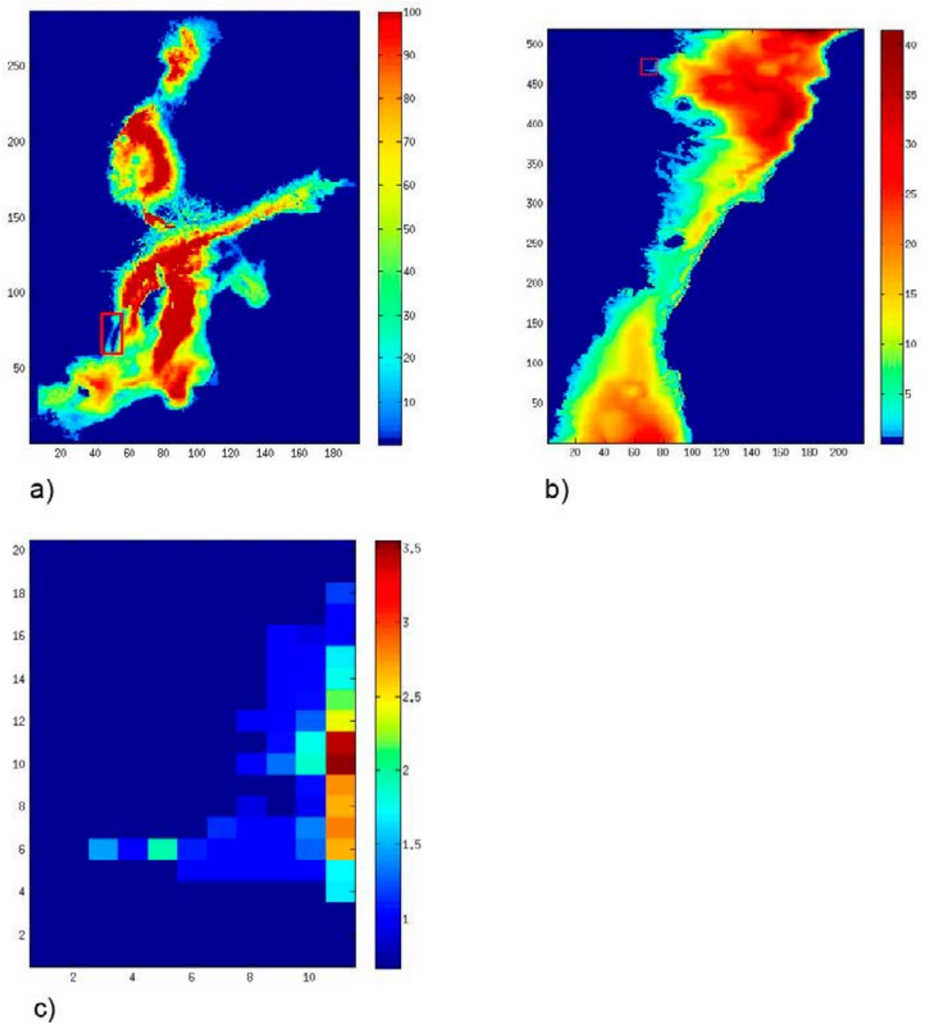


Figure 7-11. *Scate transition from the Baltic Sea to the Oskarshamn harbour: a) Bathymetry of the Baltic Sea with resolution of 5 km; b) Bathymetry of the mid-scale region with resolution 250 m; c) Oskarshamn harbour scale with resolution of 10 m.*

Outcomes

A major work on the hydrodynamic and transport characteristics of the Baltic Sea has been completed (Dargahi and Cvetkovic 2014); it will serve as a scientific basis for the forthcoming would within the BALSYS – Nova FoU project.

Spin-off

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

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

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

7.3.9 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 a geographical focus on coastal regions. KLIV investigation sites include the Swedish Water Management District of Southern Baltic Proper, which in turn includes the Äspö Hard Rock Laboratory (HRL) and the wider Oskarshamn coastal region related to the National Geosphere Laboratory (NGL). Methodological development and comparative catchment studies are also carried out for other parts of the world. During 2014, the KLIV research group has continued with research into its main research questions. Formulated in last year's report, these are:

1. How does general environmental-climate variability and change interact with water resource changes (in quantity, quality, waterborne nutrient-pollutant loads)?
2. How can and should society identify and detect water resource changes (in water availability/quality, flood/drought risks) in order to appropriately prioritize and respond to them?
3. What governance changes and measures in the landscape can contribute to efficiently control (promote desirable and reduce undesirable) anthropogenic changes to water resources?

Based on answers to these questions, KLIV research provides new insights and knowledge on water system change and its possible management.

To arrive at the answers, KLIV research integrates the inland water system and its adjacent coastal waters, following the path of water flow and waterborne transport of tracers, nutrients and pollutants, as well as the climate change effects on these, along the different water pathways from the respective effect boundaries/entrance zones (land surface for main climate effects, main sources of water, nutrient, pollutant inputs), through the associated hydrological catchments, into coastal waters. Main KLIV working hypotheses are that:

i) This water-following approach provides new advancements, methods and tools for efficiently detecting-monitoring, modeling-projecting and controlling-reducing undesirable water resource changes.

ii) The results contribute to efficient achievement of water-resource and water-related environmental management goals, specifically regarding reduction of water pollution and eutrophication and adaptation to climate change in coastal regions.

Status of the project

2014 was the final year of the KLIV project, which started in 2012. Some work and publications are due to be completed in 2015; thus, the final report from the whole KLIV project will be submitted next year.

Post-doc Andrew Quin, recruited to KLIV in December 2012, has continued development of the KLIV website during 2014, in addition to carrying out research described further below. The website provides a record of the KLIV project, outlining KLIV's research questions and approach, summarizing KLIV research and outreach activities, and presenting members of the KLIV research group.

The main KLIV research activities and results published in 2014 or in-press are summarized below, categorized according to the research questions stated above. Peer-reviewed articles authored by KLIV researchers during 2014 are listed further below in the Literature section.

Work finalized and published or in-press, 2014

1 – Environmental-climate change interactions with water resource change

Local, regional and global studies by KLIV researchers described in this sub-section address the effect of climate change and land-use change on water resources.

Together with other researchers, Georgia Destouni has worked on identifying primary causes for water resource changes (driven by atmospheric climate change or anthropogenic drivers in the landscape) in regions and catchments in Sweden (Van der Velde et al. 2014) and across the globe (Jaramillo and Destouni 2014). Other research into water resource changes has focused on changes to soil moisture (Destouni and Verrot 2014, Verrot and Destouni 2015). Specifically, Destouni and Verrot (2014) present a conceptual and analytical framework for linking hydro-climatic change at the surface to subsurface changes in soil water and groundwater conditions. They used the framework to assess historic variability and long-term change of soil moisture conditions in a Swedish drainage basin, revealing a major increase in the frequency of dry soil events during the last century, suggesting that hydrological and agricultural droughts may become more frequent in the future in spite of an anticipated increase in preciption. Verrot and Destouni (2015) further investigated variability and change in soil moisture focusing on the effects of snow dynamics. A further regional study has highlighted climate change effects on the often overlooked coastal environment of the Baltic Sea, including hydrological and water resource changes (Strandmark et al. 2015). Overall, such knowledge developments related to hydro-climatic and water resource changes can inform water management and adaptation strategies, and highlight the need to differentiate strategies regionally depending on main change drivers and their impacts in order to protect water resources and vulnerable ecosystems.

KLIV's international research collaboration has resulted in two studies focussed on the Selenga River, an unregulated basin in Russia and Mongolia, contributing to > 60% of Lake Baikal's inflow (Chalov et al. 2014, Törnqvist et al. 2014). Chalov et al. (2014) investigated the significance of peak flows for sediment loading, erosion/deposition patterns, suspended particulate matter and heavy metal transport. Analysis of field data and hydrological modelling revealed that annual sediment loading and pollution increases by 70–80% during peak flows. Also, a long-term, decadal trend of reduced sediment transport was identified, caused by abandonment of cultivated lands and, also, hydro-climatic change. Törnqvist el al. (2014) assessed the effects of climatic change on historical and future water discharge of the Selenga River. From 1938–2009, with regional temperatures rising nearly twice as fast as global, the intra-annual variability of discharge has decreased – indicating degradation of permafrost in the region. In the future, increased regional warming may be expected to bring about further permafrost thaw and associated hydrological changes. However, it is difficult to project future water changes due to major water-related uncertainties in climate models, which largely failed to reproduce historical hydro-climatic behavior and change. In-depth studies of hydrological basins, like the studies of the Selenga River and Lake Baikal basins, can advance understanding of hydrol-climatic changes and inform management and adaptation decisions for future change scenarios.

2 – Identification-detection of water resource changes

The sources and processes which control trace metals in groundwater have been studied in two different settings: fractured crystalline rock and a black-shale mining area. The studies in the rock setting include identification and quantification of the mechanisms controlling high Cesium concentrations in groundwater of predominantly marine origin (Mathurin et al. 2014a), and relatively low concentrations but variable fractionation patterns of rare earth elements in groundwater throughout the upper kilometer of the crust (Mathurin et al. 2014b, Alakangas et al. 2014). The study in the mining area focuses on the controls and leaching potential of Nickel, Uranium and Arsenic in various types of black shale materials, via a long-term humidity cell, sequential chemical extractions and X-ray absorption spectroscopy (Yu et al. 2014).

KLIV research has also investigated dominant processes of waterborne chemical transport through catchments and groundwater systems. Selroos and Destouni (2015) assess how separate and combined spatial flow variability and temporal flow variability influence solute transport in catchments. Cvetkovic et al. (2014) present a time-domain random walk aproach for modelling solute transport in three-dimenionsal aquifers. Cvetkovic and Gotovac (2014) propose a methodological development using a time-domain random-walk approach to modeling chemical transport in fractured rock. Overall, these research results for waterborne chemical transport can be used to quantify variability, change and uncertainty of water quality in a landscape.

3 – Governance and landscape measures for control of water resource changes

KLIV researchers have carried out research related to: mitigation measures and management of the environmentally-stressed Baltic Sea; human-health and environmental issues of chemical release into and transport by water; and means of assessing groundwater resource potential in crystalline bedrock terrain.

A number of KLIV studies focused on the management and mitigation of nutrient loading to the Baltic Sea (Andersson et al. 2014, Bring et al. 2015, Quin et al. 2015). Andersson et al. (2014) focused on phosphorus loading to the Baltic Sea, showing that catchments with a high degree of inland water eutrophication may not be high exporters of phosphorus to the Baltic Sea. Consequently, catchments of lakes with high phosphorus inputs from agriculture may not considerably contribute to phosphorus loading into the Baltic Sea due to the phosporus retention occurring in the lakes. Similarly, Quin et al. (2015) showed that nutrient retention by wetlands is not statistically detectable at catchment scales. Instead, nutrient retention in catchments is primarily correlated with the distance of waterborne transport through the catchments, along their flow network from nutrient sources to the Baltic Sea and, also, with the presence of large lakes. To further disseminate these results, a popular article summarising this work was published in the Baltic Sea magazine, *Havsutsikt*, aimed at spreading Baltic Sea science to the wider public. Bring et al. (2015) further showed how the latest generation of global climate models (in the IPCC Coupled Model Intercomparison Project 5, CMIP5) project future changes in long-term water flow and waterborne nutrient loading from rivers to the Baltic Sea. Overall, these studies show how water management decisions and goals need to take into account spatial variability and temporal change within and across hydrological catchments.

A further challenge to effective water management concerns institutional developments for increased stakeholder participation. Franzén et al. (2015) analyzed how institutional legacy affects organizational arrangements and stakeholder participation in two adjacent catchments in southern Sweden. Organisational arrangements differ, despite the proximity of the catchments and their similar characteristics and overarching national and regulatory frameworks. Institutional development needs include a means of recognizing and organizing stakeholders, their voluntary involvement and clear leadership.

Regarding human and environmental health effects of chemical exposure, Augustsson and Berger (2014) assess the risks of excess fluoride intake among Swedish children in households with private groundwater wells. The study presents a way of improving on typically static, single-source methods by assessing exposure by using a probabilistic multi-exposure pathway approach. Amneklev et al. (2015) further address the question of whether the use of bismuth and silver in cosmetic products should be a source of environmental and, also, resource concern.

With regard to freshwater availability, it is often particularly difficult to predict the occurrence of typically limited, but potentially useful, groundwater resources in crystalline bedrock terrain. Earon et al. (2014) developed a method for assessing groundwater resource potential in such terrain based on geographical and topographical factors. The method, which only requires geological maps, feature maps and topography, is suitable for municipal or regional-level planning.

Ongoing research activities continuing into 2015

1 – Environmental-climate change interactions with water resource change

KLIV's water-following approach, as mentioned in the *Aim of the project*, has been further advanced through joint project work of all KLIV researchers from 2012 through to today. A joint manuscript is now being developed based on this work, arguing that gaps and inconsistencies exist in freshwater system understanding and management that need to be overcome. To do so, the joint manuscript propose a new conceptualization of freshwater as a continuous system, emphasizing in particular often neglected aspects of: i) coastal divergent catchments; ii) zones of freshwater changes (surface, subsurface, coastal, observational); iii) water pathways as system-coupling agents, linking and partitioning change between zones, iv) interactions with the anthroposphere as integral system pathways across zones. Using this conceptualization as a framework of understanding human-driven changes and their water impacts is expected to advance the science, policy and management of freshwater.

2 – Identification-detection of water resource changes

Research due to continue during 2015 includes a study where fluorine sources and mobility will be identified and characterised in a setting with high natural fluorine concentrations in the geological materials of Laxemar in SE Sweden. The study will include soil sampling and analytical work such as sequential chemical extractions and scanning electron microscopy. The aim is to unravel the mechanisms leading to high (harmful/toxic) fluorine concentrations in surface waters.

Another study aims to detect metal leaching from acid sulfate soils via geochemical studies of sediments in recipient estuaries. A long sediment core has been sampled in the Vörå creek estuary, western Finland, and analysed by a variety of chemical and mineralogical techniques. The overall aim is to characterize: (i) the extent of metal leaching from the acidic soils, and (ii) by what mechanisms metals are ultimately removed when acidic metal-rich waters are neutralized.

3 – Governance and landscape measures for control of water resource changes

Following the aforementioned research on the catchment-scale role of wetlands for nutrient retention (described in the previous section), further investigation will address how wetlands regulate water flow variability. On a local scale, wetlands can help to regulate water flow – reducing local flooding and providing a slow release of locally stored water during drier periods. Thus protection, restoration and creation of wetlands are often suggested as a means of mitigating undesirable effects of flow variability. However, effects of wetlands on catchment-scale flow regulation remain to be assessed quantitatively.

A preliminary analysis has been carried out for 85 catchments (with areas ranging in size from 0.8 km^2 to 15,395 km^2) in both the North and South Water Management Districts (WMDs) of Sweden. Preliminary results show that wetlands play a relatively small role in regulating catchment-scale water flow relative to the role played by other landscape features: catchment size and, also, the area of lakes relative to the catchment size are more strongly correlated with flow regulation. This was assessed by plotting the coefficient of variation of runoff (standard deviation divided by the mean) against catchment size (Figure 7-12) and the area of lakes relative to the catchment size (Figure 7-13) for the North and South WMD catchments. However, unlike the previously mentioned undetectable effect of catchment-scale nutrient retention by wetlands, the latter are found to have some effect on catchment-scale flow regulation (Figure 7-14).

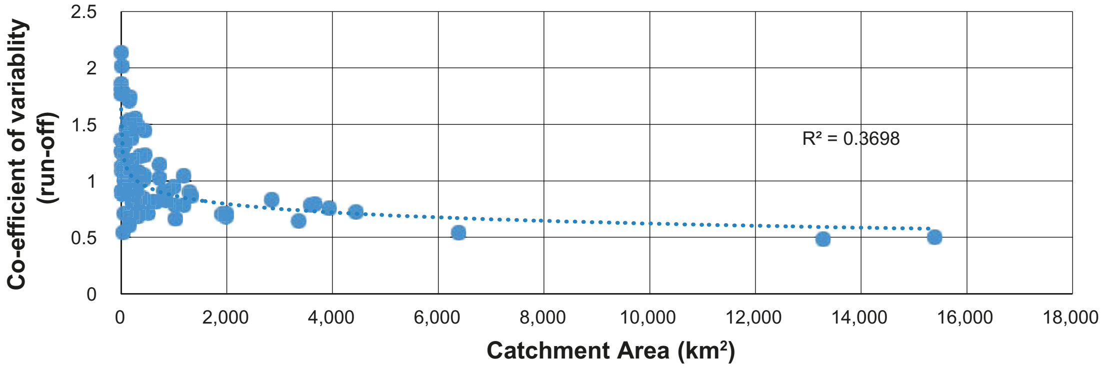


Figure 7-12. *The coefficient of variation for runoff versus catchment area (km2) for 85 catchments in the Swedish Water Management Districts of North and South Baltic Proper.*

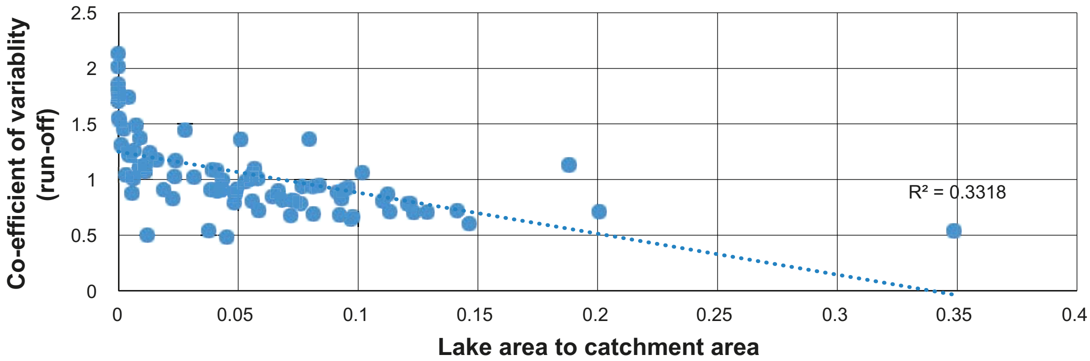


Figure 7-13. *The coefficient of variation for runoff versus the relative area of lakes within each catchment for 85 catchments in the Swedish Water Management Districts of North and South Baltic Proper.*

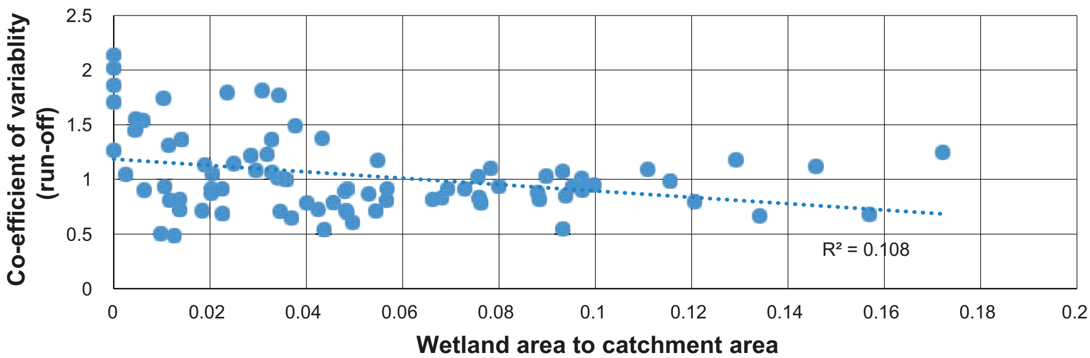


Figure 7-14. *The coefficient of variation for runoff versus the relative area of wetlands within each catchment for 85 catchments in Swedish Water Management Districts of North and South Baltic Proper.*

Spin-off

In 2014, Georgia Destouni from KLIV, together with the Stockholm University team of Arvid Bring, Zahra Kalantari, Lea Levi and Rebecka Segerstöm, along with Anna Rockström from Nova FoU, coordinated and arranged the second Annual Science Meeting of the National Geosphere Laboratory (NGL), held 3–4th November, 2014, in Oskarshamn. The Annual Science Meeting was covered by different media. The first NGL Annual Science Meeting was held 7–8th November, 2013, as described in the previous year's report. Information about NGL, its activities and the Annual Science Meetings is available at the website, developed by Arvid Bring and Georgia Destouni. In summary, the purpose of the Annual Science Meetings is to build up, support and integrate the NGL research community and further the development of NGL as a national research infrastructure. In addition to Georgia Destouni's coordinating role, other KLIV members have also been actively involved in NGL activities.

KLIV members, Berit Balfors, Jerker Jarsjö and Andrew Quin, have been involved in the project, ECOPOOL, together with researchers from Södertörn University and other research institutions and companies. The overall aim of the project is to contribute to an improved understanding of the feedbacks between ecosystems and society for sustainable governance. Thus, considering KLIVs research aims – especially those regarding governance measures for control of water resource changes, there are clear links to the ECOPOOL project. Research by KLIV members in conjunction with the ECOPOOL project includes identification of key needs for development of institutions to better enable stakeholder participation in local water management (Franzén et al. 2015) and strategies and priorities for managing phosphorus loads to the environment (Andersson et al. 2014).

KLIV member Anna Augustsson started a project investigating the risks of living near to former glasswork sites situated throughout Southeast Sweden. Starting with support from KLIV, this research has been expanded to become an own NOVA FoU project: *Exposure to arsenic, lead and cadmium via drinking water consumption near contaminated glassworks sites*, with Anna Augustsson as PI.

7.3.10 Transparent Underground Structure (TRUST) – Management (Maria Ask, Luleå University of Technology)

Aim of the project

The TRUST project (http://www.trust-geoinfra.se/) is the largest geoinfra research project in Sweden. The aim of TRUST is to improve methods and tools for planning, design and construction of underground facilities. Better quality and improved productivity will be the result of clarifying, considering and adapting to geological, technical, environmental, as well as economical uncertainties and risks. TRUST Management, is responsible for coordination and dissemination of the different subprojects in the themes and providing guidelines for innovation and implementation of the research result.

Status of the project

In the large TRUST project, much effort is focusing on identifying and conducting fieldwork. Two common case studies have been identified, the access ramp of Äspö HRL at NE-1 and the traffic interchange Vinsta of Bypass Stockholm. Within TRUST Management, coordination and dissemination of the different subproject have been concudted according to with respect to execution of biannual workshops and monthly telephone meetings. The delays in the Bypass Stockholm project have, however also resulted in a 1 year delay in the TRUST Management project: The first of two TRUST conferences has been postphoned by 1 year. During 2014, general guidelines within TRUST have been agreed upon (signed Partering Declaration and draft of a joint publication policy). Aspects of innovation and implementation have been discussed at workshops and initiation to start a thesis project was started in the end of 2014. TRUST 1 has obtained access to the SICADA database allowing the construction of a GEO-BIM model within the TRUST 4.1 project.

Figure 7-15. *Participants at the TRUST #4 workshop in Luleå, 140819–20.*

Spin-off

To join the Nova FoU research platform is a spin-off from the TRUST project. In turrn, TRUST members have become involved in NGL planning and proposal activities.

7.3.11 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

The project has been reported in a Ph.D. dissertation during 2014 including the presentation of a methodology for prediction of hydrochemistry in conjunction with underground construction. As a part of research related to the proposed methodology, hydrochemical modelling has been carried out and summarized in a scientific article that will shortly be submitted for review.

The project has previously carried out extensive field investigations at the Hallandsås tunnel project as well as at the Kattleberg tunnel project NE of Gothenburg. Two scientific papers on groundwater chemical changes during the excavation works are currently under peer-review. The articles have been written in collaboration with the Swedish Transport Administration.

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.

7.3.12 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

We have 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.

In revising the scientific papers submitted 2013, the project have done further work, which has led to some important discovery. The submitted papers are subsequently withdrawn and the work is being written for Physical Review Letters (a very high impact journal).

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.

7.3.13 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.

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 7-16).

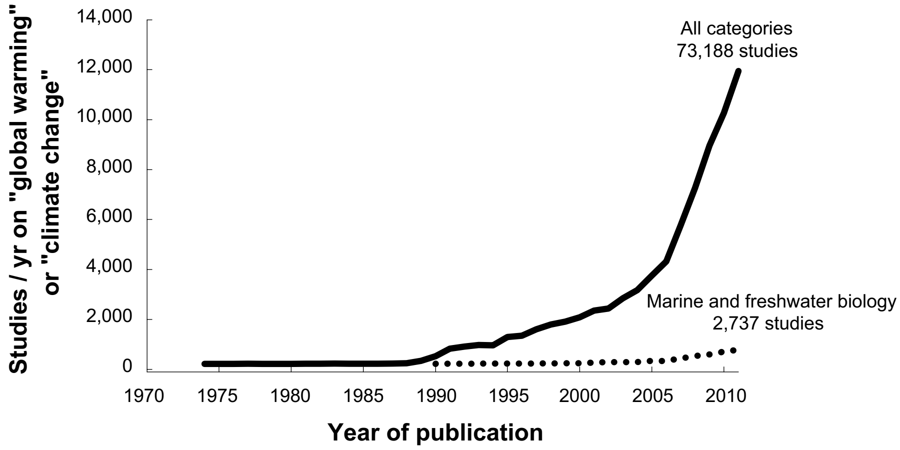


Figure 7-16. *Trends in research output on global warming across all disciplines (filled line) and for marine and freshwater biology (dotted line). Figure shows number of publications per year and is based on data extracted February 2, 2012, from ISI Web of Knowledge.*

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.

7.3.14 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 understanding regarding groundwater storage and extraction in hard rock coastal regions as well as the its spatial behaviour. The project also focuses on developing decision support tools for municipal planners who are tasked with managing limited water supply resources in coastal regions. In hard rock terrains, heterogeneity in the fracture network and geology limit the application of point-based hydrogeological tools. This study aims to develop methodologies which rely on existing continuous digital databases (such as geological maps, topography, land use) or simple field measurements of kinematic porosity which can complement existing data.

Status of the project

The project has three primary deliverables. The first is a study based on the development of a new methodology which uses geological indicators (such as distance to lineament, distance to water, soil type, bedrock type) in order to estimate the groundwater resource potential (GRP) of an area. This study uses analysis of variance (ANOVA) and principal component analysis (PCA) to generate regional GRP maps which correlate with specific capacity values estimated from the Geological Survey of Sweden's well archive with more than 95% confidence. Parameters are classed according to a positive or negative influence on specific capacity estimates using ANOVA. PCA is then used to weight the different parameters by identifying the principal components which are most influenced by specific capacity and then weighting the other parameters based on their loadings on these components. Finally, classes and weights are combined to produce a statistical indicator of the GRP of a particular area. The results of this deliverable were published in *Groundwater* in 2014

The second scientific deliverable of this project is a study which uses superficial fracture measurements to estimate local kinematic porosity values. Estimates are based on a geometric model which incorporates hydraulic aperture, fracture spacing and orientation, as well as length of fracture and type. Results show that the estimates of porosity correlate with hydrogeological indicators such as specific capacity. Additionally, spatial statistical behaviour of hydrogeological data is examined to better understand subterranean hydraulic properties. Finally, the last part of this project is a water balance methodology which is specifically adapted for Swedish terrain. The method accounts for the limited storage values which are often found in Swedish coastal regions, and attempts to spatially account for well extraction in order to implement water balance calculations. Rather than making regional simplifications which often overlook pockets of soil which have porosity values orders of magnitude higher than crystalline bedrock, the method calculates storage, extraction and recharge locally in order to best account for the extreme heterogeneity typical to Swedish coastal regions.

Presentations were made at several conferences in 2013–2014, including *SGU's Groundwater Days* in Lund (Oct 16–17, 2013) , the *28th Nordic Hydrological Conference* in Stockholm (Aug 11–13 2014), and *Hydrology Days* at Stockholm University (Mar 18 2014). Additionally, a poster was presented at the *NGL Annual Science Meeting 2014* in Oskarshamn (Nov 2014).

Spin-off

Municipal planners in near-coast regions as a rule have limited resources with which to manage their water reservoirs. The methods presented in this synopsis illustrate three new approaches to groundwater characterization which do not rely on large amounts of data or over-simplifications which often hinder engineering solutions to such problems. Instead, the methods rely on easily collected data or existing digital datasets. The methods are executed in a GIS environment, and can directly contribute to aiding municipal planners in water resources management.

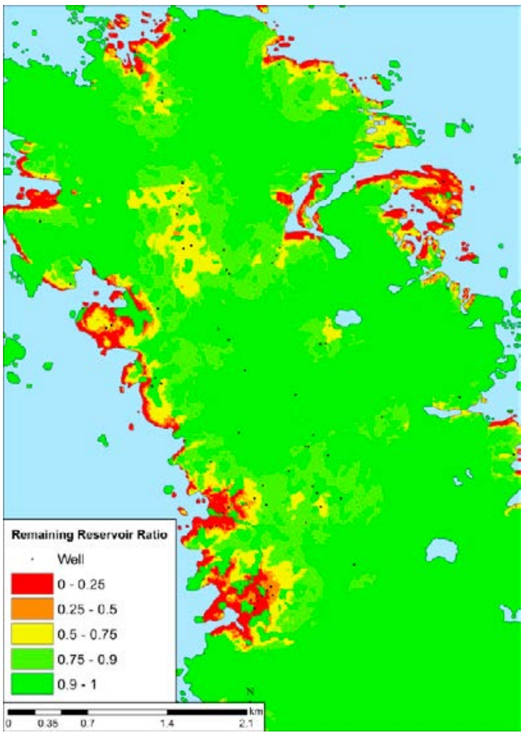


Figure 7-17. *An example of a spatial groundwater balance scenario run over 8 months in Östhammar Municipality.*

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

Aim of the project

Major goals of the project were 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 recent and ancient 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 7-18), NASA 2156B, TASF. These flow reactors enable a contamination-free study of the spatial and temporal development of microbial mats and associated mineral precipitates. NASA 2156B will not further be investigated, as the aquifer seems empty. In 2014 there were no research activites conducted at Äspö, the main focus was on finalizing the current research actitivies and preparing manuscripts. Long-term experiments at TASF and TASA 1327B are planned to continue for indefinite time.

Different aspects of the flow reactor studies, lead to several manuscripts, now under review and publications respectively:

- The flow reactor experiments allowed to investigate the accumulation and fractionation of trace and rare earth elements (TREE) under controlled conditions of the subsurface continental biosphere, and enabled us to assess potential biosignatures evolving within the microbial iron oxyhydroxides. Microbial mats dominated by iron-oxidizing bacteria, namely Mariprofundus sp. and Gallionella sp. were investigated. After two, respectively nine months, concentrations of Be, Y, Zn, Zr, Hf, W, Th, Pb, and U in the microbial mats were 103- to 105-fold higher than in the feeder fluids whereas the rare earth elements and Y (REE+Y) contents were 104 and 106 fold enriched. The microbial iron oxyhydroxides from the flow reactors were compared to iron oxyhydroxides that were artificially precipitated from the same feeder fluid. Remarkably, these abiotic and inorganic iron oxyhydroxides show the same REE+Y distribution patterns. Our results indicate that the REE+Y mirror quite exactly the water chemistry, but they do not allow to distinguish microbially mediated from inorganic iron precipitates. Likewise, all TREE studied showed an overall similar fractionation behaviour in biogenic, abiotic and inorganic iron oxyhydroxides. Exceptions are Ni and Tl, which were only accumulated in the microbial iron oxyhydroxides and may point to a potential utility of these elements as microbial biosignatures. (Heim et al. 2015)
- Green phototrophic microbial mats from the illuminated and aerated flow reactor at TASA 1327B were investigated and analysed with ToF-SIMS (time-of-flight secondary ion mass spectrometry) and gas chromatography–MS (GC–MS). A wide range of lipid biomarkers was identified with ToF-SIMS in the microbial mat cryosection. Spectra and ion images revealed that individual biomarkers, including fatty acids, mono-, di- and triacylglycerols, carotenoids and chlorophyll were localized with diatom cells identified as Planothidium lanceolatum using optical microscopy. This diatom species can thus be regarded as a major lipid source within the microbial mat system. (Leefmann et al. 2015)
- The microbial community in these reactors clusters according to the water type while the exposed tunnel microbial community is more homogenous. This suggests that the reactors represent a suitable model system to approximate aquifer-dependent microbial communities. Therefore the reactors can potentially be used to study biogeochemical process occurring in inaccessible fluid conduits of the host rock. Modeling shows that the overall diversity of the microbial community is controlled by salinity as well as carbon and nitrogen sources. However, the composition of IOB is driven by the availability of Fe^{2+} as well as by the pH and O2 concentration. Given sufficient Fe^{2+} micro-aerophilic IOB as well as anaerobic nitrate dependent IOB may coexist. The overall diversity and versatility of the IOB in the Äspö HRL tunnel is far greater than previously shown by previous analysis. (Ionescu et al. 2015b)

- We used iron oxidizing microbial mats to assess the potential impact of microbial activity on the deposition of banded iron formations (BIF). The mats were collected during several years from experimental tanks connected to groundwater aquifers with different Fe^{2+} concentrations. To separate between biotic and abiotic iron oxidation, live and killed mats were incubated with $^{57}Fe^{2+}$. Separate analyses of the water and solid phase revealed that the iron oxidation and reduction rates per ml of solid matter (biomass and iron precipitates) were 0.4–73 mmol L-1d-1 and 30–280 mmol L-1d-1, respectively. No significant differences in iron oxidation rates were observed between the live and killed samples. The iron reduction rates, however, were higher in the live samples in mats from 3 out of 4 environments. We suggest that in natural systems, in the presence of organic matter, biotic and abiotic iron oxidation and reduction are not separable processes. Fe^{2+} 30 will be biotically and abiotically oxidized as well as bind to exposed charged groups of organic substances. Either way, this iron may serve as a nucleation matrix for further abiotic iron precipitation. The oxidized iron is then susceptible to iron reduction, which can likewise be a direct metabolic or an abiotic process. Nevertheless, it is important to note the significance of organic matter, since both the abiotic oxidation and reduction of iron are often mediated by substrates of biological origin. (Ionescu et al. 2015a)

Furthermore, in collaboration with SP (Technical Research Institute in Borås) ToF-SIMS 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. (Leefmann et al. 2015)

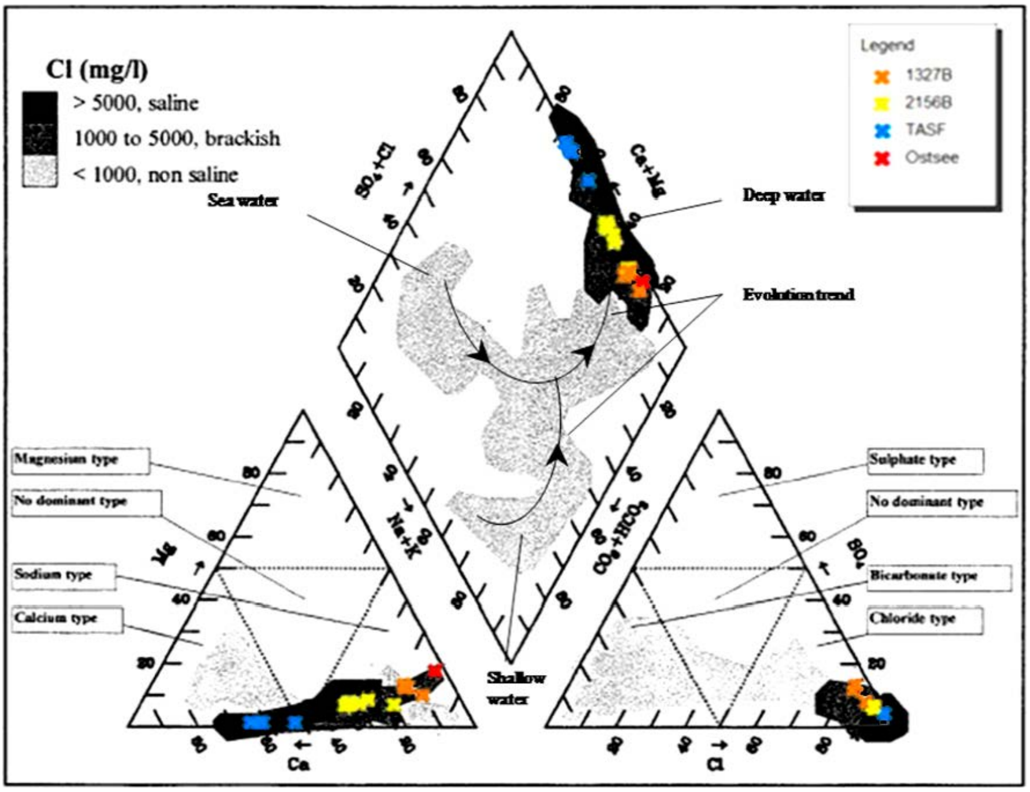


Figure 7-18. A standard Piper Diagram shows the three types of aquifers investigated. They can be separated according to their salinity, especially the Ca and Mg content. Diagram modified after Laaksoharju et al. (1999).

An open pond system consisting of several different subsystems was studied to explore the diversity and spatial distribution of microbial communities and associated mineral precipitates. A further focus was placed on the establishment of inorganic biosignatures (especially trace and rare earth element (TREE) fractionation patterns) for biogeochemical processes involving subsurface microorganisms. The TREE enrichment pattern of the iron oxidizing microbial mat largely reflects the environmental conditionsprevailing throughout the activity of the microbial mat. In contrast, black microbial mats, dominated by sulphate reducing bacteria, showed a TREE fractionation that significantly differs from both, the iron oxidizing microbial mat and the pond water. The accumulated TREE can mainly be attributed to the microbially formed pyrite within this mat. These observations point at a potential utility of this fraction pattern as a distinctive biosignature, but a further validation and comparison with other microbial mats and biotically and abiotically formed pyrites is necessary.

Fracture minerals within several SKB drill core of the Äspö Diorite and Småland granites were investigated for fossil biosignatures of subterranean microbial activity using various analytical techniques.

- One study focused on a fluorite and calcite containing fracture within the Äspö Diorite and it was possible to chemically and microscopically characterize a thin (20–100 μm), dark organic layer lining the boundaries between different fracture minerals. The organic matter, corrosion marks, branched tubular structures, and TREE accumulation were interpreted as remains of a microbial biofilm system that established much later than the initial cooling of the Precambrian host rock. (Heim et al. 2012)
- A second study revealed a concentration of organic matter inside Mn-rich calcite fractures, especially at the boundary to the rock matrix. The presence of organic matter, especially carbohydrates (e.g. fucose), amino sugars and amino acids, suggests the existence of a conditioning film. The presence of the amino acid phenylalanine in the L-and the D-configuration occurring in both rock types and the water samples demonstrates the rather recent formation and an influence of the overlying water seeping through the fracture system. (Schäfer et al. 2015)

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.

Algal cells within a phototrophic microbial mat growing in the flow reactors at TASA 1327B, identified as diatom P. lanceolatum, contain high amounts of triacylglycerols (TAGs). Diatoms with a high TAG content are important for the research and development of microalagal biofuels (Hildebrand et al. 2012).

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.

7.3.16 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

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 7-19) and the biogenicity of these possible microfossils are being established with raman spectroscopy and ToF-SIMS. Raman analysis has confirmed the presence of carbonaceaous material which is a strong indication

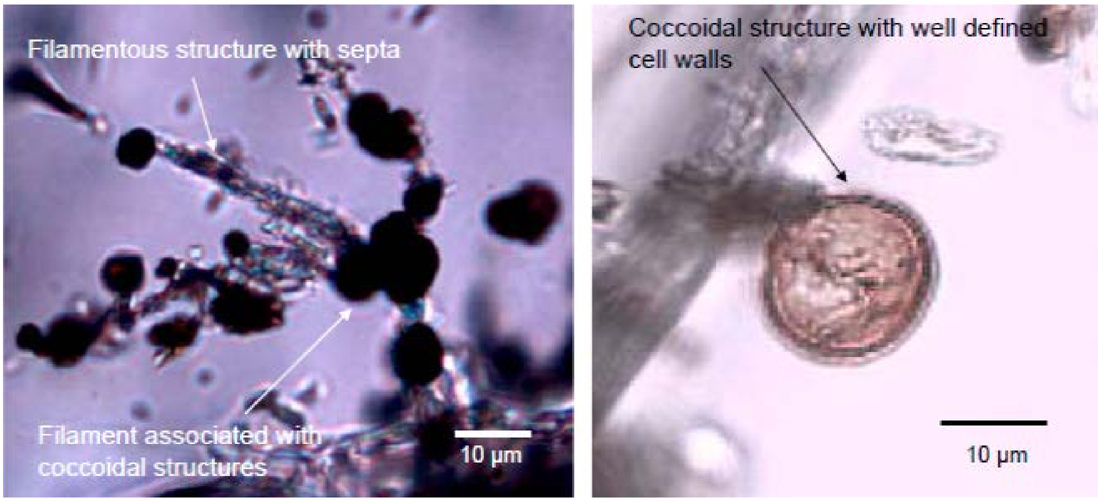


Figure 7-19. Fossilized microorganisms in calcite.

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.

The analytical part of the project is finished and during 2015 a manuscript will be prepared in collaboration with Henrik Drake, Linneus University, Kalmar. Thus, the project is in its final stage and will probably end during 2015.

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.

7.3.17 Structure and function of microbial communities in the deep biosphere (Mark Dopson, Linnaeus University)

Aim of the project

The purpose of the activity is to sample deep sub-surface boreholes containing meteoric water, Baltic Sea water, deep saline water, and a mixture thereof to understand the microbial populations and their functions at the sub-surface interface between a terrestrial and marine environment. The goals that will be addressed are:

1. The majority of microorganisms in the deep terrestrial biosphere are uncultured and likely unknown. The community DNA analysis will identify all of the microorganisms in the population by comparison of near complete genomes to sequences within the database. This will be utilized to answer how the cells are able to grow in the oligotrophic environment including potential novel metabolisms?; are the cells lithotrophic or heterotrophic?; are the cells using indigenous or exogenous (i.e. from meteoric water) carbon and energy sources?; are the microorganisms using other potential energy sources than the hypothesized abiotic H_2 generation?; and what are the roles of microorganisms in altering the geochemical environment?
2. The community DNA will be compared to previously published surface, shallow sub-surface, and marine deep sub-surface metagenomes. This will help answer questions such as if the deep biosphere microorganisms' indigenous populations or immigrants from the (near) surface (most relevant for boreholes containing meteoric and Baltic Sea waters)?

3. Bacteriophages have been recently discovered in the deep biosphere at the Äspö HRL. However, the role they play in this environment is completely unknown and community viral DNA analysis will identify if they limit the bacterial population, if they are temperate, and if they mediate DNA transfer between cells?
4. The active species in the deep biosphere (as opposed to dormant cells) and the genes that they use under *in situ* conditions will be identified by community RNA sequencing and matching sequences to the species identified by metagenomic "binning". This will provide exact data regarding the active species within the population and the metabolic processes they are using.

Status of the project

Community DNA has been sequenced from "modern marine", "old saline", and "undefined mixed" groundwaters, the data analyzed, and sequences allotted to species by binning. These sequences are presently being compared to known microorgansisms to understand the metabolic potential of the microorganisms. Once this has been completed, the comparisons to published surface, shallow sub-surface, and marine deep sub-surface metagenomes will be carried out.

DNA from a time series taken from boreholes containing "recent" Baltic Sea and meteroric groundwaters (retention time ~4 weeks), "intermediate" meteoric water (retention time 5 years), and "ancient" glacial melt and meteoric waters (4,000 to 5,000 years old) have been sampled in collaboration with Christine Heim (University of Göttingen) and Danny Ionescu (MPI for Marine Microbiology). These samples are being analysed in collaboration with Valerie Hubalek and Stefan Bertilsson, Uppsala University.

Viral community DNA has been prepared from the "modern marine", "old saline", and "undefined mixed" groundwaters and initial data analysis carried out. The analysis will be continued to identify the role of viruses in the deep biosphere.

The *in situ* RNA sampling device (Figure 7-20) required to obtain valid RNA preparations from boreholes (i.e. under *in situ* pressure and redox potential) has been constructed and tested. Additional funding has been granted from Vetenskapsrådet for a three year project to carry out analysis of the active populations within the groundwater communities that will begin in 2015.

Figure 7-20. *Sampling vessel for preservation of RNA from borehole water maintained under in situ conditions.*

Spin-off

The spin-off effects will be to create a complete model of the Äspö HRL deep biosphere. The systems biology and geochemical data will be utilized to create a holistic model of the environment that can then be used to understand the links between biological and chemical processes.

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

Aim of the project

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.

Status of the project

When performing 2D resistivity profiling, the multi-gradient array was found to be suitable, with electrode spacings on the order of 1.5 the expected HDZ thickness being optimal. The lower frequency GPR antenna (centered around ~1,500 MHz) was found to be most useful in identifying individual fractures, whereas the higher frequency antenna (centered around ~2,500 MHz) provided EDZ dimension estimates more consistent with those provided by other methods.

At both sites, the HDZ was found to vary in depth from 5 cm to 10 cm, and the EDZ was found to vary in depth from 15 cm to 35 cm. The results of the geophysical surveys at NASA 2376A and 2715A are shown in Figures 7-21 and 7-22, respectively, with borehole camera observations of fracture quality overlaid.

A paper has been published (Walton et al. 2015).

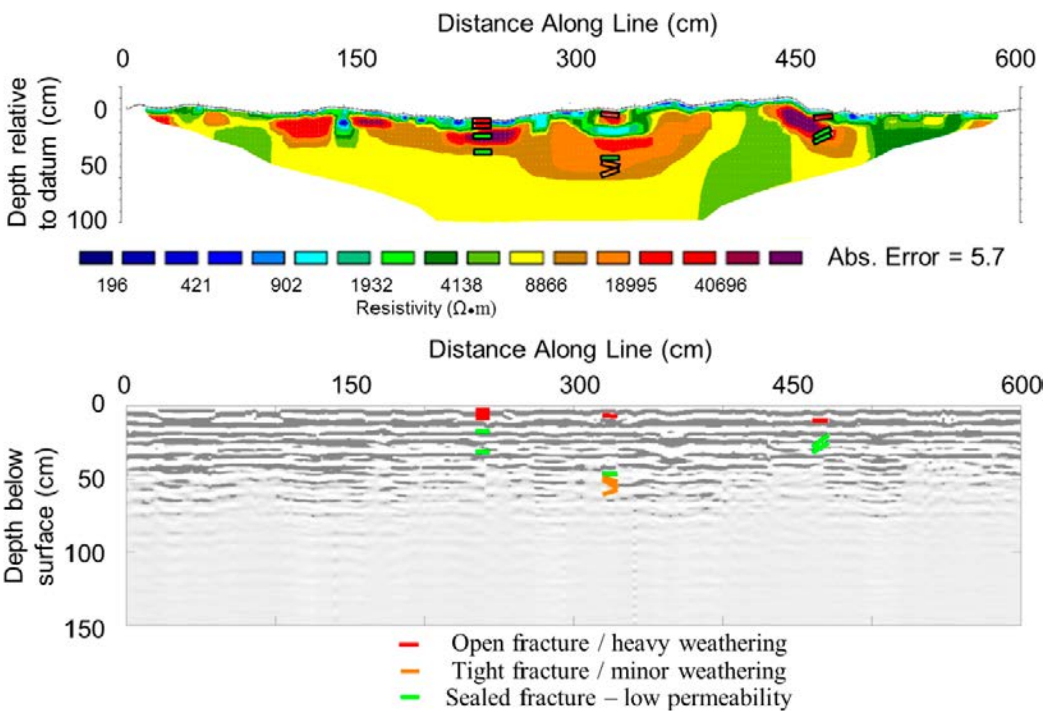


Figure 7-21. The inverted resistivity model and stacked GPR data (lower frequency) overlain with known fracture locations from boreholes at NASA 2376A.

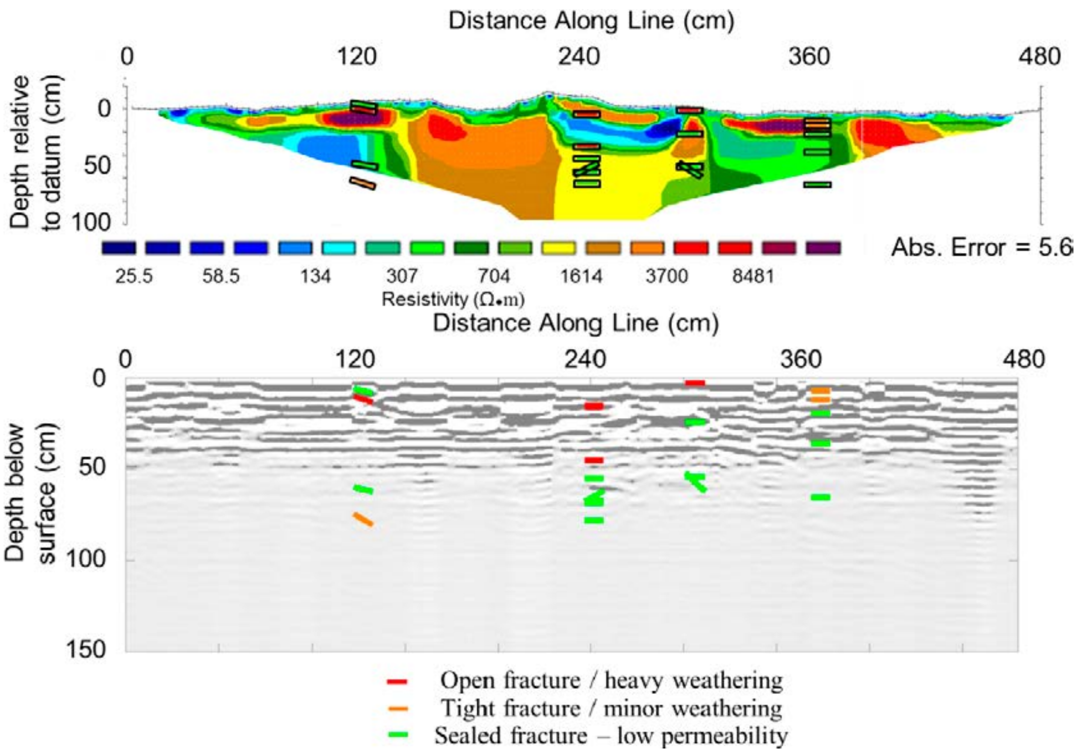


Figure 7-22. *The inverted resistivity model and stacked GPR data (lower frequency) overlain with known fracture locations from boreholes at NASA 2715A.*

Spin-off

This research project is a preliminary proof of concept phase of a potentially larger project. Research in 2013 was focused 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. Optimizing existing geophysical equipment for EDZ/HDZ detection.
2. Developing methodologies and equipment specifications for geophysical detection of EDZ/HDZ underground excavations.
3. 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 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.

7.3.19 Apatite fission-track analysis of samples from SKB Oskarshamn drillcores (Peter Japsen, Geological Survey of Denmark and Greenland, GEUS)

Aim of the project

The aim of the project is to obtain apatite fission-track analysis (AFTA) data from samples from SKB's Oskarshamn drillcore.

The AFTA data will allow us to constrain palaeo-geothermal gradients during Phanerozoic palaeo-thermal events in southern Scandinavia and hence to estimate the thickness of the cover at the time of these events (e.g. Green et al. 2002). We find that such data from southern Sweden will provide us with a link between the well-known burial and exhumation in the eastern North Sea and Denmark on one hand and that of both Norway and Finland on the other hand. Furthermore, the study will build on the available literature about the thermochronological development of southern Sweden (e.g. Cederbom et al. 1999, Larson et al. 1999a, Söderlund et al. 2005). GEUS and Geotrack have previously undertaken and published results from such investigations in different settings; e.g. in Greenland, the North Sea and Brazil (Japsen et al. 2005, 2007, 2012).

Status of the project

Seven samples from SKB drillcore KLX-02 were collected in Oskarshamn, April 2013. The samples have being processed and the results have been presented at the Geological Winter Meeting in Lund in January "Japsen P, Green P F, Erlström M, 2014. Burial and exhumation history of southern Sweden estimated from apatite fission-track analysis data, Nordic Geological Winter Meeting, Lund 2014, 1 p". The results are planed to be published 2015.

Spin-off

We intend to publish the data from Oskarshamn together with AFTA data from outcrop samples from central and south Sweden and so far unpublished AFTA data from the 6.8 km deep Gravberg-1 borehole in the Siljan impact structure.

The Phanerozoic burial and exhumation history of Scandinavia is a field of intense scientific interest. The collapse of the Caledonian mountain chain in the late Paleozoic has been recognized since long, but the subsequent thermotectonic history in Mesozoic and Cenozoic times is a field of ongoing research (e.g. Rohrman et al. 1995, Cederbom 2001, Cederbom et al. 1999, Larson et al. 1999a, b, Hendriks and Redfield 2005, Söderlund et al. 2005, Hendriks et al. 2007) and certainly also a field of ongoing debate (e.g. Hendriks and Redfield 2006, Larson et al. 2006).

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

Expert meetings (Figure 7-23) 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 7-23. 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 7-24.

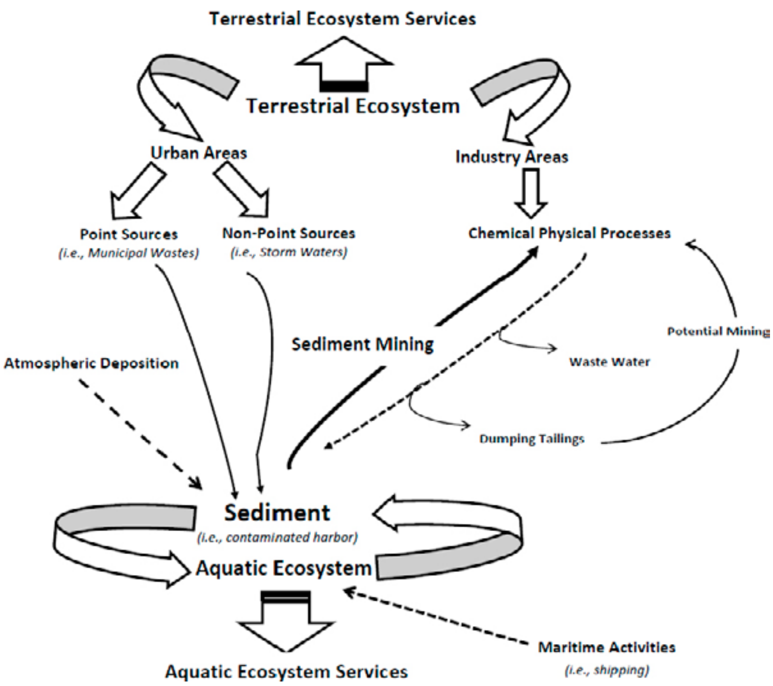


Figure 7-24. Conceptual diagram of the link between different loops (sediment, urban and industry areas, atmospheric deposition, maritime activities) and ways (sediment mining to return them to the anthropogenic closed loop systems).

Status of the project

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 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.

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. 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.

7.3.22 Title: Rock, harbor/bay/lagoon sediment and soil metal analyses instrument for fast areal distribution estimations (William Hogland, Linnaeus University)

Aim of the project

The XRF Delta Instrument (Figure 7-25) was bought as a field-portable equipment that can be used to test soils, sediments, solids, snow, ice, sludge, mixed waste and debris, wood, bagged soils, coring's, filters, wipes, coatings, and more. The instrument has been applied to: 1) Community and Residential Development, 2) Monitoring of high levels of contamination in soils in developing countries and, 3) Hazardous Waste screening.

The XRF equipment is able to identify a number of different toxic metals (Pb, As, Hg, Cr, Cd) and nutrients (phosphorus) at very low levels (PPM) and can be effectively used in rocks, old industrial sites, old landfills, brownfields and others. It has a crucial importance in remediation programs where contaminated soils/sediments, or even landfill excavations are carried out where a high level of contamination can be found. The instrument can bring the information and basic knowledge on how to proceed when dealing with these contaminated materials.

Status of the project: The XRF equipment has been bought and used both in research and education. The instrument has mainly been used in the by Swedish Institute sponsored project "Closing the Life Cycle of Landfills – Landfill Mining in the Baltic Sea Region for future". It has also been used in thre PhD courses organized by William Hogland and Mait Kriipsalu;

1) Fullscale Landfill Mining tests, at Saaremaa landfill, Estonia, 31 January – 9 April 2013.
2) Landfill mining in Practice part I, at Högbytorp landfill in Sweden, 21–25 April 2014.
3) Landfill mining in Practice part II, at Högbytorp landfill in Sweden, 07–13 July 2014.

Results from use of the instrument have been presented at:

1) Recycling dagen, kl 13.40, 24 April 2013, Dunkers Kulturhus, Helsingborg.
2) Visning av Landfill Mining projekt Vika Deponin, Katrineholm, 2013-04-25.
3) Fou och aktuellt inom deponering, fredagen den 26 april 2013, Örebro.
4) International seminar, Landfill Mining – experiences, future challenges, and planning of full-scale projects, 19 September 2013, Saaremaa, Estonia.
5) ERASMUS visits and International seminar"Landfill mining in the context of global environmental mitigation", Department of Environmental Technology, Kaunas University of Technology, Kaunas, Lithuania, 06-11.04.2014.
6) Linnaeus Eco-tech 2014, 9th International Conference on Natural Sciences and Technologies for Waste and Wastewater Treatment, Remediation, Emissions Realted to Climate, Environmental and Economic Effects, 24–26 November 2014, Kalmar, Sweden.

Spin-off

The instrument has a very high potential in the research and education activities that the ESEG (Environmental Science and Engineering Research Group) are carring out. More research is planned in landfill mining, harbour mining and glass mining in the Baltic Sea Region. Just in Saaremaa there were 17 researchers from 7 countries learning how to use the instrument. The ESEG expect the instrument to be used a lot during the coming years now in particular when running in to research studies of landfilled sludge and recovery potential.

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

Aim of the project

Linnaeus University in cooperation 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 several

Figure 7-25. *Dr Fabioc Kaczala using the XRF-instrument.*

times and includes now cooperation with Professor Waclaw Gudowski, Nuclear and Reactor Physics, KTH (Royal Institute of Technology). The course takes place at Äspö Hard Rock Laboratory and the lectures are given at Nova (Nova Center for University Studies, Research and Development) in the beginning of June. The fieldwork takes place at Äspö HRL one week later. A total of 7.5 study credits are given for the training course.

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 PETRUS III meeting was held in in Kalmar 30/9–1/10 including a visit to the Äspö hard Rock Laboratory.

Status of the project

The course Elements of the Back-end of the nuclear fuel cycle: Geological Storage of Spent Nuclear Fuel – SH262V was given during 2014. The course is registrated at KTH Royal Institute of Technology and key cooperating partners were Linneus University and KTH Royal Institute of Technology together with Nova Center for University Studies, Research and Development and Swedish Nuclear Fuel and Waste Management Company (SKB).

The four partners brought together their academic and technological leadership and excellence in nuclear waste management research, technology and education in order to create a unique opportunity for students, experts and professors alike, to work together on fundamentals of the back-end of the nuclear fuel cycle and nuclear spent fuel management. During 2 weeks in June 2014. A total of 29 international students had an opportunity to learn about the key issue of nuclear spent fuel storage in precambrian geological formations and then to perform field studies deep underground at a very unique location: the Äspö Hard Rock Laboratory near Oskarshamn.

Other cooperating universities contributing with students and lectures were: University of Illinois (USA), The AGH University of Science and Technology (Poland), The , Tsinghua University and University of Latvia and the Swedish universities in Stockhom and Gothenburg.This course was also a part of the EMINE program – European Master in Innovation in Nuclear Energy. The two-year MSc EMINE programme teaches students about energy management issues and gives them in-depth knowledge of the nuclear industry. The first year is spent learning the fundamentals of nuclear engineering plus safety and radiation protection as well as the design and management of power plants, all mandatory for any nuclear engineer. During their second specialization year, students have the opportunity to gain a closer insight into innovation issues through a live case study where they apply a methodological 'learning-by-doing' approach in projects coached by KIC In-no Energy. http://www.kic-innoenergy.com/education/our-master-school-in-sustainable-energy/

Spin-off

The students on the course are from countries that in the 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. The interest for the course and Äspö-HRL is large both nationally and internationally. The aim of the project is to permanent the course.

7.3.24 Baltic Aquaculture Innovation Center (BIC) (Anders Kiessling, Swedish University of Agricultural Sciences)

Aim of the project

The project has been performed with the aim to study possibilities, preconditions, techniques and possible production systems for a land based aquaculture research and development (R & D) centre, using surplus heat to decrease energy cost and environmental impact. Furthermore, the centre will function as a demonstration and education facility, housing breeding facilities, as well as the brood stock and fry production. A case study in which the possibility to use surplus heat from the nuclear power plant in Oskarshamn have been made.

Specific aims of the project were:

- To gather, put together and compile the current knowledge in the area.
- Description of activities and function of BIC.
- Evaluation of physical conditions to establish BIC.
- Construction and running costs of BIC and a feasible construction and economic time plan.
- The potential to expand BIC and include greenhouse development and production.

Status of the project

Two reports have been published and several expert and stakeholder meetings have been held with the work group. The first report gives a description about aquaculture in general, explanatory statement of BIC and possible outcomes, suitable production systems (recirculating aquaculture systems (RAS)), multitrophic system integreated with waste heat (Figure 7-26), suitable species (turbot and pike perch), breeding program, fry production, construction of BIC etc. The second report is a case study with BIC at Simpevarp.

Spin-off

During the year 2012 a future Swedish Surplus Energy Collaboration (SSE-C) 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 surplus heat. In 2014 SSE-C decided to continue the work for an establishment of BIC and a meeting with invited stakeholders were held. A work goup was formed to find and present potential investors for BIC and a project manager.

Further, some other spossible spin-off effects off the current project are:

- Reduced energy costs for aquaculture businesses leading to establishment of a number of new businesses and new work possibilities.
- Less environmental load from the production of Nordic warm water fish species since surplus heat is used.
- Establishment of an R & D centre for RAS, using surplus heat in the Municipality of Oskarshamn for research and demonstration of technology and biology.
- Intensified research concerning energy conservation in RAS systems, multi trophic production systems, fish feed production, fish nutrition, breeding and production.
- Further cooperation between Oskarshamn and SLU in a number of areas.

The project has been presented at several national and international, scientific conferences.

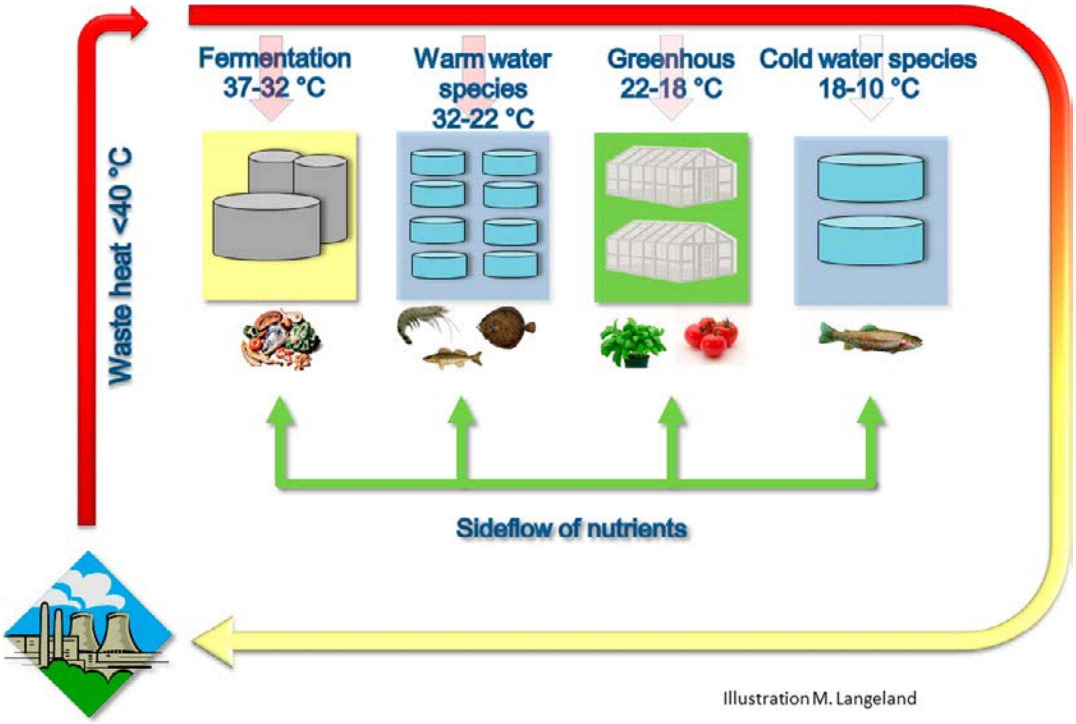


Figure 7-26. Usage of waste hest from an industry for food and feed production. Production of food and feed demand different temperatures which are used in this system. In addition, waste nutrients from the different organisms produced may be used for production of another organism (Original picture; A. Kiessling. F. Indebetou and H. Sandin).

7.4 The spin off effects from the Nova FoU work

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

- **University education:** International 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 environment, environments and to study rock weaknesses and corrosion problems underground. Development of new characterisation techniques to be used for tunnel construction projects.
- **Commercialisation:** Identification and commercialisation of research results in projects and from 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 actual situation by the end of year 2014 was:

- 24 ongoing scientific projects representing a value of 44 million SEK.
- 100 researchers.
- 9 domestic and international universities.
- 3 public organizations.
- 1 company.
- 34 peer review pubplications, 2 Ph.D. dissertations and 7 reports.

7.6 The Nova FoU Steering Committee and personnel

Nova FoU steering committee

Mats Ohlsson, Manager of the Äspö Laboratory, SKB (Chairman)
Peter Wikberg, Research Manager, SKB
Ann-Christin Vösu, Municipality Chief Executive, Municipality of Oskarshamn
Bengt Karlsson, Rector, Nova Center for University Studies, Research and Development
Margareta Norell Bergendahl, Professor, Royal Institute of Technology
Bo Bergbäck, Professor, Linnaeus University

Personnel

Marcus Laaksoharju, Chief coordinator
Anna Rockström, Administrator.

8 International co-operation

8.1 General

During 2014 nine organisations from seven countries in addition to SKB participated in the cooperation at Äspö HRL. Three of them; BMWi, RWM and NUMO formed together with SKB 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:

a) Modelling of Groundwater Flow and Transport of Solutes, which is a forum for cooperation in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock.

b) THMC modelling of Engineered Barrier Systems, which is a forum for code development on THMC processes taking place in a bentonite buffer and gas migration through a buffer.

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

8.2 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. In 2003, the agreement was prolonged for the first time. In 2008, it was extended a further five years, and in 2012 for another year. In 2013, it was agreed to continue the cooperation for another three years. On behalf of and/or funded by the Bundesministerium für Wirtschaft und Energie (BMWi) the following research institutions are presently participating in experiments and activities related to the Äspö HRL programme: The Federal Institute for Geosciences and Natural Resources (BGR), Hannover, and Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig.

The general purpose of the co-operation is to complete the state of knowledge on crystalline rock as potential host rock for high-level waste repositories, and, particlularely to extend the knowledge on the behaviour of the engineered barrier system. Topics of special interest are:

- Studying and investigating buffer material(s), the behavior and all the related basic processes occurring in a repository system by laboratory and in situ experiments.
- Modelling coupled processes.
- Improvement, refinement and test of codes.

The work carried out in 2014 is described below.

8.2.1 Task Force on Engineered Barriers

Both BGR and GRS are involved in the TF EBS.

The contribution of GRS is described as follows.

Task 8 concerns the buffer-rock interaction during buffer re-saturation and is thus addressed in the Task Force on EBS (TF EBS) with emphasis on bentonite re-saturation as well as in the Task Force on Groundwater flow and Transport of Solutes (TF GWFTS) with emphasis on groundwater flow.

Taking the flow rates from a flow model for the Buffer-Rock-Interaction Experiment (BRIE) (c.f. subsection TF GWFTS) the final prognosis for the re-saturation of the bentonite was performed. Comparison of outflow rates from the rock with uptake rates in the bentonite indicated that flow from the fractures exceeds even the initially high demand of the bentonite buffer for water while water supply from the rock matrix would count as limited for a certain period of time.

In the framework of TF GWFTS a comparison of the blind predictions for the water uptake of the bentonite from all participants was given. The results depicted in Figure 8-1 show that the measured water uptake under unlimited water supply, i.e. in the vicinity of fractures, was met quite well while in case of the limited water supply, i.e. at the bentonite-matrix contact, the match was rather poor. However, the predictions of most groups matched among each other demonstrating once more that the extended vapour diffusion model forming the basis of GRS-code (Kröhn 2011) appears to be viable. Only the ClayTech-model came close to both measurements but this group was admittedly "closer to the data".

A draft report concerning the work on subtasks 8b to 8d was written and has already been reviewed. Further work has been suspended, though, when it became clear that a Task 8f would commence in 2015.

Task 8f will be concerned with the re-calculation of the BRIE with due regard to the results of the post-test investigations. Including the referring results in the report about Task 8 was considered to be sensible by both Task Forces.

BGR's activity within the Task Force on Engineered Barrier Systems was focused 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.

The sensitivity analysis task is extended by a code comparison, serving as a benchmark example for coupled thermo-hydro-mechanical simulations of the near field. The code comparison is divided into different stages with increasing complexity:

1. Thermo-hydraulic calculation neglecting vapour diffusion.
2. Thermo-hydraulic calculation considering vapour diffusion.
   a. with constant fluid properties.
   b. with temperature dependent fluid properties.
   c. using a two-phase flow approach.
3. Thermo-hydro-mechanical calculation.

Currently, five teams are participating in this subtask using five different numerical codes. BGR, who is also the task leader, is using the finite-element code OpenGeoSys for their simulations. Comparisons of the results were presented and discussed at the Task Force meetings in Tokyo and Berkeley. For some of the above mentioned stages an excellent agreement between the results of different codes was already achieved.

8.2.2 Task Force on Groundwater Flow and Transport of Solutes

GRSs contributions in the Task Force on Groundwater Flow and Transports of Solutes in Tasks 8b to 8d were as follows:

GRS has modelled groundwater flow with the code d³f (Schneider 2012). As a good representation of the flow field is the very basis for a successful simulation of the buffer-rock interaction modelling flow at the BRIE site was done with particular care.

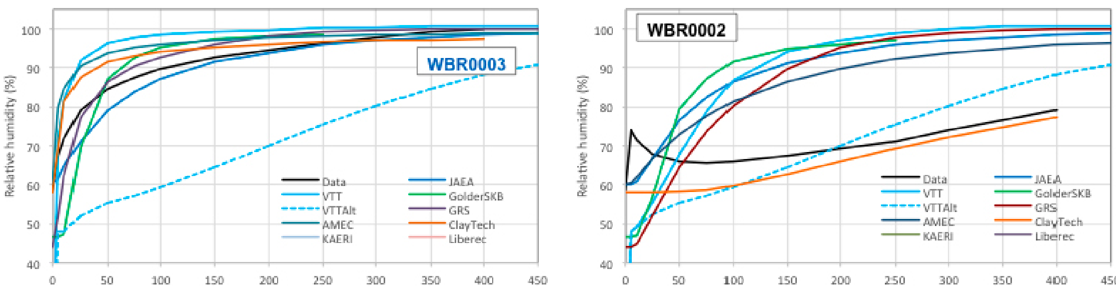


***Figure 8-1.** Development of the relative humidity. left: in the vicinity of a fracture, right: at a bentonite-matrix contact.*

Besides the two tunnels TASD and TASO, 25 boreholes and three large-scale fractures the flow model for Task 8d includes a skin zone around all geotechnical openings that allows variations of matrix as well as fracture properties within this zone. The chosen modification of the permeabilities in the skin zone was based on observations at Stripa and at Äspö. Note that almost 20 years after the first reported evidence of a skin the physical reason for this "skin-effect" lies still in the dark. The comparison of the calculated pressure fields for Task 8c and 8d in Figure 8-2 shows a shift of higher pressures towards tunnels and boreholes due to this skin.

The calculated outflow rates for the boreholes as well as the total outflow of the tunnel were compared with the measurements. They matched rather well immediately and could only be marginally improved by parameter variations. The quite high outflow rates from boreholes KO0018G01 and KG0020G01 might be attributable to inhomogeneities caused by background fractures.

General conclusions from the work on Task 8b to 8d were:

- The concept of a skin in combination with single-phase flow was successful. The nature of the "skin-effect" is still unclear, though.
- Background fractures provide high contributions to the flow field.
- Heterogeneities have considerable influence on the outflow at borehole distance.
- The stochastic nature of significantly contributing background fractures thus precludes deterministic predictions on borehole scale.

Task 8e

Activities in the benchmark "Prototype Repository" (PR) are initiated. The objectives of GRS with regard to Task 8e are:

- Setup of a calibrated large-scale flow model.
- Influence of heat on flow.
- Influence of TASS-tunnel on flow.
- Non-isothermal re-saturation in the buffer.

A similar approach as for the BRIE case has been chosen for this task. Since GRS had applied separate models for different problems, i.e. flow and re-saturation, the codes d^{3}f, COMSOL (COMSOL 2013) and VIPER were/will be used to simulate thermo-hydraulic flow, heat transport and re-saturation, respectively.

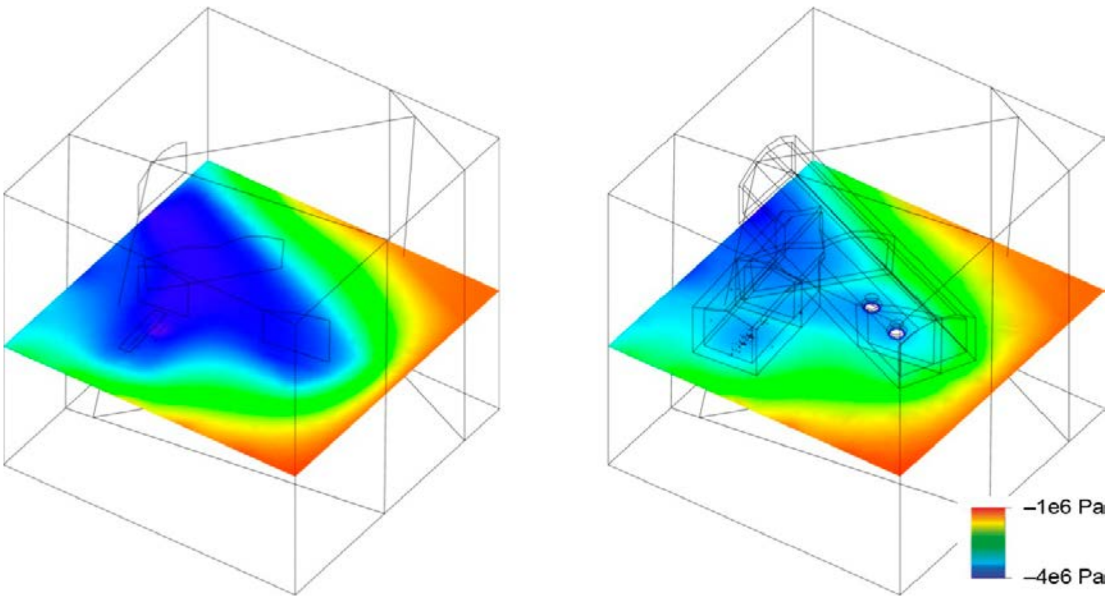


Figure 8-2. *Effect of a skin on the pressure field; left: results for Task 8, right: results for Task 8d.*

For the pre-installation flow model a set of fractures and fracture zones connecting the PR-tunnel with the model boundaries had been defined to make the expected model results consistent with the outflow data from the rock. Closer inspection of the literature especially (Forsmark et al. 2001) revealed, however, that firstly, such large fractures would not have gone unnoticed by the extensive hydraulic testing around the PR-tunnel and, secondly, during this testing program 8 deterministic fractures had actually been identified already. These 8 fractures fit astonishingly well in terms of orientation and position with the fractures and fracture zones that had been previously postulated (see Figure 8-3) giving rise to considerable confidence in the model geometry. The discretization of the revised large-scale flow model including the eight deterministically known fractures had appeared to be completed but a bug in the grid prevented tetrahedralisation. This work had to be put on hold at that point until the developer of this pre-processor becomes available again.

Simulation of heat flow with the code COMSOL has therefore been brought forward. The model size was chosen to be 200 m × 150 m × 50 m as in the flow model. Material data for granite, air, backfill, bentonite and copper were taken either from the task description or from the COMSOL material library. The curves for the heater power were simplified to a visually well-fitting series of step functions.

The measured temperatures were caught rather well without calibration as exemplarily depicted in Figure 8-4. The biggest error of about 2–3°C is probably caused by a mistake in the model set-up. Compacted bentonite had wrongly been assigned to the top metre of the boreholes instead of the backfill material of the tunnel that has a 50% higher thermal conductivity than the compacted bentonite. However, as an input for the non-isothermal flow model as well as for the bentonite-resaturation model the accuracy of heat flow model results appears to be sufficient.

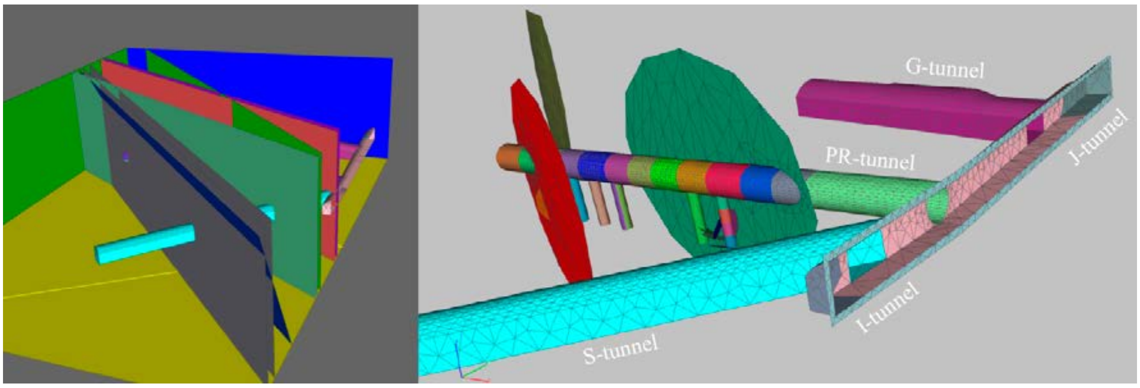


Figure 8-3. *Fractures at the PR; left: assumed, right: measured.*

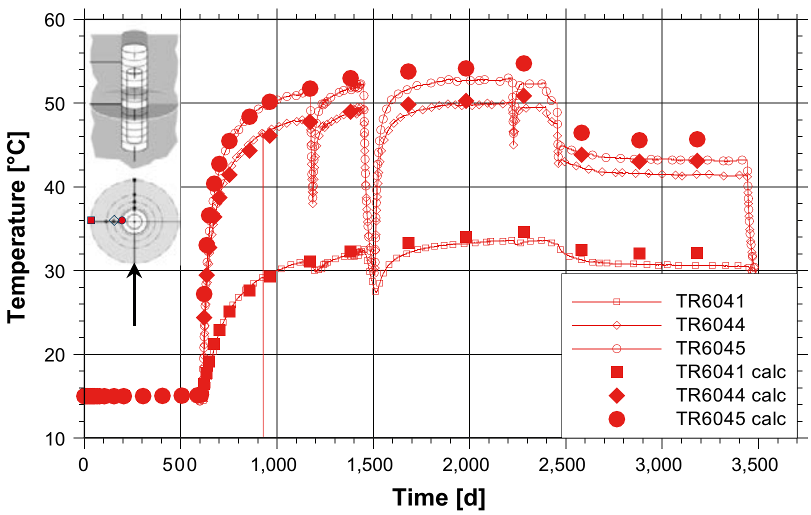


Figure 8-4. *Rock temperature at borehole 6 orthogonal to the tunnel direction.*

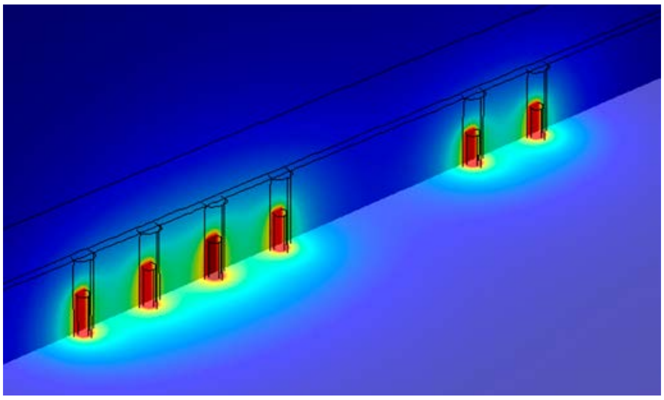


Figure 8-5. Simulated temperature distribution at the PR after 2,000 days; Tmax~80°C.

From the high temperature gradients shown in Figure 8-5 it can be concluded that the temperature increase induced by the heaters did not reach beyond about 15 m into the rock. The heat flow model could thus have been considerably smaller without loss of accuracy.

8.2.3 Alternative Buffer Materials

In 2014, BGR analysed samples of "ABM2". Sampling was performed on all blocks, with samples taken from the contact between the bentonite and the heater (up to 1 mm) and another 4 samples deeper into the blocks (horizontal profiles). 2 blocks in the center were totally destroyed. These blocks were not analysed.

BGR has analysed CEC and exchangeable cation (EC) values of the samples of all profiles of 29 blocks plus all reference clays. These first results on were presented at the PEBS meeting in February 2014 in Hannover, Germany. In 2014, BGR made mineralogical and geochemical analyses of all these samples using XRF, XRD, IR, DTA-MS, Leco-TIC, TOC and S. It is foresen to continue the interpretation of results in 2015.

8.2.4 Lasgit

BGR's activities within the Lasgit project focused on the investigation and modelling of processes and interactions that occured in the experiment, particularly with regard to the behaviour of the engineered barrier system.

Test evaluation and modelling exercises are executed using the finite-element code OpenGeoSys.

8.2.5 Prototype Repository

GRS finished the activities in connecton with the Prototype Repository end of 2013. A final report was written and published in 2014 (Wieczorek et al. 2014).

In 2012 BGR received four samples of the Prototype Repository test (P5 + P6). After sampling mineralogical and chemical analyses were performed and discussed at 2013 PR meetings in Lund and Stockholm. A peer-reviewed paper was published (Dohrmann and Kaufhold 2014).

BGR work on Prototype Repository experiment (Section 2) has been finished.

8.3 NUMO

In 2014 the Nuclear Waste Management Organization of Japan (NUMO) participated in the Äspö International Joint Committee (IJC) and Technical Information Meeting in September 2014.

NUMO, JAEA and CRIEPI held a meeting at NUMO's head office in August 2014, to share the technical information obtained from the activities of the Task Forces and experiments.

8.3.1 KBS-3H Multi-Purpose Test

NUMO has been studying an alternative disposal concept which is called "Prefabricated EBS Module (PEM) concept" since 2011. NUMO's PEM concept is similar to SKB's KBS-3H concept using the super container which is an integrated module pre-assembling the spent fuel, copper canister and buffer material on the ground. During studying, NUMO had sent attachments to Äspö HRL in order to obtain direct experience on site for, in total, 8 months in the period from October 2012 to December 2013.The involvement in the KBS-3H Multi-Purpose Test (MPT) provided valuable information and experience, which will contribute to NUMO's PEM study.

During 2014, NUMO submitted technical papers on KBS-3H MPT to the Japan Society of Civil Engineers (JSCE) with an SKB engineer as co-author.

Currently NUMO is considering the involvement in the dismantling phase of KBS-3H MPT in the future.

8.3.2 Prototype Repository

NUMO participated in the final meeting of the Prototype Repository project, held in Stockholm on 4^{th} and 5^{th} February in 2014. Information and experience from the Prototype Repository were of value for NUMO to proceed with the design of EBS and disposal facilities which is currently on-going.

8.4 CRIEPI

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

THM benchmark simulation of Prototype Repository (PR) is carried out in Task Force on Engineered Barrier System. 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-modelling of the PR after installation, and the third is THM-modelling concerning on deposition hole 6 which is outermost one. All three tasks had been conducted in 2012. Measured THM behaviour in PR was not symmetric and was affected by the existence of fractures. Then CRIEPI decided to revise the modelling of PR considering the effect of fractures in surrounding rock mass.

The smeared fracture model was installed into LOSTUF in order to consider water inflow from fractures. In smeared fracture model, hydraulic conductivity of rock mass is obtained as the volume average of hydraulic conductivity of rock matrix and fractures in each finite element (see Figure 8-6).

Figure 8-7 is made from the CAD data about fractures around PR. CRIEPI conducted fracture permeability calibration based on this CAD data in order to reproduce the water inflow in TBM tunnel and deposition holes in PR before installation. Figure 8-8 shows the analytical domain. Its size is 135 m long, 60 m wide and 60 m high. It is divided into 93,868 finite elements. Water pressure is fixed on bounraries, 4.77 MPa on the bottom, 4.15 MPa on the top and 0 MPa on the tunnel wall.

At first flow rate in each "section" was calculated in the simulation modelling no fractures. Here "section" refers to every 6 meters sections of TBM tunnel and deposition holes. Secondly, flow rate was calculated in the simulation modelling only one fracture to evaluate each fracture's contribution to the inflow of each section. 40 cases of simulation had to be conducted because 40 fractures are defined in the CAD data. After that, simulation modelling all fractures was started. If calculated water inflow was different from the measured inflow, permeability of fractures was re-evaluated using the result from one fracture simulations. This was repeated until calculated water inflow was sufficiently close to the measured inflow in each section. Figure 8-9 shows the calibrated permeability of 40 fractures after 27 simulations. The thickness of fractures was assumed to be 0.001 m. Figure 8-10 shows the comparison between calculated and measured water inflow. Figure 8-11 shows three fractures that have largest permeability. It must be checked whether these high permeable fractures are identical to the fractures from which water inflow had been observed on tunnel wall.

CRIEPI has plan to conduct TH simuation of PR after installation with this updated hydraulic model in surrounding rock mass.

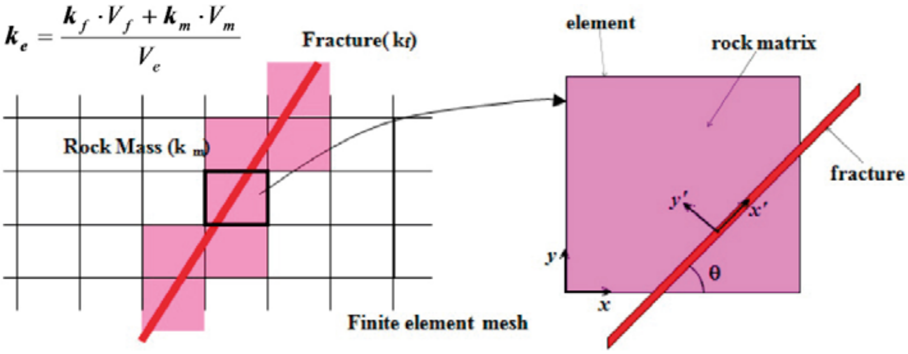


Figure 8-6. *Smeared fracture model.*

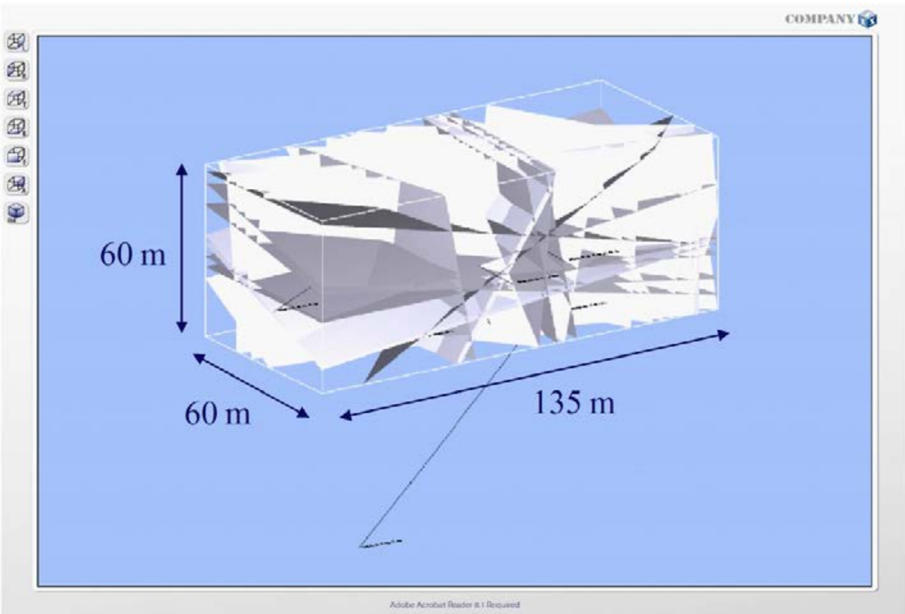


Figure 8-7. *Fractures around Prototype Repository.*

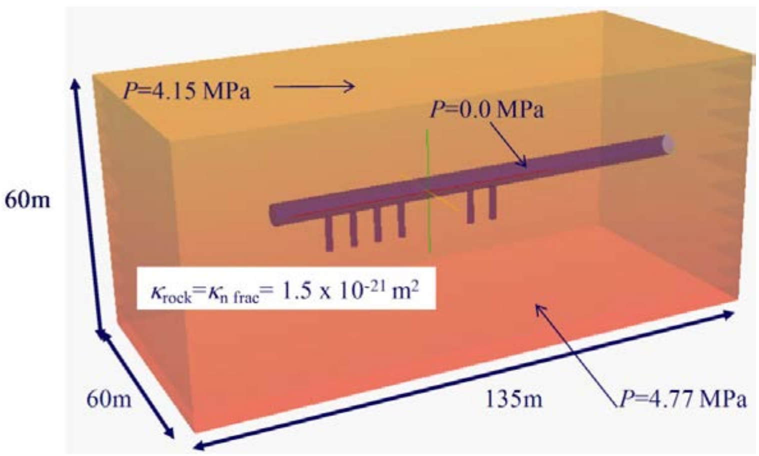


Figure 8-8. *Analytical domain.*

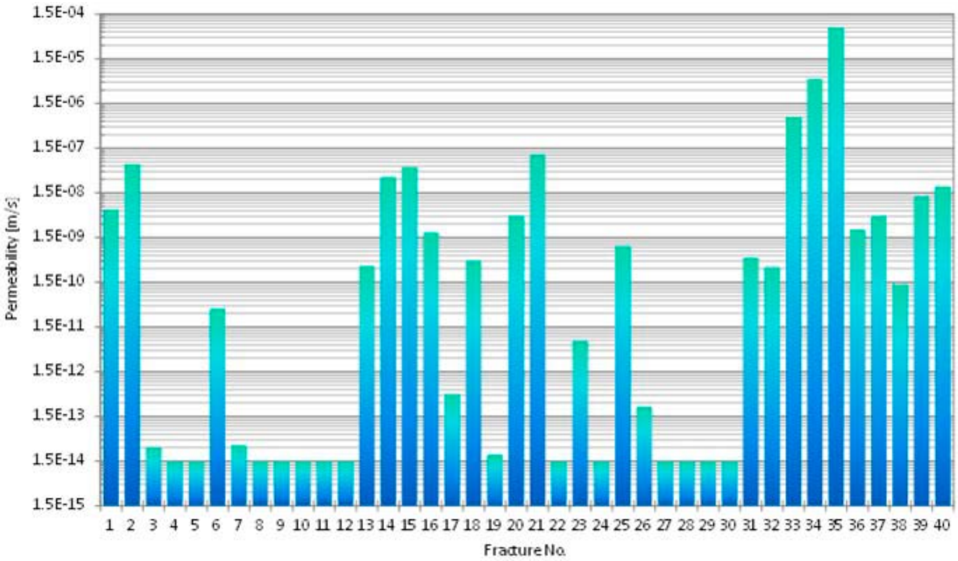
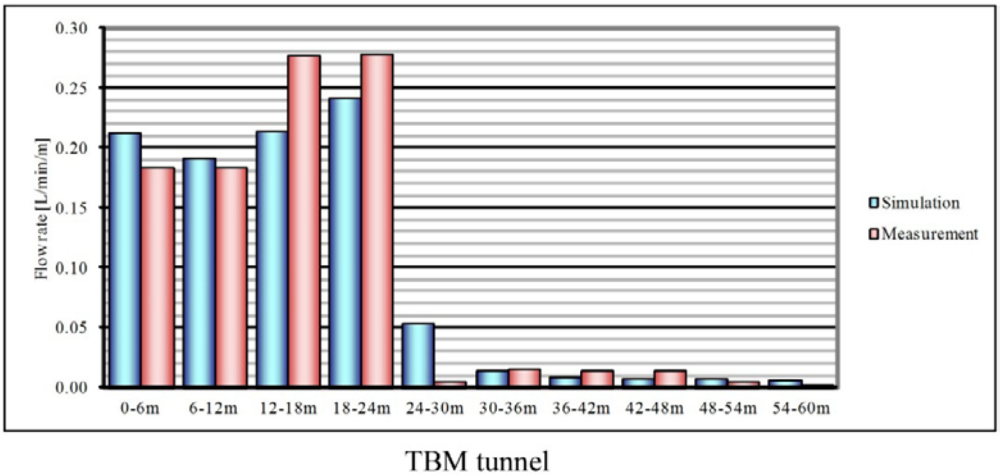


Figure 8-9. *Calibrated permeability of 40 fractures.*



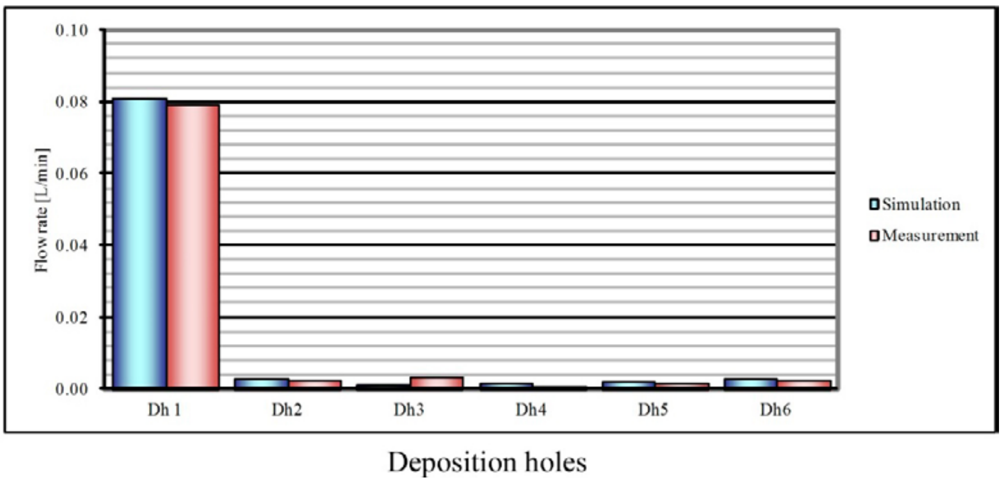


Figure 8-10. *Comparison between calculated and measured water inflow.*

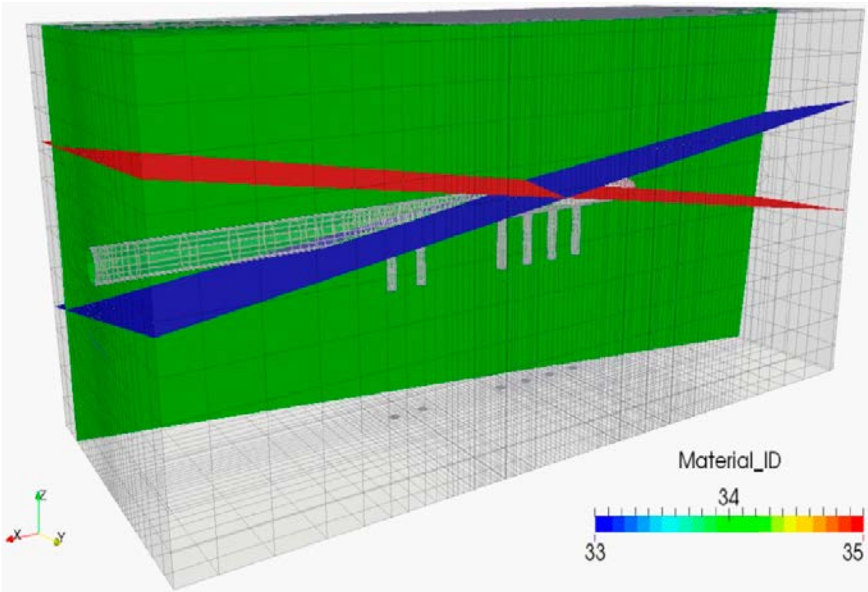


Figure 8-11. *Three fractures of largest permeability after calibration.*

8.5 JAEA

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 2014 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 focused on development of modeling capabilities for coupled flow in fractured rock and bentonite, within the context of "Task 8". The objective of JAEA's 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 deposition hole. In 2014, the modeling activity focused to the evaluation for the influence of fractures on the resaturation hydraulic behavior of the Prototype Repository (PR) experiment at Äspö Hard Rock Laboratory.

During 2014, JAEA participated in the Groundwater Flow and Transport of Solutes Task Force meeting at Daejeon, Korea, April, 1st–3rd, the Task 8 modeling workshop at Arlanda, Sweden, September, 16th–17th, and the Groundwater Flow and Transport of Solutes Task Force meeting at Berkeley, U.S.A., December, 10th–12th.

Task 8E – Modeling the Prototype Repository Experiment

Task 8E is a modeling task for evaluating the Prototype Repository (PR) experiment, and is primarily intended to be a coupled fracture-flow hydrogeological modeling exercise including heat transport and bentonite and backfill saturation. This task is designed to help integrate and demonstrate the lessons learned from Task 8A–D, and particularly from Task8C–D modeling of the BRIE (Bentonite Rock Interference Experiment).

The PR experiment is located at 450 m depth in the Äspö HRL, and was designed, constructed and tested, to the extent possible, to simulate the real deep repository system, KBS-3V, regarding preparations, machinery for installation and deposition, geometry, materials, and rock environment. The Prototype Repository tunnel (TADSA), 65 m long and 5 m in diameter, was excavated using a Tunnel Boring Machine. Six full-scale vertical deposition holes, 8.37 m deep and 1.75 m in diameter, were bored in the TADSA tunnel as shown in Figure 8-12. The PR experiment consists of two sections. The installation of Section 1 was made during summer and autumn 2001 and Section 2 was installed in spring and summer 2003.

One of the lessons learned from the modeling exercise of BRIE is that even low transmissivity fractures seem to be significant in controlling the heterogeneous hydration behavior in bentonite. The features are not only the water conducting features identified by PFL or observation at rock walls, but also the low transmissivity features which have transmissivity below the sensitivity of the measurements (for example, $< 10^{-9}$ m^2/s). Consequently, it is important to develop and demonstrate modeling methodologies to sufficiently represent the spatial structure of those fractures which could potentially feed groundwater to bentonite, leveraging the data collected at and around tunnels and deposition holes. The heterogeneous hydration behavior observed by BRIE was under the isothermal condition. It is also important to examine the effect of the thermal loading on to the heterogeneous hydration behavior.

A simulation system developed for simulating BRIE is planned to be applied for modeling PR experiment. Figure 8-13 shows conceptual illustration of the simulation system, implemented by implicitly coupling two codes, FracMan/MAFIC (Dershowitz et al. 2012, Miller et al. 2001) and Thames (Chijimatsu et al. 2000). The discrete fracture network (DFN) structure of the potentially water flowing fractures is modeled by FracMan, and a saturated fluid flow based on Darcy law through the DFN is calculated by FracMan/MAFIC. In the simulations carried out to date in FracMan/MAFIC, groundwater movement in rock matrix adjacent to the fractures has been neglected, in order to study an effect of how fracture flow contributes re-saturation behavior in bentonite. Thames is a thermo-hydro-mechanical coupling code for continuous porous media. For simulating PR experiment, the coupling of hydraulic behavior in the bentonite and heat conduction in rock and bentonite was solved.

During 2014, JAEA focused primarily on modeling hydrogeological structure around the PR tunnel and deposition holes, within a 150 m × 150 m × 100 m block region (Figure 8-14). The hydrostructural model examination was started with the same stochastic DFN parameter values as used for BRIE modeling. The DFN model was then conditioned to measured data, fracture trace map at PR tunnel and deposition holes, transmissivity and head values measured at each borehole packer section, groundwater flow rate measured at each weir along PR tunnel and at the deposition holes. Figure 8-15 shows an example of the DFN model based on the stochastic parameter values as used for BRIE modeling, after conditioning of the fracture size distribution, by adjusting the power low distribution parameters. Figure 8-16 compares the fracture trace length distribution at the PR tunnel. To reproduce the measured trace length distribution (red open circle), the exponent, b, of the power low distribution was adjusted from 3.6 (black line) to 3.2 (blue line). Groundwater flow to the PR tunnel and deposition holes were simulated by 1,000 stochastic FracMan/MAFIC DFN realizations, and the results were compared to measured data (Figure 8-17). Further model conditioning will be carried out during 2015 to better match the tunnel inflow, particularly in the anomalous high flow measured around 3,535 m and 3,580 m, and the inflow to deposition holes.

Comparison between the PR deposition holes and the DFN model realizations indicates that the fracture transmissivity below PR tunnel is lower than that which provided the basis for the DFN model, as shown in Figure 8-18 (a). In addition, low pressure below the PR tunnel and high pressure at both side of PR tunnel can also influence inflow (Figure 8-18 (b)). Based on the comparison, JAEA will update the DFN model during 2015 to better condition fracture hydraulic characteristics and boundary conditions.

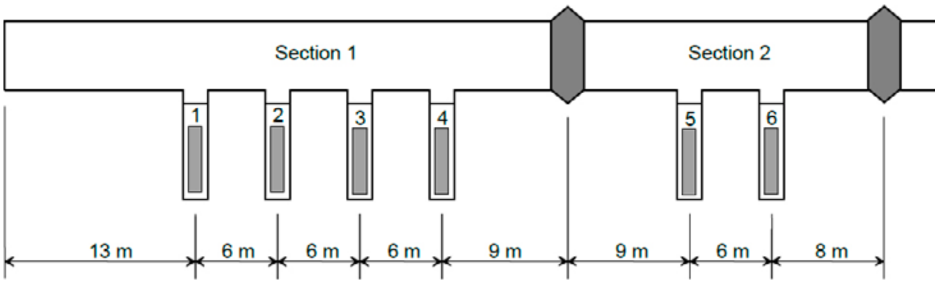


Figure 8-12. *Schematic view of the Prototype Repository experiment.*

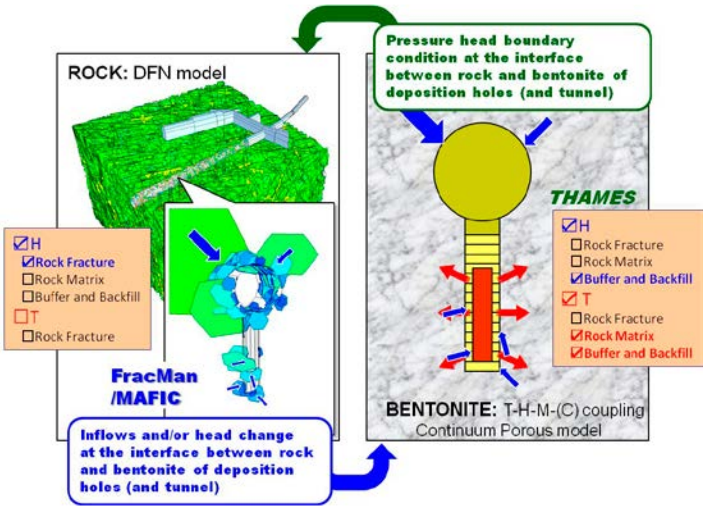


Figure 8-13. *Conceptual illustration of the simulation system implicitly coupling two codes, FracMan/ MAFIC and Thames.*

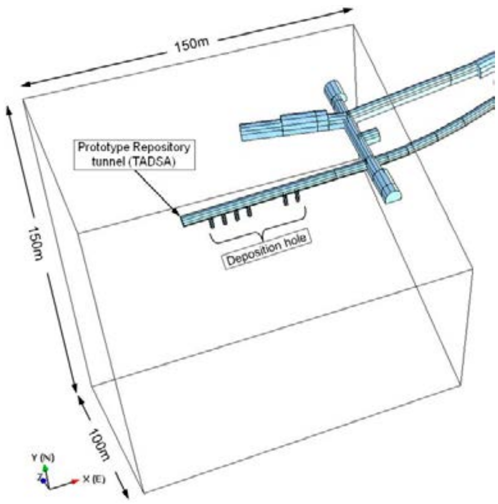


Figure 8-14. *Task 8E modeling region, tunnels and deposition holes.*

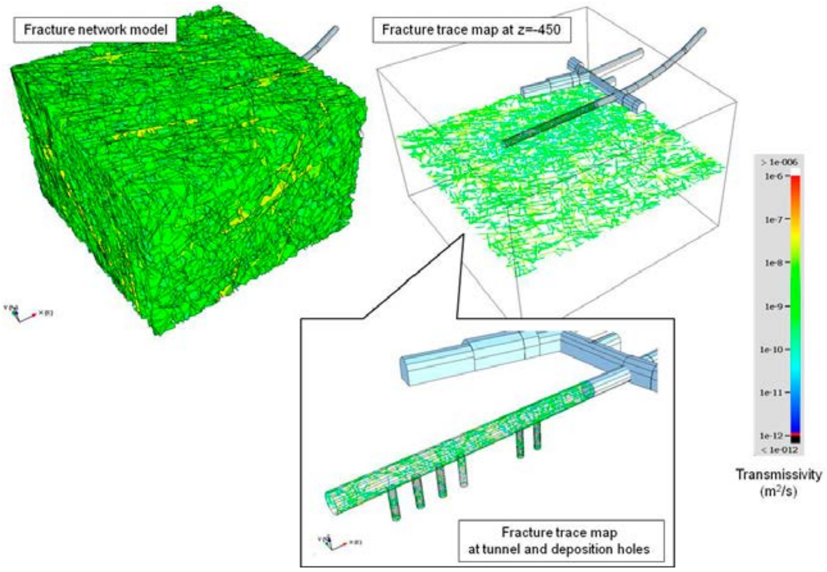


Figure 8-15. *Example of the DFN model.*

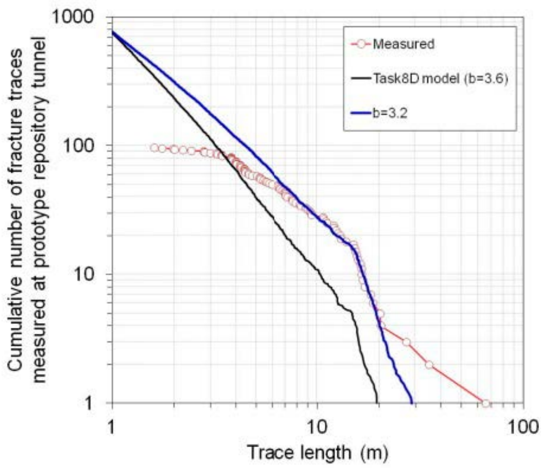


Figure 8-16. *Comparison of fracture trace length distribution at PR tunnel (TADSA).*

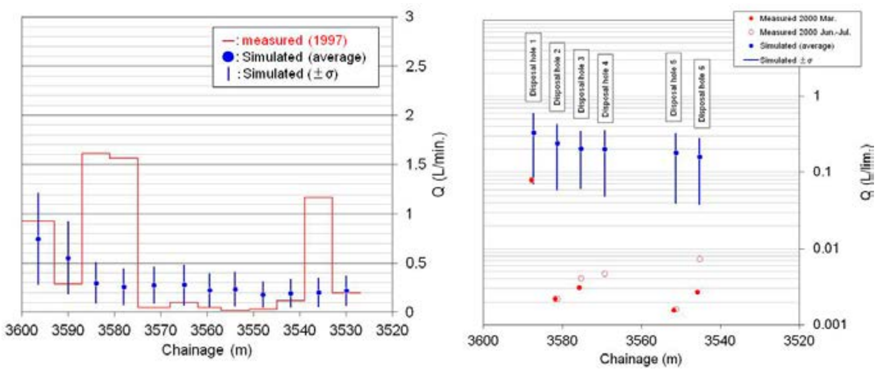
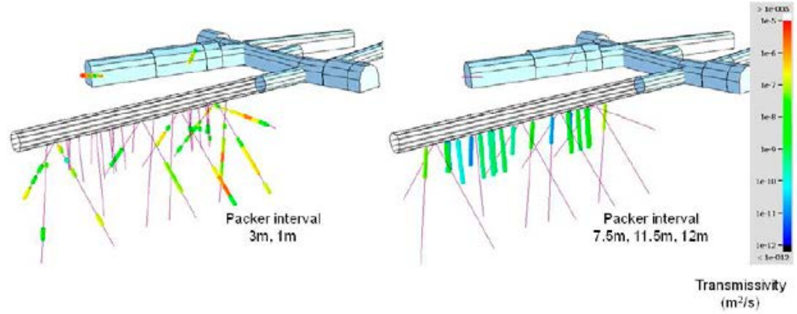
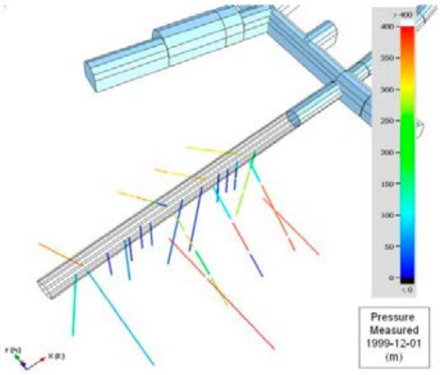


Figure 8-17. *Comparison of fracture trace length distribution at PR tunnel.*



(a) Transmissivity distribution measured at each packer interval



(b) Measured pressure distribution

Figure 8-18. *Heterogeneous hydraulic characteristics around PR tunnel.*

8.5.2 Alternative Buffer Materials

Bentonite material (Kunigel V1, Kunimine Industries) retrieved from parcel 2 was analysed by electron probe microanalyser (EPMA), high-resolution transmission electron microscopy (HRTEM) and atomic force microscope (AFM). The samples for the analyses were prepared from the bentonite pieces adjacent to the iron heater including the surface in contact with iron heater.

Figure 8-19 shows the EPMA mapping images of bentonite sample. The upper side on each image is the contact surface with iron heater. The size of images is 50 μm square. As shown on the mapping images, the area where Fe was concentrated included high concentration of Mg. This mineral was identified to be saponite by energy dispersive X-ray spectroscopy (EDS) elemental analysis. The small particles of several μm in size including high concentration of Si were found around the saponite particle. The thin layer consisting of mainly Ca and S, which was considered to be gypsum or calcite, were observed on the surface in contact with iron heater.

HRTEM images are shown in Figure 8-20. The aggregates of mineral particles under 10 nm in size, which are encircled on the image, were observed on the montmorillonite sheets. Rolled edges of montmorillonite sheets were also observed. The mineral forming the rolled edge is considered to be formed by the alteration of montmorillonite.

Figure 8-21 shows the images of bentonite sample analysed by AFM and the results of height analysis. The montmorillonite sheets were observed on the image (a). The magnified image of the area framed by a white line on the image (a) is shown on the image (c). Image (d) shows the height of mineral particles analysed along the line described on the image (c). The minerals with a height of 0.6–0.8 nm were found as well as the minerals with 1.2 nm height. The height of mineral particles was comparable to the thickness of basal spacing of clay minerals. The thickness of 1.2 nm corresponds to the basal spacing of montmorillonite. The mineral with the layer thickness of 0.6–0.8 nm is considered to be classified into a 1:1 clay mineral. The distribution of this clay mineral has a similar shape with the particles found on the montmorillonite sheets by HRTEM observation.

The analyses of EPMA, HRTEM and AFM indicated that the alteration minerals were formed in the compacted bentonite on the surface in contact with iron heater. However, the alteration minerals

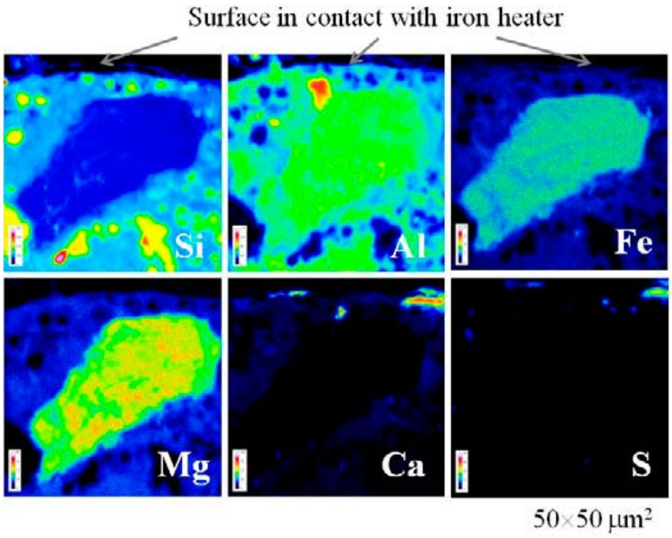


***Figure 8-19.** EPMA mapping images of bentonite sample adjacent to the iron heater. The upper side on each image is the surface in contact with iron heater.*

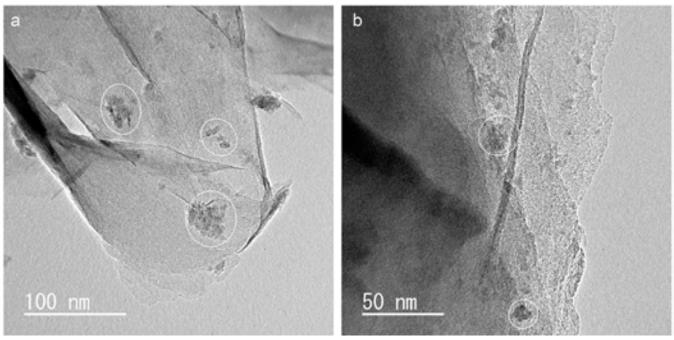


***Figure 8-20.** HRTEM images of the alteration minerals with montmorillonite sheets. The encircled particles and the rolled edge of montmorillonite sheets were considered to be the alteration minerals.*

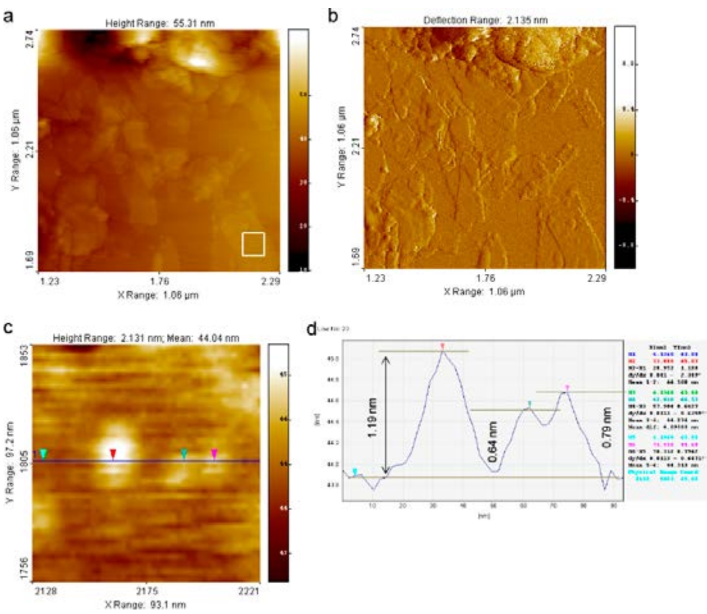


***Figure 8-21.** AFM images and the result of height analysis (a: topographic image, b: amplitude image, c: magnified image of the area framed by a white line in the image (a), d: result of height analysis along the line described in the image (c))*

were detected only by the high-resolution analyses such as HRTEM and AFM, suggesting that the trace amount of alteration mineral were formed in the compacted bentonite.

These analyses were partly funded by the Ministry of Economy, Trade and Industry of Japan.

8.6 NWMO

In 2014, Nuclear Waste Management Organization (NWMO) participation under the Äspö Project Agreement was supported by the University of British Columbia and the University of New Brunswick. The results of this work are briefly described below.

8.6.1 Task Force on Engineered Barrier Systems

The NWMO joined the Äspö Task Force on Engineered Barriers – Chemistry (EBS TF-C) work program in 2012. A team from the University of British Columbia and the University of New Brunswick has been performing reactive transport modelling to simulate the mineralogical/chemical processes occurring within the engineered barriers (compacted bentonite) with the code MIN3P-THCm. In 2014, MIN3P-THCm was used to simulate four EBS TF-C benchmark experiments. Benchmark 1 consists of a set of laboratory through-diffusion experiments to investigate the salt diffusion properties, without ion exchange, in purified homo-ionic Na- or Ca-montmorillonite. Benchmark 2 includes three diffusion experiments with increasing complexity by considering diffusion, kinetic mineral dissolution and ion exchange. Benchmark 3 includes a set of Na/Ca and Ca/Na ion exchange experiments using compacted (initially) homo-ionic Na- and Ca-montmorillonite at different dry densities. Benchmark 4 is based on the flow-through experiment on a bentonite core obtained from an in-situ experiment.

The simulated results were compared with the experimental data sets for Benchmarks 1–4. The simulations of the most complex benchmarking experiment (Benchmark 5) also involved a code inter-comparison of MIN3P-THCm and the reactive transport code CrunchFlow. The simulations for Benchmark 4 were executed for three scenarios with increasing geochemical complexity and showed better agreement with the experimental results for higher levels of complexity. Benchmark 4 also illustrates that, for the conditions considered, differences between a standard diffusion model (based on Fick's law) and the multicomponent species-dependent diffusion approach are limited and dissipate over time. Figure 8-22 shows that simulated results obtained with MIN3P-THCm have very good agreement to results obtained with CrunchFlow for the most complex Benchmark 4 case which includes transport, mineral reactions, ion exchange, and species-dependent diffusion coefficients. The results of the modelling were documented in a NWMO technical report (Xie et al. 2014).

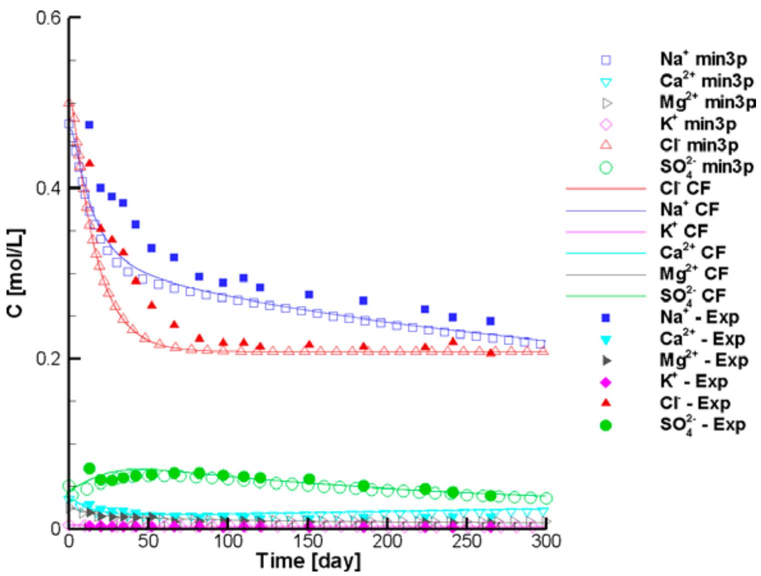


Figure 8-22. *Comparison of MIN3P-THCm and CrunchFlow reactive transport simulations to the Benchmark 4 experiment including transport, mineral reactions, ion exchange, and species-dependent diffusion coefficient (note: in legend min3p is MIN3P-THCm; CF is CrunchFlow. Xie et al. 2014)*

8.7 Posiva

Posiva's co-operation with SKB continues with the 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 together with SKB as joint projects. 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 has been initiated 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 Geosciences or Natural Barriers.

Posiva is participating to the following projects, which has demonstrating or test activities at Äspö HRL:

- KBS-3 Method with Horizontal Emplacement.
- Large Scale Gas Injection Test.
- Alternative Buffer Materials.
- Task Force on Modelling of Groundwater Flow and Transport of Solutes.
- Task Force on Engineered Barrier Systems.
- Retrieval of Prototype Repository.
- System design of dome plug for deposition tunnels.

The role of Posiva and the projects are described more detailed in the main chapters. In addition Posiva and SKB agreed on continued extensive co-operation in different areas for years 2014–2018 in December 2014.

8.8 Nagra

8.8.1 Task Force on Engineered Barriers Systems

Nagra participates actively in both the THM- and the C-Group. The C-Group is headed by U. Mäder (University of Berne). The modelling team of P. Alt-Epping is involved in reactive transport modelling of chemical processes in the bentonite backfill at Olkiluoto. 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.

8.8.2 Alternative Buffer Materials

Collaboration with SKB on the investigation of Fe-Bentonite interactions has started and subsamples from ABM-2 test could be taken at the Äspö rock laboratory. The chemical and mineralogical investigations are being done at University of Bern in Switzerland under supervision of Paul Wersin.

8.8.3 Prototype Repository

Nagra joined the final project meeting.

8.9 Rawra

Technical University Liberec (TUL) participated in Prototype Repository task and Task 8 (BRIE), NRI took part in Chemistry Session.

Work by the TUL team

(Milan Hokr)

The participation of TUL in the Task Force EBS project was a continuation of the tasks and approaches from the previous year. They worked on the Prototype Repository task and Task 8 (BRIE).

For the **Prototype Repository**, the team revisited the model of tunnel and borehole water inflow fitting. Three fractures corresponding to the places in the rock wall mapping charts and containing the main places of observable water inflow (Figure 8-23) was selected. Each fracture had one value of transmissivity with an independent value on a ring around intersection with each borehole. Such model with 9 parameters (3 fractures and 6 rings) was calibrated by the inverse solver UCODE so that the total inflow rates to each borehole and tunnel section was fitted with error below 10%. The team used the code Flow123D for the water flow in the fracture network.

Next, the bentonite water saturation in the boreholes 5 and 6 has been simulated. The team used the same model as in the previous results – nonlinear diffusion derived from the Richards equation, solved in the ANSYS software (using the heat equation mathematical analogy), with more variants of the boundary condition (simplified or derived from a larger-scale model with rock). Additionally, more variants of inflow distribution processed from both the direct total or point inflow measurement and diaper matrix measurement of spatial distribution was used. The resulting water distribution is strongly dependent on these rock water availability assuptions. Examples of results are presented in Figure 8-24. The results well distinguish areas with larger and smaller saturation in most cases, but sometimes the orientation does not fit.

For the **Task8/BRIE** problem, the team solved the set of model problems for the **Water Uptake Test**, which are in very good correspondence with the previously presented results of SKB on the identical equation. The team also verified two used softwares, commertial general multiphysics ANSYS and in-house developed ISERIT (for coupled thermal and water transport) on this problem – from general different model concepts, both were set to solve the same nonlinear diffusion equation with the "same" results.

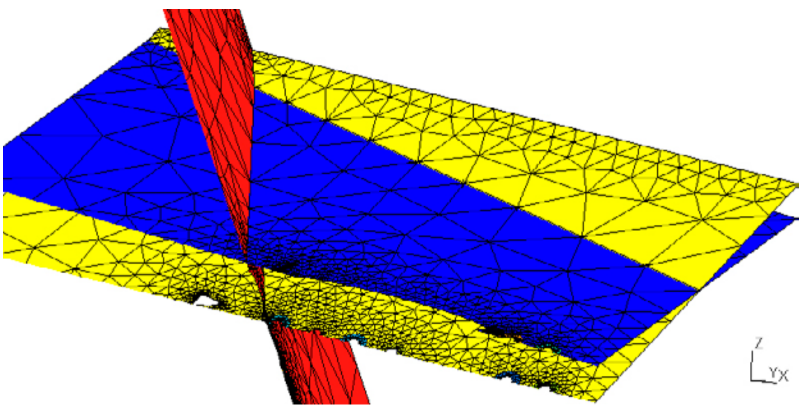


Figure 8-23. *The set of fractures used for the Prototype Repository water inflow simulation (intersections with the boreholes visible in the yellow plane and with the tunnel in the blue and red plane).*

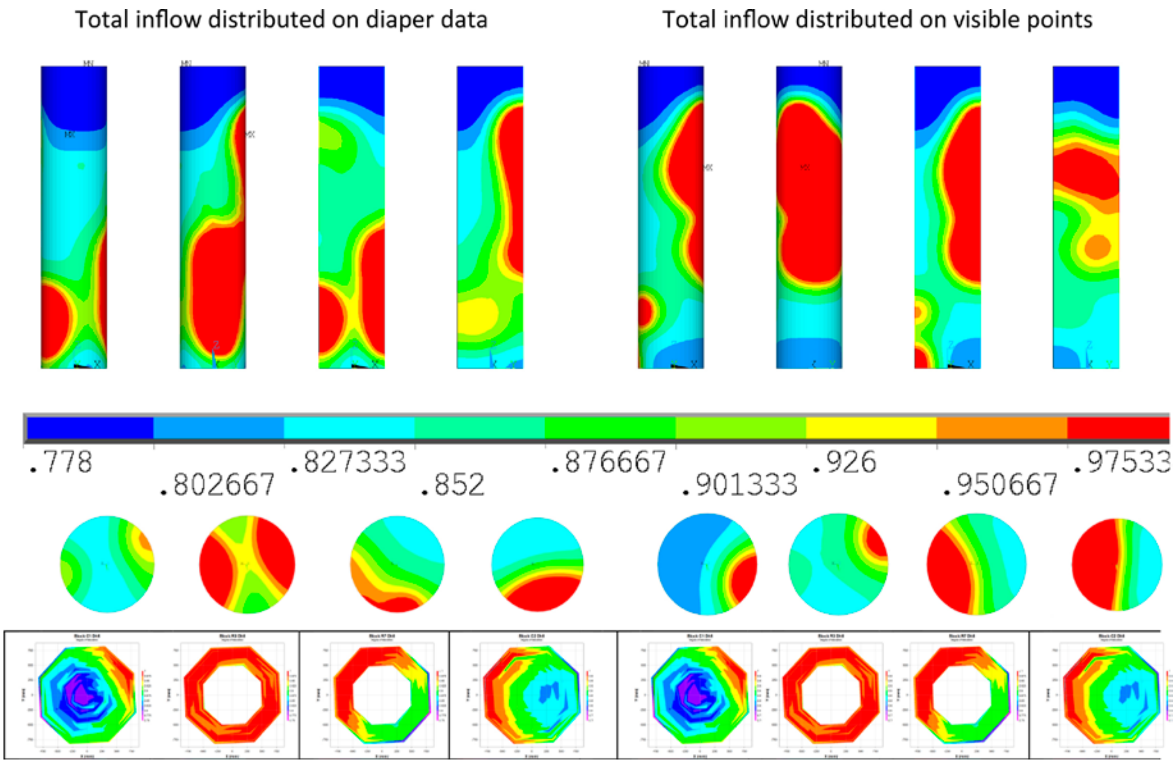


***Figure 8-24.** Example of results for the Borehole 5, sets for two variants of prescribed inflow distributions, columns represent different directions and section positions, compared with the measured data in the bottom line.*

Work by the NRI team

(Eva Hofmanová, Radek Červinka, ÚJV Řež, a. s.)

Within the Chemistry section of EBS Task Force project, ÚJV Řež, a. s. prepared the new Benchmark 5 (distributed in April 2014). This benchmark summarised the results from diffusion of chloride, iodide and selenate through the Czech compacted bentonite B75, conducted by Eva Hofmanová during her PhD studies. The main aim was to understand the diffusive behaviour of anionic species of critical radionuclides, such as $^{36}Cl^-$, $^{129}I^-$ and $^{79}SeO_4^{2-}$. Traditional geochemical approach comprises that anions cannot access the total pore volume due to the electrostatic repulsion between negatively charged clay surfaces and anions (known as anion exclusion effect) and therefore its transport is reduced. The selected anions differ mainly in the charge and ionic radius and therefore distinct effective diffusion coefficients and effective porosities, especially between monovalent and divalent anions were expected. All experiments were performed under ambient conditions and at the ionic strength of 0.1 mol/l. Already out of Benchmark 5, the results were extended by diffusion experiments with two anions, TcO_4^- and ClO_4^- (presented in December 2014).

The experimental data (break-through curves, tracer profiles) were fitted by modelled curves simulated in house developed diffusion model EVALDIFF (prepared in GoldSim software). The model also includes the influence of filters, porosity heterogeneity and radioactive decay. As can be seen from Figure 8-25, the effective porosities (i.e. accessible porosities) differ for measured anions.

For selenate as divalent anion, the effective porosity is greater than for monovalent anions such as chloride, iodide or perchlorate. This contradicts the concept of anion exclusion (multiple porosity model) where one can expect that higher charged anion will be more intensely repelled by the negatively charged clay surface and therefore enter into a smaller space. It is one of the open questions in Benchmark 5, which is adressed to the other project partners. Diffusion behaviour of perchlorate, chloride and iodide is very similar. Pertechnetate diffusion coefficients lay between monovalent anions and bivalent selenate.

Part of our aim was also dedicated to modelling of previous Benchmarks 1–3.

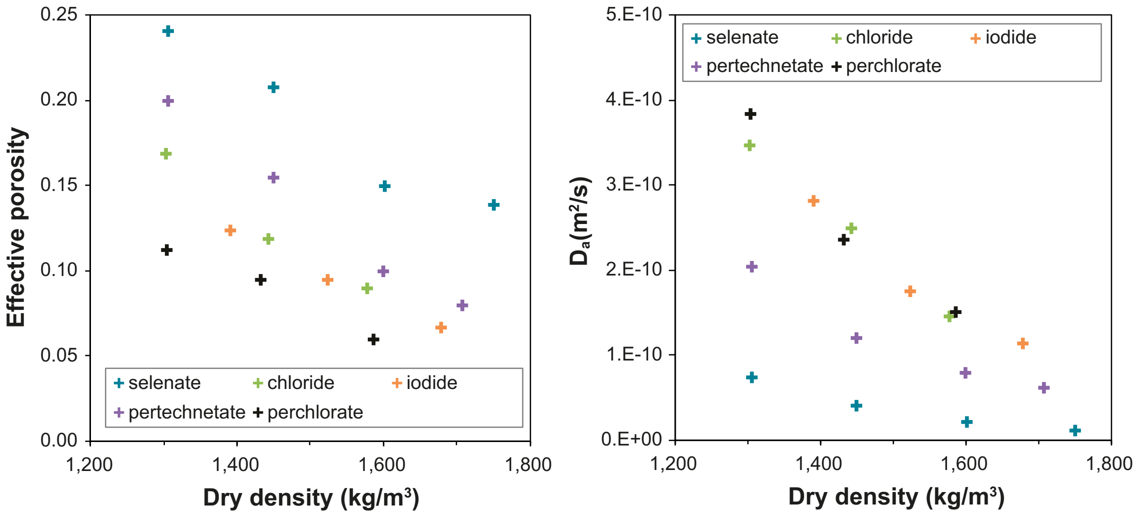


Figure 8-25. *Results of effective porosities and apparent diffusion coefficients D_a for selected anions obtained on compacted bentonite B75 at different dry densities.*

8.10 RWM

Radioactive Waste Management Limited (RWM) of the United Kingdom has had long standing involvement in experiments conducted at Äspö HRL[1]. In March 2012, NDA signed an agreement with SKB International AB to further increase access to scientific and technical information and results from experiments performed by SKB at Äspö HRL. This is designed to support an increase in involvement of RWM personnel in field work and facilitate a step-change of the R&D programme from (predominately) laboratory-scale activities to activities that include large-scale demonstration experiments. Through 2013 and 2014, RWM has been actively supporting and contributed to the experiments and initiatives considered of greatest relevance to the current stage of the UK disposal programme, including the EBS Task Force, the Lasgit experiment, and the Prototype Repository experiment.

8.10.1 Task Force on Engineered Barrier Systems (EBS)

The SKB Engineered Barrier System Task Force offers a unique opportunity to develop methodologies, software and modelling approaches to develop understanding of bentonite saturation and coupled thermal, hydraulic, mechanical, and chemical (THMC) processes. RWM, through its contractor AMEC Foster Wheeler, is actively involved in this project with emphasis on Task 8, a collaborative research project between the Groundwater Flow and Transport of Solutes (GWTS). In 2014, we continued to be members of the SKB EBS Task Force. As part of this work, AMEC Foster Wheeler undertook, on our behalf, modelling of bentonite resaturation under Task 8D using data supplied by SKB from Äspö (BRIE) using a combination of CONNECTFLOW and TOUGH2. The feasibility of using a physically realistic approach, explicitly representing the heterogeneity of the fractured bedrock, to simulate the interface between bentonite and fractured host rock has been demonstrated. The permeability of the rock matrix is found to strongly determine the resaturation times of the emplaced bentonite and different calculated realisations can give up to tens of years of difference in time of resaturation. Modelling has also been carried out as part of the Sensitivity Analysis Task of the EBS Task Force, investigating the effects of parameter uncertainty on model results. One important result from the study is confirmation that the prediction of temperature is only weakly dependent on the rock intrinsic permeability, with thermal conduction being more important. AMEC Foster Wheeler are also undertaking modelling under the EBS Task Force in support of the Prototype Repository Experiment.

[1] RWM is a wholly-owned subsidiary of the Nuclear Decommissioning Authority (NDA), created in April 2014. Involvement in activities at Äspö commenced through RWM's predecessor, NDA's Radioactive Waste Management Directorate (RWMD).

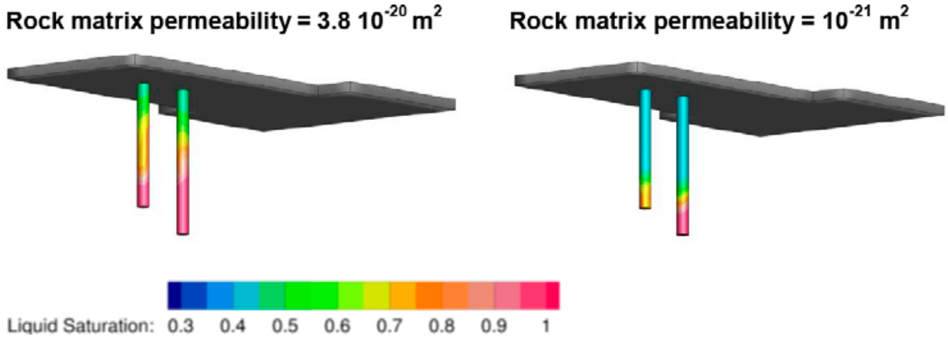


Figure 8-26. *Task 8D – Calculated resaturation profiles (BRIE) of emplaced bentonite in two boreholes after one year, showing effect of different rock matrix permeabilities (On the left a realisation with a rock matrix permeability of $3.8 \cdot 10^{-20}$ m^2 and on the right a realisation with a rock matrix permeability of $1 \cdot 10^{-21}$ m^2).*

8.10.2 Large Scale Gas Injection Test (Lasgit)

As part of a wider programme of international research focussed on the processes and mechanisms governing gas flow in compact bentonite, RWM commissioned the British Geological Survey (BGS) to undertake a series of laboratory scale experiments to complement other Äspö Lasgit-based work, examining the impact of gas flow and its interaction with the stress state variables, in particular total stress and pore water pressure. Specific objectives are to better understand:

- the minimum pressure gas will become mobile and enter the clay,
- 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
- 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.

Over the past 12 months, the key advance arising from the laboratory scale experiments has been in furthering understanding of how gas behaves at pressures close to the total stress acting within the bentonite. At gas pressures below total stress, advective gas migration was not observed. As gas pressure increases above total stress, gas entry occurs through a series of pressure induced pathways. These features developed in a dynamic and unpredictable way, with both spontaneous self-sealing events and the creation of new pathways observed, redistributing the flow of gas within the system. Slowing the rates of gas pressurisation successfully avoided large peak gas pressures which were observed in some of the earlier experimental observations. However, spontaneously restricting the number of outlets through which gas could exit the system resulted in a significant increase in peak gas pressure, the formation of a new network of pathways and the redistribution of stress within the bentonite.

Further additional insights into the processes governing hydration and homogenisation of the clay were obtained from these studies. Of particular relevance were the development of persistent 'locked-in' stresses and the slow rate at which bentonite appeared to attain hydraulic equilibrium. Further work is planned to examine this behaviour.

In combination, these results, along with other Lasgit-influenced experiments, provide a unique dataset with which to help develop and verify conceptual and numerical models aimed at GDF assessment studies of gas migration and bentonite homogenisation in the engineered barrier system.

8.10.3 Prototype Repository

At the beginning of 2014, RWM actively contributed to the final stages of the Prototype Repository Project by providing detailed (informal) review comments of the final project report from three of their technical experts. The input provided was well received and contributed to the successful closure of the project. Beyond capitalising on the outcome of specific technical results (a very successful project), RWM input was geared at identifying key areas of learning, to help planning and delivery of other similar projects in the future.

9 Literature

9.1 References

Aghili B, 2014. Korrosionsprovning av ingjutna stålstänger i betongblock och ingjutna bergbultar. Fem års exponering i Äspölaboratoriet. SKB R-14-27, Svensk Kärnbränslehantering AB.

Alakangas L J, Mathurin F A, Faarinen M, Wallin B, Astrom M E, 2014. Sampling and characterizing rare earth elements in groundwater in deep-lying fractures in granitoids under in situ high-pressure and low-redox conditions. Aquatic Geochemistry 20, 405–418.

Amneklev J, Augustsson A, Sörme L, Bergbäck B, 2015. Bismuth and silver in cosmetic products: a source of environmental and resource concern? Journal of Industrial Ecology. doi:10.1111/jiec.12251

Andersson I, Jarsjö J, Petersson M, 2014. Saving the Baltic Sea, the inland waters of its drainage basin, or both? Spatial perspectives on reducing P-loads in eastern Sweden. Ambio 43, 914–925.

Arlinger J, Bengtsson A, Edlund J, Eriksson L, Johansson J, Lydmark S, Rabe L, Pedersen K, 2013. Prototype Repository. Microbes in the retrieved outer section. SKB P-13-16, Svensk Kärnbränslehantering AB.

Arvidsson A, Josefsson P, Sandén T, Ojala M, 2015. System design of backfill. Project results. SKB TR-14-20, Svensk Kärnbränslehantering AB.

Augustsson A, Berger B, 2014. Assessing the risk of an excess fluoride intake among Swedish children in households with private wells – Expanding static single-source methods to a probabilistic multi-exposure-pathway approach. Environment International 68, 192–199.

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.

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 TR97-19, 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.

Bring A, Rogberg P, Destouni G, 2015. Variability in climate change simulations affects needed long-term riverine nutrient reductions for the Baltic Sea. Ambio 44, 381–391.

Börgesson L, Hernelind J, 2014. Modelling of bentonite block compaction. SKB P-14-10, Svensk Kärnbränslehantering AB.

Börgesson L, Sandén T, 2002. Äspö Hard Rock Laboratory. Prototype Repository. Instrumentation of buffer and backfill in section II. SKB IPR-03-21, Svensk Kärnbränslehantering AB.

Cederbom C, Larson S Å, Tullborg E L, Stiberg J P, 1999. Fission track thermochronology applied to Phanerozoic thermotectonic events in central and southern Sweden. Tectonophysics 316, 153–167.

Cederbom C, 2001. Phanerozoic, pre-Cretaceous thermotectonic events in southern Sweden revealed by fission track thermochronology. Earth and Planetary Science Letters 188, 199–209.

Chalov S R, Jarsjö J, Kasimov N S, Romanchenko A, Pietroń J, Thorslund J, Promakhova E V, 2014. Spatio-temporal variation of sediment transport in the Selenga River Basin, Mongolia and Russia. Environmental Earth Sciences. doi:10.1007/s12665-014-3106-z

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. Internationl Journal for Numerical Analytical Methods in Geomechanics 24, 403–424.

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.

COMSOL, 2013. COMSOL Multiphysics reference manual version 4.4., COMSOL AB. Available at: http://www2.humusoft.cz/ftp/comsol/guides/COMSOL_ReferenceManual.pdf

Cuss R J, Harrington J F, Noy D J, 2010. Large Scale Gas Injection Test (Lasgit) performed at the Äspö Hard Rock Laboratory. Summary Report 2008. SKB TR-10-38, Svensk Kärnbränslehantering AB.

Cvetkovic V, Gotovac H, 2014. On the upscaling of chemical transport in fractured rock. Water Resources Research 50. doi:10.1002/2014WR015505

Cvetkovic V, Fiori A, Dagan G, 2014. Solute transport in aquifers of arbitrary variability: A time-domain random walk formulation. Water Resources Research 50. doi:10.1002/2014WR015449

Dargahi B, Cvetkovic V, 2014. Hydrodynamic and transport characterization of the Baltic Sea 2000–2009. TRITA-LWR.REPORT 2014:03, Kungliga Tekniska högskolan, Stockholm.

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.

Dessirier B, Jarsjö J, Frampton A, 2014. Modeling two-phase-flow interactions across a bentonite clay and fractured rock interface. Nuclear Technology 187, 147–157.

Destouni G, Verrot L, 2014. Screening long-term variability and change of soil moisture in a changing climate. Journal of Hydrology 516, 131–139

Dohrmann R, Kaufhold S, 2014. Cation exchange and mineral reactions observed in MX 80 buffers samples of the Prototype Repository in situ experiment in Äspö, Sweden. Clays and Clay Minerals 62. doi:10.1346/CCMN.2014.0620501

Earon R, Dehkordi S E, Olofsson B, 2014. Groundwater resources potential in hard rock terrain: a multivariate approach. Ground Water 53. doi:10.1111/gwat.12265

Eng A, Nilsson U, Svensson D, 2007. Äspö Hard Rock Laboratory. Alternative Buffer Material. Installation report, SKB IPR-07-15, Svensk Kärnbränslehantering AB.

Eriksson M, Lindström L, 2008. KBS-3H post-grouting. Mega-Packer test at –220 m level at Äspö HRL. SKB R-08-42, Svensk Kärnbränslehantering AB.

Eriksson P, 2014. Basic engineering of buffer production system. SKB P-14-11, Svensk Kärnbränslehantering AB.

Eriksson S, 2008. Äspö Hard Rock Laboratory. Prototype Repository. Analysis of microorganisms, gases and water chemistry in buffer and backfill 2004–2007. SKB IPR-08-01, Svensk Kärnbränslehantering AB.

Forsmark T, Rhén I, Andersson C, 2001. Äspö Hard Rock Laboratory. Prototype Repository. Hydrogeology – Deposition- and lead-through boreholes: Inflow measurements, hydraulic responses and hydraulic tests. SKB IPR-00-33, Svensk Kärnbränslehantering AB.

Fransson Å, Funehag J, Thörn J, Lehtimäki T, Sjöland A, Vidstrand P, Åkesson M, 2014. Characterization of fractured crystalline rock: two Swedish in situ field experiments. In Proceedings of DFNE 2014, the 1st International Conference on Discrete Fracture Network Engineering, Vancouver, Canada, 19–22 October 2014.

Fransson Å, Thörn J, Ericsson L O, Lönnqvist M, Stigsson M, 2012. Hydromechanical characterization of fractures close to a tunnel opening: a case study. In Proceedings of Eurock 2012, ISRM International Symposium, Stockholm, Sweden, 28–30 May 2012.

Franzén F, Hammer M, Balfors B, 2015. Institutional development for stakeholder participation in local water management - An analysis of two Swedish catchments. Land Use Policy 43, 217–227.

Fälth B, 2015. Simulating Earthquake rupture and off-fault fracture response. Lic thesis. Institution of Geosciences, Uppsala University, Sweden.

Goudarzi R, 2014. Prototype Repository – Sensor data report (period 20010917–20130101). Report No 25. SKB P-13-39, Svensk Kärnbränslehantering AB.

Grahm P, Karlzén R, 2015. System design of Dome Plug. Experiences from full-scale wire sawing of a slot abutment for the KBS-3V deposition tunnel plug. SKB R-14-24, Svensk Kärnbränslehantering. AB.

Green P F, Duddy I R, Hegarty K A, 2002. Quantifying exhumation from apatite fission-track analysis and vitrinite reflectance data: precision, accuracy and latest results from the Atlantic margin of NW Europe. Geological Society, London, Special Publications 196, 331–354.

Hallbeck L, Pedersen K, 2008. Explorative analyses of microbes, colloids, and gases together with microbial modelling. Site description model. SDM-Site Laxemar. SKB R-08-109, 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.

Heim C, Lausmaa J, Sjövall P, Toporski J, Dieing T, Simon K, Hansen B, Kronz A, Reitner J, Thiel V, 2012. Ancient microbial activity recorded in fracture fillings from granitic rocks (Äspö Hard Rock Laboratory, Sweden). Geobiology 10, 280–297.

Heim C, Simon K, Quéric N-V, Reitner J, Thiel V, 2015. Trace and rare earth element accumulation and fractionation in microbial iron oxyhydroxides. Frontiers in Earth Science 3, 1–15.

Hendriks B W H, Redfield T F, 2005. Apatite fission track and (U-Th)/He data from Fennoscandia: an example of underestimation of fission track annealing in apatite. Earth and Planetary Science Letters 236, 443–458.

Hendriks B W H, Redfield T F, 2006. Reply to: Comment on "Apatite fission track and (U–Th)/He data from Fennoscandia: an example of underestimation of fission track annealing in apatite. Earth and Planetary Science Letters 248, 569–577.

Hendriks B, Andriessen P, Huigen Y, Leighton C, Redfield T, Murrell G, Gallagher K, Nielsen S B, 2007. A fission track data compilation for Fennoscandia. Norwegian Journal of Geology 87, 143–155.

Hildebrand M, Davis A K, Smith S R, Traller J C, Abbriano R, 2012. The place of diatoms in the biofuels industry. Biofuels 3, 221–240.

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.

Ionsecu D, Heim C, Polerecky L, Thiel V, de Beer D, 2015a. Biotic and abiotic oxidation and reduction of iron at circumneutral pH are inseparable processes under natural conditions. Geomicrobiology Journal 32, 221–230..

Ionescu D, Heim C, Polerecky L, Ramette A, Haeusler S, Bizic-Ionescu M, Thiel V, De Beer D, 2015b. Diversity of iron oxidizing and reducing bacteria in flow reactors in the Äspö Hard Rock Laboratory. Geomicrobiology Journal 32, 207–220.

Ittner H, Cristiansson R, 2014. Quality control, traceability and verification of the process for construction of deposition tunnels. In Proceedings of ARMS8: 8th Asian Rock Mechanics Symposium, Sapporo, Japan, 14–16 October 2014.

Ittner H, Lehtimäki T, Christiansson R, 2014. Design and control of the EDZ for a deep repository in crystalline rock. In Alejano L R, Perucho Á, Olalla C, Jiménez R (eds). Rock Engineering and Rock Mechanics: Structures in and on Rock Masses, 835–840.

Japsen P, Green P F, Chalmers J A, 2005, Separation of Palaeogene and Neogene uplift on Nuussuaq, West Greenland. Journal of the Geological Society 162, 299–314.

Japsen P, Green P F, Nielsen L H, Rasmussen E S, Bidstrup T, 2007. Mesozoic-Cenozoic exhumation events in the eastern North Sea Basin: a multi-disciplinary study based on palaeothermal, palaeoburial, stratigraphic and seismic data. Basin Research 19, 451–490.

Japsen P, Bonow J M, Green P F, Cobbold P R, Chiossi D, Lilletveit R, Magnavita L P, Pedreira A J, 2012. Episodic burial and exhumation history of NE Brazil after opening of the South Atlantic. Geological Society of American Bulletin 124, 800–816.

Jaramillo F, Destouni G, 2014. Developing water change spectra and distinguishing change drivers worldwide. Geophysical Research Letters 41. doi:10.1002/2014GL061848

Johannesson L-E, 2014a. Prototype Repository. Measurements of water content and density of the excavated buffer material form deposition hole 5 and 6 and the backfill in the outer section of the Prototype Repository. SKB P-13-14, Svensk Kärnbränslehantering AB.

Johannesson L-E, 2014b. KBS-3H. Manufacturing of buffer and filling components for the Multi Purpose Test. SKB P-14-07, Svensk Kärnbränslehantering AB.

Johannesson L-E, Hagman P, 2013. Prototype Repository. Method for opening and retrieval of the outer section. SKB P-13-15, Svensk Kärnbränslehantering AB.

Johannesson L-E, Kristensson O, Åkesson M, Eriksson P, Hedin M, 2014. Tests and simulations of THM processes relevant for the buffer installation. SKB P-14-22, Svensk Kärnbränslehantering AB.

Kröhn K-P, 2011. Code VIPER: theory and current status. Status report, FKZ 02 E 10548 (BMWi), Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-269, Braunschweig, Germany.

Laaksoharju M, Tullborg E-L, Wikberg P, Wallin B, Smellie J, 1999. Hydrogeochemical conditions and evolution at Äspö HRL, Sweden. Applied Geochemistry 14, 835-859.

Larson S Å, Tullborg E L, Cederbom C, Stiberg J P, 1999a. Sveconorwegian and Caledonian foreland basins in the Baltic Shield revealed by fission-track thermochonology. Terra Nova 11, 215.

Larson S Å, Tullborg E L, Cederbom C, Björklund L, Plink-Björklund P, Stiberg J P, 1999b. The Caledonian foreland basin in Scandinavia: constrained by the thermal maturation of the Alun Shale. Final comment. GFF 121.

Larson S Å, Cederbom C, Tullborg E-L, Stiberg J-P, 2006. Comment on "Apatite fission track and (U-Th)/He data from Fennoscandia: an example of underestimation of fission track annealing in apatite" by Hendriks and Redfield [Earth Planet. Sci. Lett. 236 (443-458)]. Earth and Planetary Science Letters 248, 561–568.

Leefmann T, Heim C, Lausmaa J, Sjövall P, Ionescu D, Reitner J, Thiel V, 2015. An imaging mass spectrometry study on the formation of conditioning films and biofilms in the subsurface (Äspö Hard Rock Laboratory, SE Sweden). Geomicrobiology Journal 32, 197–206.

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.

Lönnqvist M, Hökmark H, 2013.Thermal and thermo-mechanical evolution of the Äspö Prototype Repository rock mass. Modelling and assessment of sensors data undertaken in connection with the dismantling of the outer section. SKB R-13-10, Svensk Kärnbränslehantering AB.

Malm R, 2012. Low-pH concrete plug for sealing the KBS-3V deposition tunnels. SKB R-11-04, Svensk Kärnbränslehantering AB

Maskenskaya O M, Drake H, Mathurin F A, Åström M E, 2015. The role of carbonate complexes and crystal habit on rare earth element uptake in low-temperature calcite in fractured crystalline rock. Chemical Geology 391, 100–110.

Mathern A, Magnusson J, 2015. System design of Dome plug. Experience of low-pH concrete mix B200. Material properties from laboratory tests and full-scale castings. SKB P-14-26, Svensk Kärnbränslehantering AB.

Mathurin F A, Drake H, Tullborg E-L, Berger T, Peltola P, Kalinowski B E, Åström M E, 2014a. High cesium concentrations in groundwater in the upper 1.2 km of fractured crystalline rock – Influence of groundwater origin and secondary minerals. Geochimica et Cosmochimica Acta 132, 187–213.

Mathurin F A, Åström M E, Drake H, Maskenskaya O M, Kalinowski B E, 2014b. REE and Y in groundwater in the upper 1.2 km of Proterozoic granitoids (Eastern Sweden) – Assessing the role of composition and origin of groundwaters, geochemistry of fractures, and organic/inorganic aqueous complexation. Geochimica et Cosmochimica Acta 144, 342–378.

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.

Morosini M, 2013. Hydrogeological monitoring at Äspö HRL – Motivation and case study. In Monitoring in geological disposal of radioactive waste: objectives, strategies, technologies and public involvement: proceeding of an International Conference and Workshop, Luxembourg, 19–21 March 2013. Deliverable D-No: 5.4.1, European Commission.

Nilsson U, 2014. Prototype Repository. Validation of retrieved sensors from the Prototype experiment at Äspö Hard Rock laboratory. SKB P-13-31, Svensk Kärnbränslehantering AB.

Nyblad B, Luterkort D, Lundqvist M, 2014. Buffer protection for the installation phase. Design and testing. SKB P-13-51, Svensk Kärnbränslehantering AB.

Ojala M, von Numers T, 2015. KBS-3H. Upgrading the deposition machine for the Multi Purpose Test. SKB P-14-08, Svensk Kärnbränslehantering AB.

Olsson S, Jensen V, Johannesson L-E, Hansen E, Karnland O, Kumpulainen S, Svensson D, Hansen S, Lindèn J, 2013. Prototype Repository. Hydro-mechanical, chemical and mineralogical characterization of the buffer and backfill material from the outer section of the Prototype Repository. SKB TR-13-21, Svensk Kärnbränslehantering AB.

Pedersen K, 2013. The Microbe project. Achievements of a 10-year research programme. SKB R-13-49, Svensk Kärnbränslehantering AB.

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.

Quin A, Jaramillo F, Destouni G, 2015. Dissecting the ecosystem service of large-scale pollutant retention: the role of wetlands and other landscape features. Ambio 44, 127–137.

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.

Rohrman M, van der Beek P, Andriessen P, Cloetingh S, 1995. Meso-Cenozoic morphotectonic evolution of southern Norway: Neogene domal uplift inferred from apatite fission track thermochronology. Tectonics 14, 704–718.

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.

Schneider A, 2012. Enhancement of d^3f und r^3t (E-DuR). Final report, FKZ 02 E 10336 (BMWi), Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-292, Braunschweig, Germany.

Schäfer N, Schmidt B C, Quéric N-V, Röring B, Reitner J, 2015. Organic compounds and conditioning films within deep rock fractures of the Äspö Hard Rock Laboratory, Sweden. Geomicrobiology Journal 32, 231–242.

Selroos J-O, Destouncomsoli G, 2015. Influence of spatial and temporal flow variability on solute transport in catchments. Hydrological Processes 29, 3592–3603.

SKB, 2001. RD&D-Programme 2001. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste. SKB TR-01-30, Svensk Kärnbränslehantering AB.

SKB, 2010. Ramprogram för detaljundersökningar vid uppförande och drift av slutförvar för använt kärnbränsle. SKB R-10-08, Svensk Kärnbränslehantering AB. (In Swedish.)

SKB, 2012. KBS-3H Complementary studies, 2008–2010. SKB TR-12-01, Svensk Kärnbränslehantering AB.

SKB, 2013. RD&D Programme 2013. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste. SKB TR-13-18, Svensk Kärnbränslehantering AB.

SKB, 2014. Äspö Hard Rock Laboratory. Annual Report 2013. SKB TR-14-17, Svensk Kärnbränslehantering AB.

SKB, 2015. System design and full-scale testing of the Dome Plug for KBS-3V deposition tunnels. Main report. SKB TR-14-23, Svensk Kärnbränslehantering AB. POLE

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 R, Rance A P, Reddy B, Fennell P, Winsley R J, 2012. Analysis of SKB MiniCan. Experiment 3. SKB TR-12-09, Svensk Kärnbränslehantering AB.

Smart N, Rose S, Nixon D, Rance A, 2013. Metallographic analysis of SKB MiniCan Experiment 3. SKB R-13-35, Svensk Kärnbränslehantering AB.

Smart N R, Rance A P, Reddy B, Hallbeck L, Pedersen K, Johansson A J, 2014. In situ evaluation of model copper-cast iron canisters for spent nuclear fuel: a case of microbiologically influenced corrosion (MIC). Corrosion Engineering, Science and Technology 49, 548–553.

Strandmark A, Bring A, Cousins S A O, Destouni G, Kautsky H, Kolb G, de la Torre-Castro M, Hambäck P A, 2015. Climate change effects on the Baltic Sea borderland between land and sea. Ambio 44, S28–S38.

Svensson D, 2013. Early observations in a large scale 6½ year iron-bentonite field experiment ABM2 at Äspö hard rock laboratory, Sweden. Conference abstract, 50th annual meeting of Clay Mineralogical Society, Urbana-Champaign, Illinois, 6–10 October.

Svensson P D, Hansen S, 2013. Redox chemistry in two iron-bentonite field experiments at Äspö hard rock laboratory, Sweden: an XRD and Fe K-edge XANES study. Clays and Clay Minerals 61, 566–579.

Söderlund P, Juez-Larre J, Page L M, Dunai T J, 2005. Extending the time range of apatite (U-Th)/He thermochronometry in slowly cooled terranes: Palaeozoic to Cenozoic exhumation history of southeast Sweden. Earth and Planetary Science Letters 239, 266–275.

Tullborg E-L, Smellie J, Nilsson A-C, Gimeno M J, Brüchert V, Molinero J, 2010. SR-Site – sulphide content in the groundwater at Forsmark. SKB TR-10-09, Svensk Kärnbränslehantering AB.

Törnqvist R, Jarsjö J, Pietroń J, Bring A, Rogberg P, Asokan S M, Destouni G, 2014. Evolution of the hydro-climate system in the Lake Baikal basin. Journal of Hydrology 519, 1953–1962.

Van der Velde Y, Vercauteren N, Jaramillo F, Dekker S, Destouni G, Lyon S W, 2014. Exploring hydroclimatic change disparity via the Budyko framework. Hydrological Processes 28, 4110–4118.

Verrot L, Destouni G, 2015. Screening variability and change of soil moisture under wide-ranging climate conditions: snow dynamics effects. Ambio 44, S6–S16.

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.

Walton G, Lato M, Anschütz H, Perras M A, Diederichs M S, 2015. Non-invasive detection of fractures, fracture zones, and rock damage in a hard rock excavation – Experience from the Äspö Hard Rock Laboratory in Sweden. Engineering Geology 196, 210–221.

Wieczorek K, Komischke M, Miehe R, Moog H, 2014. Geoelectric monitoring of bentonite barrier resaturation in the Äspö Prototype Repository. Final report, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-352, Braunschweig, Germany.

Xie M, Rasouli P, Mayer K U, MacQuarrie T B, 2014. Reactive transport modeling of diffusion in low permeable media – MIN3P-THCm simulations of EBS-TF-C compacted bentonite diffusion experiments. Technical report, NWMO TR-2014-23, Nuclear Waste Management Organization, Canada.

Yu C X, Lavergren U, Peltola P, Drake H, Bergback B, Åstrom M E, 2014. Retention and transport of arsenic, uranium and nickel in a black shale setting revealed by a long-term humidity cell test and sequential chemical extractions. Chemical Geology 363, 134–144.

Åkesson M, Fransson Å, Vidstrand P, Sjöland A, 2014. The Bentonite Rock Interaction Experiment. In Schäfers A, Fahlund S (eds). Proceedings: International Conference on the Performance of Engineered Barriers: Physical and Chemical Properties, Behaviour & Evolution, Hannover, Germany, 6–7 February 2014. Hannover: BGR, 91–96.

9.2 List of papers and articles published 2014

Alakangas L J, Mathurin F A, Faarinen M, Wallin B, Astrom M E, 2014. Sampling and characterizing rare earth elements in groundwater in deep-lying fractures in granitoids under in situ high-pressure and low-redox conditions. Aquatic Geochemistry 20, 405–418.

Andersson I, Jarsjö J, Petersson M, 2014. Saving the Baltic Sea, the inland waters of its drainage basin, or both? Spatial perspectives on reducing P-loads in eastern Sweden. Ambio 437, 914–925.

Ask M, Rosqvist H, Svensson M, 2014. Transparent Underground Structure (TRUST) – Sveriges största Geo-FOU någonsin. Grundläggningsdagen, 2014-03-13, Stockholm. Available at: https://www.google.se/?gws_rd=ssl#q=http:%2F%2Ftrustgeoinfra.se%2Fpublikationer%2FGD2014_Maria_Ask_artikel.pdf

Augustsson A, Berger B, 2014. Assessing the risk of an excess fluoride intake among Swedish children in households with private wells – Expanding static single-source methods to a probabilistic multi-exposure-pathway approach. Environment International 68, 192–199.

Bennett D P, Cuss R J, Vardon P J, Harrington J F, Thomas H R, 2014. Phenomena exposure from the Large Scale Gas Injection Test (Lasgit) dataset using a bespoke data analysis toolkit. In Norris S, Bruno J, Cathelineau M, Delage P, Fairhurst C, Gaucher E C, Hohn E H, Kalinichev A, Lalieux P, Sellin P (eds). Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Geological Society, London, Special Publications 400, 497–505.

Chalov S R, Jarsjö J, Kasimov N S, Romanchenko A, Pietroń J, Thorslund J, Promakhova E V, 2014. Spatio-temporal variation of sediment transport in the Selenga River Basin, Mongolia and Russia. Environmental Earth Sciences. doi:10.1007/s12665-014-3106-z

Cuss R J, Harrington J F, Noy D J, Graham C C, Sellin P, 2014. Evidence of localised gas propagation pathways in a field-scale bentonite engineered barrier system; results from three gas injection tests in the Large Scale Gas Injection Test (Lasgit). Applied Clay Science 102, 81–92.

Cuss R J, Harrington J F, Noy D J, Graham C C, Sellin P, 2014. Observations from four gas injection tests conducted in a full scale KBS-3v setup; the Large Scale Gas Injection Test (Lasgit) conducted at the Äspö Hard Rock Laboratory, Sweden. In International Conference on the Performance of Engineered Barriers: Physical and Chemical Properties, Behaviour & Evolution*,* Hannover, Germany, 6–7 February 2014.

Cvetkovic V, Gotovac H, 2014. On the upscaling of chemical transport in fractured rock, Water Resources Research 50. doi: 10.1002/2014WR015505

Cvetkovic V, Fiori A, Dagan G, 2014. Solute transport in aquifers of arbitrary variability: A time-domain random walk formulation. Water Resources Research 50. doi:10.1002/2014WR015449

Dessirier B, Jarsjö J, Frampton A, 2014. Modeling two-phase-flow interactions across a bentonite clay and fractured rock interface. Nuclear Technology 187, 147–157.

Earon R, 2014. Water supply in hard rock coastal regions: The effect of heterogeneity and kinematic porosity. Lic thesis. Royal Institute of Technology, Stockholm. (TRITA-LWR LIC-2014:03)

Earon R, Olofsson B, 2014. Groundwater balance in hard rock terrains with limited soil cover. The importance of spatial data. In Gustafsson D, Zhang L (eds). Nordic Water 2014, XXVIII Nordic Hydrological Conference, 11–13 August 2014. (TRITA-LWR Report 2014:04)

Earon R, Olofsson B, 2014. Groundwater balance in hard rock terrains with limited soil cover: The importance of spatial data. NGL Annual Science Meeting, Oskarshamn, 3–4 November 2014. (poster)

Earon R, Dehkordi S E, Olofsson B, 2014. Groundwater resources potential in hard rock terrain: A multivariate approach. Ground Water 53. doi: 10.1111/gwat.12265

Fathollahzadeh H, Kaczala F, Bhatnagar A, Hogland W, 2014. Speciation of metals in contaminated sediments from Oskarshamn Harbor, Oskarshamn, Sweden. Environmental Science And Pollution Research 21, 2455–2464.

Fransson Å, Funehag J, Thörn J, Lehtimäki T, Sjöland A, Vidstrand P, Åkesson M, 2014. Characterization of fractured crystalline rock: two Swedish in situ field experiments. In Proceedings of DFNE 2014, the 1st International Conference on Discrete Fracture Network Engineering, Vancouver, Canada, 19–22 October 2014.

Fujiyama T, Kaku K, Kitagawa Y, Kronberg M, 2014. Study on the disposal technology options in Japan. In 69th Annual conference of Japan Society of Civil Engineers, Osaka, Japan, 10–12 September 2014, 85–86.

Drake H, Heim C, Hogmalm K J, Hansen B T, 2014. Fracture zone-scale variation of trace elements and stable isotopes in calcite in a crystalline rock setting. Applied Geochemistry 40, 11–24.

Heim C, Quéric N-V, Ionescu D, Simon K, Thiel V, 2014. Chemolithotrophic microbial mats in an open pond in the continental subsurface – implications for microbial biosignatures. In Wiese F, Reich M, Arp G (eds). Spongy, slimy, cosy & more. Göttingen: Universitätsverlag Göttingen. (Göttingen Contribution to Geosciences 77), 99–112.

Ionescu D, Buchmann B, Heim C, Haeusler S, De Beer D, Polerecky L, 2014. Oxygenic photosynthesis as a protection mechanism for cyanobacteria against iron-encrustation in environments with high Fe2+ concentrations. Frontiers in Microbiology 5. doi:10.3389/fmicb.2014.00459

Ittner H, Bouvin A, Fogdeby M, Kainulainen A, Karlzén R, 2014. Kontursprängning i Äspö utbyggnad – Dokumentation av strängladdning med emuslsion i tunnelkontur. (Contour blasting in the Äspö HRL Expansion project – Documentation of string emulsion in the tunnel perimeter.) In Vikane K, Tvedt G, Mathiesen T K, Engen S (eds). Fjellsprengningsdagen, 27 November 2014. Norsk Forening for Fjellsprengningsteknikk (NFF), 7.1–7.12. (In Swedish.)

Karlsson C, Jamali I, Earon R, Olofsson B, Mörtberg U, 2014. Comparison of methods for predicting regolith thickness in previously glaciated terrain, Stockholm, Sweden. Geoderna 226–227, 116–129.

Langeland K, Kiessling A, Lekang O I, 2014. Baltic Aquaculture Innovation Centre (BIC). Rapport, Vattenbruks Centrum Ost, Nova FoU, Sveriges Lantbruksuniversitet, Sweden. Available at: http://vattenbrukscentrumost.se/wp-content/uploads/2014/05/BICrapport.pdf (In Swedish.)

Maskenskaya O M, 2014. Abundance and fractionation of rare earth elements in calcite and other secondary minerals in fractures in the upper kilometre of crystalline bedrock, SE Sweden. PhD thesis. Linnaeus University, Sweden. (Linnaeus University Dissertations 197/2014)

Maskenskaya O M, Drake H, Broman C, Hogmalm K J, Czuppon G, Åström M E, 2014. Source and character of syntaxial hydrothermal calcite veins in Paleoproterozoic crystalline rocks revealed by fine-scale investigations. Geofluids 14, 495–511.

Mathurin F A, Åström M E, Drake H, Maskenskaya O M, Kalinowski B E, 2014. REE and Y in groundwater in the upper 1.2 km of Proterozoic granitoids (Eastern Sweden) – Assessing the role of composition and origin of the groundwater, geochemistry of the fractures, and organic/inorganic aqueous complexation. Geochimica et Cosmochimica Acta 144, 342–378.

Mathurin F A, Drake H, Tullborg E-L, Berger T, Peltola P, Kalinowski B E, Åström M E, 2014. High cesium concentrations in groundwater in the upper 1.2 km of fractured crystalline rock – Influence of groundwater origin and secondary minerals. Geochimica et Cosmochimica Acta 132, 187–213.

Mossmark F, 2014. Prediction of groundwater chemistry in conjunction with underground constructions : field studies and hydrochemical modelling. PhD thesis. Chalmers University of Technology, Sweden.

Rasul H, Earon R, Olofsson B, 2014. Environmental impact on soil and water from a new highway section: Long term resistivity results. In Gustafsson D, Zhang L (eds). Nordic Water 2014, XXVIII Nordic Hydrological Conference, 11–13 August 2014. (TRITA-LWR Report 2014:04)

Smart N R, Rance A P, Reddy B, Hallbeck L, Pedersen K, and Johansson A J, 2014. In situ evaluation of model copper-cast iron canisters for spent nuclear fuel: a case of microbiologically influenced corrosion (MIC). Corrosion Engineering, Science and Technology 49, 548–553.

Törnqvist R, Jarsjö J, Pietroń J, Bring A, Rogberg P, Asokan S M, Destouni G, 2014. Evolution of the hydro-climate system in the Lake Baikal basin. Journal of Hydrology 519, 1953–1962.

Van der Velde Y, Vercauteren N, Jaramillo F, Dekker S, Destouni G, Lyon S W, 2014. Exploring hydroclimatic change disparity via the Budyko framework. Hydrological Processes 28, 4110–4118.

Yu C, Lavergren U, Peltola P, Drake H, Bergback B, Åstrom M E, 2014. Retention and transport of arsenic, uranium and nickel in a black shale setting revealed by a long-term humidity cell test and sequential chemical extractions. Chemical Geology 363, 134–144.

Åkesson M, Fransson Å, Vidstrand P, Sjöland A, 2014. The Bentonite Rock Interaction Experiment. In Schäfers A, Fahlund S (eds). Proceedings: International Conference on the Performance of Engineered Barriers: Physical and Chemical Properties, Behaviour & Evolution, Hannover, Germany, 6–7 February 2014. Hannover: BGR, 91–96.

Arkitektkopia AB, Bromma, 2015

SKB is tasked with managing Swedish nuclear and radioactive waste in a safe way.

skb.se

SVENSK KÄRNBRÄNSLEHANTERING