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Äspö Hard Rock Laboratory

Annual Report 2013

Svensk Kärnbränslehantering AB

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Abstract

The Äspö Hard Rock Laboratory (HRL) is an important part of SKB's work with the design and construction of a deep geological repository for the final disposal of spent nuclear fuel. Äspö HRL is located in the Simpevarp area in the municipality of Oskarshamn. One of the fundamental reasons behind SKB's decision to construct an underground laboratory was to create opportunities for research, development and demonstration in a realistic and undisturbed rock environment down to repository depth. The underground part of the laboratory consists of a 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 2013 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".

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.

In the project *Sulphide in repository conditions* the aim is to study the processes behind microbial sulphide production and the regulating factors for dissolved sulphide. An experimental activity in Äspö HRL was performed in 2012 that focused on the possible effects from the borehole instrumentation on the microbial sulphide production in groundwater of drilled boreholes. Evaluation and reporting of results has been finalised during 2013.

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 2013, the modelling work within Task 7 is more or less completed, and the focus is on result analysis, result presentation, reporting, and optional publishing. The Task 8 work mainly contained modelling of *BRIE* with different levels of detailed data.

The *BRIE* project is 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. This work included: Hydro-mechanical characterisation of buffer material, Chemical characterisation of buffer and backfill material and Microbiological investigations. The examination of the canisters was also finalised during 2013.

The objective of the project *Alternative Buffer Materials* is to study clay materials that in laboratory tests have shown to be conceivable buffer materials. Three test parcels with different combinations of clay materials are installed in boreholes at Äspö HRL. The parcels are heated carefully to increase the temperature in the buffer materials to 130°C. Parcel #1 was retrieved after about 1.5 years operation at the target temperature and parcel #2 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.

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 2013 (day 2,890–3,255) the test programme of Lasgit concentrated on the fourth gas injection stage. This test focused on a lower canister filter, which had been used for the first two gas injection tests. Three years of artificial hydration of filter FL903 had occurred since gas test 2, meaning that the buffer would be in greater hydraulic equilibrium than in the previous tests.

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.

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. The bentonite specimens will be prepared and installed during 2014. Altogether a total of 150 bentonite blocks will be deposited in 5 packages in the tunnel TAS06 during 2014.

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 will be 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 2013; one in London, England on the 21st–23rd of May and one in Bern, Switzerland on the 5th–7th of November.

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 prototype equipment for backfilling has been improved with a laser scanner on the lifting tool and a feeding system that has been integrated on the platform. The concept for installation has been further improved and will be tested in a demonstration test in full scale underground as the final activity in the project during the beginning of 2014.

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 test programme will continue throughout 2014 and at the end of 2014 a technical evaluation will be reported. 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 2013 development work for refinement of buffer design, production, installation and inspection was initiated and carried out. This report provides details from work on *Early effects of water inflow*, *Test and simulations of THM processes relevant for buffer installation*, *Test of buffer protection system* and *Test of controlled atmosphere*.

Mechanical and system engineering

At Äspö HRL and the Canister Laboratory in Oskarshamn, methods and technologies for the final disposal of spent nuclear fuel are being developed. Established as well as new technology will be used in the final repository. The approximately 200 technical systems, machines and vehicles that are needed in the final repository have been identified and listed in a database called FUMIS. Extensive work has been put into assessing the degree of development and prototyping needed, costs, schedule, deadlines etc. Several projects within mechanical and system engineering are ongoing, 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. Important tasks of the Äspö facility are the administration, operation, and maintenance of instruments as well as development of investigation methods. The main goal of the operation of the facility is to provide a safe and environmentally sound facility for everybody working or visiting the Äspö HRL.

In *the Bentonite Laboratory* different methods and techniques for installation of pellets and blocks in deposition tunnels and tests on piping and erosion of buffer and backfill material are performed. 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, test and simulations of THM processes relevant for buffer installation and test of buffer protection system.

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. Example of activities performed during 2013 are geologic samples of unknown minerals from the Äspö underground, bentonite samples from the KBS-3H Multi Purpose Test (see Section 4.4) with unexplained color variations in the full scale blocks, unknown precipitates from low pH cement, unknown solid material from within the Prototype canisters, determination of sulphide equilibrium concentrations of water bentonite mixtures and analysis of bentonite from within the SFR silo.

The operation of the facility during 2013 has been functioning very well, with a very high degree of availability. The rock maintenance work in the Äspö tunnel completed its two year cycle with surveying and reinforcement of the raise bored elevator shaft. Upgrades have been made to the tunnel elevator brake system during the latter half of 2013. Fitting and equipping of the new tunnels produced in the expansion of Äspö 2011–2012 has been completed during 2013.

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 2013, 4,918 people visited the Äspö HRL and with the visitors at Clab and the Canister Laboratory included it resulted in a total of 7,224 people. The total number of visitors to SKB´s facilities in both Oskarshamn and Forsmark was 14,703 people. The unit arranged a number of events and lectures during 2013. In August, the Swedish championships in 3D-archery were held on the island of Äspö with almost 400 participants.

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 2013 nine organisations from seven countries in addition to SKB participated in the cooperation at Äspö HRL. Six of them; BMWi, NDA, NUMO, CRIEPI, JAEA and NWMO together with SKB formed the Äspö International Joint Committee (IJC), which is responsible for the coordination of the experimental work arising from the international participation.

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

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

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

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 2013.

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.

Naturliga barriärer

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

I projektet *Svavelväte i förvarsliknande förhållanden* är syftet att studera processer bakom den mikrobiella produktionen av sulfider och reglerande faktorer för löst sulfid. Under 2012 utfördes ett experiment på Äspölaboratoriet som fokuserade på möjliga effekter av borrhålsinstrumentering på sulfidproduktion i grundvatten i borrhål. Under 2013 har resultaten utvärderats och rapporterats.

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 2013 har modelleringsarbetet inom Task 7 i stort sett slutförts, och fokus ligger vid analys av resultat, presentation av resultat, rapportering och eventuell publicering. Arbetet med Task 8 har mest inneburit modellering av *BRIE* med 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. Även undersökningar av de återtagna kapslarna avslutades 2013.

Målet med projektet *Alternativa buffertmaterial* är att studera olika lermaterial som i laboratorietester har visat sig vara tänkbara buffertmaterial. Tre paket med olika kombinationer av lermaterial har installerats i borrhål i Äspölaboratoriet. Paketen ska värmas för att försiktigt höja temperaturen i bufferten till måltemperaturen 130°C. Paket #1 togs upp efter ca 1,5 års drift vid måltemperatur och paket #2 togs upp i april 2013. Tre nya testpaket installerades i november 2012.

Ett forskningsprogram för ett *KBS-3-förvar med horisontell deponering* (KBS-3H) genomförs som ett samarbetsprojekt mellan SKB och Posiva. Nu pågår en fortsättningsfas av projektet med målsättningen att utveckla KBS-3H till en sådan nivå att en jämförelse mellan 3V/3H och förberedelser inför en PSAR är möjlig. Den nuvarande projektfasen är planerad till 2011–2016. Ett delprojekt fokuserar på systemtestet (Multi Purpose Test) som även är del i EU-projektet LucoeX, vars finansiering stöds från Euratoms Seventh Framework Programme FP7/2007–2013. Systemtestet installerades under 2013.

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 konstgjord väg och utvecklingen av vattenmättnadsgraden i bufferten mäts kontinuerligt. Under 2008 avslutades de preliminära hydrauliska testerna och gasinjekteringstesterna. Under 2013 fokuserade testprogrammet på det fjärde stadiet av gas-injektionsfasen.

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 har proverna analyserats vidare med flera olika metoder.

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. Under perioden 2010–2014 kommer ca 15 experiment att förberedas och deponeras på olika platser i Äspölaboratoriet. Under 2013 har förberedelser gjorts för installation av fem paket med bentonit som ska utföras under 2014.

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 kommer att publiceras 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 2013; ett i London, England under 21–23 maj och ett i Bern, Schweiz under 5–7 november.

Huvudmålet med projektet *Systemdesign av Återfyllnad för Deponeringstunnlar* är att säkerställa att vald metod för återfyllnad fungerar med önskad effektivitet. Prototyputrustningen för återfyllnad har förbättrats med laserscanner på lyftverktyget och ett matningssystem har integrerats på plattformen. Konceptet för installation har har förbättrats ytterligare och kommer att testas i full skala under jord som den sista aktiviteten i projektet under början av 2014.

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 kommer fortsätta under 2014. 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 2013 har arbete utförts för att vidareutveckla design, produktion, installation och inspektion av buffert. I denna rapport beskrivs arbete inom *Tidiga effekter av vatteninflöde*, Test *och simulation av THM-processer relevanta för buffertinstallation*, *Test av buffertproduktionssystem* och *Test med kontrollerad atmosfär*.

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 systemen, maskiner och fordon som behövs har identifierats och har dokumenterats i en databas, FUMIS. Ett omfattande arbete har gjorts för att bedöma grad av nyutveckling, behov av prototypframtagning, kostnad, tidplaner etc. Flera utvecklingsprojekt inom mekanik- och systemkonstruktion pågår, bland annat Deponeringsmaskinen, 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 eller besöker anläggningen samt att driva anläggningen på ett miljömässigt korrekt sätt.

I *Bentonitlaboratoriet* provas olika metoder och tekniker för installation av pelletar och block i deponeringstunnlar och tester av rörledningar och erosion av buffert och återfyllningsmaterial utförs. Flera projekt har haft aktivitet i Bentonitlaboratoriet under 2013, däribland tester och vidareutveckling av robotutrustning för återfyllnad och test av buffertskydd.

Under året har ett nytt *Laboratorium för Materialstudier* konstruerats på Äspö, med fokus på materialkemi för bentonitfrågor och kompetensutveckling. De största fokusområdena är metodutveckling för kvalitetskontroll av bentonit buffert och fyllnadsmaterial ur ett långtidssäkerhetsperspektiv. Aktiviteter som utförts under 2013 inkluderar prover av okänt material från Äspötunneln, bentonitprover från KBS-3H och analys av bentonit från SFR-silon.

Driften av anläggningen under 2013 har fungerat mycket bra med en mycket hög tillgänglighet. Bergunderhållet avslutade under året sin två-åriga cykel för inspektion och förstärkning av hisschaktet. Hissens bromssystem uppgraderades under slutet av 2013. Nya tunnlar producerade i projektet Utbyggnad av Äspölaboratoriet 2011–2012 har inretts och utrustats under 2013.

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 2013 besöktes Äspölaboratoriet av 4 918 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. Sex av dem; BMWi, NDA, NUMO, CRIEPI, JAEA och NWMO 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: ”*Task Force on Modelling of Groundwater Flow and Transport of Solutes*” och ”*Task Force on Engineered Barrier Systems*”.

Contents

1 General

1.1 Background

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

The underground part of the laboratory consists of a 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.

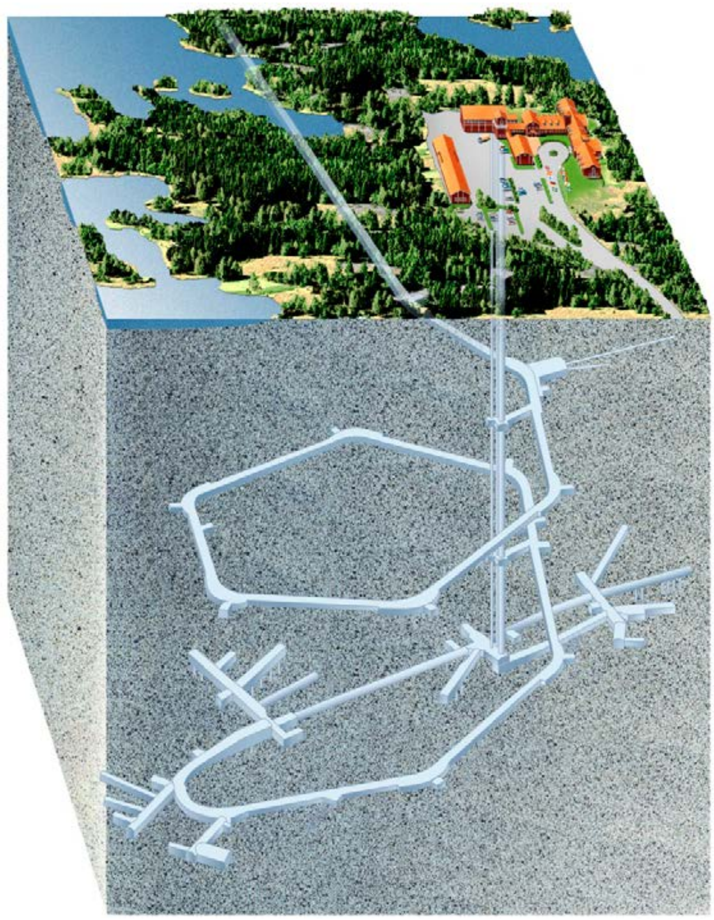


Figure 1-1. *Overview of the Äspö HRL facilities, including the new areas produced in the tunnel expansion, and the Simpevarp peninsula.*

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

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

The Operational phase began in 1995. A preliminary outline of the programme for this phase was given in SKB´s Research, Development and Demonstration (RD&D) Programme 1992. Since then the programme has been revised every third year and the detailed basis for the period 2014–2019 is described in SKB´s RD&D-Programme 2013 (SKB 2013a).

1.2 Goals

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

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

The task in stage goals 1 and 2 were after completion at Äspö HRL transferred to the Site Investigations Department of SKB. The investigation methodology has hereafter been developed in the site investigations performed at Simpevarp/Laxemar in the municipality of Oskarshamn and at Forsmark in the municipality of Östhammar. Since the Site Investigations Programme has been 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´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 has been 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 and plugging of investigation boreholes.
- *Mechanical and system engineering (TDM*), responsible for the development, testing and demonstration of equipment, machines and vehicles needed in the final repository.
- *Project and experiment service (TDP),* responsible for the co-ordination of projects undertaken at the Äspö HRL, providing services (administration, design, installations, measurements, monitoring systems etc) to the experiments.
- *Facility operation (TDD),* responsible for the operation and maintenance of the Äspö HRL offices, workshops and underground facilities and for development, operation and maintenance of supervision systems.
- *Administration, quality and planning (TDA),* responsible for planning, reporting, QA, budgeting, environmental co-ordination and administration. The staffing of the Äspö reception and the SKB switchboard are also included in the function.
- *Rock 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 2013 nine organisations from seven countries in addition to SKB participated in the cooperation at Äspö HRL. Six of them; BMWi, NDA, NUMO, CRIEPI, JAEA and NWMO together with SKB formed the Äspö International Joint Committee (IJC), which is responsible for the coordination of the experimental work arising from the international participation.

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

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 particiption in the IAEA Network of Centres of Excellence for training in and demonstration of waste disposal technologies in underground research facilities.

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

Between September 2013 and December 2013, the NDA RWMD seconded one of its employees to the Äspö HRL to gain a better understanding of the work being carried out in the facility and how the learning from the ongoing experimental programmes could be transferred into the UK work programmes.

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

1.5 Allocation of experimental sites

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

1.6 Reporting

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

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.

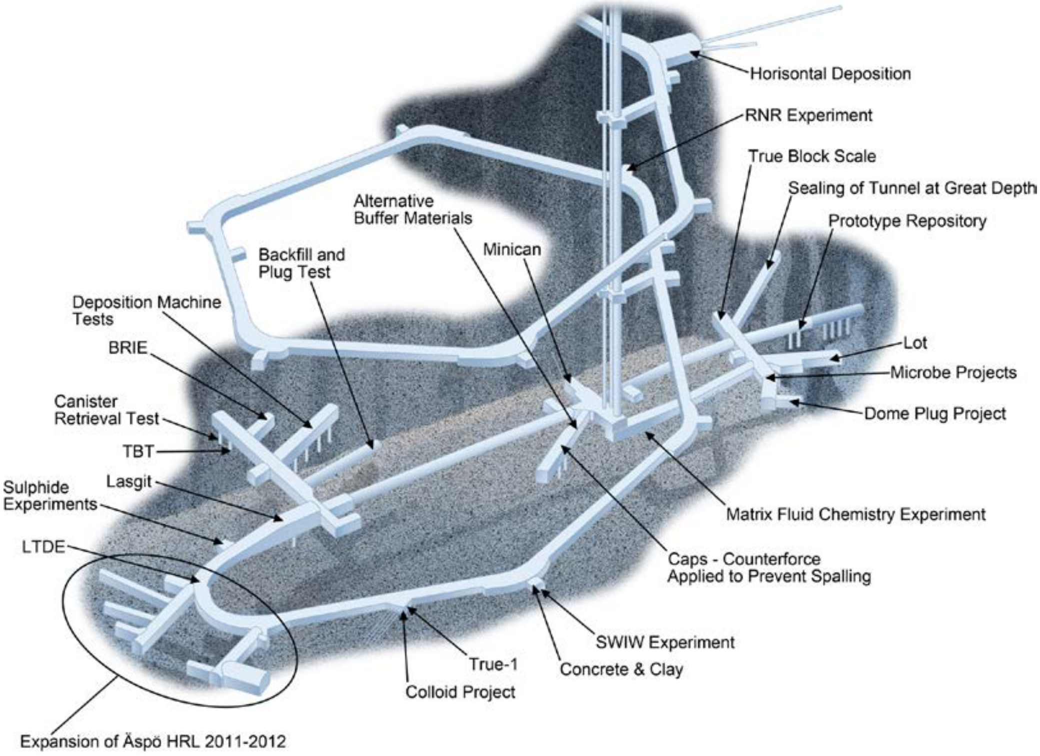


Figure 1-2. *Allocation of experiment sites from –220 m to –460 m level.*

1.7 Management system

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

1.8 Structure of this report

The achievements obtained at Äspö HRL during 2013 are in this report described in seven chapters:

- Geoscience – experiments, analyses and modelling to increase the knowledge of the surrounding rock.
- Natural barriers – experiments, analyses and modelling to increase the knowledge of the repository barriers under natural conditions.
- Engineered barriers – demonstration of technology for and function of important engineered parts of the repository barrier system.
- Mechanical and system engineering – developing of technologies for the final disposal of spent nuclear fuel.
- Äspö facility – operation, maintenance, data management, monitoring, communication etc.
- Open research and technical development platform, Nova FoU.
- International co-operation.

2 Geoscience

2.1 General

Geoscientific research is a part of the activities at Äspö Hard Rock Laboratory as a complement and an extension of the stage goals 3 and 4;

3. *Test models for description of the barrier functions at natural conditions* – Further develop and at repository depth test methods and models for description of groundwater flow, radionuclide migration and chemical conditions during operation of a repository as well after closure.
4. *Demonstrate technology for and function of important parts of the repository system* – In full scale test, investigate and demonstrate the different components of importance for the long-term safety of a final repository and show that high quality can be achieved in design, construction and operation of repository components.

Studies are performed in both laboratory and field experiments, as well as by modelling work.

The objectives are to:

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

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

The development of the Äspö Site Descriptive Model was runned as a project wich ended in the beginning of 201. The development and the updating of the site descriptive model will be performed within the Äspö organisation. For this purpose, a management plan will be developed.

2.2 Geology

The geological work at Äspö HRL is covering several fields. Major responsibilities are mapping of tunnels, deposition holes and drill cores, as well as continuous updating of the geological three-dimensional model of the Äspö rock volume.

In addition, the development of new methods in the field of geology is a major responsibility. As a part of the latter, the continuation of the Rock Characterisation System (RoCS) project is being conducted, see Section 2.2.2.

2.2.1 Geological mapping and modelling

Background

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

Types of mapping

Drill cores are logged with the help of Boremap core logging system often in combination an image of the borehole (BIPS, Bore Hole Image Processing System). A less detailed variety is the overview mapping where only major rock types and amount of fractures are logged.

The mapping of rock surfaces in the tunnels and deposition holes have been performed by the use of TMS (Tunnel Mapping System) in 2D. Lately, however, the digital RoCS (Rock Characterisation System) in 3D is in use (see 2.2.2), with or without complimentary overview mapping depending of the objectives for the mapping.

Results

Overview mapping has been performed on some short drill cores (1 m and 4 m respectively) taken from the floor of the niches TAS04 and TAS06. Overview mapping was also done on the drill core from the approximately 100 m sub-horizontal borehole K03009F01. All the cores have been photographed.

The expansion of Äspö HRL 2011–2012 has been completed. The geological work mainly consisted of photogrammetry documentation and mapping of the tunnel surfaces with RoCS, see Section 2.2.2. The tunnel roofs, walls and most of the tunnel faces were documented. Figure 2-1 shows the result of mapped fractures in 3D-models. The floor in the niches TASN, TAS04, TAS05 and TAS06 was also documented (Figure 2-4). The mapping of the tunnels of the Äspö expansion project was completed during the autumn 2013.

During the Äspö expansion project overview mapping of the tunnel surfaces was performed as a compliment to the RoCS-mapping. The overview mapping took place after each round during the excavation of the new tunnels/drifts to give the modellers quick information about the geology. Only major structures, such as FPI:s, and wet areas/structures were documented on paper within the overview mapping. Simplifications were made by combining groups of single fractures and recording that as as one fracture.

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

Background and objectives

The project Rock Characterisation System (RoCS) was initially conducted as an SKB-Posiva joint project. The purpose was to investigate if a new system for rock characterisation could be adopted for the construction of a final repository for spent fuel. The major reasons for the RoCS project are aspects on objectivity and of the collected data and presition of the geometries, as well as traceability of the mappings performed, time saving and elimination of manual work in the mapping process such as digitising geometries and manual data handling. These aspects all represent areas where the present mapping technique may not be adequate. After finishing the feasibility study concerning modern geological mapping techniques, SKB commenced a new phase of the RoCS project. This project concentrated on benchmarking existing systems and founded photogrammetry and/or laser-scanning solutions best suitable documentation of tunnel surfaces. The resulting mapping system shall operate in a colour 3D environment where the xyz-coordinates are known.

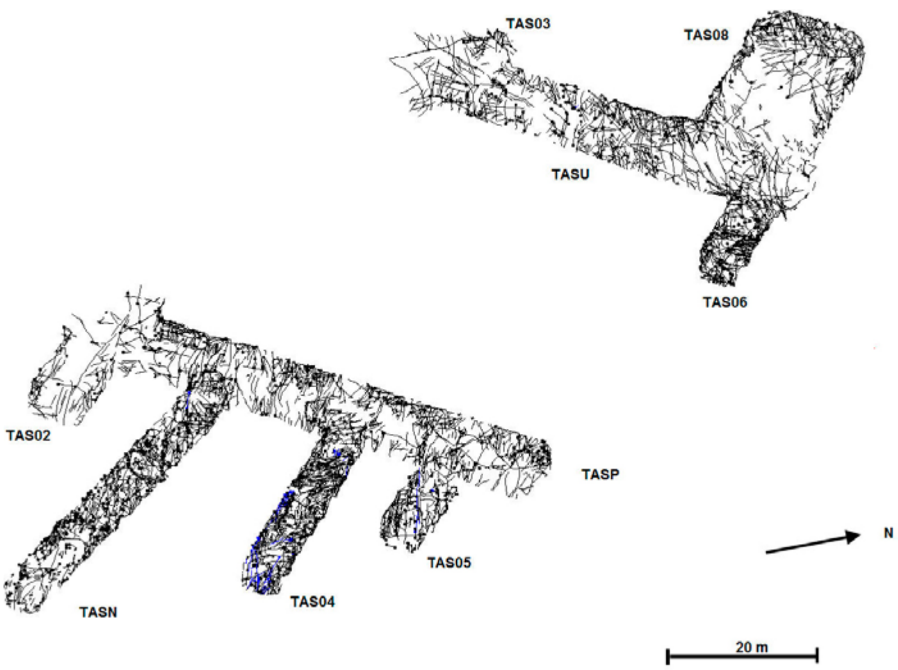


Figure 2-1. *Mapped and then RVS-modelled fractures in the tunnels of the expansion of Äspö HRL project.*

Experimental concept

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

Results

The company Ergodata had prevpiously, on behalf of SKB, developed the core logging software Boremap. Ergodata was given the commission to develop the mapping module in RoCS. After a series of test versions and acceptance tests, SKB eventually approved a version of RoCS. The project team has delivered the module to the administration of mapping systems. It should be remembered, however, that even now when the RoCS project as such is finished RoCS needs to be further developed.

The RoCS system was implemented in the Äspö HRL Expansion Project. For each round (drilling, blasting and unloading) digital photos were taken to make it possible to create a 3D-model of the newly excavated section. Only a limited amount of time for geological tunnel characterisation was given while excavation of a tunnel took place. Therefore only the tunnel faces were mapped after each round and only a 3D-model of the face was created in the tunnel by the geologist team. Altogether, cleaning the tunnel section (4–5 m), placing reference markers on the walls and front, surveying of the markers, photography of the tunnel section, creating a 3D-model of the tunnel face and mapping of the face took about 3–4 hours. The mapping of walls and roof took place after a tunnel/drift had been completed (Figures 2-2 and 2-3). 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. Suggestions for improvements of the mapping system were given to the RoCS project team continiusly during the project. Changes in the mapping system were made and the quality of the system was increasing over time. Unfortunately the latest improvements (from version 2.0 and onwards, today 2.2) could not be tested in the tunnel environment since they were made for Windows 7 which is not yet available on SKB computers.

At the time being, the disadvantage with RoCS is that too much time is needed in the tunnels while the excavation is on-going. 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).

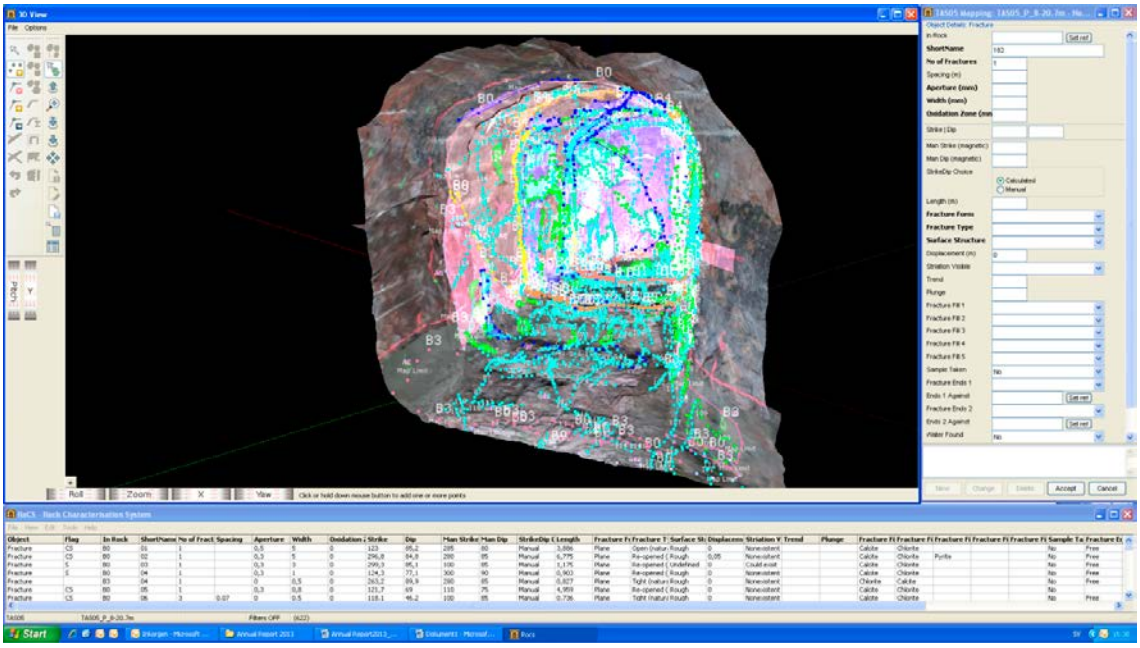


Figure 2-2. *Print out from the computer screen showing the RoCS layout*

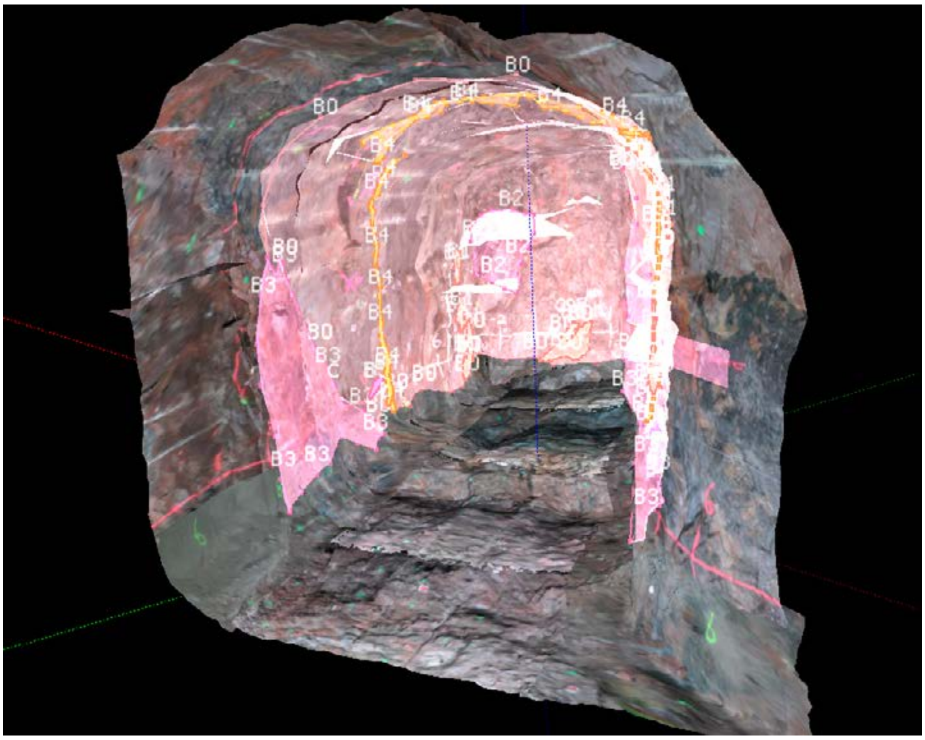


Figure 2-3. Print out from the computer screen showing only mapped rock types in pinkish and yellowish colours, the TAS05-tunnel. Fractures, water leakage etc has been hidden.

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 for predictions in support of the experiments in the laboratory as well as to test hydrogeological hypotheses in order to improve the conceptual understanding.

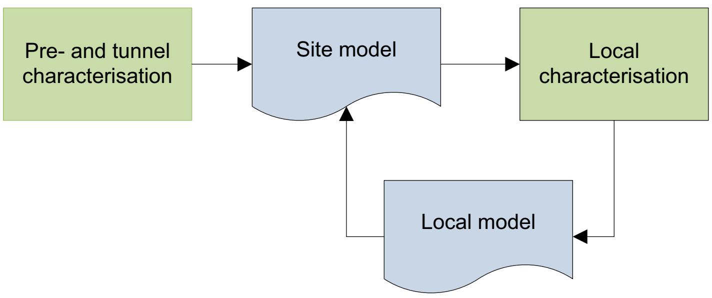


Figure 2-4. Evolution of local- and site descriptive model.

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

Due to a change in priorities SKB discontinued the site descriptive modelling as of 2012-12-31 and no work was undertaken in this respect during 2013.

Hydrogeological resources were to a major extent provided to the Äspö Expansion Project and to some 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.

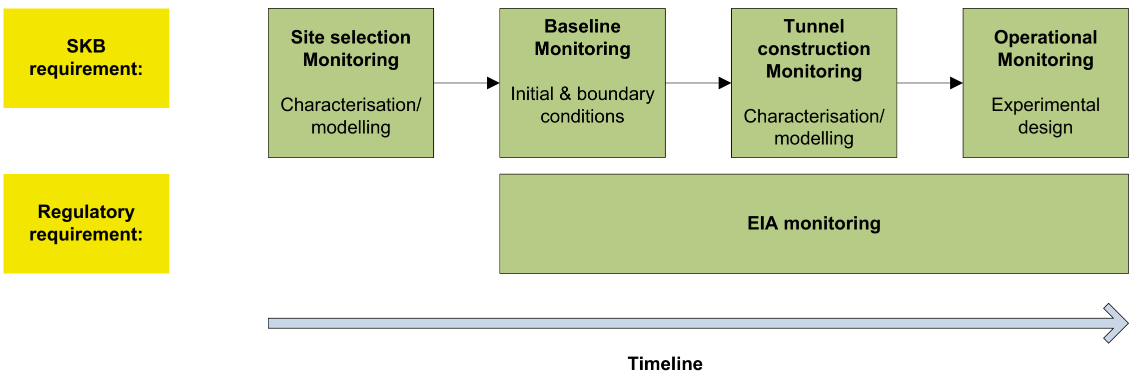


Figure 2-5. *The staged approach of monitoring.*

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 minimise 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 station were later incorporated to the Äspö HRL monitoring system.

Results

The monitoring system is continuously maintained and data is collected, quality controlled and stored in the Sicada database. 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.

The process of upgrading the hydro monitoring system software to 64-bit Windows operating system was initiated. The upgrade also includes a transition to a database platform, enhanced access to the system through the world wide web, as well as additional functionality for system administrators as well as for end users. The system that is phased out was commissioned in 1995, it has 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.

2.4 Geochemistry

Background

Hydrogeochemical monitoring and sampling of surface and groundwater at Äspö has been performed during the last 20 years. The sampling campaigns are designed as biannual or monthly depending on what type of water and analyses takes place at Äspö chemical laboratory as well as in external laboratories. 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.

Experimental concept and results

The first 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 as well as data has been compiled and will be published in a scientific publication in 2014. Further sampling with the technique DGT is planned for 2014.

On-line measurements of the parameters pH, EC, Eh, O_2, redox and temperature on groundwater n the tunnel has been tested during 2013. Preliminary result shows that the system is performing well and can be operated with a remote control over the local Internet. Different boreholes in the tunnel have been the target for the experiments. A status report is planned to be completed during 2014.

A new liquid isotope analyzer was installed in the chemical laboratory at Äspö for ^{2}H and ^{18}O analyses of ground- and surface waters. The instrument will provide data on a regular basis for the monitoring program and any changes, such as groundwater mixing during the experiments and future tunnel excavations.

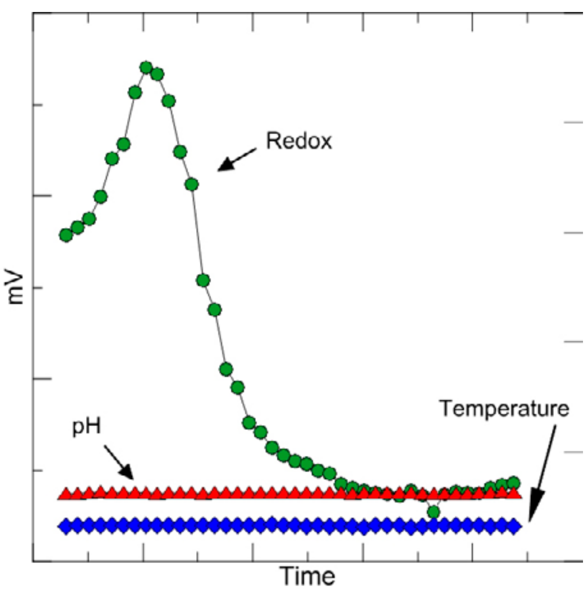


Figure 2-6. *Diagram showing pH and Redox over time in the on-line experiment in the tunnel.*

Figure 2-7. *Borehole sections connections to the on-line experiment device in the tunnel.*

Figure 2-8. *Liquid isotope analyzer and its inlet system.*

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 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 organisations 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 2013 two groundwater sampling campaigns have been made in Äspö HRL, one completed in May and the other in November. The spring sampling included a total of 19 boreholes sections and the autumn collection of groundwater was performed in 24 different borehole sections. This discrepancy between the two campaigns and the reduced number of sampled sections in the spring campaign was due to the experimental activity in the tunnel. All analytical results are expected to be reported during the first four month of 2014.

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 Sulphide in repository conditions

Background

In a repository, knowledge of the groundwater sulphide concentration and its variability is important, since sulphide affects the stability of the copper canister. During the early pre-investigations at Äspö, the site investigations at Laxemar and Forsmark, and the subsequent monitoring programmes, variations in sulphide concentration were obtained (Hallbeck 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.

Objectives

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

Experimental concept

An experimental activity in Äspö HRL was performed in 2012 that focused on the possible effects from the borehole instrumentation on the microbial sulphide production in groundwater. Borehole instrumentations in two boreholes drilled in the 1990's were dismantled and investigated. The boreholes showed different groundwater sulphide concentrations and an important objective was to compare the conditions in the boreholes and determine any differences in the instrumentation that can be related to the extent of microbial sulphide production.

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

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

Results

Evaluation and reporting of results has been finalised during 2013 (Drake et al. 2014). The main conclusions can be summarised as follows:

- The $\delta^{34}S$ in the dissolved sulphide and sulphate in the groundwater in both boreholes indicated on-going SRB-activity in the section water but also in the fracture water. Analyses of $\delta^{34}S$ in precipitates of pyrite suggest that the sulphide production has been faster than the supply of sulphate from the fractures, in local micro-environments in the section where the water has been close to stagnant.
- Precipitates of Al-oxyhydroxides and Si-rich precipitates were found close to the PVC-tape. Precipitates of calcite were abundant on the stainless steel surfaces of the packers, the stainless steel acting as a cathode with higher pH than the surroundings. $\delta^{13}C$ values in calcite were either within or lower than the range expected for precipitates from the groundwater $\delta^{13}C$ composition. The lower values may be due to local fractionation of C during oxidation of organic matter to HCO_3^- which is eventually incorporated into calcite.
- The pipe of aluminium had been subjected to corrosion beneath the tape. It was obvious that corrosion occurred where plastic (tape or tubing) and metal was in contact. The corrosion process was similar in both boreholes.
- There was no significant difference in TNC or SRB numbers between the instrumentation in the two boreholes with high and low sulphide concentration (KA3110A and KA3385A respectively). TNC and SRB were lower on the stainless steel surface of the packers than on the other material. There were no significant difference in TNC and SRB on the surfaces of plastics, aluminium and tape.
- It was not possible to make an identification of the species of the microorganisms on the equipment due to small amounts of DNA in the samples.

3.3 Task Force on modelling of groundwater flow and transport of solutes

Background

The work within Äspö Task Force on modelling of groundwater flow and transport of solutes constitutes an important part of the international co-operation within the Äspö HRL. The group was initiated by SKB in 1992. A Task Force delegate represents each participating organisation and the modelling work is performed by modelling groups. The Task Force meets regularly about once to twice a year. Different experiments at the Äspö HRL, with the exception Task 7, are utilised to support the modelling tasks.

The modelling tasks and their status are as follow:

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

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

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

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

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

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

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

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

Objectives

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

Task 7 was presented at the 19th International Task Force meeting in Finland, 2004. Hydraulic responses during construction of a final repository are of great interest because they may provide information for characterisation of hydraulic properties of the bedrock and for estimation of possible hydraulic disturbances caused by the construction. Task 7 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.

Results

During 2013, the modelling work within Task 7 is more or less completed, and the focus is on result analysis, result presentation, reporting, and optional publishing. The Task 8 work mainly contained modelling of BRIE with different levels of detailed data. The BRIE project is on-going, and has couplings to Task 8 in terms of data deliveries but also predictive modelling within the task may provide support to the experiment. It also provides a possibility to compare the modelling results to the experiment.

The 30th international Task Force meeting was held in Helsinki in June. The final results for Task 7 were presented with several people from Posiva in the audience. The other presentations were mainly addressing modelling results on sub-tasks 8C and 8D. 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. Next step in Task 8 is to model the Prototype experiment. It is possible 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 November where modelling approaches and plans for the future modelling were presented and discussed. The venue took place at Rånäs Slott. Minutes of both venues (TF meeting 30 and workshop) have been distributed to the Task Force together with presentation material. The description and the status of the specific modelling sub-tasks within Task 7 and 8 are given in Table 3-1.

Table 3-1. Descriptions and status (within brackets) of the specific sub-tasks in Task 7 and 8.

7	**Reduction of Performance Assessment uncertainty through modelling of hydraulic tests at Olkiluoto, Finland.**
7A	Long-term pumping experiment. (Final results of sub-task 7A1 and 7A2 are reported as ITDs).
7B	Sub-task 7B is addressing the same as sub-task 7A but in a smaller scale, i.e. rock block scale. Sub-task 7B is using sub-task 7A as boundary condition. (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 30).
8D	Updated resulst (presented at Task Force meeting 30).

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 intended to be a joint effort of the taskforce on groundwater flow and transport (GWFTS) and the taskforce on engineered barrier systems (EBS).

Objectives

BRIE and Task 8 as a whole are intended to lead to:

- Scientific understanding of the exchange of water across the bentonite-rock interface.
- Better predictions of the wetting of the bentonite buffer.
- Better 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) and Holton et al. (2012).

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 (Figure 3-1), total pressure and pore pressure were monitored in the sections of interest. Pore pressure (hydraulic head) is 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 is planned to continue to the beginning of 2014.

The bentonite parcel in Hole 17 was dismantled, sampled and analyzed during November and December 2013, and a similar operation is planned for the parcel in Hole 18 in the beginning of 2014. The dismantling operation follows the procedure of stitch-drilling of a Ø 700 mm rock pillar which is cut in the lower end through wire sawing, after which the pillar and parcel is lifted from the site. Figure 3-2 presents a BIPS-image from Hole 17 which shows an important water-bearing fracture at 2.6–3.1 m and a pegmatite vein (left), and a photo from the dismantling of the parcel in Hole 17.

The bentonite was subsequently partitioned, sampled and analyzed with respect to water content and density. Two 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. Further the relative humidity profile from the borehole wall into the rock will be investigated since it is of interest when evaluating flow in the rock matrix.

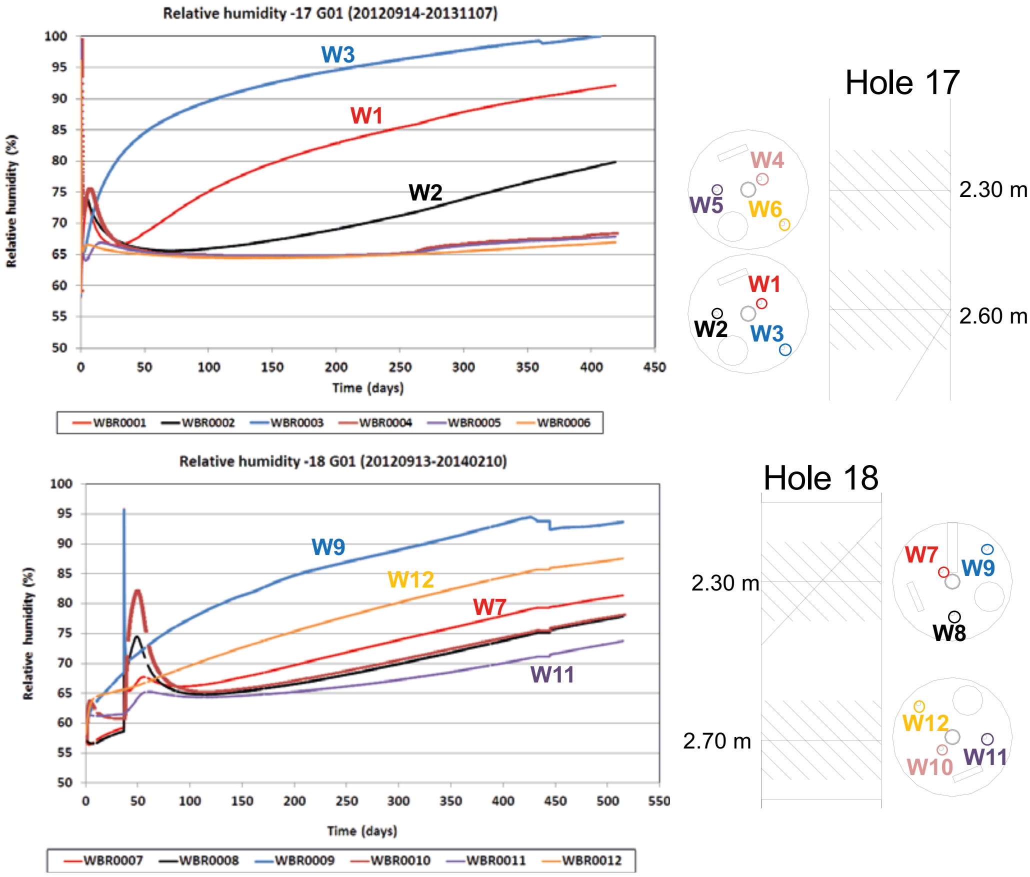


Figure 3-1. *Evolution of RH at sensor positions. Data from Hole 17 (upper graph) showed a clear response from sensors in the wet section (W1–W3), whereas the corresponding response in the dry section (W4–W6) was very slow. Data from Hole 18 (lower graph) indicated less differences between the wet (W7–W9) and dry (W10–W12) sections, although the hydration of the wet section appeared to be slightly more rapid than the dry one. Disturbances in Hole 17 (day 0) and 18 (day 50) were caused by flooding of the central tubes.*

Figure 3-2. *BIPS-image from Hole 17 which shows the fracture at 2.6–3.1 m and the pegmatite vein (left), and photo from the dismantling of the parcel in Hole 17 (right) which shows markings from the same fracture.*

4 Engineered barriers

4.1 General

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

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

During 2013 following experiments and projects within the Engineered Barriers were conducted:

- Prototype Repository.
- Long Term Test of Buffer Material.
- 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

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 finalised 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 will be finalised at the beginning of 2014.

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.

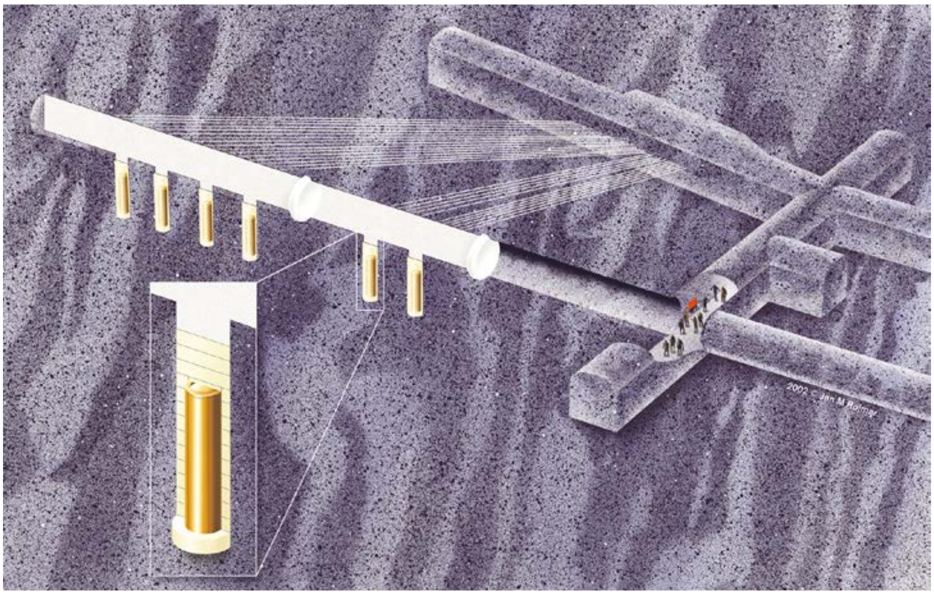


Figure 4-1. *Schematic view of the layout of the Prototype Repository (not to scale).*

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 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.

Measurements in rock, backfill and buffer

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

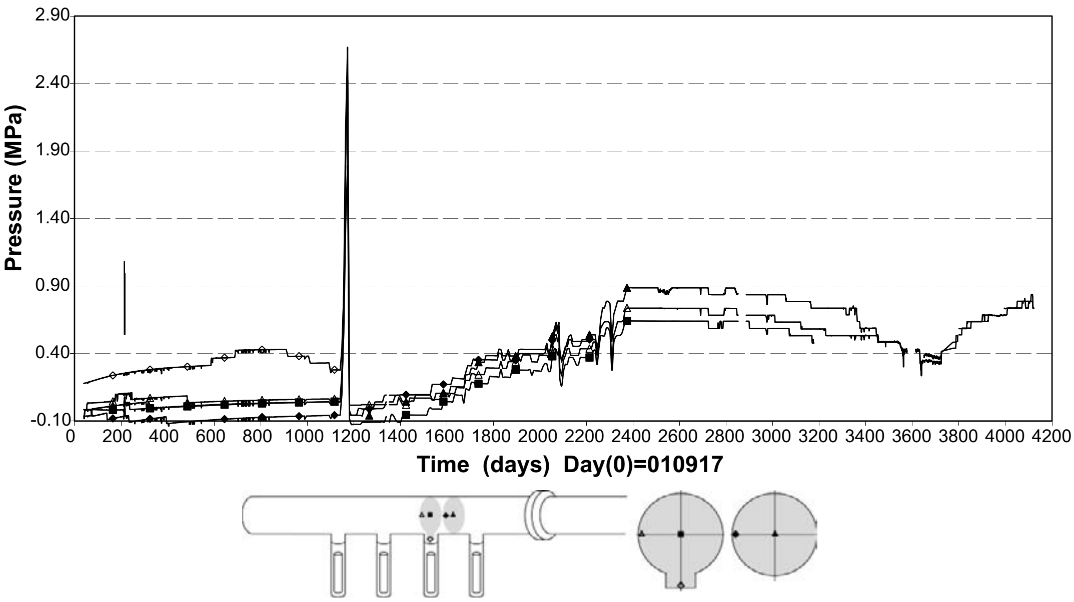


Figure 4-2. *Examples of measured total pressure in the backfill around deposition hole 3 (17th September 2001 to 1st January 2013).*

Furthermore transducers were installed for recording the displacement of the canisters in deposition hole 3 and 6 (Barcena et al. 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 2007). New gas and water samples have been taken and analysed during 2009–2010 (Lydmark 2010).

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

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

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

Corresponding measurements in the buffer in deposition hole 3 are indicating that the buffer is not saturated.

Hydration of the backfill in Section I

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

Opening and retrieval of Section II.

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

- To acquire an image of density and water saturation of buffer and backfilling of the outer section of the trial.
- To find out how the contact between buffer-backfill and backfill-tunnel wall appears after more than 7 years of wetting.
- Measurements made of the rock around the two deposition holes indicate that changes have occurred in the rock mass. After removing the backfill, buffer and canister the rock in and around the deposition holes can be studied to confirm or reject these measurements.
- To determine the position and shape of the canister after the wetting period.
- If possible any damage and changes to the plug should be recorded.
- Biological and chemical activities in the buffer and backfill have been measured during the progress of the trial by sampling of water and gas. Samples will be taken to verify these measurements if possible during progress of the retrieval.
- Tests have been made on samples taken from this trial with the object of studying possible changes in the betontonite.
- Equipment for studying corrosion of copper in the buffer has been installed in one of the holes (hole 5). Measurements from this equipment have been complemented by sampling from the buffer with the object of studying possible corrosion.

A summary report of the opening and retrieval is currently in preparation (Svemar et al. 2013). The work with the retrieval of the outer section has been organised in six sub projects according to Figure 4-3 below.

The first subproject (Removal/Field work) involved the removal of the plug, excavation of the backfill and the buffer in the two deposition holes and determinations of water content and density of the buffer and backfill. The method for opening and retrieval of the outer section has been reported in Johannesson and Hagman (2013). Samples were taken among others from the cores, with the objective of determining density and water content immediately after removing the buffer. Samples were also taken for further analysis in the laboratory. During the excavation no evidence of piping or erosion of the backfill material were observed. Furthermore the contact between the backfill material and the rocks surface of the tunnel seems to be good and the preliminary analyses of the results from the determination of the density and water content of the backfill material is showing that it was fully saturated. 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 (Johannesson 2014). The analyses indicate that the water content was depending on the location of the water baring fractures inside the deposition holes, see Figure 4-4.

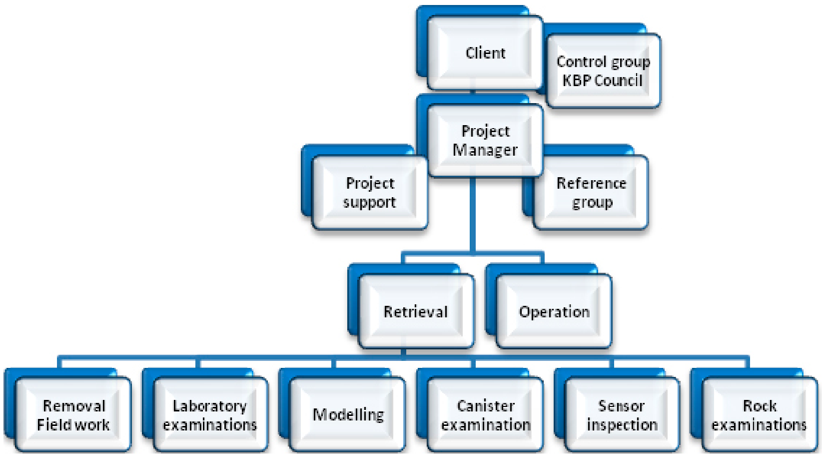


Figure 4-3. Organisation chart for the project.

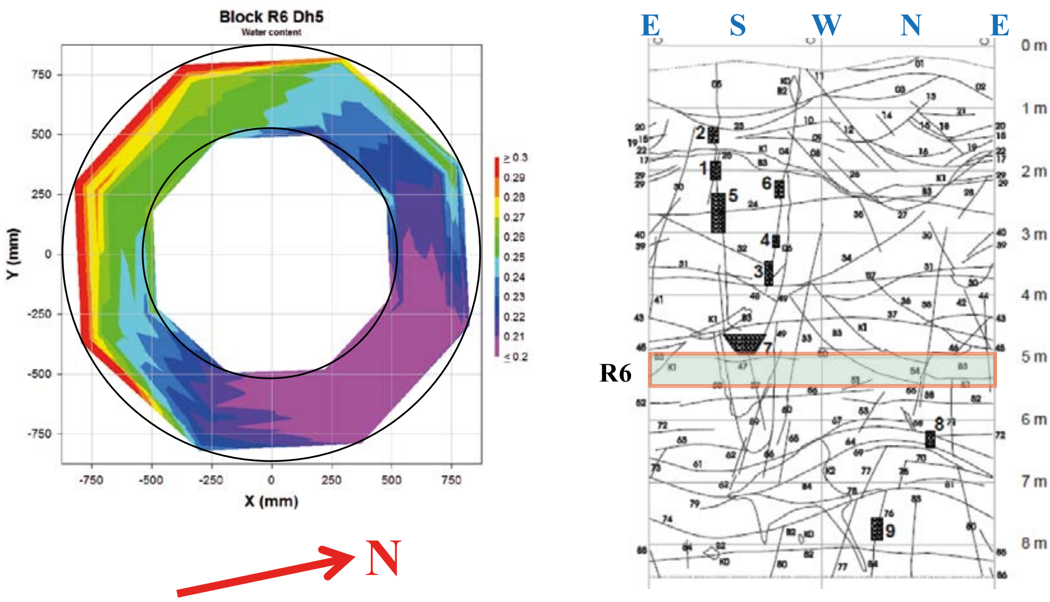


Figure 4-4. Contour plots of the water content of block R6 in deposition hole 5 together with the observed fractures on the wall of the deposition hole.

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

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

Hydro-mechanical tests were performed on samples from one radial profile from the warmest part of each of the buffers as well as on reference samples and included determinations of hydraulic conductivity, swelling pressure, unconfined compression strength, and shear strength (triaxial tests). The measurements on the field-exposed specimens showed very small changes in swelling pressure and hydraulic conductivity compare to the reference specimens. The changes observed were not correlated to the position of the samples in the buffer, and thus, not to the maximum temperature to which the samples had been exposed. An example of data from the determination of the hydraulic conductivity of the buffer is shown in Figure 4-5. The triaxial tests showed that the deviator stress at failure was larger and the strain at failure lower, for the field-exposed specimens than for the reference specimens, indicating a more brittle behaviour of the field-exposed bentonite. The unconfined compression tests showed no large differences in strength between the reference specimens and the field-exposed material. The strain at failure suggested that the field-exposed bentonite was somewhat more brittle than the reference bentonite and the brittle behavior was more pronounced for specimens taken close to the canister. (Olsson et al. 2013)

Chemical-mineralogical analyses were carried out in parallel on four radial profiles from three blocks with variable water content (one block from borehole 5 and two from borehole 6). The analyses included determinations of water-soluble salts, chemical composition, cation exchange capacity, exchangeable cations, and mineralogy. When relevant, both the bulk samples and the Na-converted <0.5 µm fractions of the bentonite were analyzed. Supplementary, specialised analyses, including determinations of the oxidation state of iron and copper (Mössbauer, XANES) and element mapping (SEM-EDX), were performed on selected intervals of some blocks. The same tests/analyses were made on reference samples. The investigation showed that dissolution/precipitation- and cation exchange reactions along with the water saturation under non-isothermal conditions resulted in redistribution of soluble accessory minerals in the bentonite, such as gypsum and calcite. These phases accumulated

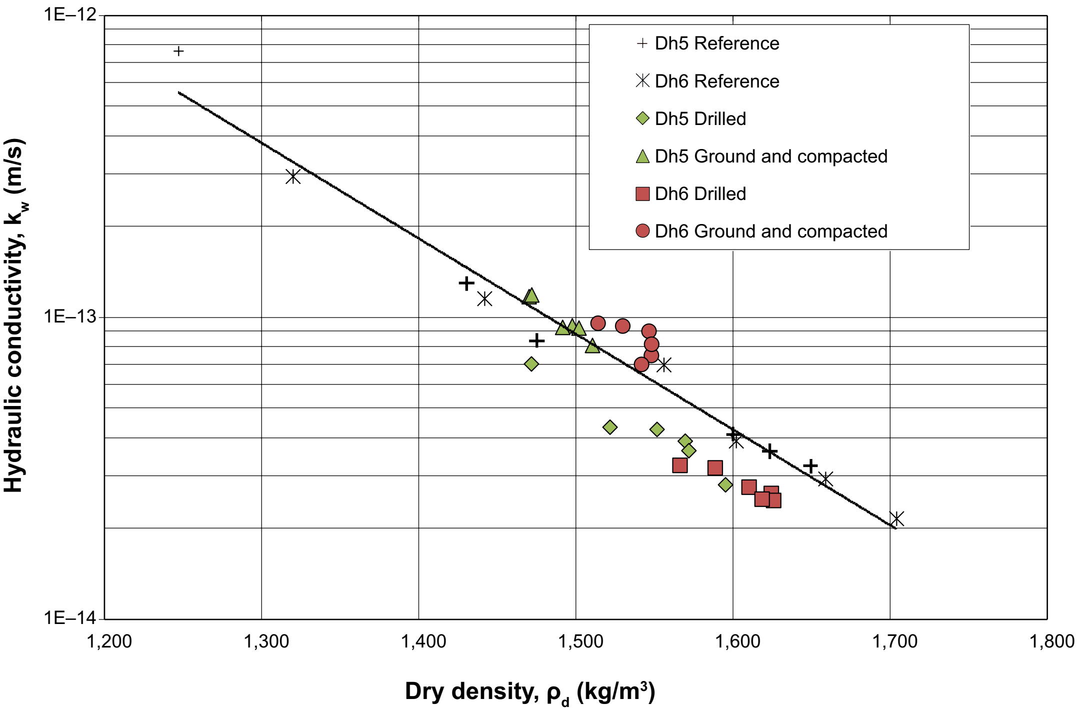


Figure 4-5. *The determined hydraulic conductivity as a function of the dry density. Green and red symbols denote deposition hole 5 and 6, respectively.*

in the warmest parts of the buffers, where also a – so far unidentified – magnesium phase of low solubility precipitated. No structural alteration of the montmorillonite was detected. At the contact with the canister, small amounts of copper had been incorporated in the bentonite due to corrosion of the canister. At the retrieval, the ratio Fe(II)/Fe(III) of bentonite from the inner part of the buffer was higher than in references indicating reduction of iron under field-conditions (Olsson et al. 2013).

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.

The examination of the canisters (subproject four) 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 finalised 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.

61 sensors from the buffer and backfill have been retrieved at the excavation of the backfill and buffer and 32 of them have been validated with good quality with equipment which have been constructed and manufactured within subproject five, see Figure 4-6.

Within the sixth subproject, rock examination, numerical thermo-mechanical modelling of the rock mass surrounding the prototype repository has been performed. The objectives of the modelling 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.

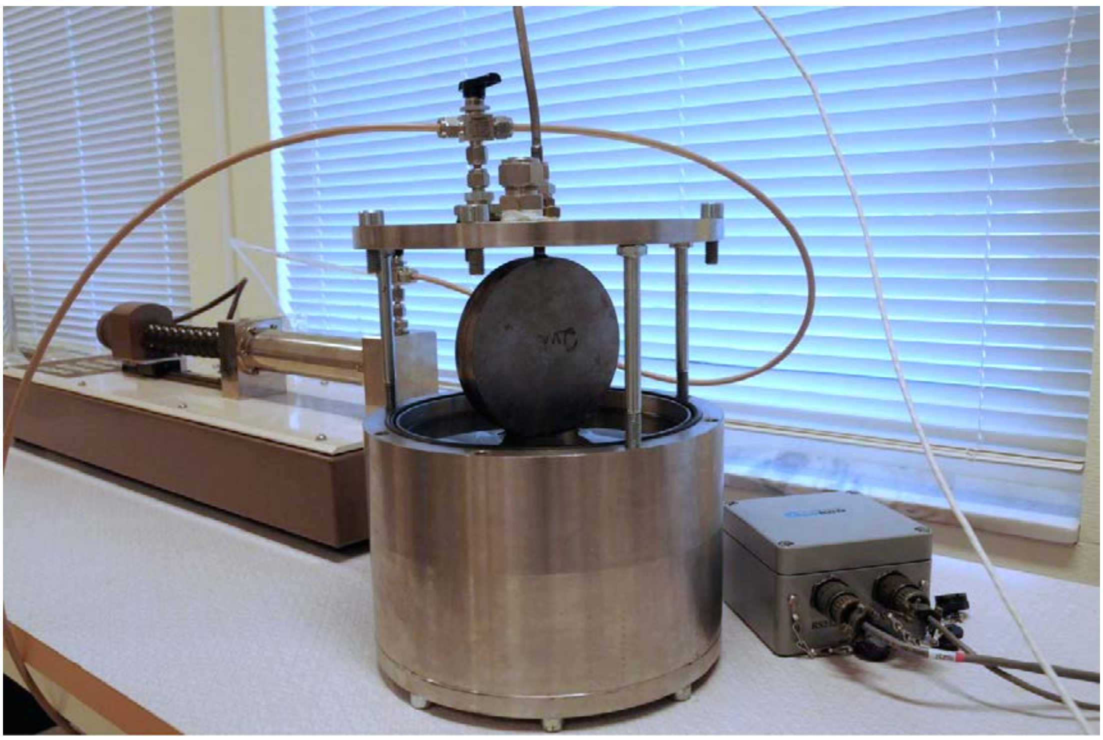


Figure 4-6. *Vessel used for verifying total pressure sensors.*

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 modelling 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 close to 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, see Figure 4-7. 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) and in November 2012 (ABM45).

Figure 4-7. *Excavation of the ABM2 experiment.*

ABM

Three test parcels were installed in 2006. ABM1 was retrieved after about 2½ years operation and parcel ABM2 was retrieved April 2013.

ABM1 and ABM2 were artificially wetted whereas ABM3, which will be in operation for the longest time, only will be artificially wetted if it at some point is found necessary.

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

ABM45

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

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

Results

ABM2 was retrieved in April 2013 after about 6 years of heating at the intended test temperature (130°C). The technique used for retrieval was to drill bore holes to a depth of 3.2 meter (length of test parcel was 3.0 m) in the rock surrounding the parcel. The rock covering the clay had a thickness of about 10 cm. This seam drilling was then completed with two core drilled holes, with diameters of 300 mm, which were used for installation of wire sawing equipment. With this equipment it was possible to saw off the rock column at the bottom. The rock column including the bentonite blocks could then be lifted up on the ground. The rock was highly fractured and not all rock could be removed. The work with division of the rock column and uncovering the bentonite blocks started immediately after retrieval. Samples from the different bentonite materials were sent out to all participating organisations that are going to contribute with analyses of the test materials.

The analysis of the ABM2 experiment will proceed within the Material Science project at Äspö and the results are communicated on the annual ABM meetings, in scientific publications and SKB reports. The next SKB report is estimated to late 2015.

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. Examples of positive effects are:

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

Technical challenges involve excavation of the deposition drifts (up to 300 m long) with strict geometrical constraints, optimised positioning and deposition of the Supercontainers and distance blocks, Figure 4-8 and Figure 4-9, and a controlled and efficient saturation process.

In 2001 SKB published a RD&D programme for the KBS-3H alternative. The RD&D programme (SKB 2001) was divided into four stages: Feasibility study, Basic design (2001–2003), Demonstration of the concept at Äspö HRL and subsequent evaluation (2004–2007). This was followed by Complementary studies of horizontal emplacement (2008–2010) after which a KBS-3H reference design, DAWE (Drainage Artificial Watering and air Evacuation) was selected (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.

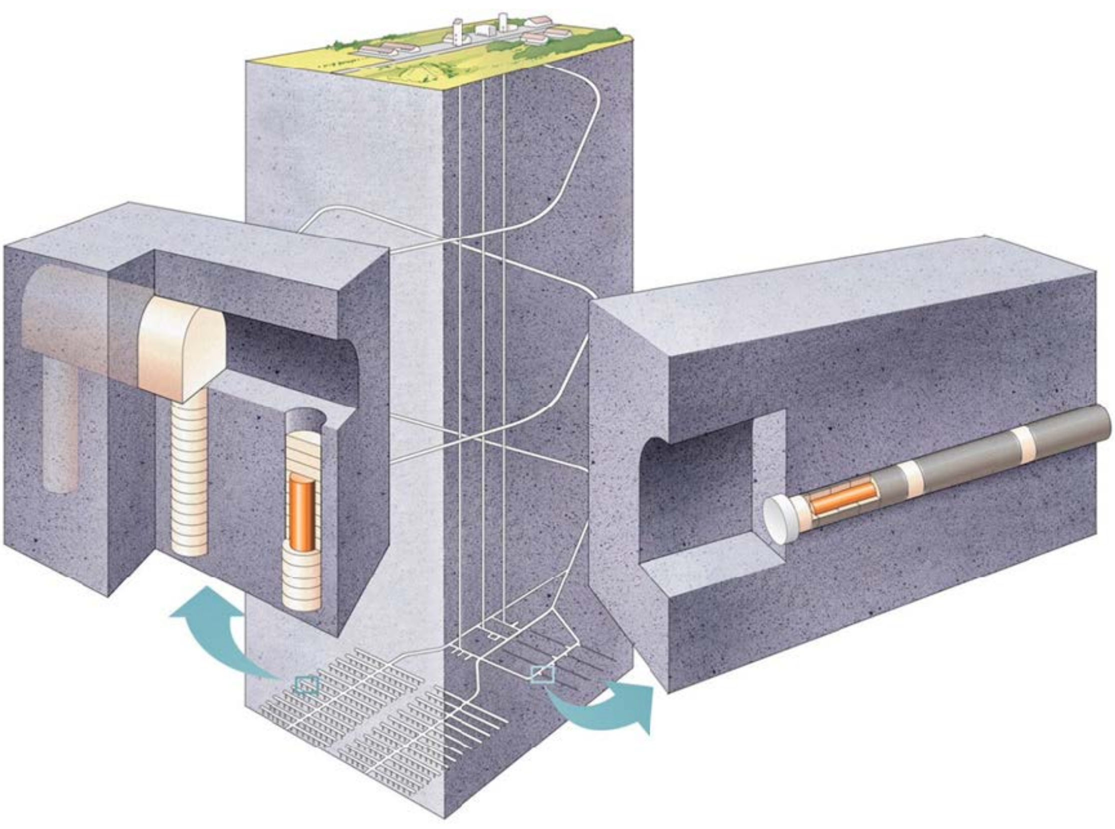


Figure 4-8. *Schematic drawing of the KBS-3V reference design (left) and KBS-3H (right).*

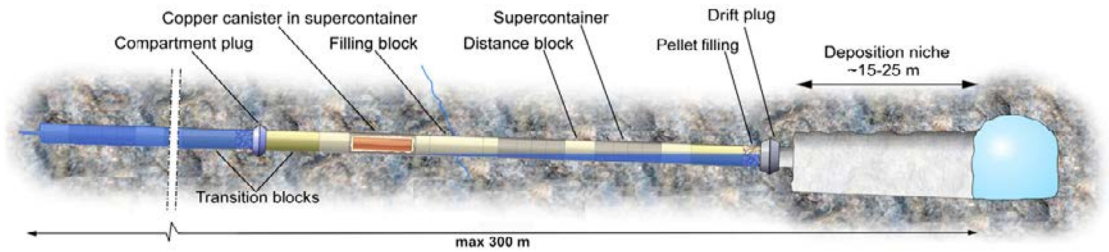


Figure 4-9. KBS-3H reference design DAWE with its main components; the plugs with their transition zones, the Supercontainers, and the distance and filling blocks. The illustration shows an ongoing artificial water filling procedure of the second compartment.

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 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 (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 mainly at the Äspö HRL as part of the Demonstration sub-project, the focus of which is to verify the functionality of equipment, methods and components developed within the KBS-3H project. The sub-project consists of two main activities that were initiated during 2011, the Multi Purpose Test (MPT) at the –220 m level which is also part of the EU-project LucoeX and the excavation and preparation of a new KBS-3H drift at the –410 m level.

The Multi Purpose Test (MPT)

The MPT is basically a down-scaled (spatial and temporal) non-heated installation of the reference design, DAWE, and includes the main KBS-3H components, see Figure 4-10. It is installed at the –220 m level which implies that the hydraulic boundary conditions differ from those foreseen at typical repository depth.

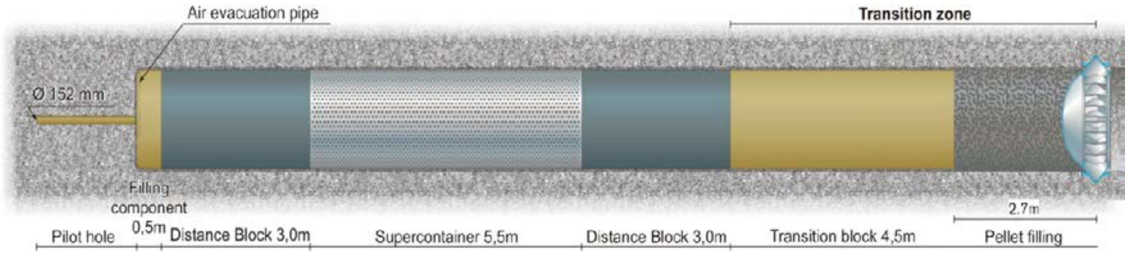


Figure 4-10. *Schematic illustration of the MPT layout. The length of the pellets filling has been increased from 1.3 m to 2.7 m; this is for practical reasons related to cabling and the manual installation. The KBS-3H reference design still has a 1.3 m long pellets section inside the plugs.*

The test itself was installed end 2013 according to the DAWE reference design in a 20 m section at the end 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 different water content.

Excavation and preparation of a KBS-3H drift

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

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

- Demonstration, comparison and verification of performance of pilot borehole drilling techniques over a 300 m length scale, including fulfilment of defined geometrical requirements. This includes:
  - test and verification of deviation measurement equipment in the deviation facility currently being developed at the Äspö HRL,
  - assessment of transferability of results and experiences between sites.
- Reaming of pilot borehole for KBS-3H experimental drift to full-size drift diameter (1.85 m diameter) over a 100 m length scale.
- Application and performance at a repository depth of KBS-3H groundwater control techniques:
  - Prediction of the hydraulic conditions in a drift based on measurements in the pilot borehole.
  - Comparison of relative information value of boreholes of different diameter and associated characterisation methods, 76 mm cored boreholes used as standard by both SKB and Posiva. No customised equipment is available for boreholes of larger diameter.
  - Post-grouting using the Mega-Packer device to verify that the technique also functions at repository level.

Results

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

MPT preparations

MPT preparations were finalised during 2013, this included several activities:

- The deposition machines soft- and hardware updates were finalised and the machine now has considerably improved control and balance. It has been extensively tested with concrete dummy components and with an actual bentonite distance block during a shorter test period. The installation itself later meant deposition work with a Supercontainer as well as distance- and transition blocks made of bentonite.
- A buffer mould was previously manufactured (2012) and all blocks for the MPT were compacted and machined, Figure 4-11. The manufacturing series was rather limited and a more extensive test-manufacturing would have been required to fine-tune all compaction parameters. Anyhow, most of the blocks fulfilled the requirements with respect to dimensions, density, water- and montmorillonite content and the deviations were very small so it is deemed that they will not limit the MPT evaluation.
- The MPT components have been assembled with sensors inside, Figure 4-12.
- Drift preparations were finalised, and all rock sensors installed, Figure 4-13.

Figure 4-11. *To the left a recently compacted distance block and to the right machining to the required dimensions.*

Figure 4-12. *To the left ongoing assembly of a transition block with sensor sections and to the right a view inside the Supercontainer before the canister was placed, four pressure sensors are visible at the bottom.*

Figure 4-13. To the left ongoing connection of the sensor pipes, five total pressure sensors are clearly visible at the drift end. To the right the MPT test section ready for installation with all cables and pipes outside the drift perimeter.

MPT installation

The MPT was installed end 2013 according to the steps and schedule in Figure 4-14. The installation was done with two shifts to limit the time the buffer was exposed to the humid air. The installation took 24 days which compares to a repository scenario (with more components) of approximately 10 days, the difference mainly lying in the time needed for the handling of sensors and manual installation of the plug.

The installation was successful and has demonstrated the feasibility of the KBS-3H DAWE reference design; all components were manufactured and installed as planned. Figure 4-15 illustrates how the pre-assembled components were moved down to the –220 m area and Figure 4-16 illustrates the deposition work.

When all components were in place a compartment plug was welded to the previously installed fastening ring, Figure 4-17, cables were taken through and connected to the data aquisition system. Pellets were filled through the plug lid and contact grouting was done before the DAWE procedure was carried out, Figure 4-17.

Monitoring is currently ongoing and the site acceptance test reporting (SAT-report) is being finalised. Data will be available for reporting during 2014.

Activity	November																	December						
	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7
Filling components pilot holes	■																							
Inner distance block and cables	■																							
Supercontiner and cables		■	■	■																				
Outer distance block and cables					■																			
Transition block						■																		
Cables and sensors on last block							■	■																
Plug and cables								■	■	■	■	■	■	■										
Pellets filling															■									
Connecting the DAS																■	■	■	■	■	■	■		
Contact grouting plug																							■	
DAWE																								■

Figure 4-14. Activites and schedule of the MPT installation.

__Figure 4-15.__ To the left, the assembled distance block is moved out of the assembly hall. To the right it has been placed in the transport tube and is moved using the heavy load vehicle MODE.

__Figure 4-16.__ To the left the deposition machine is about to pick up a component in the transport tube and to the right a picture of a distance block in place in the drift with all its sensors connected.

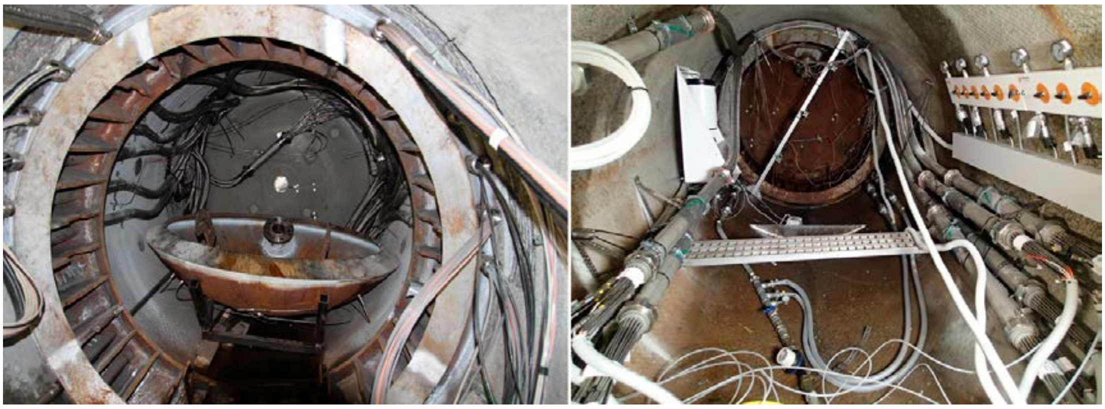


__Figure 4-17.__ To the left installation of the compartment plug and to the right the DAWE procedure is ongoing as water is pumped in and air evacuated.

Excavation and preparation of a KBS-3H drift

A new KBS-3H niche has previously been developed as part of the Äspö expansion at the –410 m level. Drilling operations has been ongoing in the DETUM-niche during 2013, also at the –410 m level. KBS-3H has been involved in the steering of these core drills and results from the steering is currently being evaluated and a new steered 100 m, 76 mm, drilling operation is planned in the KBS-3H niche during 2014. If the strict KBS-3H requirements are fulfilled it will be followed by a 300 m steered core drilling, possibly also at Äspö.

The project has been involved in the development of a deviation measurement facility at the surface of Äspö HRL; initial tests have been run within the DETUM project and are currently being evaluated. The objective is to be able to select a deviation measurement equipments for the planned KBS-3H drilling operations.

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.

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

The experiment has been in continuous operation since February 2005. The first two years (Stage 1, up to day 843) focused on the artificial hydration of the bentonite buffer. This was followed by a year-long programme of hydraulic and gas injection testing in filter FL903 (Stage 2, day 843 to 1,110). A further year of artificial hydration occurred (Stage 3, day 1,110 to 1,385), followed by a more complex programme of gas injection testing in filter FL903 (Stage 4, day 1,430–2,064). In late 2010 attention moved from the lower array filter (FL903) to the upper array (FU910). Stage 5 started on day 2,073 and was completed on day 2,725. Focus then returned to the lower array (FL903) in late 2012 and involved a gas injection test throughout 2013.

Objectives

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

- Perform and interpret a series of large-scale gas injection test based on the KBS-3 repository design concept.
- Examine issues relating to up-scaling and its effect on gas movement and buffer performance.
- Provide additional information on the processes governing gas migration.
- Provide high-quality test data to test/validate modelling approaches.

Experimental concept

Lasgit is a full-scale demonstration project conducted in the assembly hall area in Äspö HRL at a depth of –420 m (Figure 4-18). A deposition hole, 8.5 m deep and 1.8 m in diameter, was drilled into the gallery floor. A full-scale KBS-3 canister (without heater) has been emplaced in the hole. Thirteen circular filters of varying dimensions are located on the surface of the canister to provide point sources for the injection of gas to mimic canister defects. Pre-compacted bentonite blocks with high initial water saturation have been installed in the deposition hole. The hole has been capped by a conical concrete plug retained by a reinforced steel lid capable of withstanding over 5,000 tonnes of force.

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

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

The *hydration phase* began on the 1st February 2005 with the closure of the deposition hole. The aim of this phase of the experiment is to fully saturate and equilibrate the buffer with natural groundwater and injected water. The saturation and equilibration of the bentonite is monitored by measuring pore pressure, total pressure and suction at both the buffer/rock interface and key locations within individual clay blocks. The hydration phase provides an additional set of data for (T)HM modelling of water uptake in a bentonite buffer.

Results

During 2013 (day 2,890–3,255) the test programme of Lasgit concentrated on the fourth gas injection stage. This test focused on a lower canister filter (FL903), which had been used for the first two gas injection tests. Three years of artificial hydration of filter FL903 had occurred since gas test 2, meaning that the buffer would be in greater hydraulic equilibrium than in the previous tests.

Gas injection in FL903 was initiated on day 2,988 (8th April, 2013) using helium as the injection gas. The test plan was to follow similar gas pressurisation steps as gas test 2 in filter FL903 with four pressure ramps and three periods of constant pressure. Stage one saw gas pressure in filter FL903 raised from an initial 1,870 kPa to 2,870 kPa over a 25 day period. Gas pressure was then held constant for a period of 27 days. Stage 2 began on day 3,038 and saw gas pressure increased from 2,870 kPa to 3,865 kPa over 24 days, followed by a period of constant pressure for 27 days.

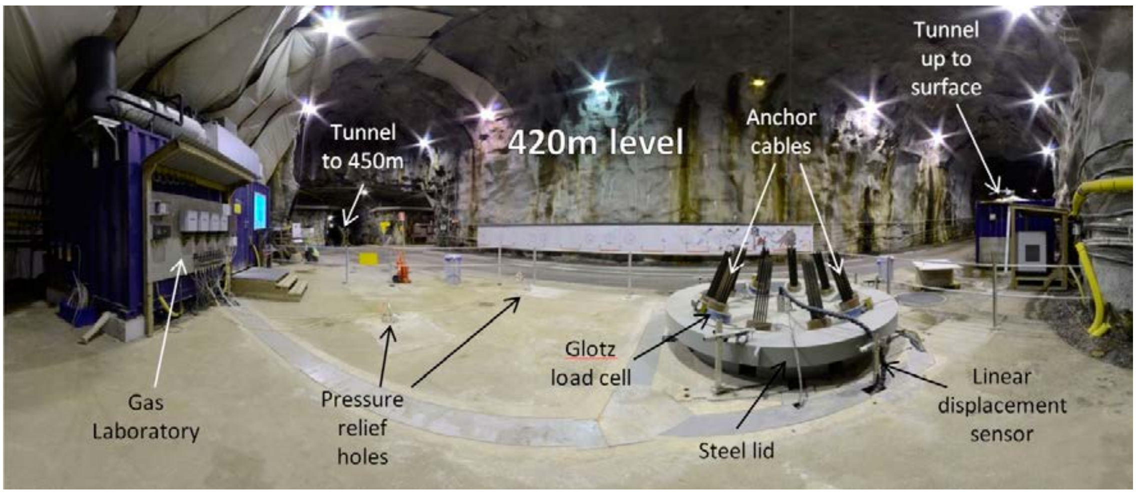


Figure 4-18. *The Large scale gas injection test at the –420 m level in Äspö HRL.*

Stage 3 began on day 3,087 and saw gas pressure increase from 3,865 kPa to 4,860 kPa over a period of 24 days. The final gas entry stage was initiated on day 3,163 (30th September), with gas pressure raised from 4,860 kPa to a pressure sufficient to initiate gas break-through. Following gas break-through, gas injection rate was varied in order to study the influence of the rate of pressurisation on gas pressure asymptote.

As can be seen in Figure 4-19a, gas breakthrough occurred on day 3,204.8 at a pressure of 6,195 kPa, which is similar to the stress recorded locally. In the two previous gas injection tests in filter FL903 the breakthrough pressure was observed at 5,660 and 5,870 kPa. Therefore gas breakthrough pressure continues to increase. This is to be expected as the stress within Lasgit continues to increase, as seen in Figure 4-20.

At the onset of gas breakthrough a hydromechanical response is seen in many of the sensors within Lasgit, as shown in Figure 4-19b. This included pore water pressure within the bentonite and at the rockwall, as well as stress sensors within the bentonite and at the rock wall. Stress and pore water pressure variations only occurred locally to filter FL903 and were seen in 14 sensors. The form of the hydromechanical response in many of these sensors was similar to that observed in gas test 1 and 2; this suggests that the physics driving gas migration has not altered between tests.

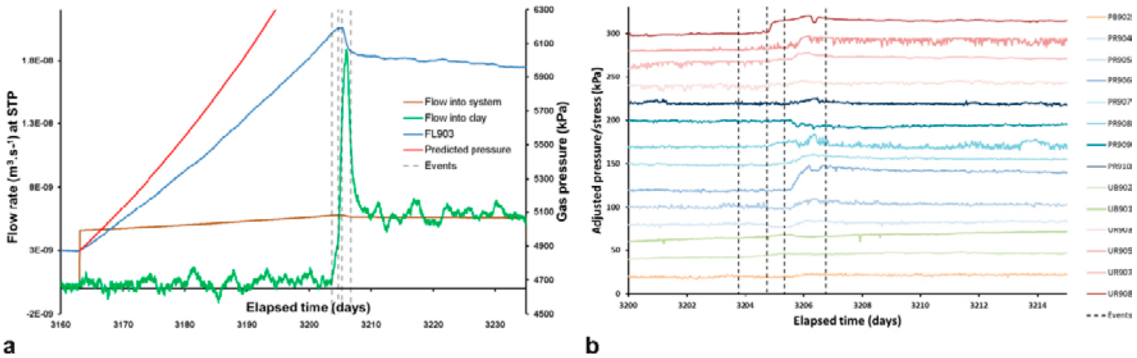


Figure 4-19. *Results for gas test four conducted in lower canister filter FL903. a) Pressure response and flow of filter FL903, showing gas breakthrough at day 3,204. Similar to previous tests a sharp drop in pressure is seen at breakthrough. b) Pore water pressure and stress readings in local sensors showing a clear hydromechanical response at the time of gas breakthrough.*

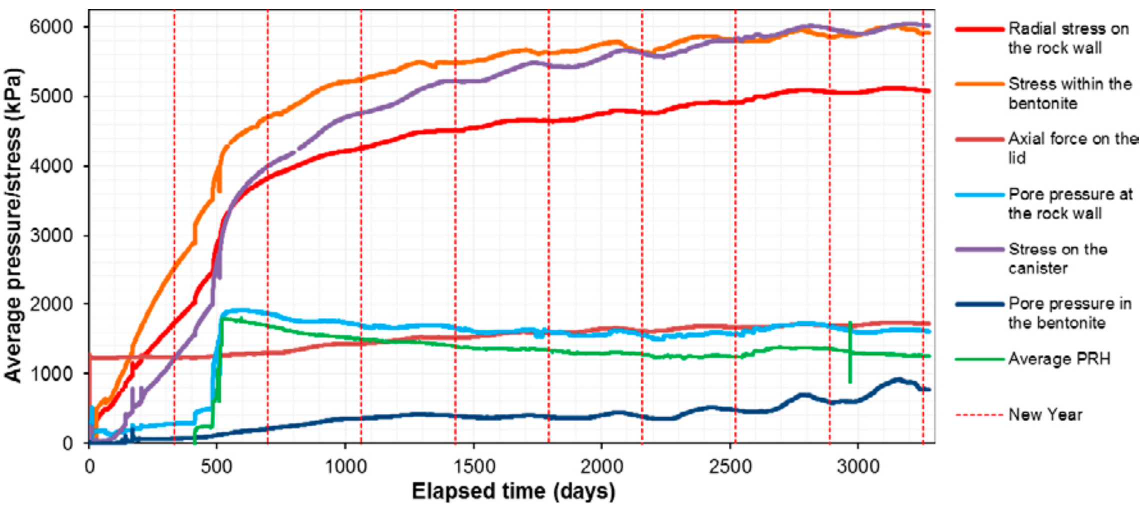


Figure 4-20. *Average pore water pressure and stress readings during the complete 9-year history of Lasgit. As can be seen pore water pressure readings at the deposition hole wall and in two pressure relief holes (PRH) was been decaying since day 500 due to the draw-down of the Äspö HRL due to pumping 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.*

One feature clearly seen in gas tests 2 and 3 was the migration of gas to other locations within the deposition hole as the gas reached sensor or filter locations. In gas test 3 a complex history was observed with gas reaching four other filter or sensor locations. Gas was not seen to reach any other filter or sensor location during gas test 4. This may suggest that as the buffer has matured the interface between the canister and the buffer is a less favourable influence. However, it may mean that the gas flow paths have not intercepted any other location due to their localised nature.

Gas injection rate was altered after gas breakthrough in order to observe the interdependence between gas pressure and injection flow rate. The initial gas injection rate following gas breakthrough was 350 $\mu l.hr^{-1}$. Following 31 days of gas injection post-breakthrough, the injection rate was changed to 175 $\mu l.hr^{-1}$ for 22 days and 88 $\mu l.hr^{-1}$ for 28 days. The lowering of gas injection rate resulted in a lowering of the asymptote of gas pressure.

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 4-21), 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 4-21. *Model canister being lowered into support cage containing bentonite pellets in annulus.*

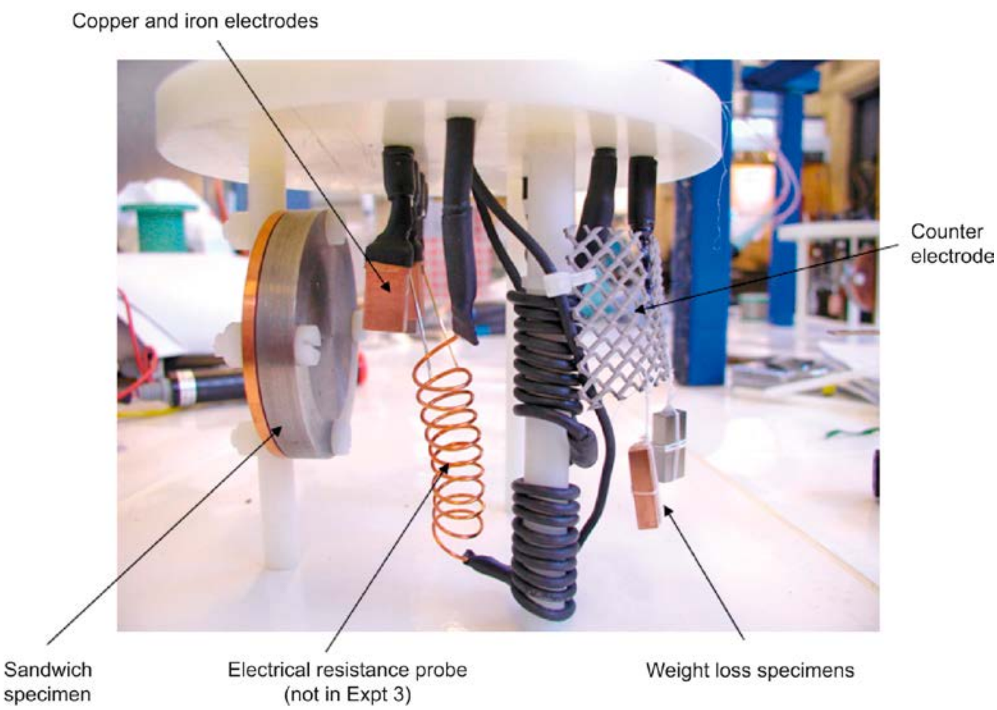
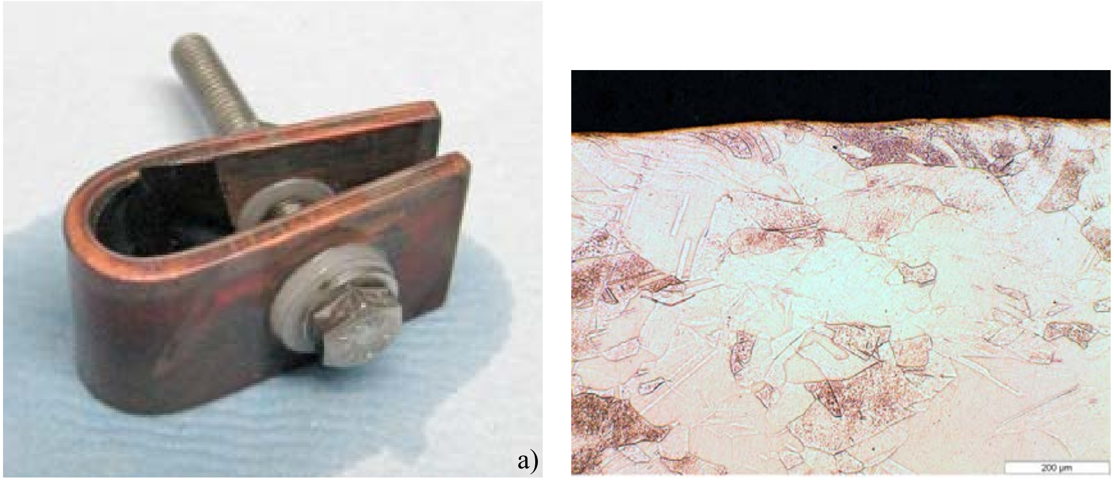


Figure 4-22. *Test electrodes inside support cage around model canister experiments.*

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 (Figure 4-25). 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.

Figure 4-23. *Stefan Grandin Svärdh and Jonas Hallberg pulling out the steel cage from the KA3386A04 bore hole.*

Figure 4-24. *Equipment for sampling of the steel cage surface.*



a) b)

Figure 4-25. *a) U-bend specimen after retrieval of canister 3. b) Optical micrograph of the outside cross-section of a U-bend specimen.*

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

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).

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.

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 has been under operation for more than 20 years, 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 has just been finalised. In this study it was 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 concrete 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 will be deposited at different locations in the Äspö HRL.

The concrete specimens, Figure 4-26, which were prepared and deposited during 2010 and 2011 were cast into cylinders with a diameter of 300 mm and a length of one meter in the Bentonite Laboratory. The cylinders were then transported to the experimental site and deposited in a Ø 350 mm hole in the tunnel floor. 3 cylinders were deposited on top of each other in each hole. After deposition, the space between the cylinders and the surrounding bedrock was filled with sand or grout and finally the deposition hole was sealed to avoid contact between the specimens and oxygen containing surface water. A total of 12 concrete cylinders in four packages were deposited in two holes in each of NASA0507A and NASA2861A respectively.

The bentonite specimens will be prepared and installed during 2014. In each bentonite block (Ø 270 mm and height 100 mm) 4 different specimens will be placed. The specimens will be manufactured from cement grout- both standard OPC and low-pH-grout – or the same type of bentonite as the block itself and contain either a metallic powder or a metal salt. Altogether a total of 150 bentonite blocks will be deposited in 5 packages in TAS06 during 2014.

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, Figure 4-27.

***Figure 4-26.** Installation of the first concrete cylinder in NASA 2861A.*

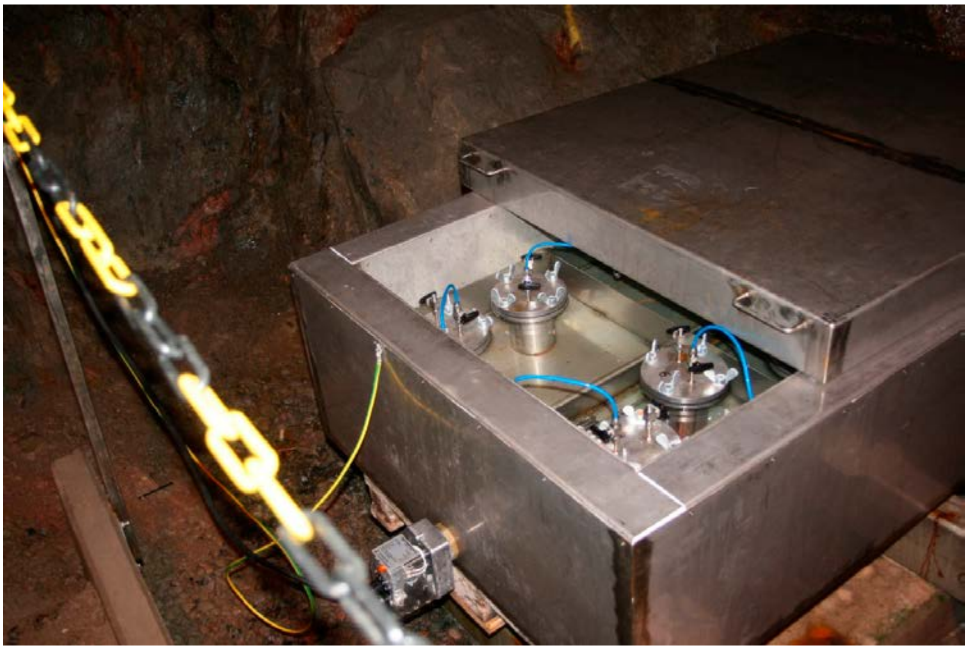


***Figure 4-27.** The steel cylinders stored at about 50°C in water in NASA2861A.*

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, i.e. around the year 2015. Experiments will then be retrieved at regular intervals and only a few will be left for the entire 30 year period.

Results

During 2010 and 2011 a 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 2013 the mud and rock debris were removed from the experimental tunnel TAS06, Figure 4-28, after which it was mapped and positions for the deposition holes identified, Figure 4-29. A total of 7 deposition holes (diameter of 300 mm) were drilled and the cores were mapped. During this work it was realised that the holes were drier than expected. For that reason it was decided to use an artificial system for saturation of the bentonite blocks comprising a system of titanium tubes connected to a pressurised tank filled with Äspö ground water.

Figure 4-28. *TAS06 after removal of rock debris and mud.*

Figure 4-29. *Mapping of TAS06 and identification of suitable positions for the deposition holes.*

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 therm properties of this material.

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. SKB together with a number of international organisations has developed an agreed procedure for measuring of pH values in low-pH concrete. This project was reported in a SKB report R-12-02 (Alonso et al. 2012).

Experimental concept

During 2009 SKB performed field test with low-pH grout for rock bolts at Äspö HRL. In total, 20 bolts were installed. These bolts are monitored and preliminary were 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 4-30 and Figure 4-31. 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 4-32. 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 R-11-08 (Bodén and Pettersson 2011).

A monolite has been casted using the same low-pH concrete in the Domplu-test (system design of dome plug for deposition tunnels) in the same area as the plug, Figure 4-33. 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.

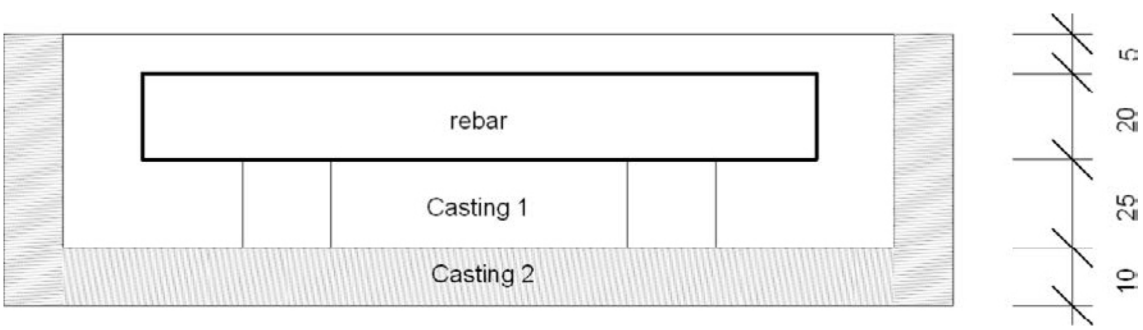


Figure 4-30. *Specimen's dimentions.*

Figure 4-31. *Mould and steel bars on support before casting.*

Figure 4-32. *Container in Äspö HRL with corrosion tests samples.*

***Figure 4-33.** Monolite in low-pH concrete.*

Results

During 2013, three rock bolts, two horizontally and one vertically emplaced, have been over-cored and investigated, Figure 4-34 and 4-35. Over-coring the vertically emplaced bolts showed to be extremely demanding and time consuming. Therefore it was decided to settle with over-coring only one vertical bolt. 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 will be published during 2014.

Concrete cores have been taken from the monolite, casted with the same material as Domplu, after 28 days, 90 days and 120 days hardening in the Äspö HRL, Figure 4-36 and 4-37. These cores have been investigated with regard to their strength. Even the modulus of elasticity has been determined in some cases. The results will be available during 2014. The testing programme will continue with more investigations after 180 days, and one year of exposure within 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 jugde to be of intresst.

Figure 4-34. *Overcoring of a horizontally emplaced rock bolt.*

Figure 4-35. *Overcoring of a vertically emplaced rock bolt.*

Figure 4-36. Concrete cores are taking out from the monolite.

Figure 4-37. Concrete cores are taking out of the monolite.

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) and NDA (England). 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 CaCl2 in Ca-montmorillonite (ClayTechnology).
2. Gypsum dissolution and diffusion in Na- and Ca-montmorillonite (ClayTechnology).
3. Ca/Na-exchange in montmorillonite (ClayTechnology).
4. Core infiltration test on material form parcel A2 in the LOT-experiment (UniBern).

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

Results

Two Task Force meetings have been held during 2013; one in London, England on May 21–23 and one in Bern, Switzerland on November 5–7. 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.

Task 8: hydraulic interaction rock/bentonite

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

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

The task concerns modelling of an Äspö test in a project called Brie (Buffer-rock interaction experiment), which was installed in 2012. This task is divided into several substasks and the modelling started 2010 and has continued during 2013. The project is described in more detail in Chapter 3. Six modelling teams are working with this task and presented the status of the work.

Homogenisation

This is a task related to erosion and loss of buffer and backfill and subsequent homogenisation afterwards but can also refer to homogenisation in general. The general understanding of bentonite is that it has excellent swelling properties but the homogenisation is not complete due to friction, hysteresis effects and anisotropic stress distributions. The task is proposed to involve two parts. In the first part a number of laboratory swelling tests that have been made are modelled and used for checking/calibrating the mechanical model. In the second part one laboratory scale test that simulates bentonite lost in a deposition hole has been started and could be preceded by predictive modelling.

During 2012 some new tests in larger scales for part 1 have been performed and the results distributed. These results were used by the Team of SKB 2 and an updated material model established. Figure 4-38 shows example of results with the updated model and comparison with measurements.

During 2013 additional tests have been started and the results shown at the meetings.

The laboratory scale test for part 2 of this task started in December 2012. This gave opportunity for a blind prediction of the test, which was delivered by SKB team 2. Figure 4-39 shows the scale test during assembly and some results of total pressure measurements. Predicted pressure values at the end of the tests are also shown. The actual swelling pressures are more equal than the predicted ones mainly due to incomplete convergence of the simulation. The test will be interrupted and dissected 2014.

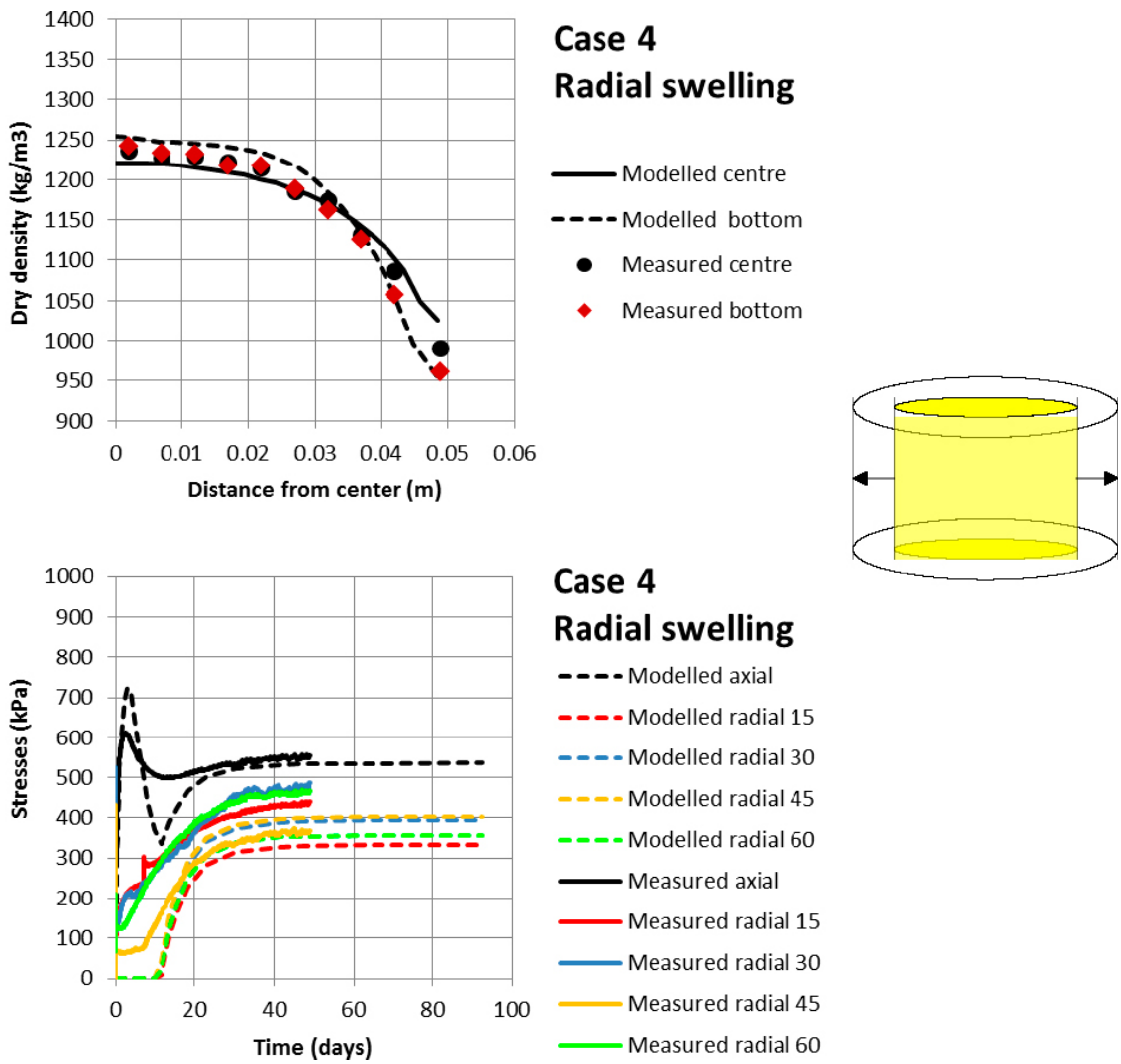


Figure 4-38. *Example of results from a homogenisation task (43% radial swelling). Upper: Void ratio distribution as function of the radial distance from the centre. Modelled with Abaqus and measured after termination (lines with symbols). Lower: Measured and modelled radial and axial stresses. Measured: solid lines; Modelled: dashed lines.*

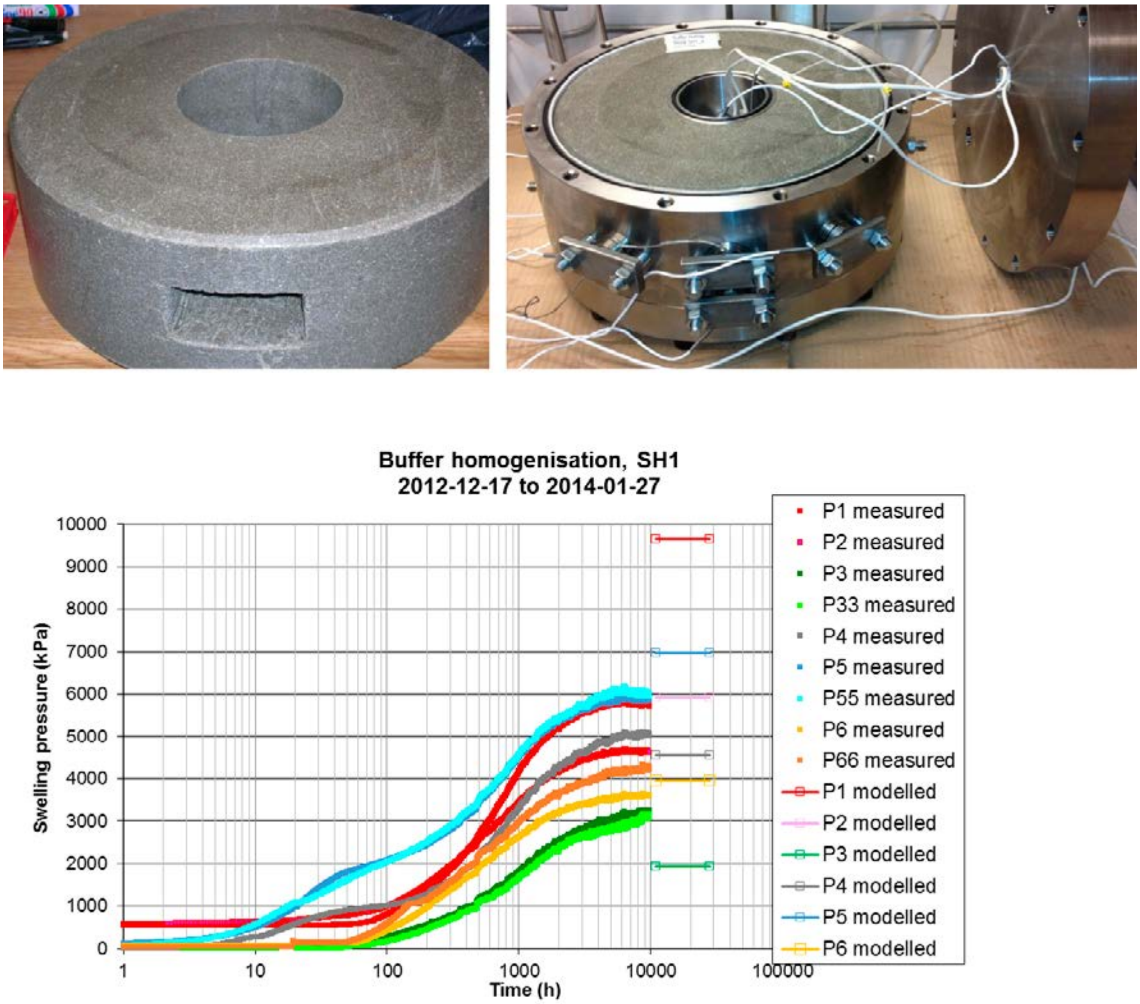


Figure 4-39. *Upper: Assembly of the scale test for homogenisation modelling. The left picture shows the bentonite ring with the rectangular cavity. Lower: Measured swelling pressure at different parts of the test. The predicted final pressures are also shown. The green lines are the swelling pressure at the centre of the cavity.*

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

Eight modelling teams are working with this task or have announced that they will join. Most of them have finished step 1 and are working with the following steps. SKB team 1 has given the following status report (see also Malmberg and Kristensson 2014):

The evolution in the Prototype Repository, and in particular, the thermo-hydraulic evolution in the buffer in deposition hole 6 (DH6), has been modeled using the FEM program Code_Bright. To represent the hydraulic transport properties of the rock without including a complex fracture network, the host rock was represented by a set of volumes equipped with different conductivities calibrated by comparing simulated and measured inflows to tunnel and DHs.

To accurately predict the evolution in DH6, the influence from the other DHs, as well as the response in the rock due to the presence of both the heater and the unsaturated clay should be taken into account. Theoretically, this could be achieved with a coupled TH model of the entire experiment; however, to include fracture flow in the rock near the DHs and to resolve the bentonite buffer well enough, such a model would lead to exceedingly long computation times and numerical instability. To avoid this, the modelling was done in three steps using two types of geometries on different scales: (i) large-scale three-dimensional models of the entire experiment with a large volume of host rock, and (ii) a local-scale three-dimensional model of one DH, with corresponding tunnel backfill and a small part of the host rock. The following models were utilised in the three-step solution strategy:

1. A large-scale hydraulic model prior to installation of the experiment, with an empty tunnel and DHs, to calibrate the rock material with respect to measured inflows.
2. Large-scale uncoupled thermal and hydraulic models after installation of the experiment to determine boundary conditions for the local model.
3. A set of local-scale, coupled thermo-hydraulic models for studying the wetting process in the buffer from installation to excavation.

Large-scale models

In the purely hydraulic model in step 1 the host rock was represented by a set of volumes with different hydraulic conductivities; calibrated by comparing simulated and measured inflows to the tunnel and DHs. The accuracy of the model was tested by comparing measured and simulated water pressure.

In step 2 the calibrated conductivities were then used when simulating the hydraulic evolution in the experiment during the operational phase. The results from this model and a thermal model on the same scale were used to determine the boundary conditions applied on the local-scale model in step 3. This strategy enabled a detailed simulation of DH6 only, while still accounting for global effects through the applied boundary conditions.

Local-scale models

The DHs were extensively characterised before buffer installation. The *total* inflow was measured and local inflows, from identified water bearing features at the DH wall, were measured using a "*plastic bag*" and a "*diaper*" technique. These two local-inflow measurements were used to design the representation of the rock close to the DHs.

A 1 m thick material embedding the DH was equipped with "*DH Rock*" material. In this layer, five 0.1 m thick partial (45°) horizontal discs at different heights were inserted, to represent the identified local-inflow zones. The partial discs were assigned materials identified as "*Local Zone* 1–5". To the right in Figure 4-40 the position of the inflow zones are indicated in a schematic way. The rock materials close to the DH were calibrated in two different ways:

Diffuse-flow model: Local-inflow zones were calibrated as to give the "plastic bag" inflows. DH Rock was calibrated as to obtain the correct measured total inflow.

Local-flow model: DH Rock was calibrated from evaluating the "diaper" measurements. Local-inflow zones were calibrated so as to obtain the total inflow, with the restriction that their relative inflow remained as measured by the "plastic bag" technique.

Final state: One important result of the models is the final state of the buffer in terms of the degree of saturation. Contour graphs of the degree of saturation in the buffer from the two models can be seen in Figure 4-40. The figures show both a vertical cut through the entire DH, as well as horizontal cuts at four different depths. The contour graphs shows the state of the buffer at the time when the dismantling excavation of the buffer in DH6 was completed.

Several important features can be observed. If the plastic-bag measurements are most accurate (as assumed in the Diffuse-flow model) the inflow mainly comes from the DH Rock volume, i.e. the inflow is of diffuse character. The results indicate that the buffer should have been almost fully saturated at excavation of the experiment; the only unsaturated part is found on top of the heater.

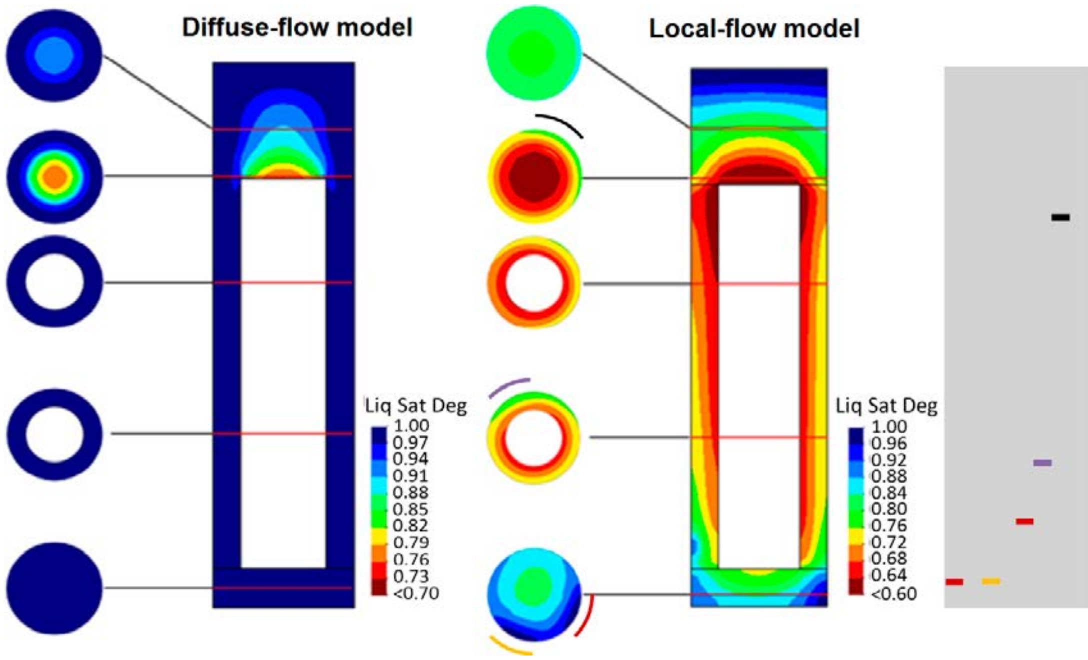


Figure 4-40. *Contour plots showing the liquid saturation at the time when the buffer was excavated in the experiment. In the right-most panel a schematic drawing, showing the position of the local-flow zones on the deposition-hole wall is included. Where appropriate, the orientation of these zones is also shown around the horizontal cuts in the figure.*

Furthermore, the degree of saturation should be essentially axisymmetric; hence no effect can be seen from the local inflow zones at this point.

On the other hand, if the diaper measurements are most accurate (as assumed in the Local-flow model) the excavated buffer should be relatively dry, with full saturation reached only just in front of the local inflow zones, as well as in the top buffer cylinder. At the latter position, the water has entered the DH via the tunnel backfill instead of through any of the local inflows zones. One important result in the local-flow models is that the wetting is far from axisymmetric.

As a conclusion, when comparing the model results with excavation data the findings above indicates that in order to make a precise prediction of the final state of the experiment, when only calibrating the model against measurements, more detailed and accurate characterisation of the water flow or transport properties of the rock close to the DH would have been needed.

Geochemistry

The basic part of the work concerns modelling of a set of four 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.

Two meetings were held during 2013, one in London and one in Bern, in which modelling results, laborartory results and conceptual considerations were presented.

In the London meeting David Holton, AMEC, showed results from modelling of Benchmark 1. Martin Birgersson, Clay Technology, discussed old experiments from the LOT tests series as potential new Benchmarks. Radek Cervinka, NRI, presented experimental results from diffusion of selected anions in compacted Rokle bentonite, which were proposed as a new benchmark. A cement-bentonite interaction experiment in 4D using a new core infiltration technique combined with X-ray tomography was presented by Andreas Jenni, Uni Bern. Magnus Hedström, Clay Technology, presented molekular dynamics simulations concerning Donnan equilibrium in a montmorillonite with 2-hydrate layers. Andrés Idiart, Amphos 21, presented the latest development and recent progress in the coupling of the COMSOL- Crunch Flow codes. Martin Birgersson, Clay Technology, discussed the bentonite system in terms of osmosis vs. capillarity. Ola Karnland, Clay Technology, presented results from ongoing laboratory experiments concerning the effect of steam on bentonite swelling capacity.

In the Bern meeting, Mingliang Xie, The University of British Columbia, showed modelling results concerning all four Benchmarks from reactive transport simulations by use of the MIN3P-THCm code. Andreas Jenni, Uni Bern, showed results from experiments and reactive transport modelling in bentonite. Florian Dolder, Uni Bern, showed experimental results from high-pH reactions in MX-80 bentonite. Radek Cervinka, NRI, showed new experimental and modelling results concerning porewater chemistry of compacted bentonite. Andres Idiart showed the state of coupling between Comsol and Crunchflow codes. Martin Birgersson, Clay Technology, discussed the concept of interlayer water chemistry. Lukas Keller, EMPA, showed results from a microstructural study of MX-80 bentonite at different densities revealed by Cryo-Focused-Ion-Beam nanotomography. Magnus Hedström, Clay Technology, presented the final results from molecular dynamics simulation of Donnan equilibrium in a montmorillonite with 2-hydrate layers.

New and especially interesting findings were the experimental results and evaluated "anion porosity" in the modelling presented by Radec Cervinka, which showed a significant difference between chloride and selenate. Further, the molecular dynamics simulation by Magnus Hedström showed that chloride enters the interlayer space also in a 2-hydrate montmorillonite.

An article with the title "Seeming Steady-State Uphill Diffusion of $^{22}Na^{+}$ in Compacted Montmorillonite" was published during the year (Glaus et al. 2013). The experimental results provide evidence for interlayer diffusion of cations, and illustrate the problems related to the use of effective diffusivity in bentonite (Figure 4-41).

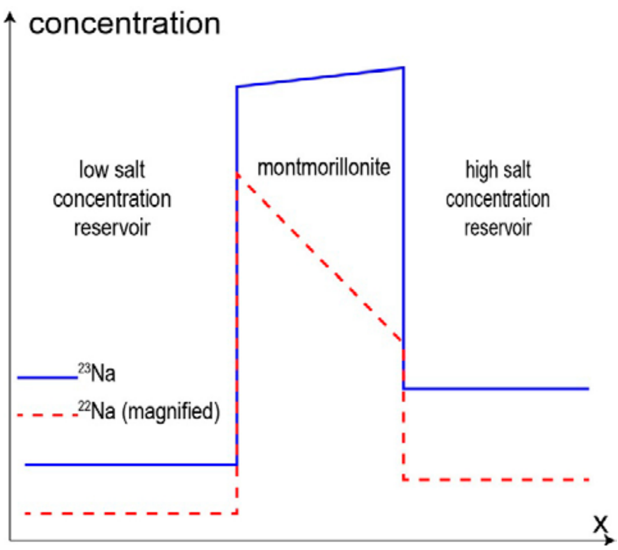


Figure 4-41. *Principle drawing of the experimental conditions in the diffusion test performed by Glaus et al. The blue line illustrate the concentration profile of $^{23}Na^{+}$ in a through diffusion experiment, and the red dashed line illustrate the concentration profile of $^{22}Na^{+}$, which in this experimental setup diffused from the left reservoir to the right reservoir, i.e. from low external concentration to high external concentration.*

4.10 System design of backfilling of deposition tunnels

Background

The KBS-3V repository 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 work consists of investigations, calculations, laboratory tests, tests in the Bentonite laboratory and underground tests at Äspö HRL.

Objectives

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

Experimental concept

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

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

Results

The prototype equipment for backfilling has been improved with a laser scanner on the lifting tool and a feeding system has been integrated on the platform (see Figure 5-1).

The different sub-systems have been integrated and tested in the Bentonite Laboratory and now the entire block installation sequence is automated, ie positioning of the mobile robot plattform, feeding of pallets with bentonite blocks to the robot, block stacking, measuring and control.

The concept for installation has been further improved and will be tested in a demonstration test in full scale underground as the final activity in the project. The full scale test will start during the beginning of 2014. The demonstration of the backfill installation in tunnel conditions will give important and valuable information for the future development and detailed design of the backfill consept for the Spent Fuel Repository.

4.11 System design of dome plug for deposition tunnels

Background

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

In the Spent Fuel Repository, the plugs will be made of low-pH concrete instead of conventional concrete. The reason for this is to avoid the negative effects that 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.

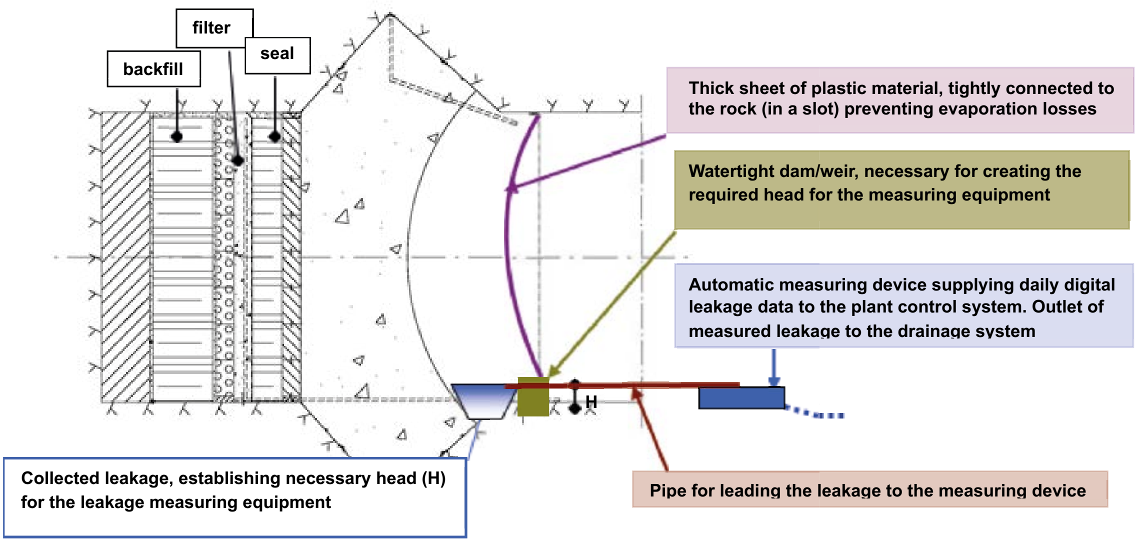


***Figure 4-42.** Layout of the full-scale experimental set-up Domplu.*

Experimental concept

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

A key objective is to monitor the water leak through the plug over time (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 sheeting) 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, stepwise up to 7 MPa for the tightness test, and up to 10 MPa for strength test verification. The experimental set-up and pressurisation program is targeted to reflect the real conditions expected in the Spent Fuel Repository.

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 minimal Excavation Damaged Zone (EDZ). The contour boreholes were 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. (Figures 4-43 and 4-44).

The wire-sawing method is assumed to minimise risk of continuous EDZ and it provides smooth rock surfaces for the concreted dome.

The tested rock excavation method was functional, but influence from rock stresses made the performance different compared to common sawing at shallower depth. As a consequence the wire-sawing took longer than initially scheduled. The originally planned pulling cuts were changed to blind cuts and accordingly a new drilling campaign was needed.

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

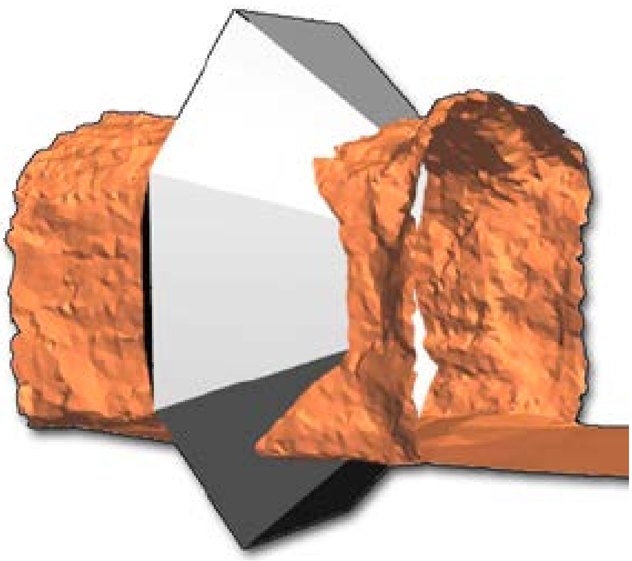


Figure 4-43. *Model of the theoretical slot layout.*

Figure 4-44. *Part of the concrete dome abutment, excavated by wire-sawing.*

The entire slot was finally measured in detail by laser scanning. The results of the rock excavation will be reported during 2014.

The installation of the inner parts of the plug began in late 2012 and was completed in the beginning of 2013. (Figures 4-45 and 4-46) Domplu was constructed with 45 sensors in the backfill and seal layer and another 56 sensors within the concrete. The sensors in the backfill and seal layers are lead through pipes in the rock to the neighboring tunnel, a distance of about 21 meters. Sensors within the concrete are lead out the front face of the concrete plug. The properties being measured by the array of sensors includes temperature, relative humidity, strain, displacement, pore pressure and total pressure.

On March 13, 2013 the casting of the concrete dome took place (Figure 4-47). The use of the B200 concrete was successful for the 94 m^3 structure. About 100 days later, to await the early shrinkage, contact grouting was performed in three sections to close any gaps in the concrete - rock interface.

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. When the drainage valves to the filter were closed, pressurisation of the experiment started 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 (about 250 kPa per week). At the end of 2013 the hydrostatic pressure had reached 1.1 MPa and the measured leakage rate past the plug was very low; 0.2 liters/hour. The leakage rate has been stable during the pressure increase, indicating a watertight function of the plug at prevailing pressure. The sensors are performing well (>95% are operational) and the monitoring is showing the expected trends. The swelling pressure of the bentonite seal is increasing slowly as expected. At the end of 2013 the measured swelling pressures in the bentonite seal were between 75–400 kPa. A fully watertight function of the seal is expected at about 500 kPa of swelling pressure. The total pressure is to be increased stepwise until 7 MPa is reached, holding this dimensioning pressure for some months.

The test programme will continue throughout 2014 and at the end of 2014 a technical evaluation will be reported. The experiment will be under continued observation until 2016.

Figure 4-45. 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 4-46. Installation of concrete delimiters, bentonite seal, macadam filter and sensors.

Figure 4-47. *Formwork for casting of the concrete dome structure.*

Figure 4-48. *The concrete dome structure after removed formwork.*

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

4.12.1 Introduction

Description of buffer design, production and installation were made as a part of the application in the production line report (SKB 2010). During 2011–2012 SKB´s development considering buffer was mainly focused on the dismantling of the outer section of the Prototype Repository.

During 2013 development work for refinement of buffer design, production, installation and inspection was initiated and carried out.

The main objectives of the work considering buffer during 2013 can be summarised:

1. Investigate behavior of the buffer in the timespan between installation and confinement by tunnel backfill.
2. Further development of buffer protection system.
3. Development of an alternative buffer protection method built on controlled athmosphere.
4. Development and industrialisation of buffer component manufacturing.
5. Develop inspection methods for the buffer material, this is described under the Section 6.3 – "New material laboratory".
6. If needed refine buffer design, installation procedures and equipment.

In this section activities that are related to ÄHRL are presented.

4.12.2 Early effects of water inflow

Background

This work is a part of 1) Investigate behavior of the buffer in the timespan between installation and confinement by tunnel backfill, that was listed in Section 4.12.1.

According to the reference design for the KBS-3V concept, the buffer is protected with an impermeable tube during the installation phase. Just before the start of the backfilling, the covering sheet will be removed and the slot between buffer blocks and rock will be filled with pellets. The interaction of buffer blocks and pellets have previously been investigated. The focuses of those studies were the following processes:

1. Erosion. Erosion of bentonite from the deposition hole up into the tunnel backfill material. This process will continue until a tunnel plug has been installed and the backfill is saturated.
2. Heave. Early wetting of the pellets filling may cause a heave of the buffer blocks into the backfill that will decrease the density of the buffer.

The laboratory tests presented here are complementing previous investigations by focusing on how the choice of manufacturing process for the bentonite blocks (isostatic or uniaxial compaction) and pellets (roller compaction or extrusion) are affecting erosion and the heaving effect. The influence of water inflow rate was also investigated.

The test has been reported by Johannesson and Jensen (2012). The text in this report is a summary.

Experimental concept

In Figure 4-49 the buffer volume simulated by the test is illustrated and the test set up is shown. In Figure 4-50 a photo of the test set up is presented.

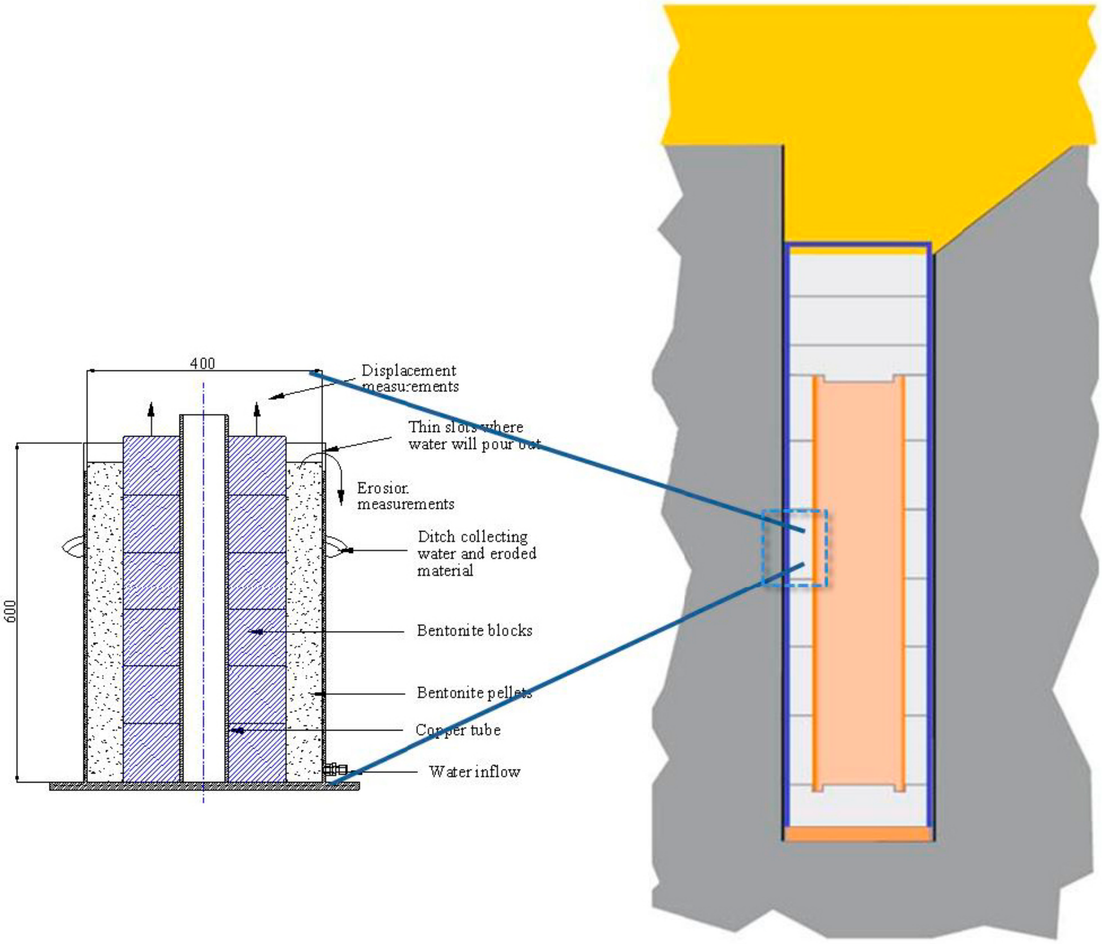


Figure 4-49. *Illustration of the buffer volume simulated in the test. The test set up is shown to the left and a schematic illustration of the installed buffer to the right.*

Figure 4-50. *Photo of the test equipment.*

The clay material used in these tests is MX-80 which is a sodium bentonite with a smectite content above 90%. Altogether three tests have been made. For two of the tests the blocks were manufactured by uniaxial compaction. The blocks for the third test were isostatic compacted and afterwards machined to similar dimensions as for the uniaxial compacted blocks. Pellets made of MX-80 were used in all of the tests. The pellets were manufactured by extrusion. Water with a salinity of 1% (50/50 NaCl/CaCl2) was used in all tests. The results from the tests are compared with previous made tests where roller compacted pellets, with the dimensions 18×18×8 mm of MX-80 were used.

Results

The important findings from the test can be summarised:

- There is a very clear influence of the applied water inflow rate regarding the rate and magnitude of the heave of the buffer. This is in accordions with previous made tests, i.e. a large water inflow results in a large heaving.
- The manufacturing technique used for the pellets seems to affect the magnitude of heaving. The test with extruded pellets showed a larger heaving compared with the tests made with roller compacted pellets. A possible explanation for this might be that for the roller compacted pellets, a less part of the pellets volume was wetted.
- The manufacturing technique of the buffer blocks have small effects on the heaving of the blocks.
- Most of the heaving occurs at the most upper blocks in the tests which indicate that the heaving is depending on the vertical stresses on the blocks.
- The heaving rate seems to be larger the first 50 hours of the tests.
- The heaving depends both on cracks which occur during the test and on the volume change of the buffer block caused by the water uptake.
- The observed pattern of wetting differs from the one observed in previous made tests with roller compacted pellets. In general larger volume of the pellets was wetted in the new test compared to the old test with roller compacted pellets.

Measurements of erosion were also performed. These results will be presented together with other maeasurement of erosion in order to discuss conclusions and this is not presented here.

4.12.3 Test and simulations of THM processes relevant for buffer installation

Background

This work is a part of 1) Investigate behavior of the buffer in the timespan between installation and confinement by tunnel backfill, that was listed inthe introduction in Section 4.12.1.

In the refence design all of the deposition holes in one tunnel are installed with bentonite blocks and canisters and after that the backfilling of the tunnel starts. After installation of canisters and bentonite blocks in a deposition hole, there will be a time period of up to approximately three months before the backfilling of the tunnel, above the deposition hole, is completed. During this time, the bentonite blocks will be covered with an impermeable tube in order to protect the bentonite from water and high relative humidity. Just before the start of the backfilling, the covering sheet will be removed and the slot between buffer blocks and rock will be filled with pellets. During the three month period it is possible that the heat from the canister will affect the buffer blocks and cause a redistribution of the water in the blocks. This test was performed to investigate THM processes relavant for the installation. The test will be reported during 2014.

Experimental concept

A full diameter test, where the buffer blocks were subjected to conditions similar to what will prevail during the installation phase in the repository, has been performed. In Figure 4-51 the buffer volume simulated by the test is illustrated and the test set up is shown.

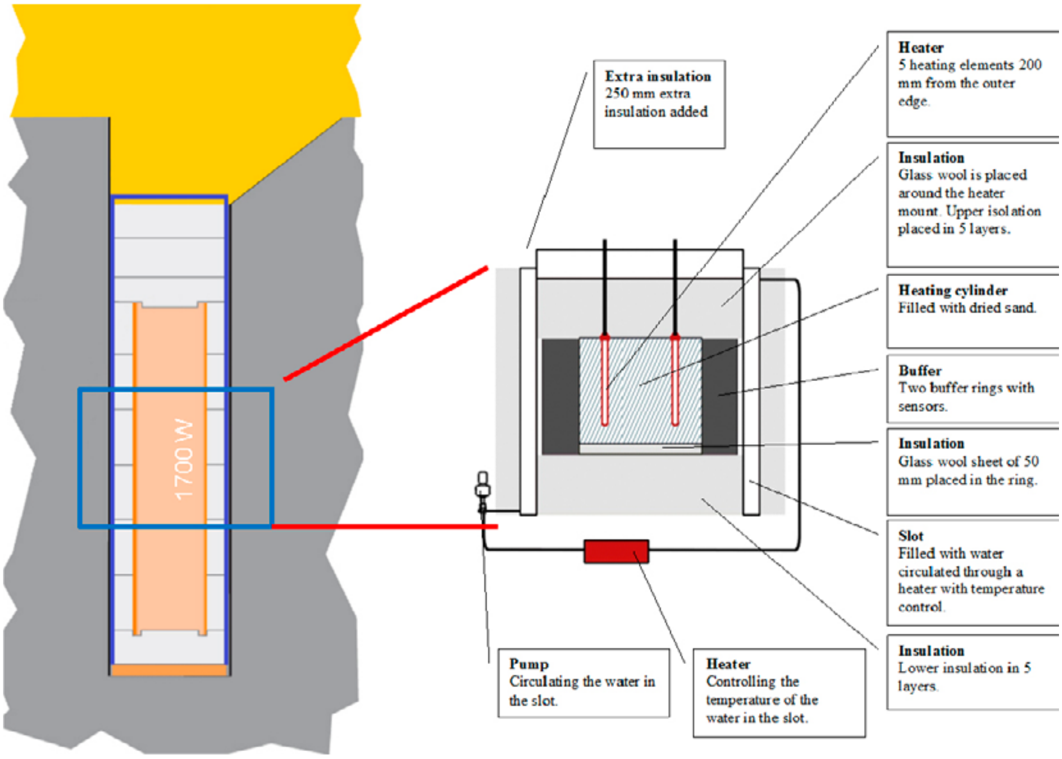
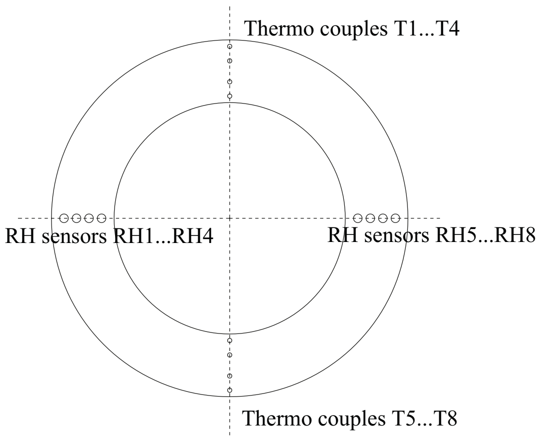


Figure 4-51. *Illustration of the buffer volume simulated in the test. The test set up is shown to the left and a schematic illustration of the installed buffer to the right.*



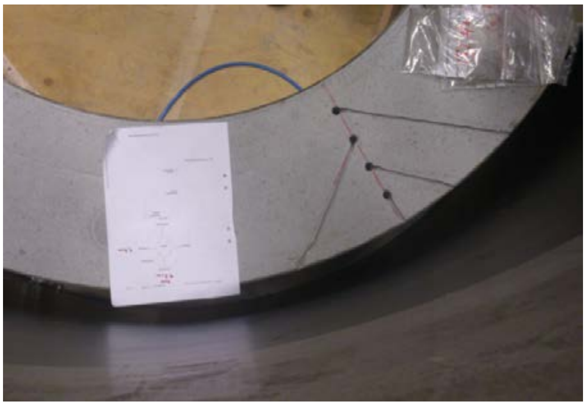


Figure 4-52. *The position of the sensors installed from the upper surface of the bottom block.*

Prior to the test the temperature was modelled in order to set the correct heater power.

The buffer in the test consisted of two ring shaped blocks of MX-80 with an average water content of 17%. The bentonite was delivered to Äspö during 2012 with an initial water content of about 11%. It was mixed with water in an Erich-mixer situated at Äspö to its final water content. The blocks were compacted uniaxially. After the compaction the blocks were machined to its final geometry.

The test was run for 4 months while monitoring temperature and relative humidity. A photo from the dismantling is shown in Figure 4-53.

Figure 4-53. Dismantling of the test.

Results

At the dismantling cracks in the bentonite blocks especially close to the heater were observed. The observations and the data from the dismantling show that a redistribution of water and density had occurred. The test was modeled with the codes Code_Bright and Comsol. The models could describe the behavior of the bentonite during the test fairly well. The test increased SKB´s knowledge on the processes in the buffer during installation. This will be used for refining buffer installation procedures and equipment in coming work with industrialisation of the deposition process.

4.12.4 Test of buffer protection system

Background

This work is a part of 2) Further development of buffer protection system that was listed in the introduction in Section 4.12.1

According to the current repository reference design (SKB 2010) a protection for the buffer is required for the installed buffer in the deposition hole until time for backfill installation. The buffer protection acts as a simple and robust answer to seepage problems that might be present in the deposition holes of the final repository. The purpose of the buffer protection system is to prevent the buffer clay from absorbing water from the time of buffer installation to backfilling of the deposition tunnel above a deposition hole. This phase of the deposition works could last up to 3 months.

This type of buffer protection was developed for the Prototype Repository and was later further developed by Wimelius and Pusch (2008).

The aim of the work presented here was to develop a design with a lightweight protection sheet that is easy to handle. An improved bottom plate with copper as the sole material and a climate lid for sealing of the top of the buffer protection has also been developed. The test will be reported during 2014.

Experimental concept

In Figure 4-54, an overview of the bufferprotection with a magnification of the connection between the buffer protection and the bottom plate is presented. The test was carried out with dummy concrete blocks. No heat was applied in the test.

Full scale tests with the purpose to answer following questions have been performed:

1. Installation:
   Was the installation of prototype of the buffer protection system successful?

2. Water tightness:
   Did the prototype for the buffer protection system preventing free water to reach the buffer dummies?
3. Water evacuation system:
   Was the water evacuation system considered compatible with the buffer protection system and did it operate as prescribed?
4. Disassembly:
   Was the disassembly of the top lid, o-ring and protective sheet successful?

The tests were conducted in the Bentonite Laboratory at SKB´s facility at Äspö. The assembled plate and sheet were lowered into the deposition hole as one unit, see Figure 4-55.

The testing was performed in a number of steps including varying the water level in the bottom of the dummy deposition hole between 0.3 and 1 meter during 18 days. The test set up is shown in Figure 4-56.

The testing of the disassembly was carried out after the test of water tightness. The opening of the closed protection sheet and removal of the top lid was carried out without any significant problems. The critical part of this test was predicted to be the disassembly of the o-ring and later lifting of the sheet and thereby remove the seal from the bottom plate groove. The removal of the O-ring worked well and it was removed by hand with a small force, see Figure 4-57. The removal of the buffer was made with the over head crane without any difficulty.

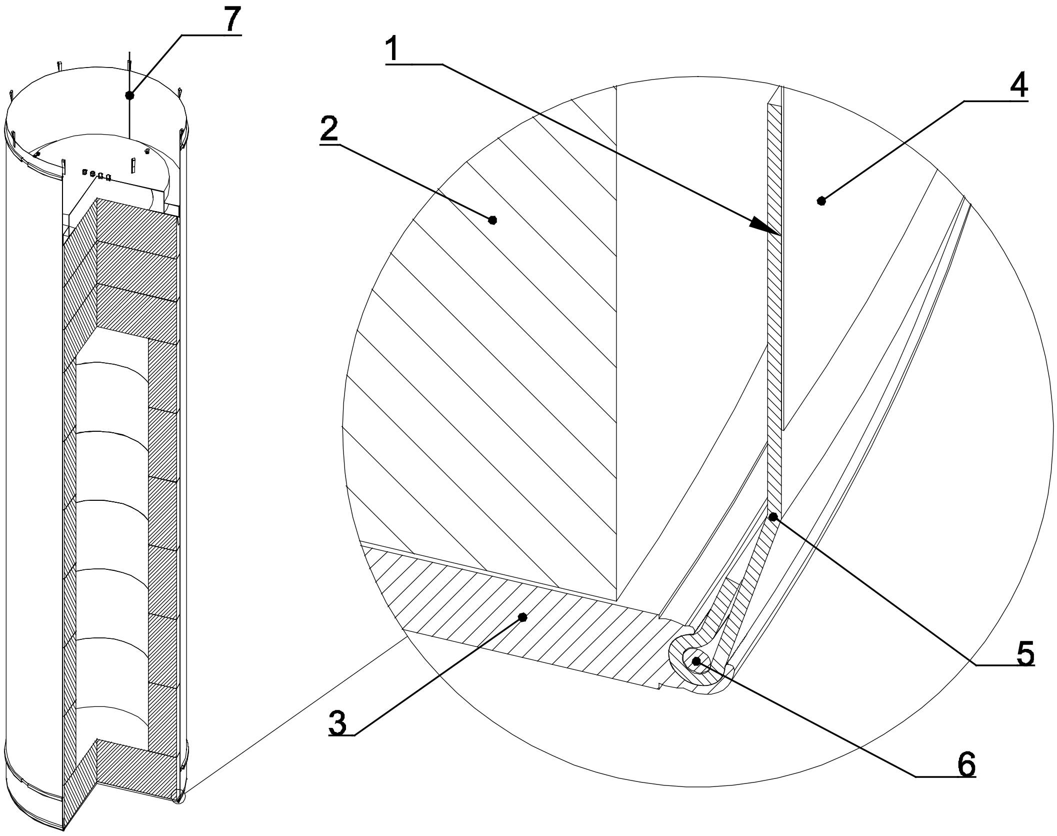


Figure 4-54. *View of lower part of sheet where a rubber seal is glued to the sheet: 1) Polyurethane polymer glue. 2) Buffer block. 3) Bottom plate.4) Protective sheet. 5) Rubber Seal. 6) Rubber O-ring. 7) O-ring extension.*

Figure 4-55. Photo taken when the assembled bottom plate and buffer protection sheet were lowered into the deposition hole in the Bentonite Laboratory at Äspö.

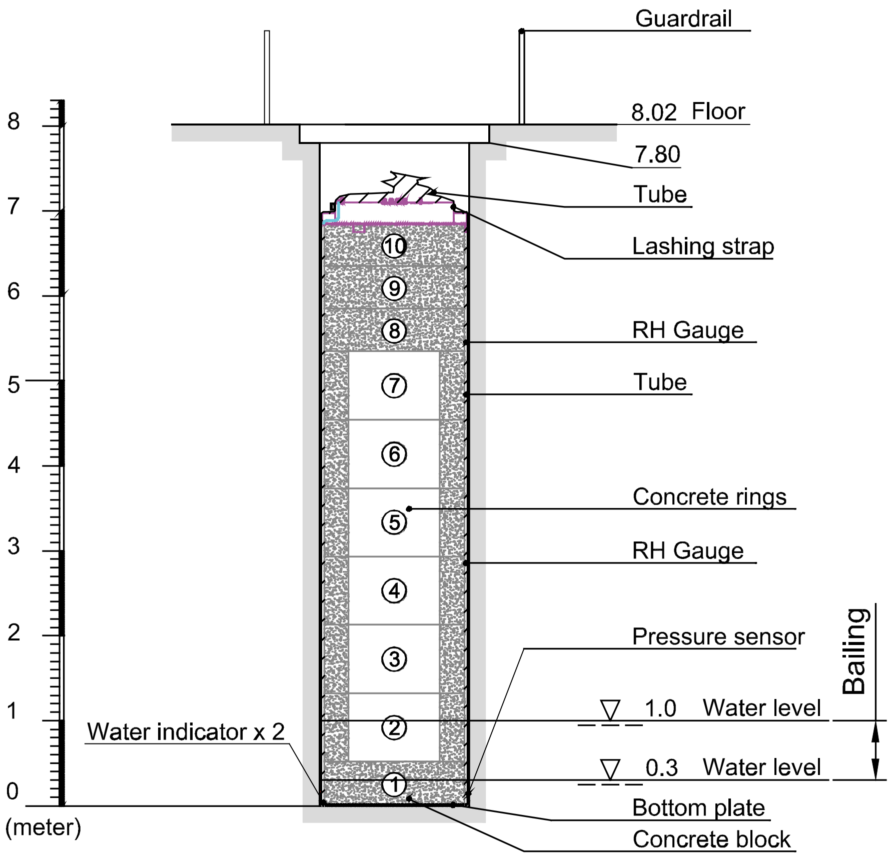


Figure 4-56. Test set up.

Figure 4-57. *Photo taken when removing the o-ring.*

Results

The installation was successful. The protection sheet was considered light weight and easy to handle. Installation of bottom plate with attached protective sheet, buffer dummies and top lid were successful.

The buffer protection system was water tight and no leakage could be detected once a small manufacturing error was corrected.

The sensors and water indicators worked as expected. Measure the level with pressure gauge worked fine and software had full control over the level.

The disassembly was successful, everything worked as expected.

This test was carried out in a laboratory environment. In the next development step the buffer protection equipment needs to be adapted to the environment in the repository.

The prototype for the buffer protection system is not adopted to be used with automated or remote controlled machines. Developing industrialised methods for installation and removal is a part of future work.

4.12.5 Test of controlled athmosphere

Background

This work is a part of 3) Development of an alternative buffer protection method built on controlled athmosphere, that was listed inthe introduction in Section 4.12.1.

The buffer protection described in the previous section has the disadvantages that it is difficult to remove in an automated process. Therefore tests have started to identify and test alternative ways to protect the buffer from humidity and drying. One of these Alternatives is to control the relative humidity in the deposition hole with a dehumidifier.

Experimental concept

The Test was performed in a full scale deposition hole with concrete blocks instead of bentonite blocks. The aim in this test was to evaluate how well the equipment could keep relative humidity constant through out the deposition hole, see Figure 4-58. The experimental setup had three tubes blowing air into the bottom of the deposition hole. The air was transported up through the outer gap between the blocks and the rock wall and was taken out i the top of the deposition hole. The air was then passed through a dehumidifier to remove exess moisture before being returned to the deposition hole.

Results

The method worked well and keept the relative humidity quite stable in the deposition hole. Further tests including heateras will be needed to find out if this is an alternative to the buffer protection presented in Section 4.12.4.

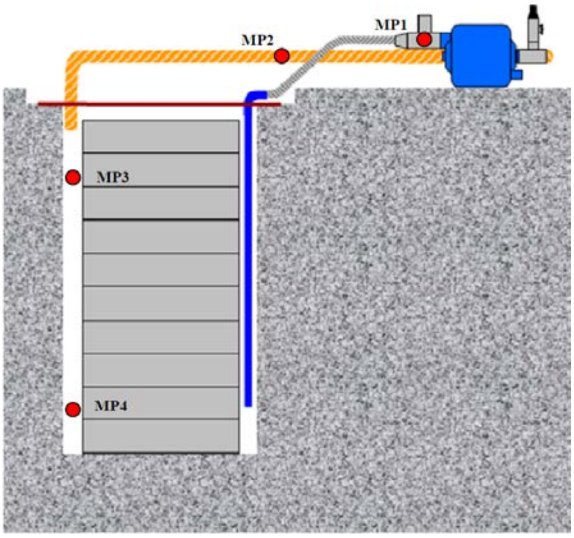


Figure 4-58. *Shematic view of the test setup.*

5 Mechanical- and system engineering

5.1 General

At Äspö HRL and the Canister Laboratory in Oskarshamn, techniques for the final disposal of spent nuclear fuel are under development. A total of over 200 different products and components known today are to be developed for the future final repository. Both well established existing technologies and new technologies will be used. As far as possible standard equipment, modified and adapted to the activity, will be used. Where no standard equipment is available new objects must be developed.

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 is due to change since the specifications are working documents. Several projects within mechanical- and system engineering are ongoing and the activities in some of the different projects are described in the text below.

5.2 Technical Development at Äspö HRL

5.2.1 Mission control system

Objectives

Within this project, a prototype of a comprehensive automatic system for the management and control of transport and production logistics for the final repository is developed. Also systems for navigation and positioning in tunnels are developed. The decision to develop a mission control system establishes a working method for the final repository that facilitates the use of automated vehicles.

Background

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

Figure 5-1. *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.*

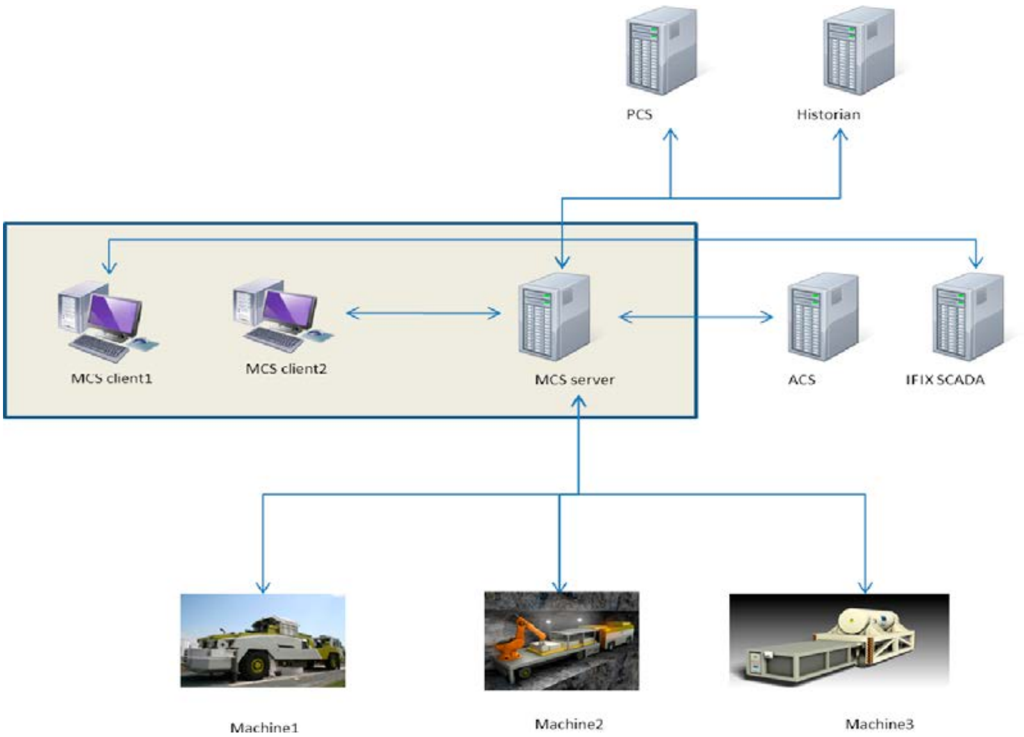


Figure 5-2. Mission Control System overview.

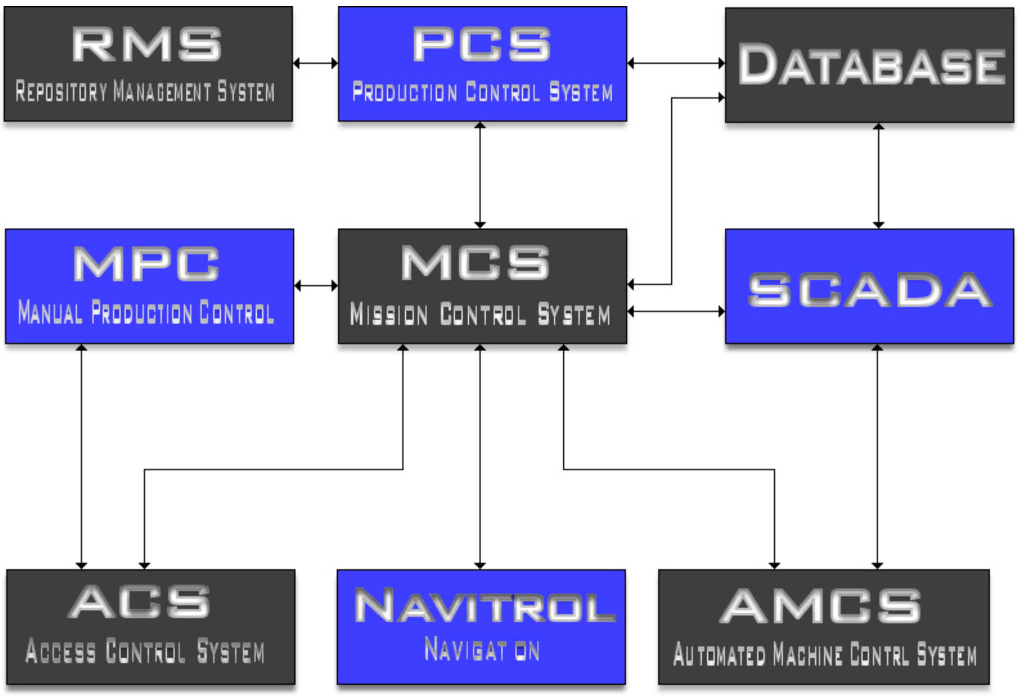


Figure 5-3. Mission Control System, in its context.

Experimental concept

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

Results

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.

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 depositions tunnels after the nuclear waste has been inserted into 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 5-4).

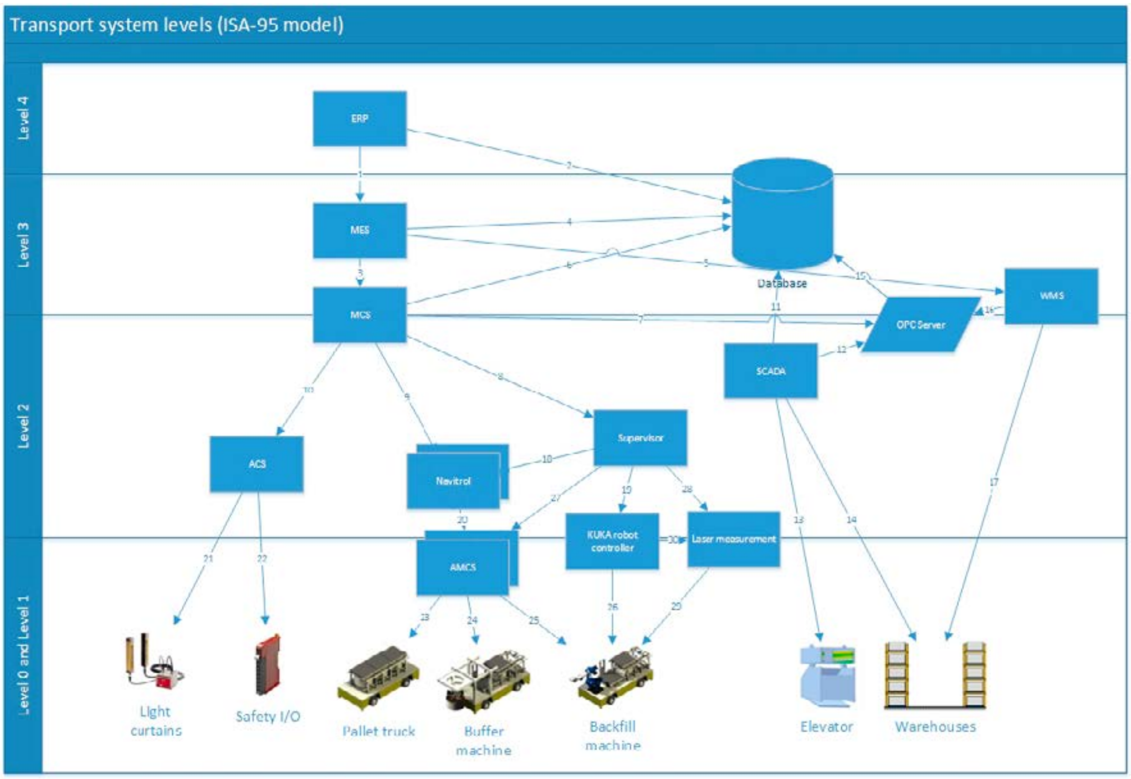


Figure 5-4. *Transport system levels and subsystems.*

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

Development is ongoing. Testing of the system, with the available machines; the deposition machine, the MPT and the backfill machine, is due during 2014.

5.2.3 Deposition Machine

Background

The equipment that performs the deposition of the canister containing the used fuel into the vertical deposition hole of the KBS3V-system, needs to lift, turn and handle 25 to 27 tonnes with an accuracy of ± 5 mm in all directions and at all times, and do it 6,000 times. There must not be any kind of damage done to the canister when deposited, and it has to be kept in a radiation shield tube until the deposition is completed. The project that resulted in the current prototype, Magne, was started in 2003. The machine was built in Germany and delivered at Äspö HLR in 2008 (see Figure 5-5).

Objectives

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

Experimental concept

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

Results

Recorded test runs of the full scale tests were started at the end of 2010 and continued through to 2012. When several full test cycles of 40 depositions had been performed without any kind of interruption or error the tests were regarded as completed. Approximatly 220 completed depositions were made within the long term test period and fine adjustment of the software was made. A test report was completed during 2013.

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

5.2.4 Equipment for backfilling

Background

After deposition of canisters in the future final repository, the tunnels will be filled with backfill material to seal the deposition tunnel. In order to perform this, and meet the requirements, a concept with a robot on a mobile platform has been developed (see 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 final deep 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 2013 the following activities has taken place:

- Software for robot and platform was developed.
- The systems were integrated with Mission Control System.
- The equipment for block and pellet feeding has been mounted on the platform, integrated and tested.
- The system has been tested in the Bentonite laboratory and is being prepared for the full scale test under ground which is to be performed during Q1 2014.

Development and testing is ongoing. More information can be found in 4.12 System design of backfilling of deposition tunnels.

5.2.5 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 5-6).

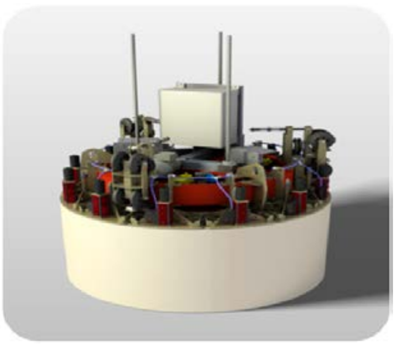


Figure 5-6. *Lifting tool for buffer emplacement.*

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

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 are ongoing and during 2014 prototypes will be constructed.

5.2.6 Multipurpose vehicle

Background

There will be frequent heavy load transports in the ramp down to the final repository. To have these transports executed, a Multi Purpose Vehicle (MPV) for heavy transports was ordered in November 2010 and delivered in August 2011. This vehicle was tested for heavy load transports in the ramp att Äspö HRL during 2013.

Objectives

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

Results

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

Figure 5-7. *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 experimental conditions and to simulate different environments.

During 2011–2012 new tunnels an experimental sites were produced. In total about 300 m new tunnel meters were constructed.

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

- Perform technical development commissioned by SKB´s programmes for spent nuclear fuel and for low- and intermediate level waste.
- Develop the horizontal application of the KBS-3-method (KBS-3H).
- Perform experiments in the Äspö HRL commissioned by SKB´s Research 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.

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

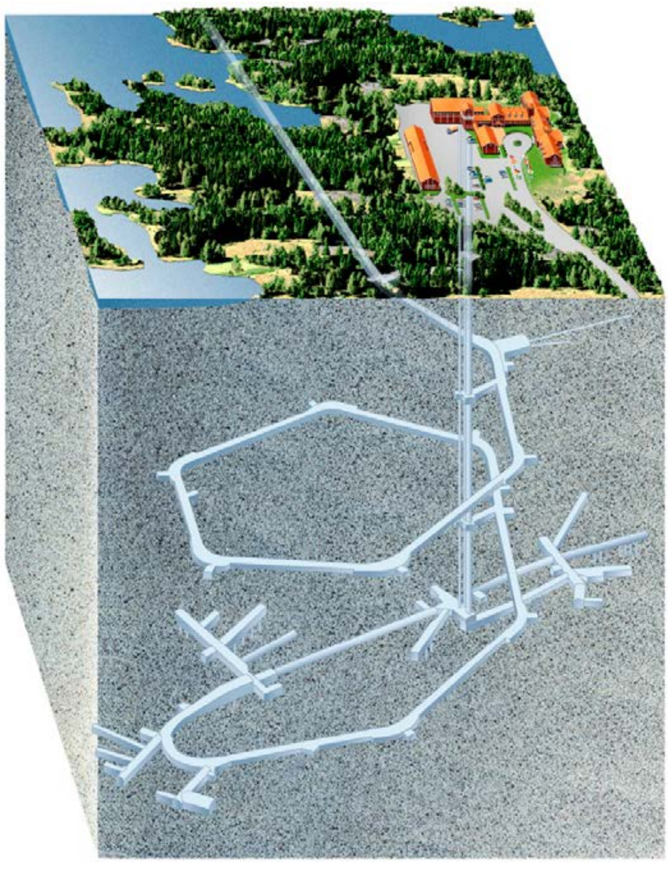


Figure 6-1. *The Äspö HRL tunnel system below the Äspö peninsula.*

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

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

Experimental concept

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 at Äspö

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 work in different fields is conducted with the purpose of competence development and problem solving in other projects or areas of SKB. Example of activities performed during 2013 are geologic samples of unknown minerals from the Äspö underground, bentonite samples from the KBS-3H Multi Purpose Test (see Section 4.4) with unexplained color variations in the full scale blocks, unknown precipitates from low pH cement, unknown solid material from within the Prototype canisters, determination of sulphide equilibrium concentrations of water bentonite mixtures and analysis of bentonite from within the SFR silo.

During 2013 three persons have been working in the laboratory and 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 (see Figure 6-3), Fourier Transformed IR (FT IR) spectroscopy for detailed analysis of the clay mineral structure and amorphous material, and UV/V is for the CEC method. A µ-Raman equipment was installed in the late 2013 (see Figure 6-2) as a complement for analysis of corrosion products, accessory minerals and precipitates all with a very high spatial resolution in a non destructive manner. Planned installations during 2014 are swelling pressure and hydraulic conductivity measurements.

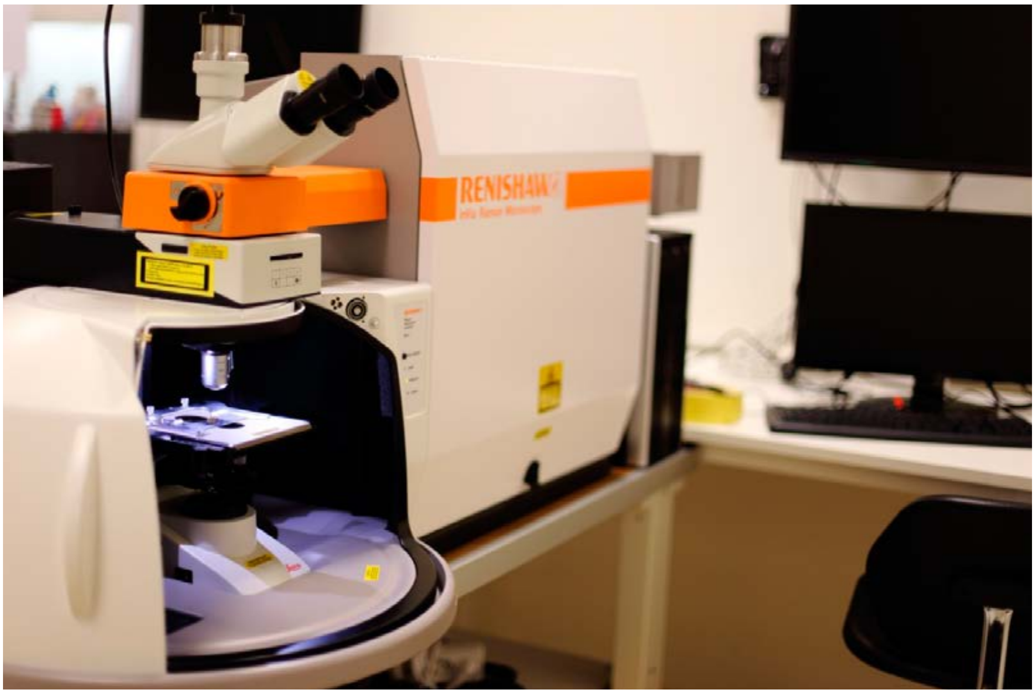


Figure 6-2. *Micro raman equipment for high spatial resolution analysis of various minerals in the bentonite clay and various phases from field experiments such as precipitates, corrosion products etc.*

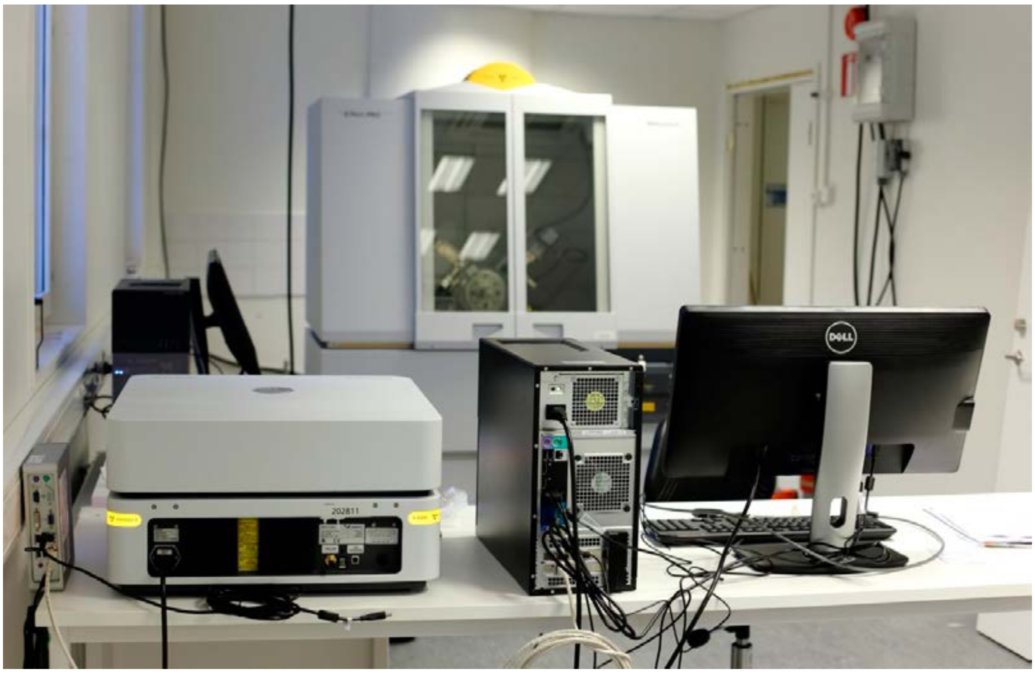


Figure 6-3. *X-ray fluorescence spectroscopy and X-ray diffraction equipment in the material chemistry lab at Äspö for bentonite research and method development.*

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 2013, with almost 100% accessibility.

The rock maintenance work in the Äspö tunnel completed its two year cycle with surveying and reinforcement of the raise bored elevator shaft. The work is associated with high risk and is classified as infrequent work. The facility operation unit worked with extensive risk analysis, risk minimisation and safety elevating methods such as pre-job brief and post-job debrief.

The entry ramp to the Äspö tunnel gate was completed during 2013, and is now heated through heat exchangers using water pumped up from the tunnel.

The new gate house by the tunnel gate was hoisted in place and will function as a backup operation control room. Everything controlled from the operation control room at Äspö will also be possible to control from the new gate house. Operational direction from rescue services personnel can now be carried out from two independent locations.

Upgrades have been made to the tunnel elevator brake system during the latter half of 2013. There is now a redundancy two-circuit brake system. This will be noticeable in a smoother stop in case of emergency breaking.

Figure 6-4. *Reinforcement of the elevator shaft using netting and expansion bolts.*

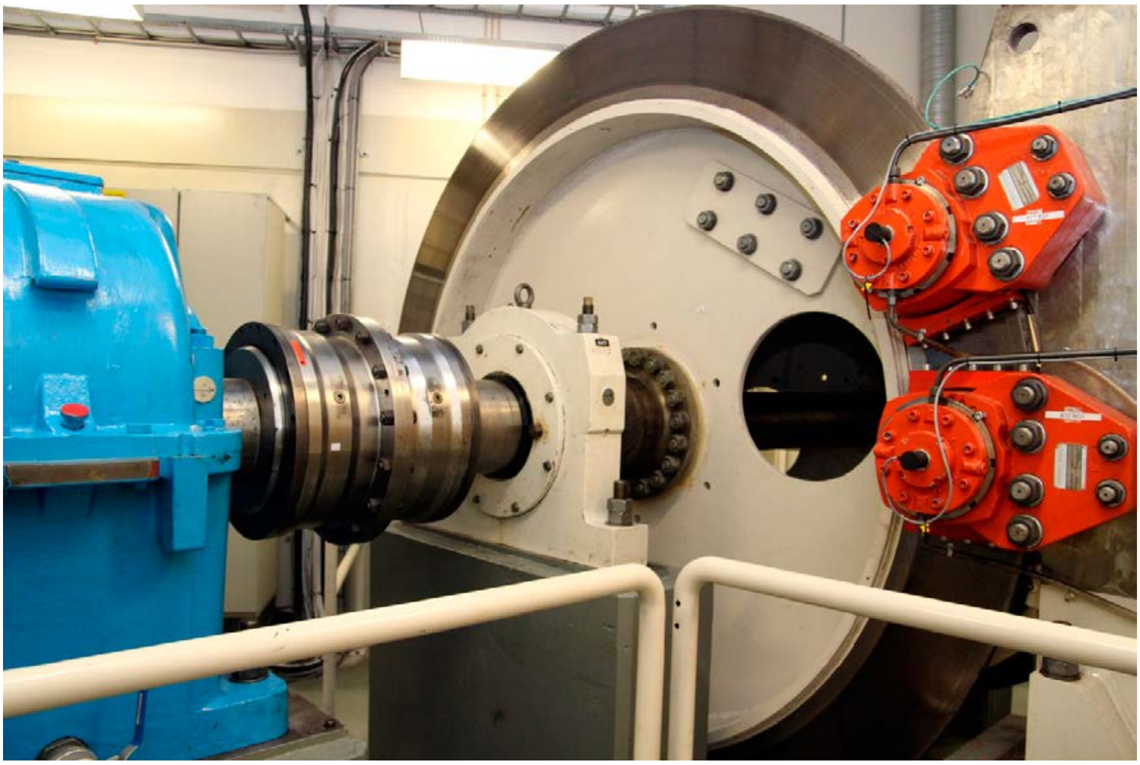


Figure 6-5. *Updated tunnel elevator brake system.*

Fitting and equipping of the new tunnels produced in the expansion of Äspö 2011–2012 has been completed during 2013. The new tunnels TASU and TASP has been paved and drained. Lighting, electricity and ventilation have been installed. Mobile rescue chambers have been placed in the tunnels TASU and TASP.

Other activities include updates to the RFID-system, telephone system and a new fire alarm. These activities are planned to be finalised during Q1–Q2 of 2014.

6.5 Communication Oskarshamn

General

SKB operates three facilities in the municipality of Oskarshamn: Äspö HRL, Central interim storage facility for spent nuclear fuel (Clab) and the Canister Laboratory. The main goal for the Communication unit in Oskarshamn is to create public acceptance for SKB, which is done in co-operation with other departments at SKB. The goal will be achieved by presenting information about SKB's facilities and RD&D work e.g. at Äspö HRL. Furthermore the team is responsible for visitor services at Clab and the Canister Laboratory. In addition to the main goal, the information 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 2013 Communication Oskarshamn consisted of 11 persons.

Special events and activities

During 2013, 4,918 people visited the Äspö HRL and with the visitors at Clab and the Canister Laboratory included it resulted in a total of 7,224 people. The total number of visitors to SKB´s facilities in both Oskarshamn and Forsmark was 14,703 people. The visitors represented the general public, teachers, students, professionals, politicians, journalists and visitors from foreign countries. The total number of foreign visitors 2013 was 437. The special summer arrangement "Urberg 500" was arranged during six weeks and about 1,103 persons took the opportunity to visit the underground laboratory. Tours for the general public also took place some Saturdays during the year.

During 2013 the unit's school information officer went to schools and high schools within the municipality of Oskarshamn to inform about SKB´s work. About 15 female students from high schools in Oskarshamn and Vimmerby 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 field otherwise highly dominated by men.

All students in 9th grade in Oskarshamn are offered a visit to the Äspö HRL and the Canister Laboratory and all students in the 3rd grade of high school are offered a visit to Clab. Newsletters and targeted invitations are sent out to teachers every year.

The unit was a part of the national event "The Geological Day" which was arranged in cooperation with *Hård Klang* at Stenhuggarmuseet in Vånevik, south of Oskarshamn. The theme this year was "to experience geology". Lectures on how quarrying was carried out was held, the smithy was in operation and the public could see how cobblestones were made. Äspö Miljöforskningsstiftelse handed out prizes to three 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 "Future Days" with a lecture on SKB´s future procurement.

During spring and autumn, SKB held well attended lectures in Oskarshamn with different themes related to SKB´s work or the area. The participants had the opportunity to learn more about inventory of the local wild life, generation IV reactors, SKB´s Greenland project and about the current status of the Baltic Sea.

Figure 6-6. *Some 7,000 people visited the Äspö Hard Rock Laboratory during 2013.*

In August, the Swedish championships in 3D-archery were held on the island of Äspö. The event had almost 400 participants. The participants and their families were offered underground tours by the unit. The organising archery club was very pleased with the arrangement.

On the 23rd of November 2013, 97 competitors participated in "the Äspö Running Competition".

During 2013, 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 6-7. *One of the participants in the Swedish championships in 3D-archery that was held on the island of Äspö during 2013. The event had 400 participants.*

7 Open research and technical development platform, Nova FoU

7.1 General

The aim is to describe major progress during the year 2013 for the research platform Nova FoU (Nova R&D). The description is made in terms of the mission, the status of the projects, spin-off effects, the organisation and the progress for the year 2013.

7.2 The Nova FoU mission

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

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

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

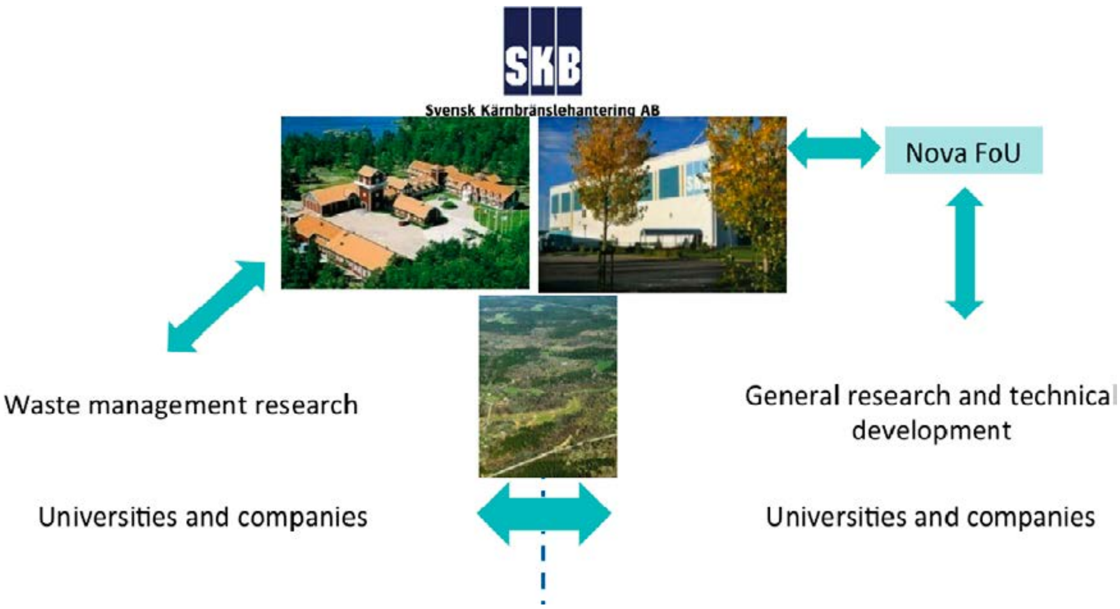


Figure 7-1. *Nova FoU provides access to the SKB facilities and data for universities and companies for general research and technical development. Nuclear waste management research is handled by SKB.*

The aim of the research and development projects at Nova FoU is to create long term spin-offs and business effects beneficial to the region.

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

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

Scientific work

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

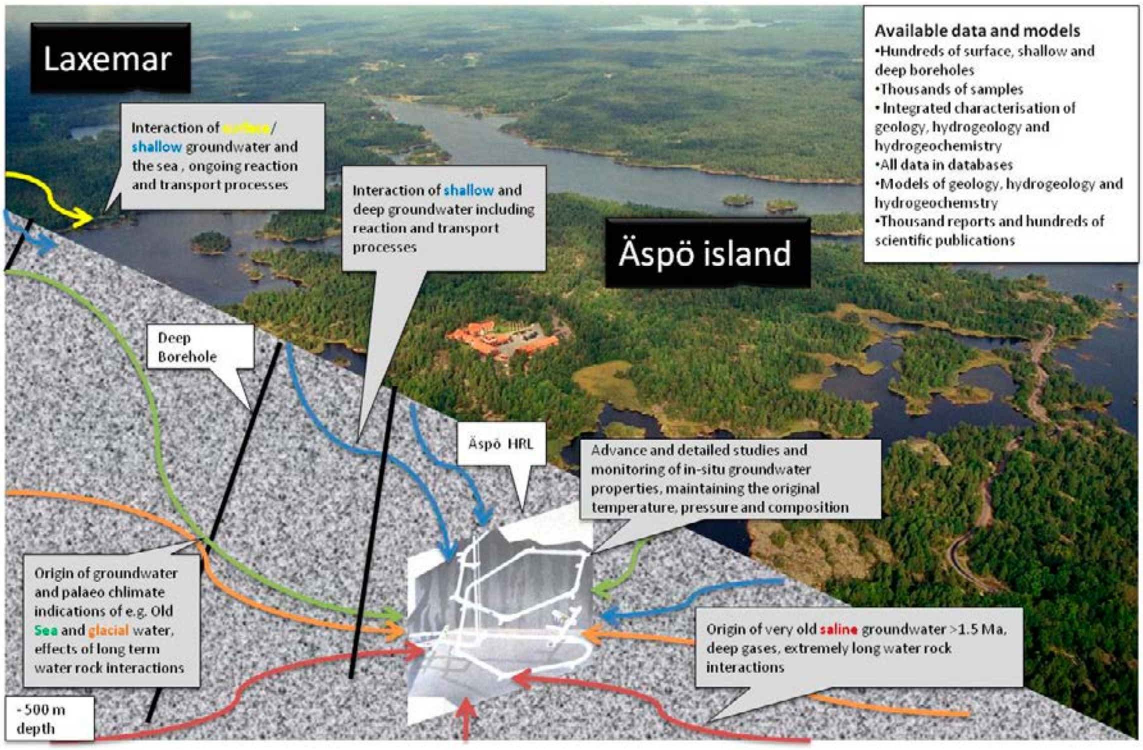


Figure 7-2. The Äspö and Laxemar areas have been studied in terms of geology, hydrogeology, hydrogeochemistry and ecology. This information can be used for a number of purposes, for example to describe the water cycle and hydrogeochemical processes in 3D.

Technical development

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

7.3 The status of the Nova FoU projects

The projects at Nova FoU range from detailed natural sciences studies to technical development and expert support in advanced projects. The status of the ongoing research and development projects within Nova FoU for year 2013 are described below.

7.3.1 Lanthanoids in bedrock fractures

Activity leader

Mats Åström, Linnaeus University.

Aim of the project

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

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

Status of the project

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

In the manuscript we present and discuss the sources, distribution, abundance and fractionation of lanthanoids and yttrium in groundwater and the abundance and fractionation of the same metals in low-temperature calcite precipitates in fractures in the upper kilometer of granitoids. We argue that the lanthanoids dissolved in the fracture groundwater were derived only to a minor extent from the overlying regolith, and therefore were released mainly *in situ* from solid phases bordering the fractures. These solid phases include both fracture coatings and primary wall-rock minerals. We also argue that the lanthanoid concentrations in calcite, when applied to existing partition coefficient for lanthanoid uptake in calcite, indicate that the groundwater precipitating the calcites were similar to the present groundwaters in terms of Ln and Ca chemistry. We cannot, however, precisely date the calcites, but indirect evidence show that they are precipitated within the past 10 million years under low-temperature conditions.

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 Ln concentrations in the groundwater (often occurring below detection limit), despite high lanthanoid abundance in several of the fracture-bordering solids, is indicative of generally high retention and low mobility of lanthanoids (and analogous actinoids) in the bedrock surrounding foreseen nuclear waste repositories.

7.3.2 Fluorine in surface and ground waters

Activity leader

Tobias Berger, Linnaeus University.

Aim of the project

The main aim of the project is to increase the understanding of the behavior of fluorine in waters at different levels in the ground (from the surface down to 1,000 m or more) in the boreal environment. In more detail the project aims to: (1) describe and explain the high fluoride concentrations in the water in the lower reaches of the Kärrsvik stream (this stream was included within Site Investigation Oskarshamn, Figure 7-4), (2) characterise and model fluoride abundance, transport and speciation in streams in the Laxemar-Äspö area, (3) characterise fluoride abundance and temporal variation in shallow (soil) and deep (bedrock) groundwaters of the Laxemar-Äspö area and (4) describe and explain fluorine abundance in soils in order to better understand how this element is distributed and released from soils to shallow groundwaters and surface waters.

Status of the project

During the autumn of 2011 two projects were initiated; (1) Temporal speciation of fluoride in three catchments in the Laxemar area and (2) Distribution and controls of fluoride in shallow (soil) groundwater of the Laxemar-Äspö area. Both projects will be finalised during 2014. A third

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

project reconnects to the fourth aim and was initiated during autumn 2012. We have thoroughly analysed fluorine and other elements in soil horizons (0 to ~ 1 m depth) across the Kärrsvik stream catchment area in order to investigate the distribution and leaching mechanisms across the catchment, along soil profile gradients and in different soil fractions. Samples have been collected and chemically analysed during 2013, including sequential extractions. SEM-WDS microanalysis of fluorine in different bedrock minerals, i.e the "end-member" of fluorine in soils and waters, has been carried out. Those results will be integrated in this study. During autumn 2013 a study on fluorine exposure in Kalmar County was submitted.

The major results are the findings and characterisation of a temporal and spatial fluoride pattern within the Kärrsvik stream and its catchment (Paper I), confirming the hypothesis of indirect influence from fluorine-rich bedrock (Götemar intrusion) as a source for elevated fluoride concentrations in the surface waters of the catchment. The mechanisms are weathering of glacial deposits, partially consisting of Götemar granite, and greisen fractures (which are strongly connected to the intrusion and, as well, rich in fluorite). Project (2) presents the importance of fluoride abundance on aluminium speciation in boreal waters, which are characterised by seasonal pH declines and richness of dissolved organic matter. Dissolved aluminium is considered toxic to aquatic organisms and extensive complexation to fluoride might influence on the toxicological effects of this metal.

Spin-off

The spin-off effects from this project will be increased knowledge on fluorine abundance and transport in surface and ground waters as well as in soils and bedrock in the Laxemar and Äspö area, Kalmar County and other areas across the world with similar geology, which has practical implications in terms of water supplies (concerning both private wells and public water resources). Many wells, both in the overburden and bedrock, in these areas contain fluoride concentrations well above the permissible limit for drinking water, an issue that will be thoroughly discussed and highlighted within the project. The findings may also lead to spin-off effects of economical value.

7.3.3 Hydrogeochemical investigation and modelling

Activity leader

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. 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.

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, after submission and reviewing of a manuscript, a solute transport modelling in dual porosity column has been developed. This allows further evaluation of the validity of the role of cation exchange processes to build up the natural high concentration of Cs found in the groundwater residing and flowing in the bedrock fractures at Äspö and Laxemar. The major results of this study, introduced in the Nova FoU Annual Report 2012, have been presented at the annual international geochemical conference Goldschmidt 2013. A revised manuscript will be resubmitted to the journal by the end of this year.

In the framework of the dissolved concentration of yttrium and REEs (YREE) in groundwater, 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 has been investigated. Focussing on the regolith and fracture groundwaters in the Laxemar and Forsmark areas, a manuscript will be submitted early next year. The major results presented in this study are:

- The natural concentration of YREEs tend to be influenced by the origin of the groundwater in spite of a moderate correlation (large scattering) found between the total YREE concentrations and the modelled proportions of the end-members (Figure 7-5).
- According to the YREE aqueous speciation modelling, the groundwater composition, including the colloidal concentration of humic substances, does not control the fractionation between light REEs and heavy REEs, which change in large extent with depth.
- Water-rock interaction processes, discussed based on the existing literature, tend to influence the fractionation between light and heavy REEs and thus the total concentration of dissolved YREEs in groundwaters of both sites.

Ongoing collaborations in other Nova Fou projects, presented at the Goldschmidt conference, are listed in the literature list below.

Spin-off

The hydrogeochemical characterisation, combined to modelling work, gives a better understanding of the evolution of the groundwater composition as a result of the past paleoclimate and modern recharge conditions. Moreover, the major hydrogeochemical changes observed during and after the construction of the Äspö HRL constitute ideal study cases for descriptions of geochemical processes likely to be affected or induced in the water-bearing fractures when constructing the final repository.

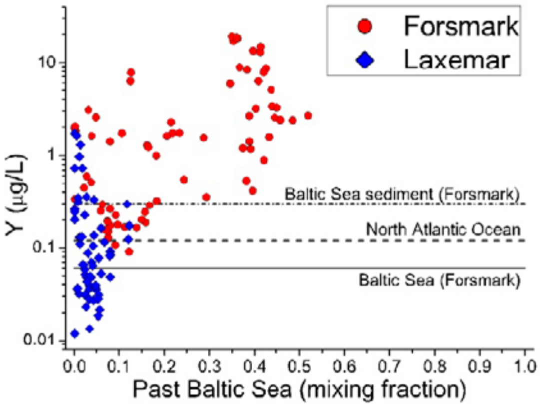


Figure 7-5. *Yttrium concentration plotted against the mixing fraction of marine water type composing the fracture groundwater in Forsmark and Laxemar according to M3 modelling.*

Literature

Some of the results of the ongoing projects and ongoing collaborations with other Nova FoU projects have been presented at the international geochemical conference Goldschmidt 2013 (Mathurin et al. 2013, Berger et al. 2013, Alakangas et al. 2013, Yu et al. 2013).

7.3.4 Detailed fracture mineral investigations

Activity leader

Henrik Drake, Linnaeus University.

Aim of the project

The aim of the project is to characterise and gain information from fracture minerals in bedrock fractures. Investigations of fracture minerals provide a useful tool to understand paleohydrogeological conditions. Groundwater in crystalline rocks is mainly transported along fractures and different groundwaters subsequently flowing along fractures may precipitate a sequence of minerals on the fracture walls. Examination of these mineral coatings ideally yields a paleohydrogeological record of formation temperatures, fluid compositions and potential origin.

Status of the project

Investigation has been focused to calcite (Figure 7-6) 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 and 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) and have been published in *Geochimica et Cosmochimica Acta* (one 2013 paper) and *Procedia* (in relation to the Water rock Interaction Meeting in Avignon, France) and have been presented through oral presentation at the Water rock Interaction Meeting (WRI-14, 2013) in Avignon, France, at Goldschmidt Conference 2013, Florence, Italy and NGL annual science meeting, Oskarshamn, Sweden.

Another study about trace element variation in calcite from Laxemar was finished in 2013 and will be published in early 2014 and include collaboration with University of Gothenburg and University of Göttingen (Christine Heim and Bent Hansen). Details for this article: H. Drake, C. Heim, K.J. Hogmalm, B.T. Hansen, 2014, Fracture zone-scale variation of trace elements and stable isotopes in calcite in a crystalline rock setting, Applied Geochemistry, v. 40, 11–24.

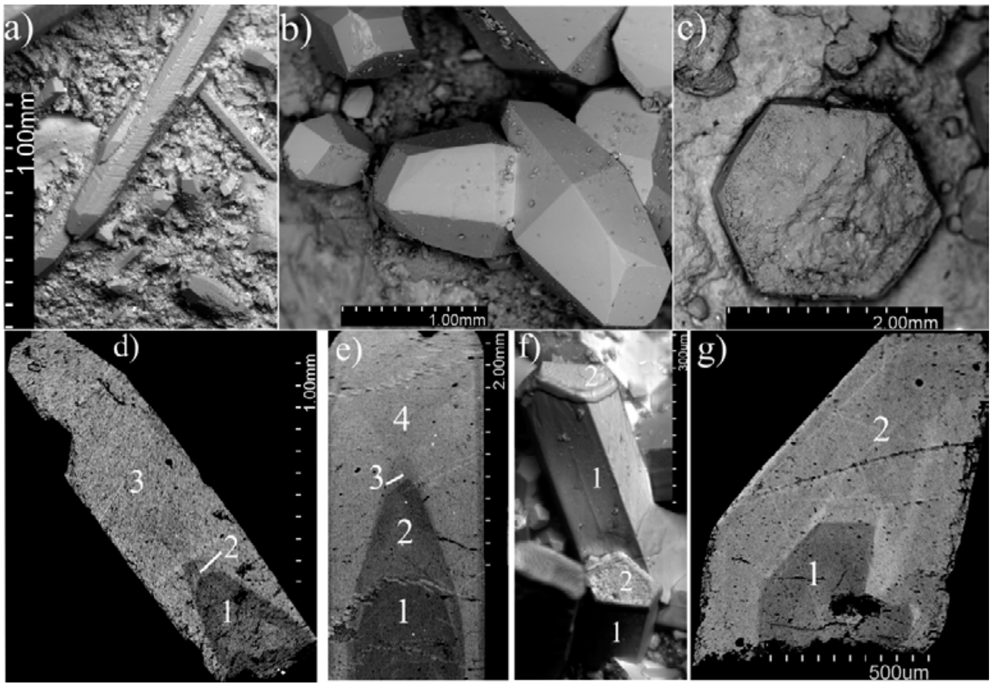


Figure 7-6. *SEM-images of calcite crystals from open fractures.*

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

- Detailed chemical, isotopic and biomarker characterisation of calcite in fracture zones – on intra-crystal, intra-fracture, inter-fracture and inter-fracture zone scales from zones in granitoid fractures at great depth at Laxemar. Analyses in progress. Collaboration with University of Göttingen, University of Gothenburg, NORDSIM.
- Greenland analogue project; redox-studies from fracture coating samples. First sampling and analytical campaign finished and presented at Goldschmidt Conference 2011, second in planning. Collaboration with University of Helsinki and Conterra AB.
- Investigation of metal uptake in calcite grown on borehole equipment in the Äspö tunnel, and comparison with groundwater data. Collaboration with University of Gothenburg.
- Stable isotope characteristics of pyrite, calcite precititated on borehole equipment in the Äspö tunnel, and comparison with groundwater data.
- Chemistry and reducing capacity of fracture coatings in water-conducting fractures and fracture zones.
- 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.

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

Activity leader

Olga Maskenskaya, Linnaeus University.

Aim of the project

The aim of the project is to characterise geochemical (with the main focus on rare earth elements) and stable isotope composition of fracture minerals which precipitated at several geological events and were emplaced in the crystalline bedrocks of the Laxemar area. The fluid that precipitated fracture minerals carries on geochemical and isotopic composition of initial hydrothermal fluid and could be changed due to interaction with the bedrock and mixing with fluids of another origin. The project consists of 4 parts.

Status of the project

A first part of the project discusses the results on sources, distribution and fractionation of rare earth elements and other metals in one of the oldest (Proterozoic) hydrothermal mineralisation residing in the upper kilometre of granitoid bedrock of the Laxemar area. The veins precipitated from the hot (200–360°C) hydrothermal fluids that were originated from fluorine-rich granite and undergon intensive interaction with the bedrock. This mineralisation provides an opportunity to discover fractionation and distribution of rare earth elements and other metals in hydrothermal process. The results of the study has been finalised in a manuscript which has been submitted to peer -reviewed journal "Lithos".

The second part of the project reports the results of a fine-scale investigation of trace elements, stable isotopes and fluid inclusions of calcite veins related to Neoproterozoic mafic magmatism occurred in the Laxemar are at ca. 0.9 Ga. Relatively thick (up to 10 cm) calcite veins are genetically related to doleriter intrusions and occurred in a close distance (<2 m) to them. The aim of the study was to define the origin and characteristics of the veins based on the determination of a variety of physico-chemical variables in transects across veins. The results of this study has been presented (as a talk) on the 14th international symposium "Water-rock interaction", published as an extended abstract (Maskenskaya et al. 2013) and were submitted as a manuscript to peer-reviewd journal "Geoflids".

The first part of the project focuses on the rare earth element geochemistry of low-temperature calcite coatings occurring on the walls of fractures throughout the upper kilometer of the Laxemar area. In this study we analysed rare earth elements in calcite, and compare those with back-calculated, modelled and initial rare earth elements in related groundwater in order to understand rare earth element uptake by the mineral. The results of the study has been finalised in a manuscript and submitted to peer-reviewed journal "Chemical geology".

The forth part of the project focuses on the geochemistry of Paleozoic hydrothermal veins that has been a precipitated in two chemically different types of granitoids occurred in the area (Götemar granite and granitoids of Transscandinavian Igneous Belt). Thes veins precipitated as a far-field effect that occurred during Caledonian orogeny at ca.0.4–0.5 Ga. The study aims to understand the influence of these two types of bedrock on the geochemistry of hydrothermal veins. The major part of the results has been processed and has been organising in the manuscript which will be submitted in early 2014.

Spin-off

Spinn-off from the project will lead to the better understanding of rare earth elements behaviour in paleohydrothermal systems. Outcome will be of particular interest for those who are working with trace elements in deep underground system, paleo and recent hydrothermal fluids, and could be used as a reference.

7.3.6 Coastal modelling

Activity leader

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 (Soltani and Cvetkovic 2013) as well as groundwater in the Forsmark region (Cvetkovic 2013); main funding for both studies was by SKB. The second part of the Nova project resources was used for completing studies of the Baltic Sea and archipelagos as important parts of studying coastal zones. In particular, our focus has been the difficult problem of scale, namely in capturing the transition from large-scale dynamics in the Baltic Sea to small-scale flow and transport, e.g. in a single bay, or part of an archipelago. The dynamic coupling and scale transition was demonstrated for the OKG cooling system outlet.

Topic 1: Hydrological flow and transport from land to sea

In Soltani and Cvetkovic (2013) we looked at simplified models for the water age distribution under transient hydrological forcing. The main result is a simple analytical model that captures well a complex phenomenon and offers a new tool in evaluating water age in the hydrological cycle that among others has high relevance for interpreting geochemical observations.

In Cvetkovic (2013) the issue of predictability of groundwater transport using experimental data from the Forsmark site, specifically the HFM14 tracer tests, was addressed. These tests were performed in a highly conductive fractured aquifer and are unique in the world to include multiple tracers (sorbing and non-sorbing) carried out in a highly heterogeneous aquifer along multiple pathways on scales that range from 70 m to 300 m, i.e., a fourfold difference. The works showed that macro-dispersion phenomenon can be modelled by relatively simple conceptualisations and that the macro-dispersivity was constant for different scales but higher than what was observed on comparable scales before (Figure 7-7a, red symbols compared to blue and green symbols). The work showed that once the mean water residence time is calibrated, tracer transport can be accurately upscaled (Figure 7-7b). Most importantly, the work showed that matrix diffusion processes were taking place, and their removal from the model reduced the accuracy of predicted transport (compared to observed) significantly. This work has important implications for groundwater transport modelling on the field scale, e.g. in a risk assessment context.

Topic 2: Dynamics of coastal processes in the Baltic Sea

Exciting new work was initiated as part of the Nova project that builds on results obtained as part of an EU Interreg project which was completed in 2012. Our focus has been during 2013 to complete the hydrodynamic analysis of the Baltic Sea, and develop methodologies for downscaling processes and being able to study small-scale flow and transport along the Swedish coast. An example for the large-scale results is the vertical temperature shown in Figure 7-8. The cross-section considered is shown in Figure 7-8a, from north to south, extending roughly 1,200 km. The temperature vertical distribution on 2000-01-15 (noon) and 2000-10-15 (noon) is shown in Figure 7-8b. Note that the colour scale for the two dates is different. The dynamic nature of the temperature is clearly seen, the patterns at the two times being very different. The strong upward temperature gradient during the winter, and strong downward gradient during early fall, are apparent (Figure 7-8b); these gradients are critical for ecosystem dynamics.

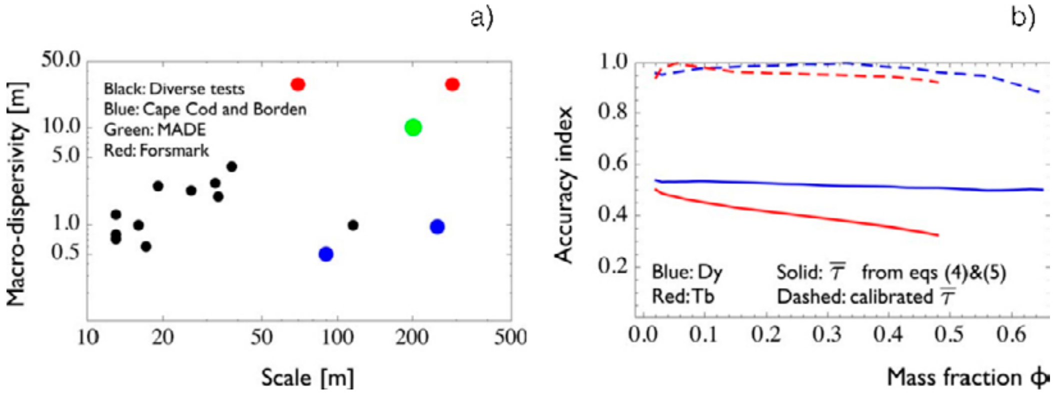


***Figure 7-7.** a) Macro-dispersivity vs scale from earlier field studies and our HFM14 tracer tests at Forsmark. b) Accuracy index when predicting tracer transport of the HFM14 tests, for different mass fractions.*

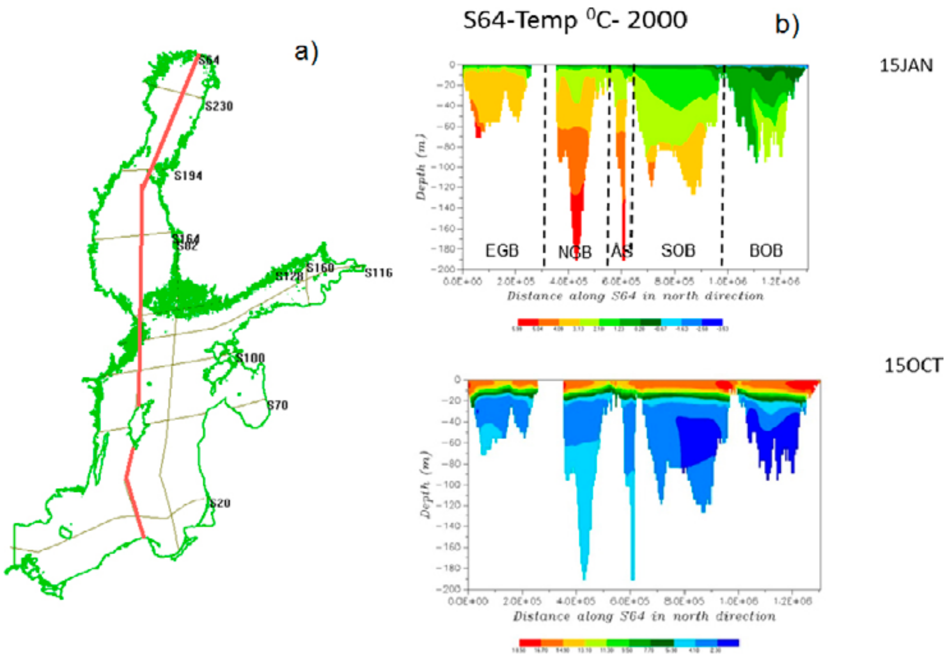


***Figure 7-8.** a) The Baltic Sea with the central north-south cross-section marked in red. b) Vertical temperature distribution along the red transect shown in (a), during winter (above) and early fall (below).*

The small-scale heat transport was exemplified by the temperature plume from the OKG cooling outlet. The small-scale numerical set-up for the area surrounding the OKG outlet (marked) is shown in Figure 7-9a. The corresponding bathymetry map is shown in Figure 7-9b. The discharge and temperature at the outlet where provided by OKG for several years during the past decade. Example simulation results from the discharge thermal plume are shown in Figure 1-10. The time difference between the two snapshots is two weeks: The first snapshot is at 2006-05-09 (noon) (Figure 7-10a), and the second snapshot is at 2006-05-23 (noon), and a significantly different pattern in observed. The difference in the temperature distribution pattern is entirely due to the large scale flow dynamics, captured by the simulations.

Outcomes

Two papers in the leading journal *Water Resources Research* for the co-financed projects were published.

A report summarising the Baltic Sea analysis is being completed. This will provide a basis for a number of manuscripts for international journals that will be completed during 2014 and 2015.

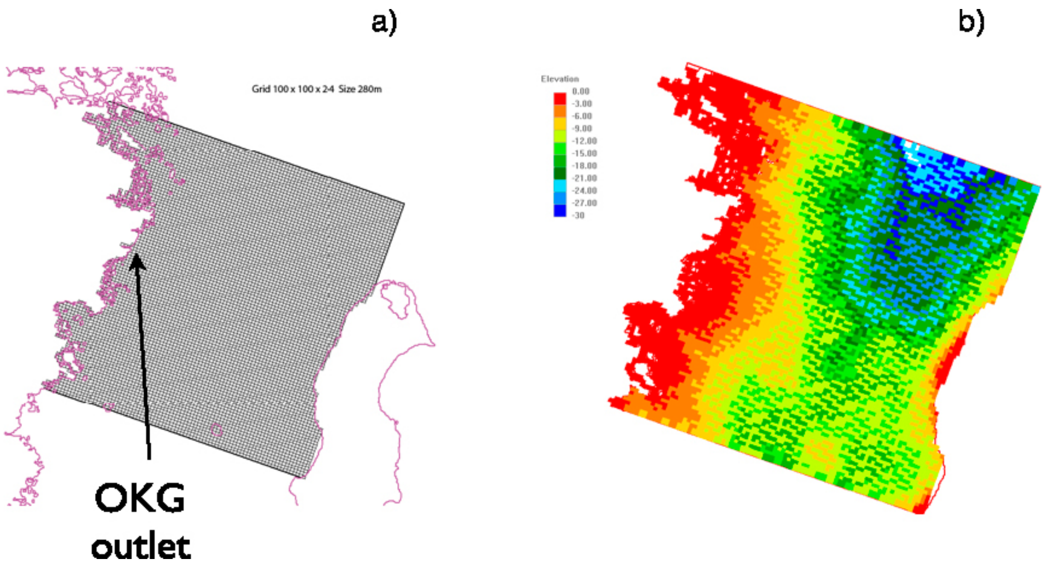


Figure 7-9. a) Numerical set-up around the OKG outlet. b) Bathymetry in the same region.

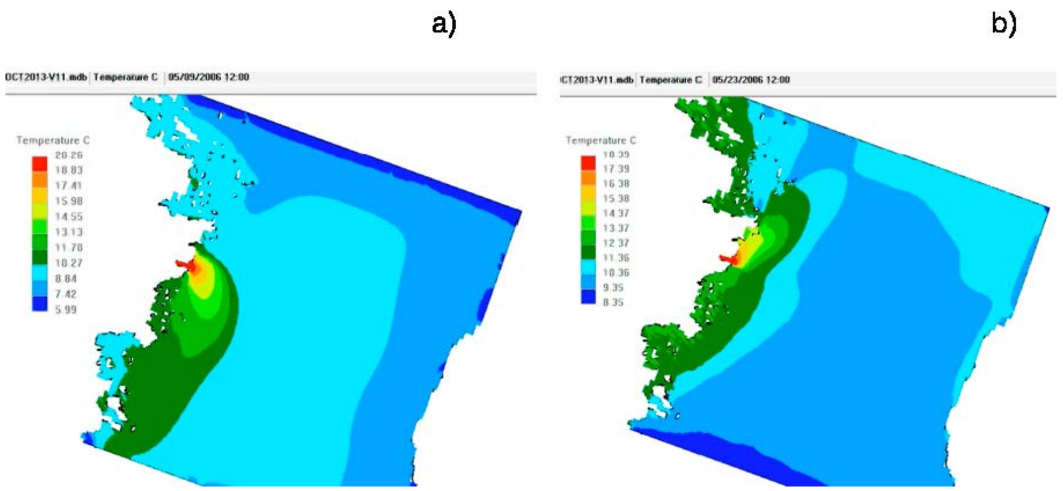


Figure 7-10. a) Temperature distribution at 2006-05-09 (noon). b) Temperature distribution at 2006-05-23 (noon).

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.

7.3.7 KLIV – Climate-land-water changes and integrated water resource management in coastal regions

Activity leader

Georgia Destouni, Stockholm University.

Aim of the project

KLIV investigates critical questions for sustainable management of water resources, with main geographical focus on coastal regions. KLIV investigation sites include the Swedish Water Management District of Southern Baltic Proper (which in turns includes the Äspö HRL and wider Oskarshamn coastal region related to the National Geosphere Laboratory (NGL) – http://www.geospherelab.se/), with methodological development and comparative catchment studies also carried out for other parts of the world. During 2013, the KLIV research group has further developed and clarified its main research questions, which are investigated across different sites, catchments and regions. These may be formulated as:

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 prioritise 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 will provide new insights and knowledge on water system change and its possible management.

To arrive at the answers, the KLIV research integrates the inland water system and its adjacent coastal waters, following the water flow and the waterborne transport of tracers, nutrients and pollutants, as well as the climate change effects on these water aspects, 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 will provide new advancements, methods and tools for efficiently detecting-monitoring, modelling-projecting and controlling-reducing undesirable water resource changes.

ii) The results will contribute to efficient achievement of main 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

The current KLIV project started in autumn 2012 and extends over a 3-year period (2012–2015). The 2-year post-doc, Andrew Quin, who was recruited to KLIV in December 2012, has during 2013, in addition to the research described below, also been responsible for the development of the KLIV website, www.klivresearch.se with contributions from all KLIV researchers. The website presents the KLIV project, its members and their research and outreach activities.

Main KLIV research activities and results during 2013 are summarised below in terms of the main research questions stated above, with the relevant peer-reviewed publications by KLIV researchers during 2013 listed further below in the Literature section.

Work finalised and published in 2013

1 – Environmental-climate change interactions with water resource change

Key studies related to this research question have addressed the effects of climate change and land-use on hydrological conditions in the landscape, with particular focus on evapotranspiration and stream discharge fluxes (van der Velde et al. 2013), and on erosion intensity and lake sediment geochemistry (Augustsson et al. 2013). Related key studies have also identified historic hyroclimatic shifts that have been driven by human water use for food and energy production (Destouni et al. 2013, Jaramillo et al. 2013).

Furthermore, hydrological and geochemical studies with subsurface water focus have investigated and quantified the variability of water age along hydrological pathways under realistic, transient flow conditions (Safeyeh and Cvetkovic 2013), and of sulphur isotope ratios in pyrite and dissolved sulphate in granitoid fractures down to 1 km depth, finding evidence for widespread activity of sulphur reducing bacteria (Drake et al. 2013).

2 – Identification-detection of water resource changes

In relation to climate-driven changes of water in the landscape, Bring and Destouni (2013) have developed a methodology for direct comparison of climate model results and actually observed such changes, as basis for prioritising options and developing strategies for relevant and efficient development of hydrological and water resource monitoring. In this first methodological development and application step, the study used the fast-changing Arctic as its concrete regional application case, precisely because this is a world region with widely recognised unprecedented climate-related change that could be used for creating relatively wide interest in the methodological development and its applicability. With this first development now published, analogous methodological applications and further developments will follow also for other regional case studies, including NGL-related ones.

Furthermore, regarding other methodological developments, in particular for how to meet hydroclimatic variability and change, Jamali et al. (2013) have investigated the question of how to use Geographical Information Systems (GIS) to efficiently locate suitable sites for construction of subsurface dams. With regard to projecting and meeting water quality changes, Cvetkovic (2013) has addressed the key question of how accurate predictive modelling of solute (tracer, pollutant) transport by groundwater may be, in particular regarding the linked key transport processes of advection, macrodispersion and diffusive mass transfer.

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

In direct relation to and parallel with the above-discussed study by Bring and Destouni (2013), on required monitoring developments for detecting and thereby being able to cope with climate-driven water resource changes in the Arctic, both Azcárate et al. (2013) and Nilsson et al. (2013) have proposed some key development pathways for adaptive environmental and water-food security governance, respectively. Using also here the fast-changing Arctic as a concrete regional case, the methodological development by Azcárate et al. (2013) pointed at the need to identify key knowledge gaps and efficiently bridge them by appropriate use and uncertainty-accounting development of the instrument of Strategic Environmental Assessment linked to hydroclimatic and water resource monitoring (Figure 7-11). Furthermore, Nilsson et al. (2013) identified a number of concrete indicators that can and should be continuously monitored for appropriate water (and more or less related food) security governance. Also for these developments, now that they have been published for the Arctic as first steps, analogous methodological applications and further developments will follow also for other regional case studies, including NGL-related ones. Additionally, recognising the key role of urban sustainability, not least for coastal regions with typically large population and urban development pressures, Snickars et al. (2013) have explored urban flows and networks, in particular regarding the sustainability of the Swedish coastal capital, Stockholm.

Ongoing research activities continuing into 2014

1 – Environmental-climate change interactions with water resource change

The whole KLIV group has during 2013 worked on a sub-project for developing a general conceptualisation framework for environmental-climate change interactions and change propagation through the whole coupled human-natural system of water on land – this work has been led by

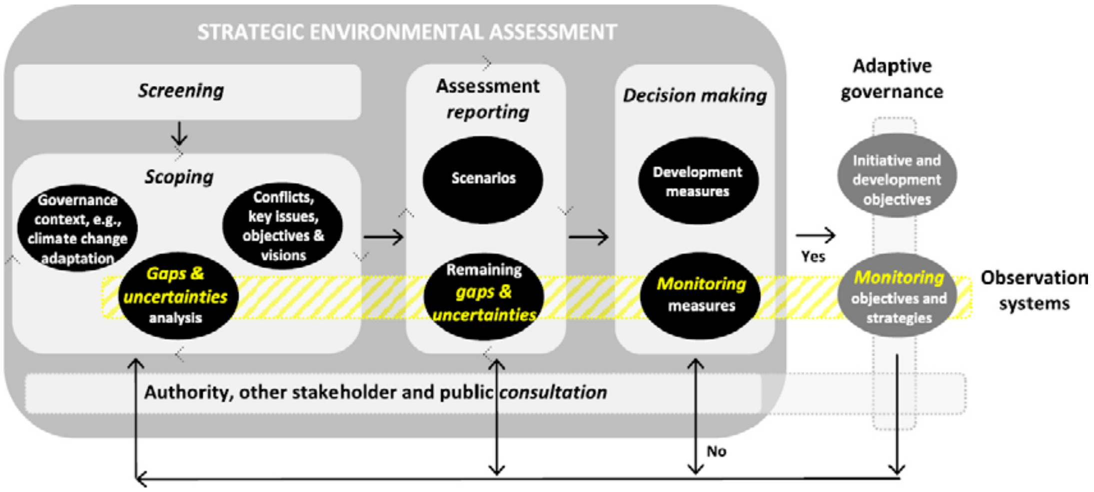


__Figure 7-11.__ Adaptive governance framework. The novelty here is the use of Strategic Environmental Assessment to explicitly recognise and handle knowledge gaps and uncertainties, and link environmental monitoring to actual observation systems.

Georgia Destouni and is planned to be finalised and submitted for publication in 2014. Water on land is closely linked to human survival and prosperity, and to ecosystem status and development. Urgent needs have been recognised for improved understanding of the changes experienced and propagated by the whole land water system (McDonnell et al. 2010, Cvetkovic et al. 2012), and of the connections of water changes with planetary boundaries (Rockström et al. 2009) and rapidly changing human systems (Montanari et al. 2013), including the linked food-energy-water demands of the latter (Howells et al. 2013). In this KLIV work, we have responded to these knowledge needs by synthesising land water data from different parts of the world and revealing consistent patterns of water quantity and quality changes, which are driven by landscape-internal human-natural water interactions and are propagated by the land water system as a whole toward its boundary interactions with the atmosphere and the sea. We have further developed a conceptualisation framework that identifies principal spatiotemporal connections and flow-transport pathways for this change propagation by water through the landscape. This development provides a basis for improved and further developed understanding of water on land as a complex coupled human-natural system, with possible emerging change properties that are not evident from traditional separate study of only individual water components. Research along these lines for the complex life-sustaining system of land water as a whole can thereby lead to novel scientific insights that can improve both water resource and general environmental governance and management.

2 – Identification-detection of water resource changes

In relation to water quality changes, we have during 2013 initiated a new sub-project, led by Anna Augustsson at Linnaeus University, aimed specifically at detecting groundwater quality changes as basis for assessing associated environmental-health risk changes around former glassworks, located throughout Kalmar and Kronoberg counties, Sweden. Assessment of environmental and health risks associated with potential groundwater pollution from such contaminated land sites, and possible necessary remedial action, is time-consuming and costly. It is therefore crucial that such risk assessment, which forms the basis for prioritisation of management interventions, is reliable. Risk assessment, however, typically entails large uncertainties. Thus, identifying and directing efforts towards decreasing critical knowledge gaps, and thereby reducing uncertainty, is important. For people living around contaminated land sites, the overall risk is a function of the total exposure, where multiple paths of exposure generally interact. For metal contaminants originating and leaching from contaminated glassworks sites, one important exposure pathway, which is subject to large uncertainty, is the consumption of drinking water from groundwater wells affected by leached metals. Earlier groundwater analyses have indicated that metals associated with glass production may contaminate local groundwater. The work initiated in this KLIV sub-project focuses on necessary further analyses of metal concentrations in groundwater collected from private wells situated at different distances from former glassworks. Results from this study will provide an important piece of knowledge to the larger puzzle of understanding human exposure to metal contaminants due to living in a Swedish region famous for its glass industry.

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

We have in 2013 also started a sub-project, led by Andrew Quin and planned to be finalised and submitted for publication in spring 2014, aimed to identify key features of a landscape that may contribute to an essential large-scale ecosystem service: retention of waterborne nutrients and pollutants from various sources. Such a retention service is indeed provided by the landscape – without it, the waterborne nutrient and pollutant loading to downstream inland and coastal waters would be greater and require more, and more costly, abatement measures in order to achieve the same level of protection for downstream waters. This retention service is also closely linked to – and may even be critical for – other types of ecosystem services, such as: clean water provision, nutrient cycling, and recreational water environments – the value of each of these ecosystem-services depends on the large-scale service of nutrient and pollutant retention in the landscape.

In particular, wetlands have been promoted as essential landscape features for the retention of nutrients and pollutants from both point (e.g. wastewater treatment plants and industry) and diffuse (e.g. agriculture, forestry, unconnected wastewater pipes, storm water and atmospheric deposition) sources in the landscape. A number of studies have assessed the local effectiveness of single wetlands in retaining nutrients and thus the reduction in nutrient loads carried by water flow through them. Generally, there is evidence that wetlands can reduce loads locally under favourable conditions. However, what is the corresponding large-scale effect of multiple wetlands distributed throughout the landscape? This question is investigated in the KLIV sub-project.

Our study tackles this question by compiling and analysing available data relevant for assessing effects of wetlands and other landscape features on large-scale nutrient retention. Nutrient retention data has been obtained from the Fifth Baltic Sea Pollutant Load Compilation (PLC5), carried out under the auspices of Sweden's Environmental Emissions Data (SMED). Data on wetlands has been obtained from the Swedish Land Cover Data (SMD) and the Swedish Wetlands Inventory (VMI). The analysis is carried out for the Swedish North and South Baltic River Basin Districts (Figure 7-12).

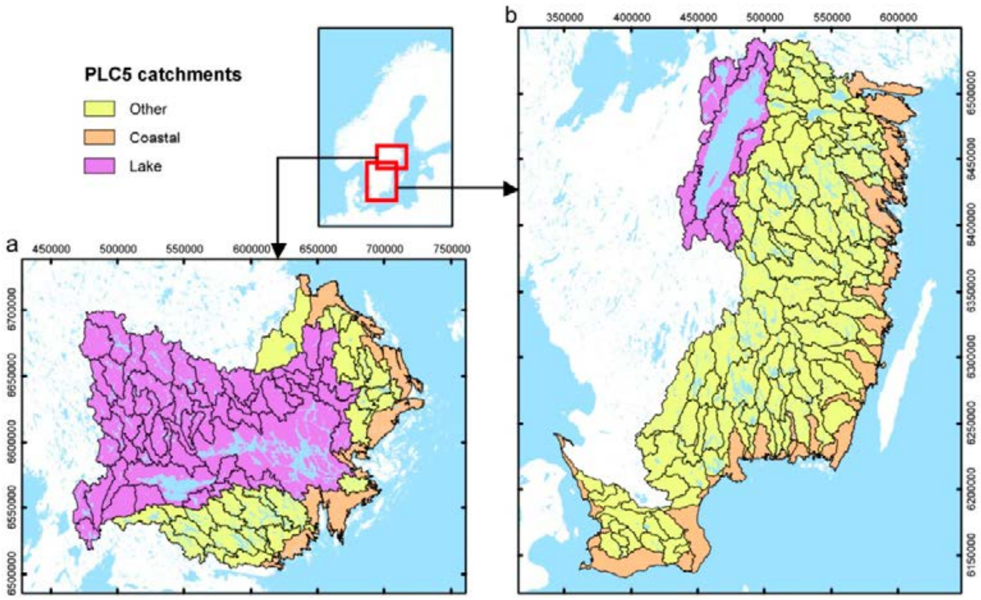


Figure 7-12. *PLC (sub)catchments for (a) the North Baltic River Basin District (RDB), and (b) the South Baltic RDB. Colors distinguish catchments with flow and nutrient transport pathways that go through a major lake on the way toward the coast (purple), catchments that have have outlets directly at the coast and have been classified as coastal zone catchments by the competent Swedish authority (orange), and other catchments (yellow).*

Already obtained results reveal negligible effect of wetlands on nutrient retention at a landscape-scale, accounting for a wide range of relative wetland areas and, also, the number of wetlands across various sections of the landscape. Instead, the waterborne transport-distance from a catchment to the coast, and the possible existence of large lakes along this transport distance emerge as key features for large-scale nutrient retention in a landscape. These results apply to different types of nutrient sources, including point, agricultural and other diffuse sources, and to both nitrogen and phosphorous transport and retention. For example, Figure 7-13 shows results for relative retention (nutrient mass retained normalised with total nutrient input mass; with values between zero and one) plotted against the wetland-to-catchment area for total nitrogen (TN, upper panels) and total phosphorus (TP, lower panels), where the wetland-to-catchment area is the ratio of the area of wetlands within a PLC5 catchment to that catchment's total area. These plots show that wetland area has no detectable effect on relative nutrient retention as there is no correlation between relative retention and relative wetland area. The effect of large lakes is seen in the results for catchments with such lakes along the pathways of their flow and nutrient transport to the coast (purple circles, Figure 7-13), which have larger relative retention than most other catchments. The transport distance effect is indicated by the results for small catchments in the close coastal zone (orange circles, Figure 7-13), which have smaller relative retention than most other catchments.

Such large-scale results must be considered in environmental management for efficient protection and restoration of good water quality, as well as in assessments and accounts of wetland ecosystem services on landscape scales. In general, such improved understanding of the large-scale nutrient and pollutant retention effects of different features and their distribution in a landscape is needed to better inform decision making aimed at reducing eutrophication and pollution of aquatic ecosystems.

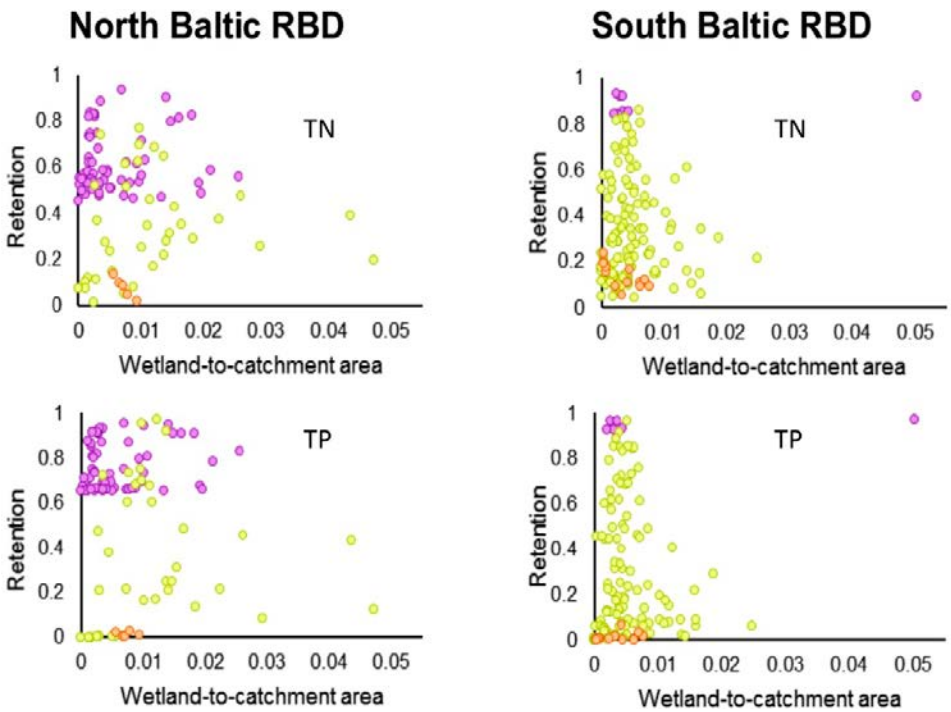


Figure 7-13. Relative nutrient retention versus relative wetland area in PLC (sub)catchments (shown in Figure 2) for the (left panels) North Baltic River Basin District (RDB) and (right panels) South Baltic RDB. Symbol colors distinguish results for catchments with flow and nutrient transport pathways that go through a major lake on the way toward the coast (purple circles), catchments that have have outlets directly at the coast and have been classified as coastal zone catchments by the competent Swedish authority (orange circles), and other catchments (yellow circles).

Spin-off

In 2013, Georgia Destouni (GD) from KLIV together with Stockholm University post-doc Arvid Bring (AB) and Nova handling officer Anna Rockström have coordinated and arranged the first Annual Science Meeting of the National Geosphere Laboratory (NGL), held 7–8th November, 2013, in Oskarshamn. AB and GD have also during 2013 developed the NGL website at www.geospherelab.se, which provides detailed information about the first annual science meeting and other NGL activities in 2013. In summary, the purpose of this first annual meeting was to build up, support and integrate the NGL research community and the further development of NGL as a national research infrastructure. In addition to GD's coordinating role, other KLIV members have also been actively involved and active in all NGL activities during 2013.

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

Activity leader

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 finalised extensive field investigations at the Hallandsås tunnel project. A scientific paper on groundwater chemical changes due to the excavation has been submitted during 2013. The article is written in collaboration with the Swedish Transport Administration.

Furthermore water sampling campaigns at the Kattleberg tunnel project NE of Göteborg has been performed. The interpretations of the results generally verify effects in the groundwater quality due to construction work. The conceptualisation of the resulting chemical processes and engineering implications has been compiled into a scientific paper.

Spin-off

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

The primary focus of the proposed project is to use acquired knowledge to create prediction models with the aim to predict hydrochemical changes in conjunction with underground construction, based on information gathered prior to the construction phase. The predictions provide a base for constructing safer tunnels with cost-effective maintenance.

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

Activity leader

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 characterise 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 minimised. Borehole data show problems with correlating effective hydraulic conductivity and density of flowing fractures, which cannot be resolved because the fracture aperture distribution is unknown. It remains a challenge to obtain representative measurements of aperture distribution within a single fracture. These field data highlight the challenges with the task to establish relationship between the effective hydraulic conductivity (K) and the density of flowing fractures (d_{op}), as studied through the numerical simulations.

Spin-off

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

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

Activity leader

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 summarise 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 7-14).

We have studied and categorised 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.

The work is completed and the project is now in the process of compiling a manuscript to be submitted.

Spin-off

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

7.3.11 Drinking water scarcity in coastal areas – prediction and decision support tools

Activity leader

Bo Olofsson, Royal Institute of Technology, KTH.

Aim of the project

The aim of this project is to improve understanding regarding groundwater in hard rock coastal regions. The study focuses on developing support tools for decision makers who are tasked with managing limited water supply resources in coastal regions and improving knowledge of the kinematic

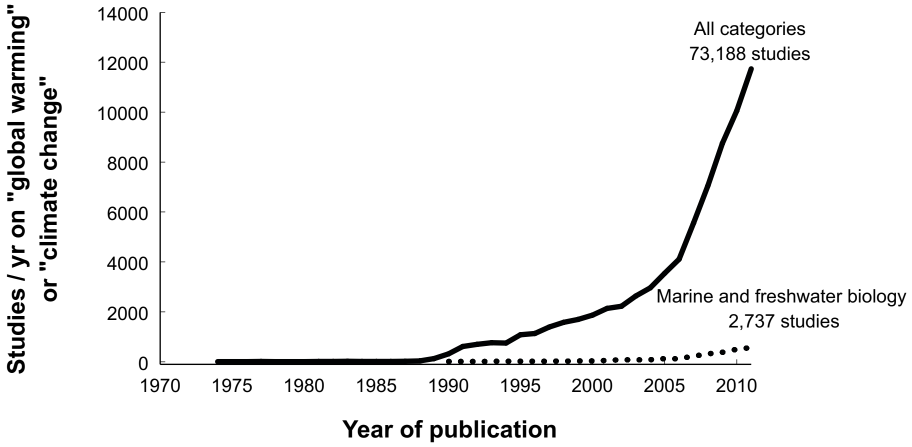


Figure 7-14. *Trends in research output on global warming across all disciplines (filled line) and for marine and freshwater biology (dotted line). Figure shows number of publications per year and is based on data extracted February 2, 2012, from ISI Web of Knowledge.*

(effective) porosity values of hard rock. 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 continuous digital data (such as geological maps, topography, landuse) or simple field measurements of kinematic porosity which can complement existing data.

Status of the project

The project currently 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 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 hydrogeogical indicators such as specific capacity. Finally, the last part of this project is a water balance methodology which is specifically customised 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.

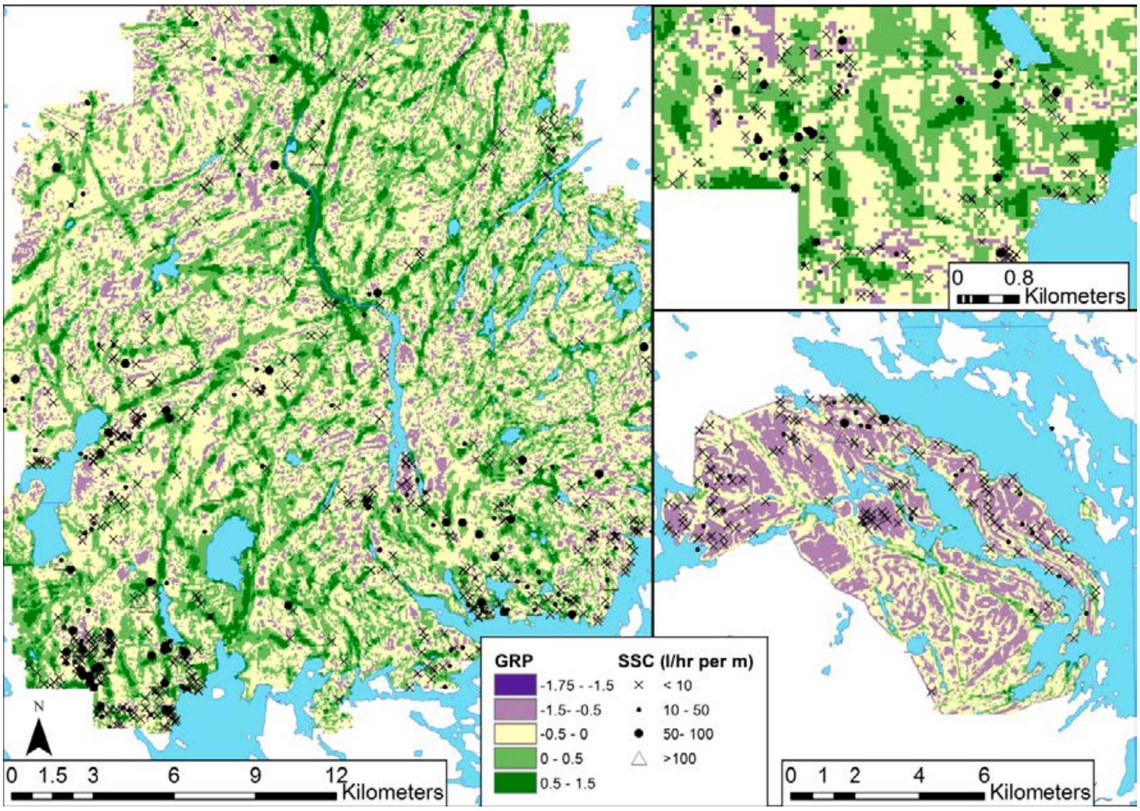


Figure 7-15. *An example of a groundwater resources potential (GRP) map from Vallentuna and Tyresö.*

Spin-off

Swedish coastal community planners 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 characterisation 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.

7.3.12 Geobiology of microbial mats in the Äspö tunnel

Activity leader

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 biomineralisation 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 7-16), NASA2156B, TASF. These flow reactors enable a contamination-free study of the spatial and temporal development of microbial mats and associated mineral precipitates. NASA2156B will not further be investigated, as the aquifer seems empty. Long-term experiments at TASF and TASA1327B are planned to continue for indefinite time.

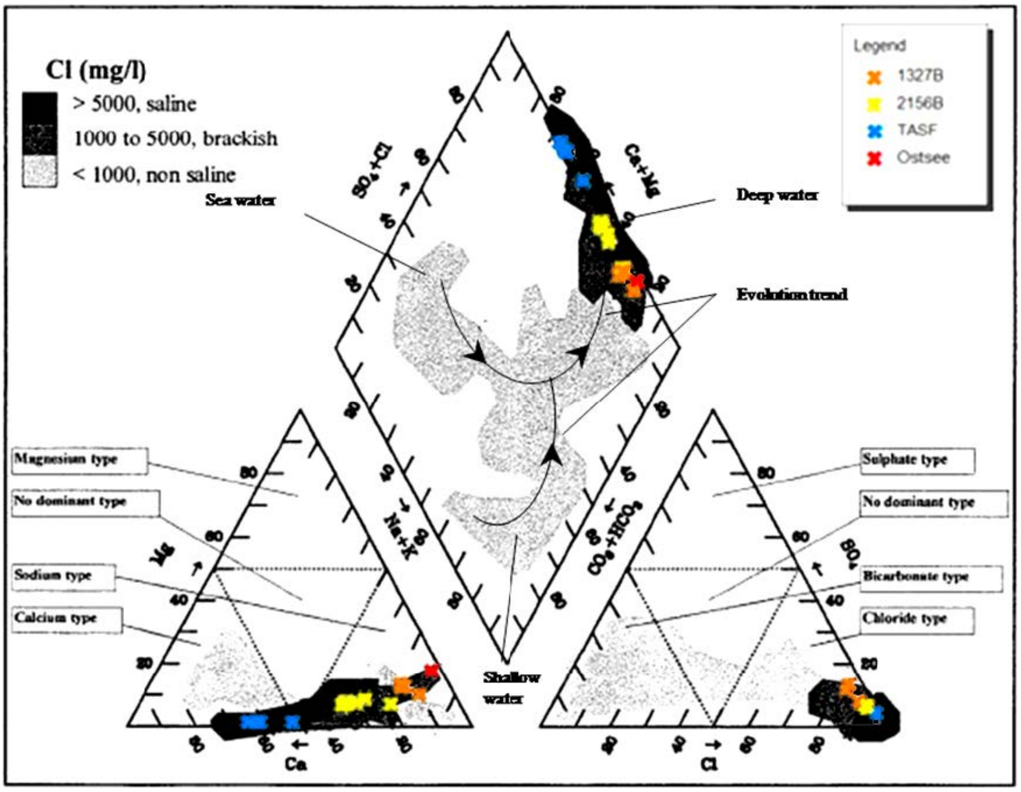


Figure 7-16. A standard Piper Diagram shows the three types of aquifers investigated. They can be separated according to their salinity, especially the Ca and Mg content. Diagram modified after Laaksoharju et al (1999).

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-oxidising 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 10^3- to 10^5-fold higher than in the feeder fluids whereas the rare earth elements and Y (REE+Y) contents were 10^4 and 10^6 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 C., Simon K., Ionsecu D., De Beer, D., Quéric N.-V., Reitner J., Thiel V. Trace and rare earth element accumulation and fractionation in microbial iron oxyhydroxides. Geochimica et Cosmochimica Acta, in review.)
- Green phototrophic microbial mats from the illuminated and aerated flow reactor at TASA1327B 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 localised 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. 2013).
- 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. Modelling 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 O_2 concentration. Given sufficient Fe^{2+} microaerophilic 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. (Ionsecu D., Heim C., Polerecky L., Ramette A., Haeusler S., Bizic-Ionescu M., Thiel V., De Beer, D. Probing the diversity of iron oxidising and -reducing bacteria in flow reactors connected to different aquifers of the continental subsurface (Äspö Hard Rock Laboratory, Sweden). Geomicrobiology Journal, in review.)
- We used iron oxidising 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 $L^{-1}d^{-1}$ and 30–280 mmol $L^{-1}d^{-1}$, 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 oxidised 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. (Ionsecu D., Heim C., Polerecky L., Ramette A., Haeusler S., Bizic-Ionescu M., Thiel V., De Beer, D. Biotic and abiotic oxidation and reduction of iron at circumneutral pH are inseparable processes under natural conditions. Geomicrobiology Journal, in review.)

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

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 oxidising 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 oxidising 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 (Heim et al. 2014).

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 characterise 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. 2013).

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 TASA1327B, 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.

7.3.13 Fossilised microorganisms at Äspö HRL

Activity leader

Magnus Ivarsson, The Swedish Museum of Natural History.

Aim of the project

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

Status of the project

The project is in its initial stage. Samples have been assembled from various drill cores and thin sections as well as single crystals have been studied with optical microscopy and Environmental Scanning Electron Microscopy (ESEM). Putative fossilised microorganisms have been observed in some samples (Figure 7-17) and at the moment the biogenicity of these possible microfossils are being established with raman spectroscopy, and during 2014 probably also with ToF-SIMS as well. Initial analysis with raman has confirmed the presence of carbonaceaous material which is a strong indication for organic remnants. The morphology of the microfossils suggests that they might be fossilised 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.

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 fossilised prokaryotes and fossilised eukaryotes in geologic material and (2) to use microfossils as paleo-indicators.

7.3.14 Structure and function of microbial communities in the deep biosphere

Activity leader

Mark Dopson, Linnaeus University.

Figure 7-17. *Putative fossilised microorganisms in calcite.*

Aim of the project

The purpose of the activity is to sample 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 16S rRNA genes and binning of sequences. The bioinformatic analysis will almost certainly provide (near) complete genome sequences of novel species.
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 water)? Are the populations in the terrestrial deep sub-surface the same as those in marine deep biospheres? How important are the recently discovered bacteriophages in the deep sub-surface to limit the bacterial population as well as mediating DNA transfer between cells?
3. Community DNA and RNA sequencing will identify the microorganisms' metabolic capacities and the genes that the microorganisms use under *in situ* conditions. This will be utilised 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 hypothesised abiotic H_2 generation?; and what are the roles of microorganisms in altering the geochemical environment?
4. Metabolic activity of deep biosphere populations. Matching community RNA to DNA sequences assigned to different species by "binning" will provide exact data regarding the active species within the population.

Status of the project

Samples have been prepared for prokaryotic metagenomes and test nucleic acid preparations have been submitted to SciLifeLab for next gneration sequencing. This quality control step will ensure high quality DNA has been prepared before all the metagenomes are submitted for sequencing. Viral nucleic acid has been prepared from 3 of the 4 tested boreholes (the deep saline water sample did not yield sufficient DNA for sequencing suggesting the viral numbers are too low). The samples have been submitted to SciLifeLab for next generation sequencing.

Further DNA preparations have been carried out in collaboration with Christine Heim and Danny Ionescu from a time series taken from reactors attached to boreholes. These samples await processing and submission for sequencing.

The *in situ* RNA sampling device (Figure 7-18) required to obtain valid RNA preparations from boreholes (i.e. under *in situ* pressure and redox potential) has been constructed and tested. Preliminary samples have been collected and await RNA preparation.

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 utilised to create a holistic model of the environment that can then be used to understand the links between biological and chemical processes.

7.3.15 Integrated fire protection, the SAFESITE project

Activity leader

Angelos Achiniotis, NeoSys AB.

Aim of the project

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

Figure 7-18. Sampling vessel for preservation of RNA from borehole water maintained under in situ conditions.

Figure 7-19. Smoke detector installed in the tunnel of Äspö HRL

Status of the project

The project has tested the instalations at Äspö during 2013.

Spin-off

Äspö and SFR will use the reports for their investments of new fire system.

7.3.16 Alfagate 2 – RFID WIRELESS- WIFI INTEGRATION in extreme environmental conditions

Activity leader

Angelos Achiniotis, NeoSys AB.

Aim of the project

The aim is to develop and integrate RFID techniques with WIFI technology in order to identify persons or objects in extreme environments (Figure 7-20). The project creates an open software structure, which will be integrated and tested with other Äspö HRL systems. This will be used for safety purposes and to increase process or production efficiencies. The project partners are involved in the oil, gas and mining industry, which also have similar requirements.

Status of the project

Installation of the system at Äspö will be completed during the first quarter 2014.

Spin-off

- To expand the company Neosys in Oskarshamn and to be able to give service and support for the products/systems in Sweden, this will lead to new employments and regional development.
- Cooperation with international companies such as Identic Solutions and Siemens is an important spin-off and several international companies can be involved in the future.
- Continuing development and testing of future technology.
- Äspö HRL has the latest system installed.
- NeoSys is developing an own active tag for specific markets.

Figure 7-20. *Possible applications for the RFID and WIFI technology.*

7.3.17 Corrosion protection of rock bolts

Activity leader

Bror Sederholm, Swerea KIMAB AB.

Aim of the project

Rock bolts made of carbon steel, galvanised zinc coated steel, zinc coated and epoxy coated carbon steel and stainless steel are alternatives for rock support in tunnels and underground rock cavities. There is an uncertainty regarding the lifetime of grouted rock bolts where the groundwater contains chlorides or where the groundwater composition is otherwise very aggressive.

In spring 2010 the research project Korrosionsskydd av bergbultar – Corrosion protection of rock bolts started, with the aim of establishing new requirements for corrosive protection of rock bolts and other products exposed to groundwater in bedrock rocks containing high chloride content. The project provide technical basis for the selection of materials and coatings.

Status of the project

Rock bolts made of carbon steel, galvanised zinc coated steel, zinc coated and epoxy coated carbon steel and stainless steel are alternatives for rock support in tunnels and underground rock cavities. There is an uncertainty regarding the lifetime of grouted rock bolts where the groundwater contains chlorides or where the groundwater composition is otherwise very aggressive.

In spring 2010 the research project Korrosionsskydd av bergbultar – Corrosion protection of rock bolts started, with the aim of establishing new requirements for corrosive protection of rock bolts and other products exposed to groundwater in bedrock rocks containing high chloride content. The project is also expected to provide technical basis for the selection of materials and coatings.

The final report presents the results of up to two years of corrosion testing of partially cast-in rock bolts exposed in rock walls in the Muskö tunnel and the Äspö tunnel. The investigation includes rock bolts made of uncoated carbon steel, stainless steel and galvanised steel and galvanised bolts with epoxy coating.

Test specimens were carbon steel round bars or commercially produced rock bolts: galvanised, galvanised with epoxy coating or made of stainless steel. In order to investigate the corrosion and the corrosion protection of grouted rock bolts, test specimens were manufactured by casting the test materials in Portland cement. Test specimens were inserted in pre-drilled holes in the Muskö and Äspö tunnels. The two tunnels were selected as test sites based on the known high concentration of chlorides in the respective ground waters.

In order to accelerate corrosion in the tunnel atmosphere, salt solution was sprayed on protruding parts of a number of rock bolts during the first year.

All tested rock bolts have been exposed to relatively stagnant water in the rock environment during most part of the test period.

Uncoated carbon steel

Corrosion pits up to 350 µm on protruding parts were found in the Muskö tunnel after two years. There was no visible local corrosion on the cast-in rock bolt parts or on steel surfaces submerged in water in the rock. On the surfaces that had been sprayed with 3% NaCl during one year the pit depth was up to 465 µm i the Äspö tunnel.

Rock bolts made of stainless steel

No visible corrosion attacks after one year of 3% NaCl spraying or after two years of corrosion testing in the tunnels.

Galvanised rock bolts

White rust was detected on surfaces exposed in the tunnels and on surfaces in the drilled holes. On bolts with an original zinc coating thickness of ca 45 µm the zinc coating was locally corroded away after being in contact with Portland cement during two years of testing. The corrosion rate for both cast-in surfaces and surfaces submerged in water in the rock were about 20 µm zinc per year. The high corrosion rate of zinc was unexpected.

Epoxy coated galvanised rock bolts

No visible corrosion on epoxy coated galvanised rock bolts were seen after two years of testing.

Effect of Portland cement on ground water

Analyses of the water in the drilled holes showed that the pH and alkalinity had increased after one year as an effect of the Portland cement. However, the water turnover was high so after two years the pH value had started to decrease and the alkalinity was again at the same level as before installation.

After two years of testing it is recommended that, unless the possibility of high chloride levels in the ground water can be excluded, rock bolts made of stainless steel, or galvanised bolts with epoxy coating should not be considered for very long technical service, since it has been shown that the alkalising effect of cement may disappear within two years and that zinc coating can be quickly consumed.

For a reliable evaluation of the technical service of various rock bolts in rock tunnels with high levels of chloride in the ground water two years is not a sufficiently long test period. The tests should continue for some more years.

Spin-off

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

Figure 7-21. *Mounted rock bolts in the Äspö tunnel are salt sprayed once a month during a period of one year.*

7.3.18 Development of a system used for quality control of rock bolt reinforcement

Activity leader

Leif Gustafsson, Malmfälten i Norr AB.

Aim of the project

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

Based on measurements with the Cavimeter equipment/method, the aim is to be able to classify grouted bolts based on Cavimeter measurements.

Status of the project

Field tests

Field tests are completed at Äspö Hard Rock Laboratory. Additional field tests were completed at LKAB in Malmberget in biotit during November 2013. Additional field tests were necessary in order to cover different rock types.

Computer simulations

Computer simulations with FLAC were completed in September 2013. The outcome was very similar to the field tests.

Cavimeter

A new version of the Cavimeter was developed with WiFi communication and a new software interface. This gave different possibilities for presentation of the results such as tablets, smartphones etc.

Spin-off

Our plan is to have the Cavimeter accepted as the international standard test method for quality control of grouted rock bolts in drifts/tunnels.

We have also developed the Cavimini as a tool that contractors can use to ensure that rock bolts are fully grouted.

Figure 7-22. *Setup of rock bolts at ÄSPÖ NASA 2376A ready to be tested.*

7.3.19 Geophysical detection of EDZ/HDZ around tunnels

Activity leader

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 utilised in optimising 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 7-23 and 7-24, respectively, with borehole camera observations of fracture quality overlaid.

The results of this work are currently under review for publication and a report will be available at nwmo.ca in mid 2014. This work has been sponsored by the Nuclear Waste Management Organisation of Canada in collaboration with the Norwegian Geotechnical Institute.

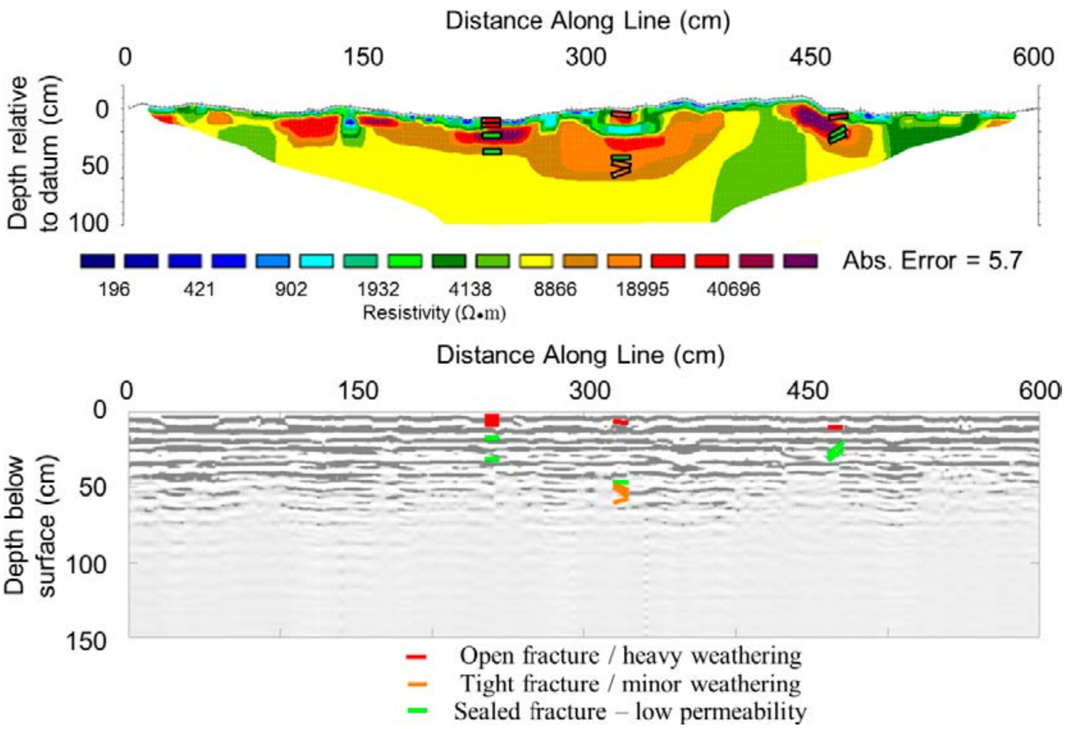


Figure 7-23. *The inverted resistivity model and stacked GPR data (lower frequency) overlain with known fracture locations from boreholes at NASA 2376A.*

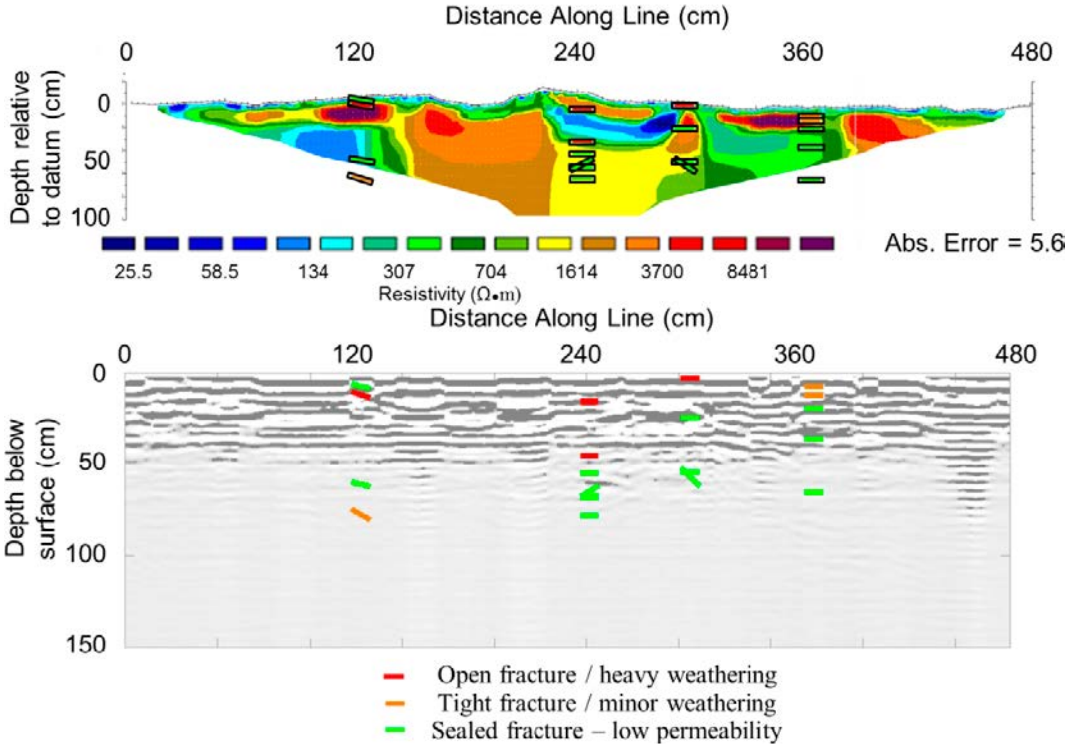


Figure 7-24. *The inverted resistivity model and stacked GPR data (lower frequency) overlain with known fracture locations from boreholes at NASA 2715A.*

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 summarised below:

1. Optimising 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. CO2 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.

7.3.20 Apatite fission-track analysis of samples from SKB Oscarshamn drillcores

Activity leader

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) and 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 KLX02 were collected in Oskarshamn, April 2013. The samples are currently being processed, but results are expected to available for presentation at the Geological Winter Meeting in Lund in January (Japsen et al. 2014).

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 recognised 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 et al. 1999, Larson et al. 1999a, b, Cederbom 2001, 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).

7.3.21 Master thesis: Hydraulictests in rock (Lisa Hernqvist, Vectura)

Activity leader

Lisa Hernqvist, Vectura.

Aim of the project

When performing construction work in rock below the groundwater table hydrogeology is an important aspect to consider. To reduce inflow of water from the rock mass to an acceptable level sealing of fractures by grouting is needed. In order to make a good grouting design the aperture of the fractures needs to be known. The actual fracture aperture varies along a fracture and cannot be measured and therefore the hydraulic aperture, which represents the open part of the fracture where flow can take place, is used. The hydraulic aperture is evaluated from hydraulic tests which are normally performed for sections of several meters at the time and does not give any information about how the flow is distributed between the individual fractures. The transmissivity distribution needs to be known to calculate the hydraulic aperture of the fractures.

Status of the project

In this thesis the distribution of transmissivity between the fractures within a section is investigated. The focus of the study is to investigate if the most water-bearing fracture can be considered to contribute to most of the flow. What can be considered to be most of the flow is a question of definition, here two different criterions have been used:

- The largest fracture contributes to 50 percent or more of the total flow in a section, *Tlargest* ≥ 50%.
- The largest fracture contributes to 80 percent or more of the total flow in a section, *Tlargest* ≥ 80%.

It has also been analysed if and how the transmissivity distribution is affected by section length, fracture frequency, borehole orientation, depth and size of total transmissivity.

The analysis is based on a large set of data for transmissivity in individual fractures and represents ungrouted crystalline rock from one test site.

In this study it was found that one fracture does not contribute to 80 percent or more of the total transmissivity. Most of the flow can however be assigned to the most water-bearing fracture for short section lengths if 50 percent or more is considered to be most of the flow. The transmissivity distribution was also found to vary with variations in section length, fracture frequency, borehole orientation, depth and size of transmissivity. All these factors do however not affect the likelihood that the most water-bearing fracture contributes to a large part of the total transmissivty even though the distribution of transmissivity is affected.

Spin-off

The project may be extended to further research after completion of the master thesis.

7.3.22 Hydraulic rock tests – Inflow Tests and Water Pressure Tests

Activity leader

Lisa Hernqvist, Vectura.

Aim of the project

Background

During rock tunnel projects, rock characterisation should be performed using test methods well suited to obtain the information of relevance for the purpose and which are easy to perform and evaluate. Two relevant topics concern (1) grouting design and (2) water inflow. For (1) grouting design the hydraulic aperture is an important parameter, suitable to assess whether a certain grout is able to penetrate the fracture. Predicting (2) water inflow is important, to assess the need of grouting and to estimate the grouting results.

Two types of hydraulic tests in boreholes in rock are inflow tests (IFT) and water pressure tests (WPT). Both these tests are performed in boreholes, as packer tests or double packer tests in sections of e.g. 3 m. the flow Q out of (for IFTs) or into (for WPTs) a section is measured, under a constant pressure (head h. Based on Q and h the transmissivity T can be estimated. The hydraulic aperture b can be calculated from T. The results from IFTs and WPTs differ to some extent. Because of the differences in the test methods, the results do not represent exactly the same thing.

Objectives

The aim of this project is to increase the understanding of what IFTs and WPTs represent, and for which purposes they are best suited.

Activities

The project included collecting data from boreholes which have been tested using IFTs and WPTs, analysing the data and to draw conclusions, and to summarise the conclusions in a report. The project is a desktop study. The project is finalised and reported.

Status of the project

The result, further understanding of the studied types of hydraulic tests and what application they are suited for, should be useful during design and interpretation of hydraulic characterisation of rock mass for grouting design.

7.3.23 Expert group for the harbour remediation project in Oskarshamn

Activity leader

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 7-25) have been held with the project leaders and personnel conducting the harbour remediation project. The expert group have reviewed the methodology, approach, monitoring program and documentation used within the project.

Figure 7-25. *The expert group supporting the harbour remediation project in Oskarshamn.*

Spin-off

The spin-off of the project is:

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

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

Activity leader

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 Linneaus University 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 7-26.

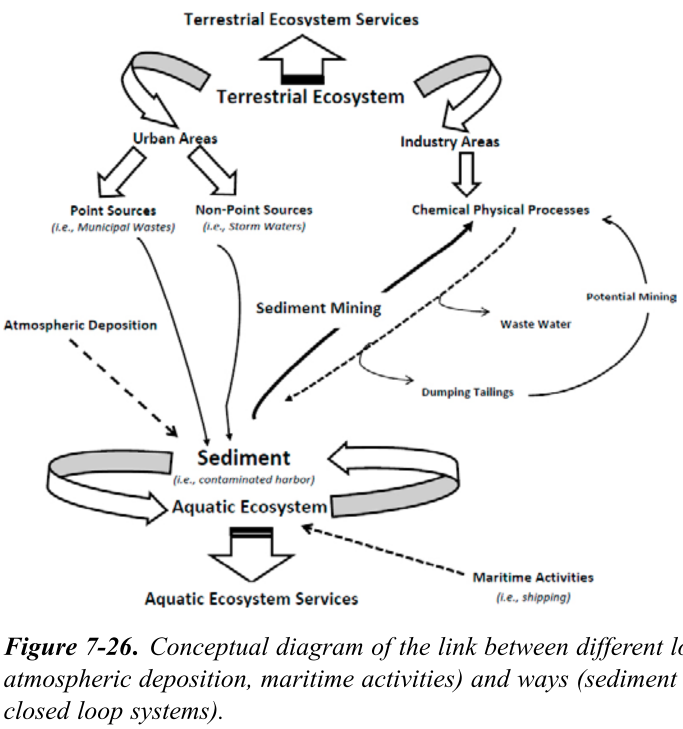


Figure 7-26. *Conceptual diagram of the link between different loops (sediment, urban and industry areas, atmospheric deposition, maritime activities) and ways (sediment mining to return them to the anthropogenic closed loop systems).*

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 Linneaus University 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 stabilisation 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.

Within the frame of the project the following has been produced:

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

The project work is completed and is in the process of compiling and submitting scientific papers.

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 Linneaus University 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.

7.3.25 Rock, harbor/bay/lagoon sediment and soil metal analyses instrument for fast areal distribution estimations

Activity leader

Wiiliam Hogland and Mats Åström, Linnaeus University.

Aim of the project

The XRF Delta Instrument is 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 can be used in projects for: 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 and 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.

Äspö HRL and Linneaus University need the instrument for studies in rocks, harbor/bay/lagoon sediments and soil metal analyses and to be used in ongoing Nova project and Swedish Institute Landfill Mining project where big volumes of harbor sediments and waste in old landfills that have been excavated and need to be properly managed.

The advantage of this equipment is that the analytical procedures can be done on-site avoiding the constraints of storage and transportation of samples to the laboratory.

A special interest will be directed towards the opportunity of performing mining of metals from contaminated sediments such as Cu, Zn, Pb, Ni, Co, Cd and Hg. The selection of metals will be based on existing data and measurements already carried out in the area and also those metals that have higher economical values and therefore higher interest in their recovery. On the other hand, metals with lower economical values can be reasonably targeted in remediation studies.

Spin-off

The instrument is very useful in many research projects and can be seen as a continuation of the research activities of ESEG (Environmental Science and Engineering Research Group) and the group of prof. Åström at Linneaus University and Äspö HRL. At Linneaus University there are 6 PhD students and 3 postdocs that have significant use of the instrument and will reduce the cost for expensive metal analyses. The results will be used in PhD and MSc theses and scientific papers.

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

Activity leader

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 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.

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

Status of the project

The course "Elements of the Back-end of the Nuclear Fuel Cycle: Geological Storage in Precambrian Bedrock" was given during 2013. The 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 2013, 33 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), University of Houston Downtown (USA), The AGH University of Science and Technology (Poland), The Warsaw University of Technology (Poland) and The Moscow Engineering Physical Institute (Russia).

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 specialisation 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/.

PETRUS II has come to an end and the work-packages have been delivered. The new application, PETRUS III, has been approved and Linnaeus University is part of this project. The project will focus on developing courses towards handling of spent nuclear fuel.

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.

7.3.27 Baltic Aquaculture Innovation Center (BIC)

Activity leader

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

A draft of the report, including information regarding aquaculture, suitable production systems (recirculating aquaculture systems (RAS)), suitable species (turbot and pike perch), breeding program, fry production, market evaluation, construction of BIC etc., was presented in September 2013. It was then decided that the report should be divided in two parts; the first part with a general description and functions of BIC (ready in January 2014), and the second part as a case study with BIC at Simpervarp/Laxemar (ready in May 2014).

Spin-off

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

Possible 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, 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.

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.
- **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 2013 was:

- 27 ongoing scientific projects representing a value of 50 million SEK.
- 100 researchers.
- 10 domestic and international universities.
- 2 public organisations.
- 5 companies.
- 29 reports (8) and publications (21).

In cooperation with SKB new research niches in the Äspö HRL tunnel have been finalised.

7.6 The Nova FoU steering committee and personnel

Nova FoU steering committee

Mats Ohlsson, Head of the Äspö Hard Rock 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 2013 nine organisations from seven countries in addition to SKB participated in the cooperation at Äspö HRL. Six of them; BMWi, NDA, NUMO, CRIEPI, JAEA and NWMO together with SKB formed the Äspö International Joint Committee (IJC), which is responsible for the coordination of the experimental work arising from the international participation.

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

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.

In 2013 SKB was actively involved in the European technology platform IGD-TP (Implementing Geological Disposal of Radioactive Waste Technology Platform) which was launched in November 2009. Up to the end of 2012 SKB held the position of Secretary General providing the Secretariat to the IGD-TP. In 2013 this position has been taken over by Andra. The platform´s vision is that by 2025 the first geological disposal facilities for spent fuel, high-level waste, and other long-lived radioactive waste will be operating safely in Europe. By the end of 2013 the platform involved twelve waste management organisations and in addition about 95 participants from industry, research organisations, research centres, academia and technical safety organisations in Europe. IGD-TP related research in the Äspö HRL according to the IGD-TP Deployment Plan has started with among others the LUCOEX and DOPAS projects. Work in the Äspö HRL is foreseen to be an increasingly important part of the joint work in the platform during coming years.

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

In the fall of 2013 NDA has also had one person stationed at the Äspö HRL. The main purpose has in particular been to follow and make a report on the development and tests of bentonite and its barrier functions.

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

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

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. The first prolongation happened in 2003. In 2008, the agreement 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 rocks for high-level waste repositories, and, especially to extend the knowledge on the behaviour of the engineered barrier system. Topics of special interest are:

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

The work carried out in 2013 is described below.

8.2.1 Microbe Project

The activities in the Microbe Project performed by Helmholtz Zentrum Rossendorf (HZDR)/ Institute of Resource Ecology (IRE), are finished.

8.2.2 Prototype Repository

GRS was the German research institution which participated in the Prototype Repository experiment since the time when the installation of the experiment was started. Electric resistivity measurements had been conducted in boreholes and backfilled tunnel sections in order to investigate time-dependent changes of the water content in the buffer, the backfill and in the rock. In these investigations advantage was taken of the dependence of the electric resistivity of geomaterials on their water content. The measuring programme included the monitoring of two electrode arrays in the backfilled drift above deposition boreholes 3 and 6, an electrode array in the buffer at the top of deposition hole 5, and three electrode chains in the rock between deposition holes 5 and 6.

In 2011, Section II of the Prototype Repository was excavated and the canisters retrieved from the deposition holes 5 and 6. As a consequence, the geoelectric measurements were reduced to measuring the backfill array in Section I. Since the backfill in Section I has been saturated for years, in 2013 these measurements were terminated as well.

In the frame of the project "Retrieval of the Prototype Repository at the Äspö Hard Rock Laboratory" electrodes retrieved from the backfill of Section II and from the buffer were inspected and the reasons for buffer electrode failure were investigated. In addition, water content and resistivity of samples from the buffer were measured in order to verify earlier calibration measurements. These investigations were performed in 2012 and are documented in brief in the 2012 Annual Report (SKB 2013b). In 2013 the contribution to the overall project final report was prepared. The report has not yet been published. A report covering all geoelectric measurements including the post-test investigations is also in preparation.

In 2012 BGR received four samples of the Prototype repository test (deposition holes 5 and 6). The blocks were sampled and investigated with respect to the mineralogical and chemical alterations including exchangeable cations. In 2013 analyses were finished and a BGR report was sent to SKB by July 31st, 2013. BGR reviewed officially the SKB-Posiva report on "Hydromechanical, chemical and mineralogical characterisation" (in press) following the instructions of the "Factual review plan". BGR visited two PR project meetings held in Lund and Stockholm. The project team and BGR agreed that BGR will submit a full peer review paper which is in the review process of the journal "Clay and Clay Minerals".

8.2.3 Alternative Buffer Materials

In 2013 the requested blocks of the second package of the alternative buffer material test were received. BGR decided to sample all blocks, i.e. the entire package two. All blocks were sampled in the established manner. The contact surface was scrapped off with a sharp knife and samples were drilled from each block with increasing distance to the heater (2, 5, and 8 cm). The quality of the samples was rather heterogeneous, see Figure 8-1. Most of them could be sampled properly but some disintegrated which complicated sampling.

All samples were dried at 60°C and ground using a mortar mill. In all samples the cation exchange capacity and the exchangeable cations were determined using the Cu-trien method. The results were summarised in the frame of the international PEBS workshop held at BGR in February 2014. Compared to the results of the ABM-package 1, the cation population is more homogeneous, i.e. most of the bentonites took up Ca leading to Ca-dominated bentonites. The cation population is displayed in the difference plot, see Figure 8-2. Not all blocks of ABM-1 were sampled, hence explaining the missing data. Data presented in Figure 8-2 was derived both from BGR and Clay Technology laboratory. The missing data of package 2 results from the fact that these blocks could not be properly sampled. Notably, the data presented in the ABM-2 plot represents excess salt corrected data which means, that if the sum of the exchangeable cations exceeded the total amount of charges (the CEC) then the cation population was corrected according to Dohrmann and Kaufhold (2010). In ABM-2 however this salt excess was much larger which has to be explained based on results of ongoing characterisation during 2014.

In the frame of the Long term test no BGR clay laboratory activities were performed in 2013.

8.2.4 Temperature Buffer Test

The activities in the Temperature Buffer Test formerly performed by DBE TECHNOLOGY are finished and reported (Jobmann et al. 2013).

8.2.5 Large Scale Gas Injection Test

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

Results of a preliminary study using an axisymmetric model and a gas pressure depended permeability approach were presented at the Lasgit meeting in Luxembourg.

Figure 8-1. *Examples for perfect blocks which were sampled in 1 mm, 2 cm, 5 cm, and 8 cm distance from the contact to the tube (left) and disintegrating blocks which were difficult to sample (right, block 26).*

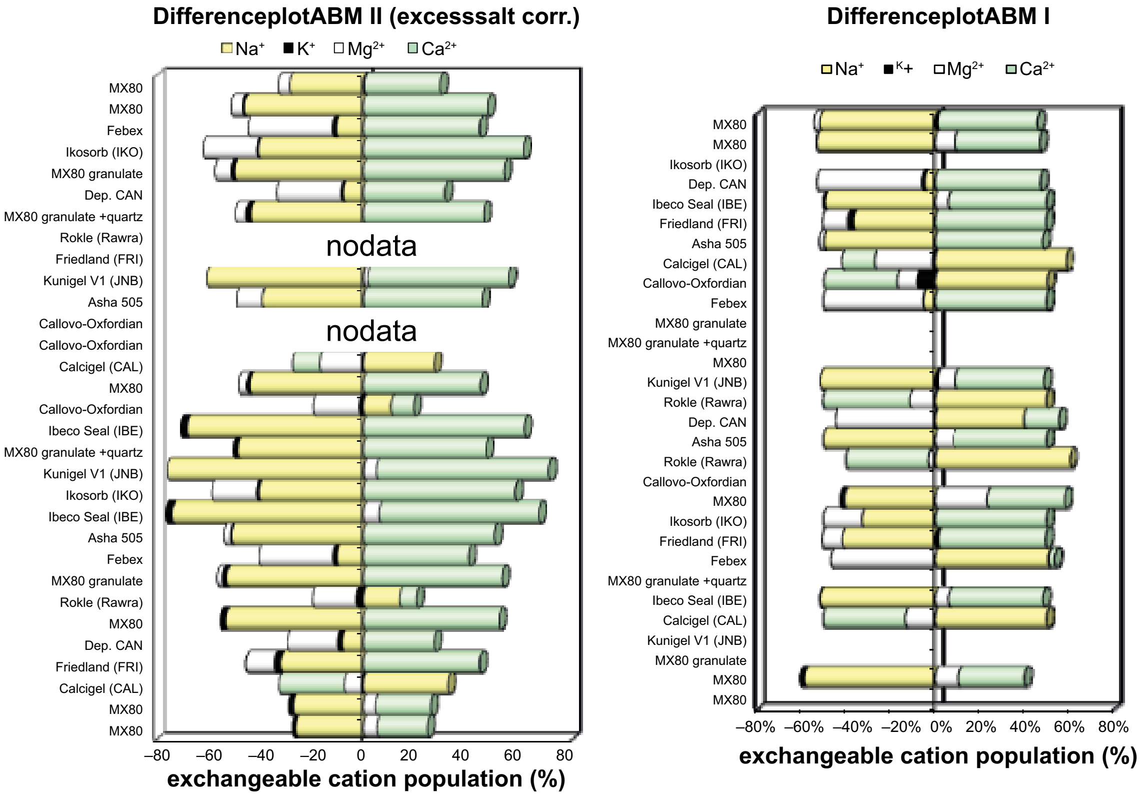


Figure 8-2. *Difference plots representing the cation population (interlayer composition) before and after the respective tests. All cation populations of ABM-2 (ABM-II) were excess salt corrected according to Dohrmann and Kaufhold (2010).*

8.2.6 Task Force on Engineered Barriers

In 2013, the focus of BGR's activity within the Task Force on Engineered Barrier Systems was on the sensitivity analysis assignment. The objectives of this task are to study the effects of parameter value uncertainties and model simplifications on the results of THM-coupled calculations of engineered barrier systems.

The sensitivity analysis task is extended by a code comparison, using the base case model as a reference case to compare the results of different codes and modelling teams. The code comparison is divided into three stages with increasing complexity of the coupled simulation:

1. Thermo-hydraulic calculation neglecting vapour diffusion.
2. Thermo-hydraulic calculation considering vapour diffusion.
3. Thermo-hydro-mechanical calculation.

To increase the significance of the code comparison, the three calculation stages are closely specified in a task description prepared by BGR. First results of the code comparison were presented and discussed at the Task Force meetings in London and Bern.

GRS´s activities comprise the following: A new boundary condition restricting water uptake to a maximum inflow rate has been formulated and implemented in the re-saturation code VIPER. This allowed in principle to calculate water uptake of the buffer in the BRIE experiment not only at the observed large water-bearing fractures but also over the areal matrix boundary.

For predictions of the water uptake in the BRIE test two cases were set up:

– Outflow from the strongly water producing borehole KO0017G01 concentrated to just one fracture of a width of 0.1 mm (case I).
– Outflow from the weakly water producing borehole KO0018G01 concentrated to a borehole section of one metre in height (case II).

The differences in the water uptake dynamics are illustrated in terms of the time-dependent distribution of the water in Figure 8-3.

The bentonite is called saturated when reaching a degree of saturation of 95%. This happens after about 240 days in case I, and after about 535 days in case II. As in case I, a localised inflow is described without considering 3D-effects. The value of 245 days for case I represents only a lower limit for the real re-saturation time.

The slightly changed trend in the water content distribution between 203 and 244 days is a consequence of the increased water mobility in the interlamellar space that comes after completing the second hydrate layer , see Figure 8-3 b. Hydration in a third layer begins above a water content of about 17%. (Kröhn 2011)

At Clay Technology a water uptake test supporting the BRIE-experiment had been performed. The results for 107 days and 203 days were the basis for an additional benchmark within Task 8d. The conditions for this test were chosen to comply with a horizontal slice of bentonite in mid-height of the vertical cylindrical bentonite column. They matched the GRS re-saturation model for unrestricted water uptake so that a model very similar to the model for Task 8c could be used to simulate the test. As the results for Task 8c were produced without knowledge of the new benchmark they could be taken as a blind prediction.

While the water content distributions calculated in Task 8c matched the measured distributions in the water uptake test qualitatively quite well already, the simulated uptake was a bit too fast. However, after adapting the model geometry and correcting the interlayer tortuosity from 0.75 to 0.28 the model results matched the measurements even better, as shown in Figure 8-4.

8.2.7 Task Force on Groundwater Flow and Transport of Solutes

GRS´s contributions in the Task Force on Groundwater Flow and Transports of Solutes were as follows: Approximately the same approach for the flow model in Task 8d was used as for Tasks 8b and 8c. The main conceptual difference was to include a so-called "skin" at the drift and borehole walls.

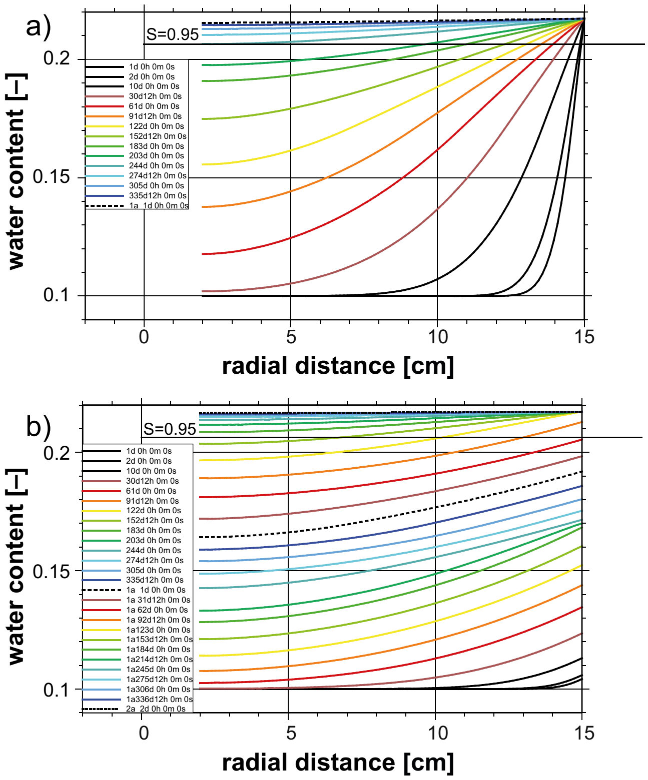


Figure 8-3. *Development of the water content distributions; case I: dynamics at free access to water, case II: dynamics at restricted water supply*

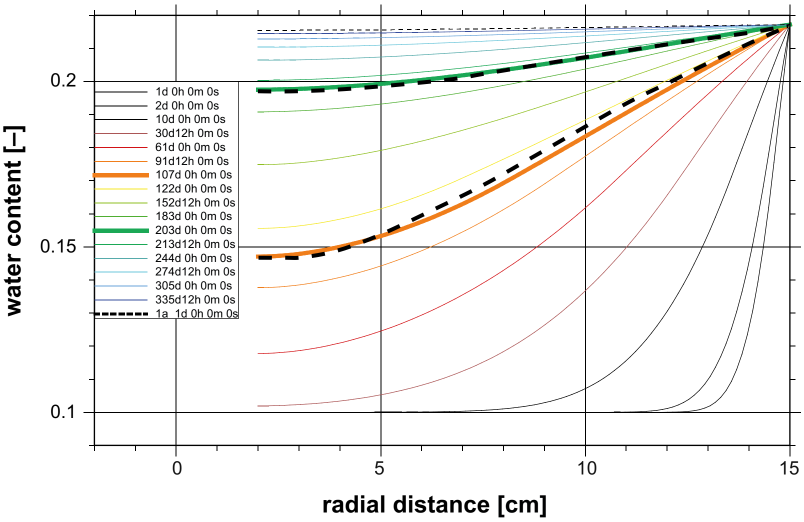


Figure 8-4. *Prediction of the transient water content distribution in the water uptake test (measured curves in dashed black lines).*

The expression "skin" means a narrow zone of significantly reduced permeability. While the idea of such a skin appears to be rather widely spread among the fractured rock modelling community there are (to our knowledge) only two reports corroborating this concept with observations from the field – namely Stripa (Olsson et al. 1992) and Äspö (Kull et al. 2002). Ideas about the extension and the related permeability reduction of such a skin were derived from these reports and formed a basis for the implementation of skins in the new flow model. The revised model allowed also a reduction of permeability where the large deterministic fractures were located within this skin. In Figure 8-5 a part of the model area is shown where the skin around the TASD-tunnel is partly removed and around the TASO-tunnel even totally omitted. Also not shown are the borehole skins outside the tunnel skins.

Surprisingly, the set of permeability values used for the reference case provided already a match with the measured and estimated outflow rates that could only marginally be improved by further calibration.

Three of six of the calculated flow rates deviate from measured values in a range of ±5, five within a range of ±10. This is certainly no proof for a correct representation of reality by the model; however, it indicates that a good approximation within the limits of the model concept has been found. The remaining differences were mostly due to the uncertainties introduced by local background fractures.

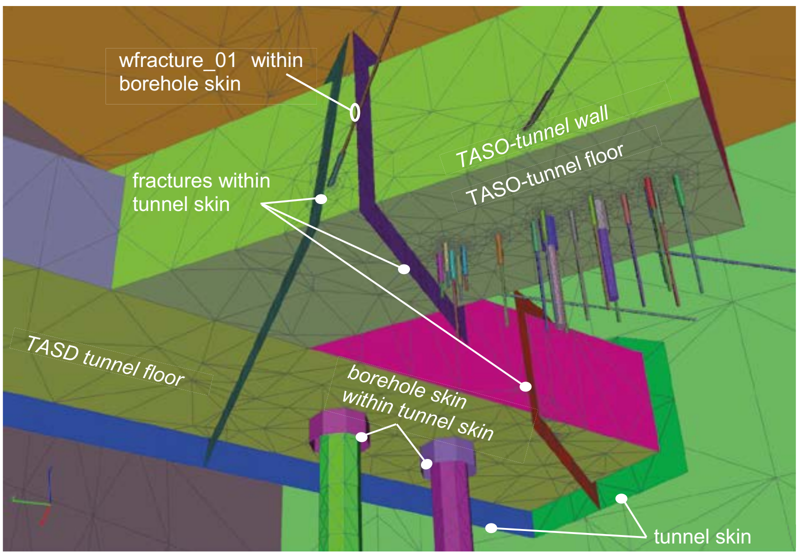


Figure 8-5. *View from below at the BRIE-model for Task 8d.*

Measured outflow rates varied from borehole to borehole up to two orders of magnitude (where outflow could be measured at all) despite the fact that they were located at a distance of only 1.5 m from each other. This introduced a considerable uncertainty in the deterministically calculated model responses. It also questions some of the tasks because a deterministic approach was applied to a problem that can be described to a great extent just in terms of geostatistics.

8.3 NUMO

In 2013 the Nuclear Waste Management Organisation of Japan (NUMO) was involved in two Äspö Hard Rock Laboratory projects, namely KBS-3H Multi Purpose Test (MPT) and Retrieval Project of Prototype Repository.

In particular NUMO sent two secondments during design phase, preparatory phase and also implementation phase of the KBS-3H MPT in order to obtain information NUMO requires and also practical experience.

In addition NUMO's public relation team visited Äspö HRL in order to produce a film to introduce the activities at Äspö.

8.3.1 KBS-3H Multi Purpose Test

NUMO has been developing a new disposal concept which is called "Prefabricated EBS Module (PEM) concept". Within the PEM concept NUMO has several options depending on the size of the gaps between tunnel surface and PEM container, and also on the type of the PEM container, namely semi-water tight container and perforated container. The study is mainly a desk study to date, except for some prototype test carried out above ground by a Japanese research organisation.

SKB and Posiva initiated a demonstration experiment for the KBS-3H concept which contains a supercontainer system. The supercontainer system has similarities with one of the NUMO's PEM concepts and NUMO thought it would be a good opportunity to obtain information and experience for evaluating the practicality of the PEM concept. Thus NUMO decided to be involved in the KBS-3H MPT. As a form of the involvement, NUMO sent secondments to Äspö HRL in order to obtain direct experience on site. The NUMO's involvement started in September 2012 with taking an intensive training course to learn the SKB's way of work at Äspö HRL. Since then NUMO sent secondments during the planning phase, preparatory phase and implementation phase between the period of October 2012 and December 2013 (see Figure 8-6). There was a total number of 8 man-months of NUMO'secondment work time at Äspö. The involvement in the KBS-3H MPT provided valuable information and experience and it will contribute to the NUMO's PEM study.

Figure 8-6. *Involvement of NUMO's engineer in the KBS-3H MPT.*

The emplacement of supercontainer was successfully completed in December 2013 and the NUMO's involvement in the KBS-3 MPT in the current stage thereby ended. Currently discussion is on-going on further involvement in the monitoring and dismantling phases in the future.

8.3.2 Prototype Repository

NUMO hosted the 4th International Project Committee on Retrieval of Prototype Repository in Japan between Thursday, 29th January and Wednesday, 30th January. The meeting was held at the NUMO's head-quarter in Tokyo.

Prior to the regular committee meeting, a half a day semi-open type seminar was organised and Japanese experts on engineer barrier systems were widely invited from NUMO, JAEA, CRIEPI and RWMC. The seminar captured a lot of interest from the Japanese experts and more than 30 participants participated in the seminar. During the seminar key findings from the Retrieval of Prototype Repository were introduced by SKB, Posiva and Clay Technology and active discussions and opinion exchange were held.

During the international committee meeting new findings from the project were introduced by the experts responsible for the project activities. The report production and reviewing procedure were also discussed during the committee meeting, see Figure 8-7.

Following the international committee meeting a field trip to the Mizunami Underground Research Laboratory (MIU) was organised on Friday, January 31st 2013, see Figure 8-8. MIU is constructed in a crystalline formation which has similar characteristics as ÄSPÖ Hard Rock Laboratory.

8.3.3 Production of a PR video at the Äspö HRL

In 2013 NUMO produced a series of video clips in order to introduce the advanced programs in European countries in the area of geological disposal. Thus NUMO visited Sweden, Finland, France and Switzerland to film in May–June 2013. In each country NUMO visited a wide range of organisations including implementer, research facilities, regulators and local municipalities. As research facility NUMO visited underground rock laboratories because they play important roles in the RD&D work in each country.

In Sweden NUMO filmed at the Äspö HRL and Canister Laboratory as research facilities. At ÄSPÖ series of interviews to the SKB's experts were organised at each experimental site, see Figure 8-9.

The video clips will be available at a specifically designed website in spring 2014 (a link will be available from the NUMO web site).

Figure 8-7. *The 4th International Project Committee meeting held at the NUMO office in Tokyo in January 2013.*

Figure 8-8. *International Project Committee visited the Mizunami Underground Reseach Laboratory in Japan.*

Figure 8-9. *Interview of SKB expert at the ÄSPÖ Hard Rock Laboratory.*

8.4 CRIEPI

CRIEPI has been developing the thermal-hydrological-mechanical (THM) coupling 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 the 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 deposition hole 6. All three tasks had been conducted in 2012. CRIEPI revised the third task of PR, THM axisymmetric modelling, in 2013.

Figure 8-10 shows the domain and boundary conditions for PR simulation. The Finite Element (FE) mesh consists of 3,669 nodes and 3,668 elements. At first, the permeability of surrounding rock mass was calibrated. Surrounding rock mass was divided into three regions, which were the regions around TBM tunnel, around the deposition hole 6 and the outer region. The permeability of outer regions was determined from the results from 3D H simulation before installation. Permeability of the other two regions was determined so that measured water inflow was reproduced in the simulation. Water inflow around TBM tunnel was converted in consideration with volume difference of the TBM tunnel in the 3D and axisymmetric model. The results of the calibration are shown in Figure 8-11.

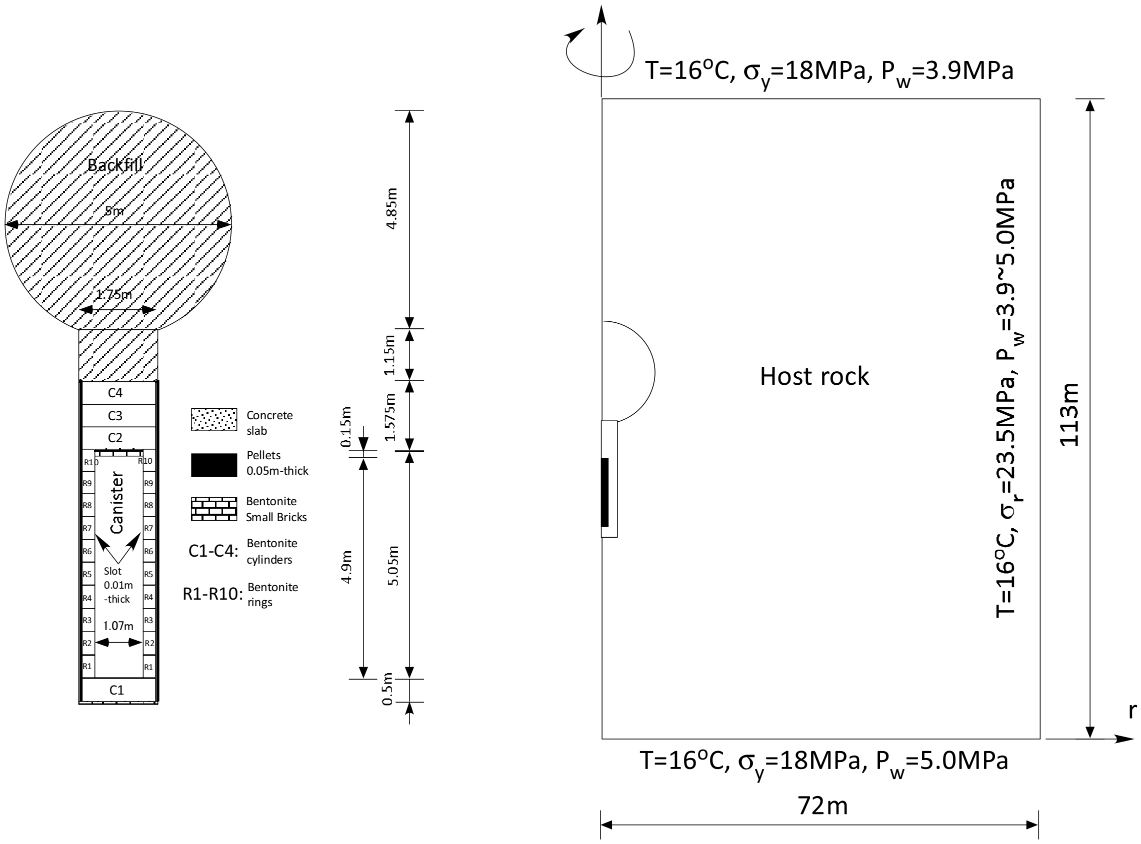


Figure 8-10. Analytical domain and boundary conditions.

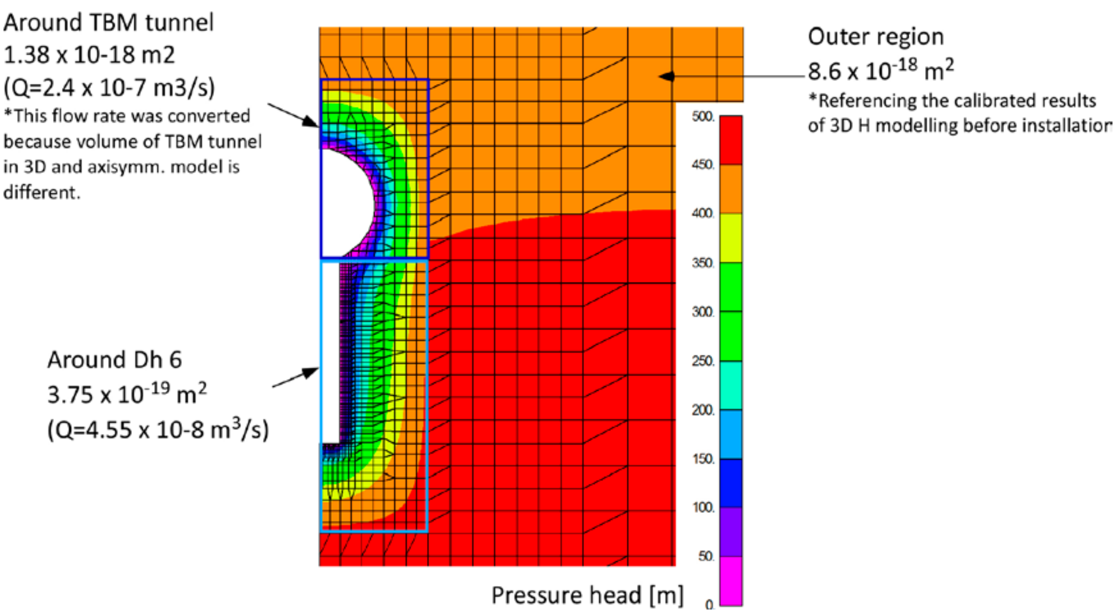


Figure 8-11. Contour of pressure head and calibrated permeability around deposition hole 6.

Figure 8-12 shows the temperature evolution in the R5 block on the mid-height of the canister in deposition hole 6. Numbers in the legend shows the distance from the center axis of the deposition hole (r) in the unit of mm. At r=585 mm, maximum temperature is almost 68 deg. C. Calculated temperature was lower than the measured because the effect of other heaters were not considered. Figure 8-13 shows the suction evolution in the R5 block in deposition hole 6. Saturation was achieved after almost 2,500 days in outer part of the R5 block. Figure 8-14 shows the calculated profile of saturation and dry density. Better agreement with measured data was obtained in 2013 after revising the hydraulic properties of bentonite.

As the other work, a series of sensitivity analyses have been conducted in order to understand which material parameters and boundary conditions have great effects on numerical results. Figure 8-15 shows the finite element mesh around the canister top and observation points. Figure 8-16 and Figure 8-17 shows the temperature and suction evolutions, respectively. Calculated maximum temperature was 81.3 degree C and calculated maximum suction was 63.3 MPa.

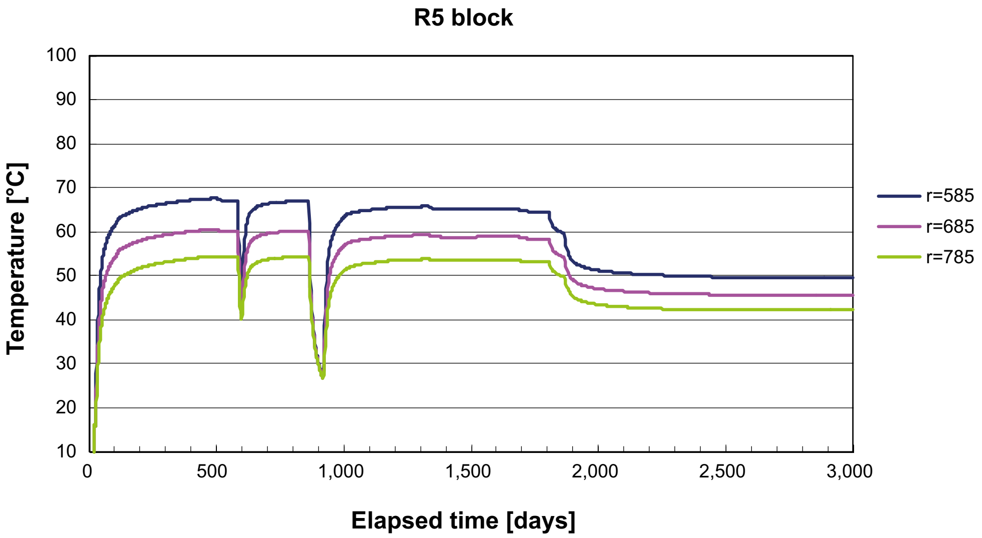


Figure 8-12. *Calculated temperature in bentonite on the canister mid-height in deposition hole 6.*

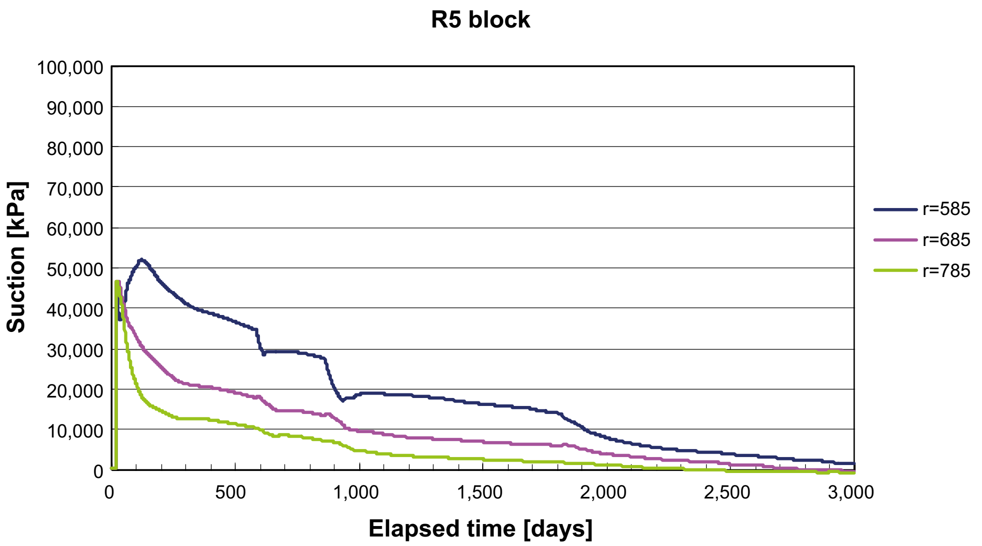


Figure 8-13. *Calculated relative humidity in bentonite on the canister mid-height in deposition hole 6.*

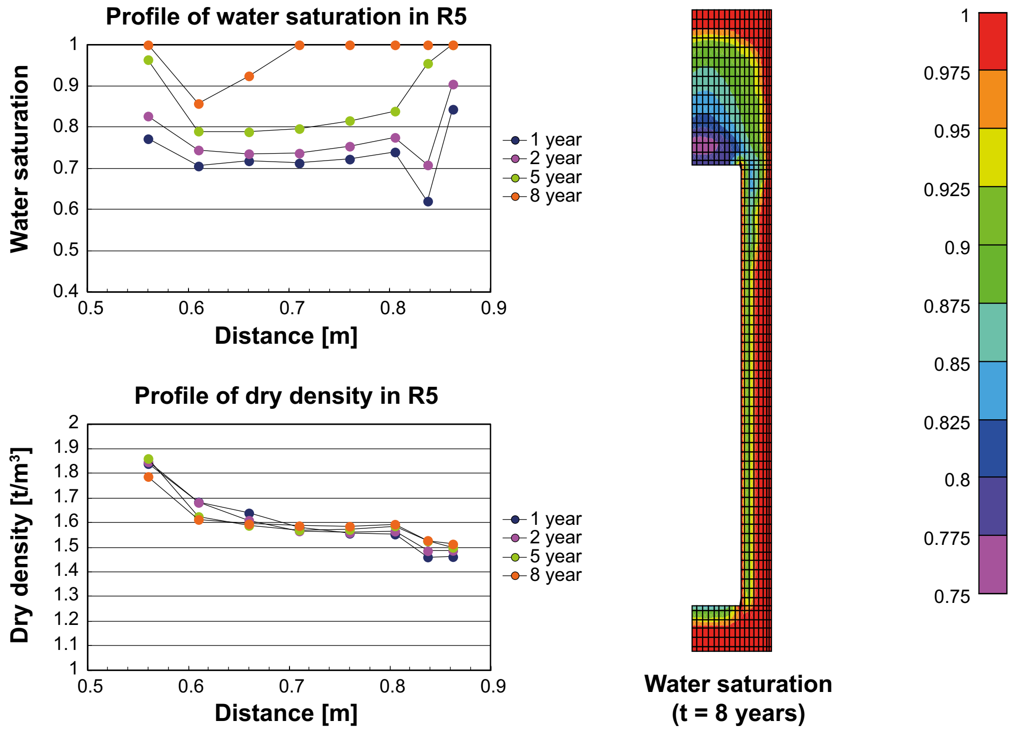


Figure 8-14. *Profile of water saturation and dry density in R5 block.*

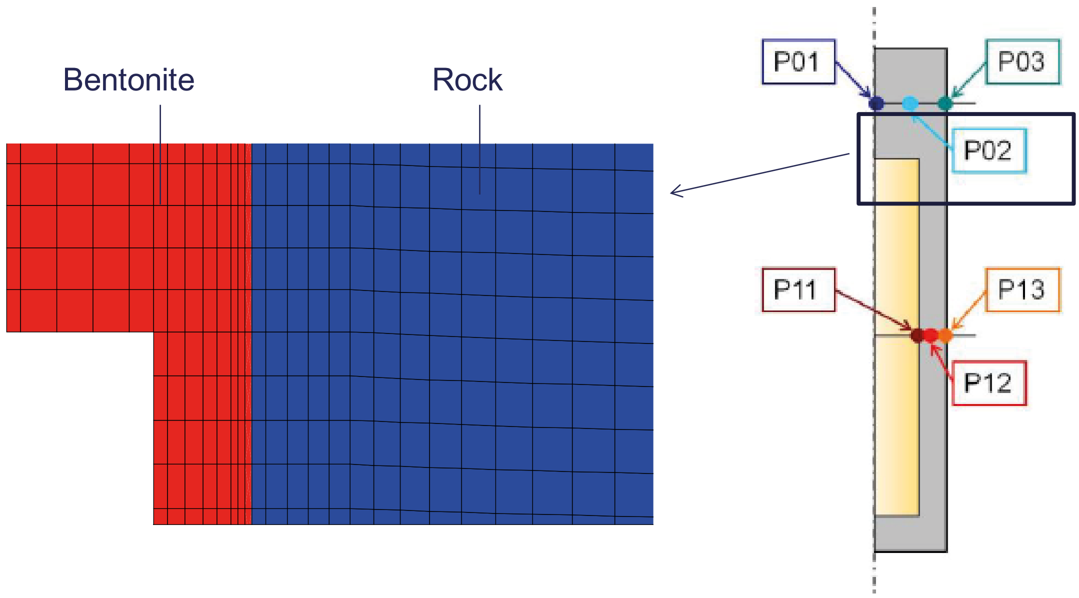


Figure 8-15. *Finite element mesh in deposition hole and observation points in Sensitivity Analysis.*

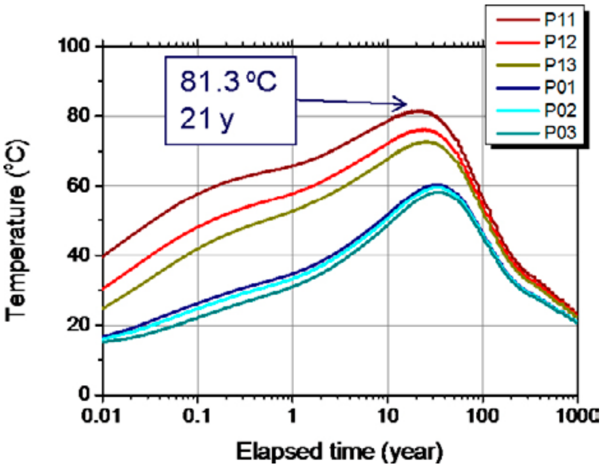


Figure 8-16. *Temperature evolution in the base case of Sensitivity Analysis.*

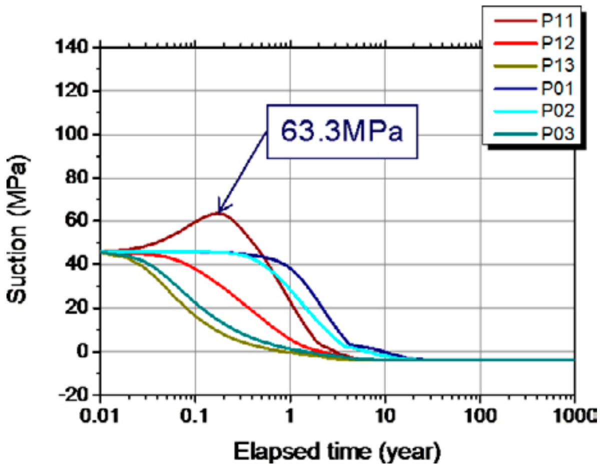


Figure 8-17. *Suction evolution in the base case of Sensitivity Analysis*

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 2013 include the following:

Improve understanding of site characterisation technologies, particularly flow logging and hydraulic interference.

- Improve understanding of flow and transport in fractured rock.
- Improve methodologies to assess uncertainty of hydrogeological model.
- Improve understanding of underground research laboratory experiments and priorities.

These activities are designed to provide and support technical basis for geological repository program of high-level radioactive waste in Japan in terms of both implementer and regulator, which includes repository siting and safety assessment.

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

JAEA participation in the Äspö Task Force on Groundwater Flow and Transport of Solutes during 2013 focused on development of modeling capabilities for coupled flow in fractured rock and bentonite, within the context of "Task 8", simulating the *in situ* experiment, Bentonite Rock Interface

Experiment (BRIE) at Äspö Hard Rock Laboratory. The objective of JAEA's participation in Task 8 is to improve understanding, characterisation procedures, and analysis methodologies for the interface between bentonite and water conducting fractures at the scale of a disposition hole.

During 2013, JAEA participated in the Groundwater Flow and Transport of Solutes Task Force meeting at Porvoo, Finland, June 3-5 and the Task 8 modeling workshop at Rånäs, Sweden, November 12–13.

Task 8 – Modelling the Bentonite Rock Interaction Experiment

During 2013, JAEA focused primarily on Task 8D, which requires modeling of the BRIE *in situ* experiment site and the TASO tunnel, within a 40 m × 40 m × 40 m block region, see Figure 8-18. The BRIE includes several probing boreholes drilled around TASO tunnel, and two 30 cm diameter boreholes enlarged along the KO0017G01 and KO0018G01 holes.. At five probe holes drilled from the tunnel floor, the inflow rate and head distribution were measured. These measured values are used to calibrate the hydrogeological model. Task 8D modeling includes predicting the inflow distribution to the enlarged boreholes, and water movement within bentonite columns emplaced in those holes.

A simulation system implicitly coupling two codes, FracMan/MAFIC (Dershowitz et al. 2012, Miller et al. 2001) and Thames (Chijimatsu et al. 2000) have been implemented in the Task 8 studies, see Figure 8-19. In rock, a 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 MAFIC. Groundwater movement in rock matrix adjacent to the fractures is neglected in this study, in order to study an effect of how fracture flow contributes to the re-saturation behavior in bentonite. Thames is a thermo-hydro-mechanical coupling code for continuous porous media. In this study, re-saturation and fluid movement behavior in the bentonite based on Richards equation (Bear 1972) is solved by Thames. Two utility programs, MTOT (Mafic to Thames) and TTOM (Thames to Mafic), have been developed to provide an interface between these two codes. Heterogeneous groundwater flow rate to 30 cm diameter boreholes for installing bentonite columns is calculated by MAFIC, and it is transferred to Thames, by the utility program MTOT. MTOT also identifies elements and nodes at the surface of bentonite column models corresponding to the location of water flowing fractures which are intersected by 30 cm boreholes, and groundwater flow rate is assigned to the bentonite surface along the fracture traces. A dumping factor to moderate high flow rate from fracture to each node of bentonite surface to prevent transferring unrealistic high flow rate is defined by MTOT. Once the surface node has been saturated, the flow boundary condition is replaced with a headboundary condition.

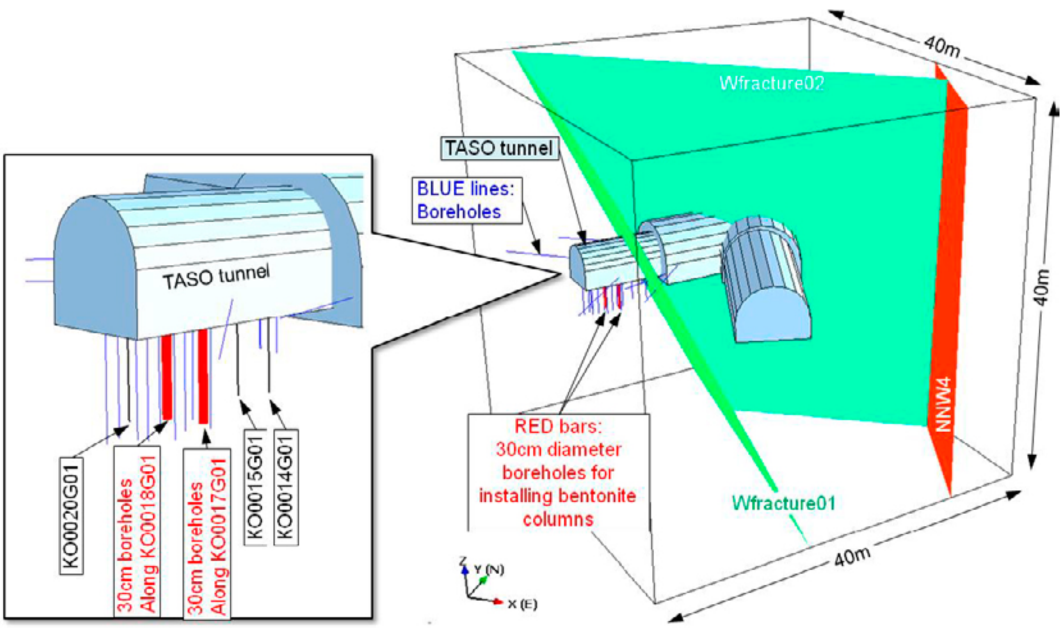


***Figure 8-18.** Location of 30 cm diameter boreholes for installing bentonite columns of BRIE in Task 8 modeling region, and deterministically defined large faults, NNW4, Wfracture01 and Wfracture02.*

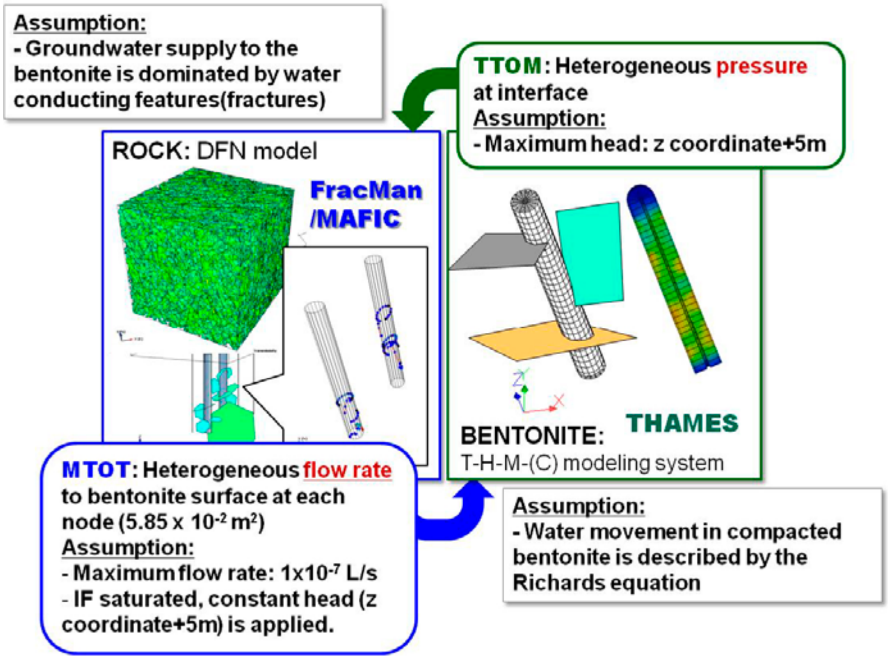


Figure 8-19. *Conceptual illustration of a simulation system coupling FracMan/MAFIC and Thames with two interface utility programs, MTOT and TTOM.*

TTOM transfers head values at surface nodes of bentonite model calculated by Thames to the adjacent fracture node for MAFIC calculations. If pressure value calculated from Thames is negative (caused by suction), atmospheric pressure is set at the walls of 30 cm boreholes MAFIC calculations. Another dumping factor to moderate high pressure from bentonite surface nodes to fracture nodes.

Task 8D is divided into two parts, Task 8D1 and Task 8D2. Figure 8-20 shows the conceptual illustration of the structure of Task 8D. Incorporation of bentonite is not considered in the Task 8D1 exercise. Instead, the inflow to the open 30 cm boreholes is addressed and is intended to be compared with field data from the BRIE experiment. Task 8D2 addresses the wetting of the bentonite based on the flow model established in Task 8D1. The wetting results are used as predictions of the field results of the on-going field experiment of BRIE.

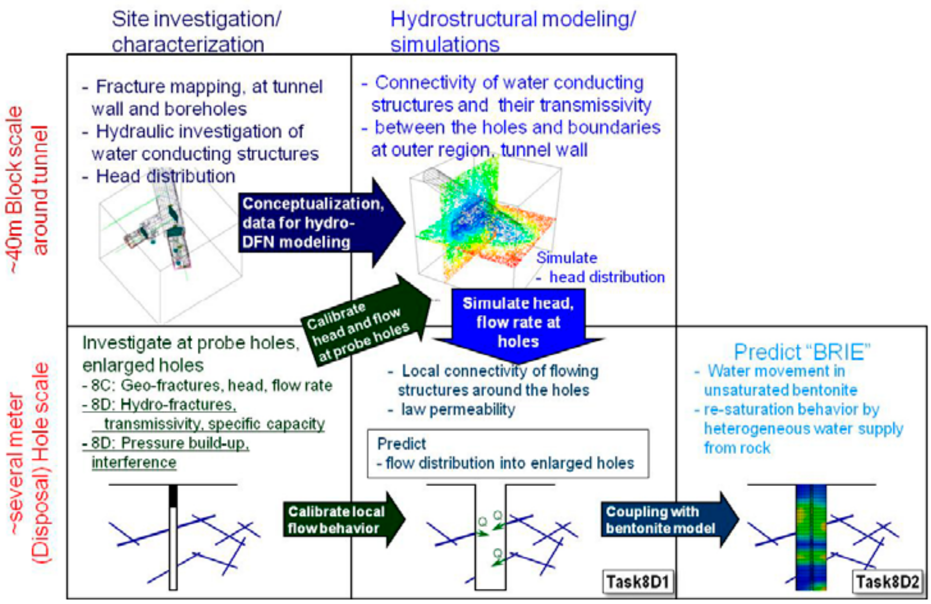


Figure 8-20. *Conceptual illustration of Task 8D exercise.*

The models previously assessed in Task 8C (see SKB 2013b, Section 8.5.1) are modified by the new data provided by Task 8D specification.

For example, observed water conducting fractures are deterministically added to the model. The location and orientation, and transmissivity of these water conducting fractures are provided. b The radius of these fractures is arbitrary defined 1 m for KO0017G01 and 0.5 m for KO0018G01, to avoid direct intersection to the other probing boreholes.

Also new specific capacity data is used to calibrate hydraulic conditions around the BRIE area. The model calibration is conducted by three steps as illustrated in Figure 8-21.

The modified models are applied to calculate the groundwater flow rate to 30 cm diameter boreholes, and to the coupling simulation for predicting "BRIE" re-saturation behavior in bentonite. Figure 8-22 and Figure 8-23 show an example of the calculation results for head distribution and groundwater flow distribution at the wall of 30 cm diameter boreholes, respectively. In the whole model region, the head distribution is smoothly decreased towards a tunnel that is caused by an effect of averaging out of heterogeneously distributed DFN. In a local scale around 30 cm boreholes, heterogeneously distributed groundwater flow due to a local connectivity of fractures to the boreholes is reproduced. Consequently, the localized groundwater flow provides the heterogeneous re-saturation behavior in bentonite columns installed in 30 cm boreholes by the coupling simulation. An example of the bentonite re-saturation simulation result is visualized in Figure 8-24, which shows the time-dependent change of saturation distribution at vertical cross section for both 30 cm boreholes. In both 30 cm boreholes, the saturated areas are initiated by the points intersecting groundwater flowing fractures and are propagated to the bentonite column center and both upward and downward of the columns.

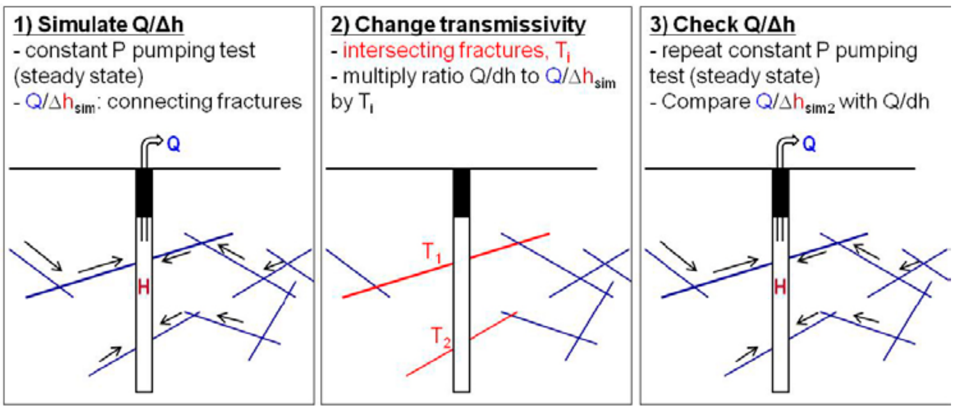


Figure 8-21. *Conceptual illustration for calibrating specific capacity around the five probe holes.*

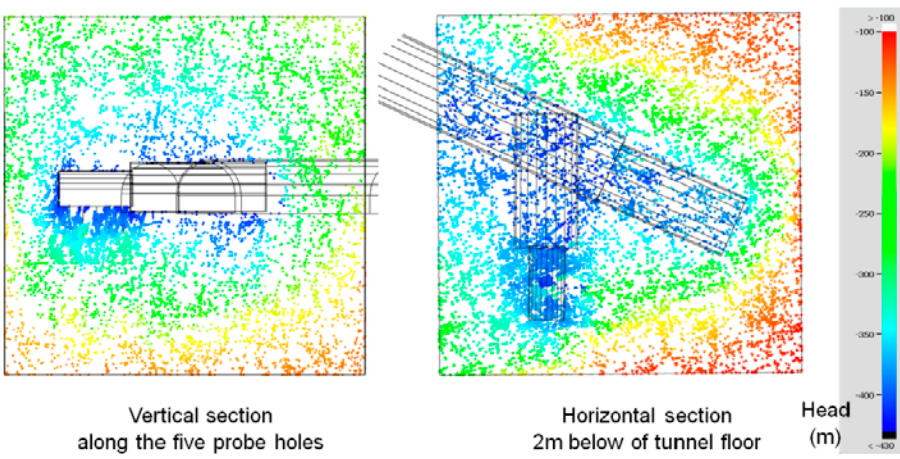


Figure 8-22. *Example of simulated head distribution at vertical and horizontal cross sections: Fracture conditioning case model.*

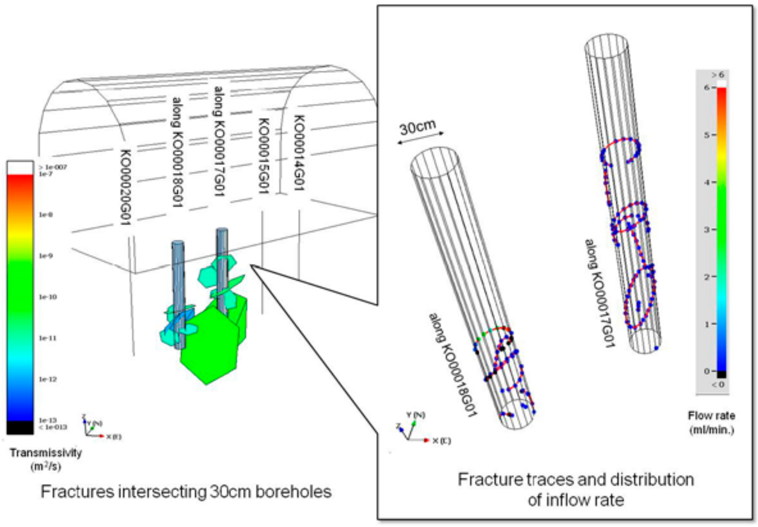


Figure 8-23. *Example of simulated flow rate to 30 cm diameter boreholes under atmospheric pressure condition at the boreholes: Fracture conditioning case model.*

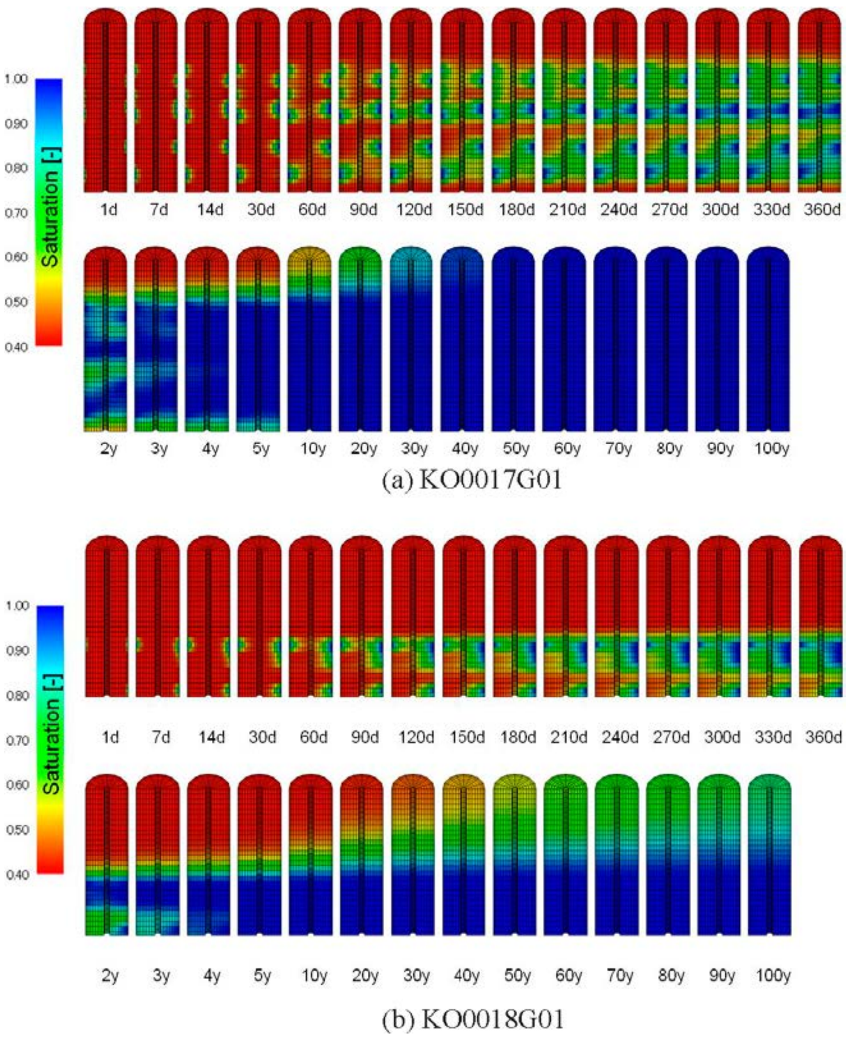


Figure 8-24. *Example of simulated saturation distribution at bentonite columns, vertical cross sectional view: Fracture conditioning case model.*

8.5.2 Alternative Buffer Materials

EPMA, HRTEM (EDS, AFM, µ-XRD and FESEM (EDS analyses were conducted on the bentonite material (Kunigel V1) retrieved from parcel 2 to identify mineralogical changes in the bentonite. Fe-rich mineral formed by the alteration of smectite was identified at the interface between the iron heater and the bentonite block by HRTEM analysis. An alteration mineral with a unit layer thickness of 0.6–0.8 nm was observed by AFM analysis. This mineral observed by these analyses is presumably identical to the alteration mineral identified in the Kunigel V1 retrieved from ABM parcel 1.

8.6 NWMO

In 2013, the Nuclear Waste Management Organisation (NWMO) effort under the Äspö Project Agreement was supported by the University of British Columbia, the University of New Brunswick and Geofirma Engineering. The results of this work are briefly described below.

8.6.1 Large Scale Gas Injection Test

NWMO is providing modelling support for the Large Scale Gas Injection Test using the TOUGH2 code modified with pressure-dependent permeability and capillary pressure to simulate microfracturing of the bentonite buffer surrounding the container. In 2011, 3D simulations using the modified TOUGH2 code were performed for the 2009 gas injection test, which revealed complex gas propagation and migration behaviour within the partially water-saturated bentonite. The modelling was promising in its ability to represent gas breakthrough at the injection port. However, the simulated gas propagation was too slow and diffuse, with gas predicted to appear at the rock wall immediately adjacent the injection port rather than at the opposite side of the container as observed.

In 2012/2013, further modelling of the 2009 gas injection test was conducted, using additional information and data. Subsequent experimental data gathered after the 2009 test suggests that all pressure responses measured during the experiment occurred at the bentonite-canister interface. Analysis of the 2010 gas injection test data, for which hydraulic test data indicate fully bentonite saturation being achieved, similarly show all responses at the bentonite-canister interface, as illustrated in Figure 8-25. The focus of modelling the 2009 and 2010 gas tests, therefore, shifted towards the bentonite-canister interface, and included modifications to the pressure-dependent permeability functions to improve the model's ability to simulate a discrete pathway. The results of the modelling will be documented in 2014.

8.6.2 Task Force on Engineered Barrier Systems

NWMO became involved in the Äspö Task Force on Engineered Barriers – Chemistry (EBS TF-C) working program in 2012. A modelling 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 2013, MIN3P-THCm was used to simulate the four EBS TF-C benchmark experiments: 1) salt diffusion in compacted Na- and Ca-montmorillonite; 2) gypsum dissolution and diffusion in compacted Na- and Ca-montmorillonite; 3) Na/Ca ion exchange in compacted montmorillonite; and 4) multi-component advective-diffusive transport experiment in MX-80 compacted bentonite. The simulated results were compared with the experimental data sets and other reactive transport codes (e.g. CrunchFlow). Numerical analyses of the diffusion experiments revealed that both effective porosity and tortuosity are important to capture the transient diffusion profiles of the experiments. Combining the reactive transport code MIN3P-THCm, and the parameter estimation software PEST, provides a structured method for quantitative estimation of both these parameters from the diffusion experiments. Good agreement was shown between the simulated and experimental results for the benchmark 2 experiment, which considers reactive transport processes involving a layer of gypsum sandwiched between two compacted Na-bentonite layers in contact with water reservoirs. In the simulation, processes such as the kinetic dissolution of gypsum, multicomponent diffusion, and cation exchange were considered, see Figure 8-27. The results of the modelling will be documented in 2014.

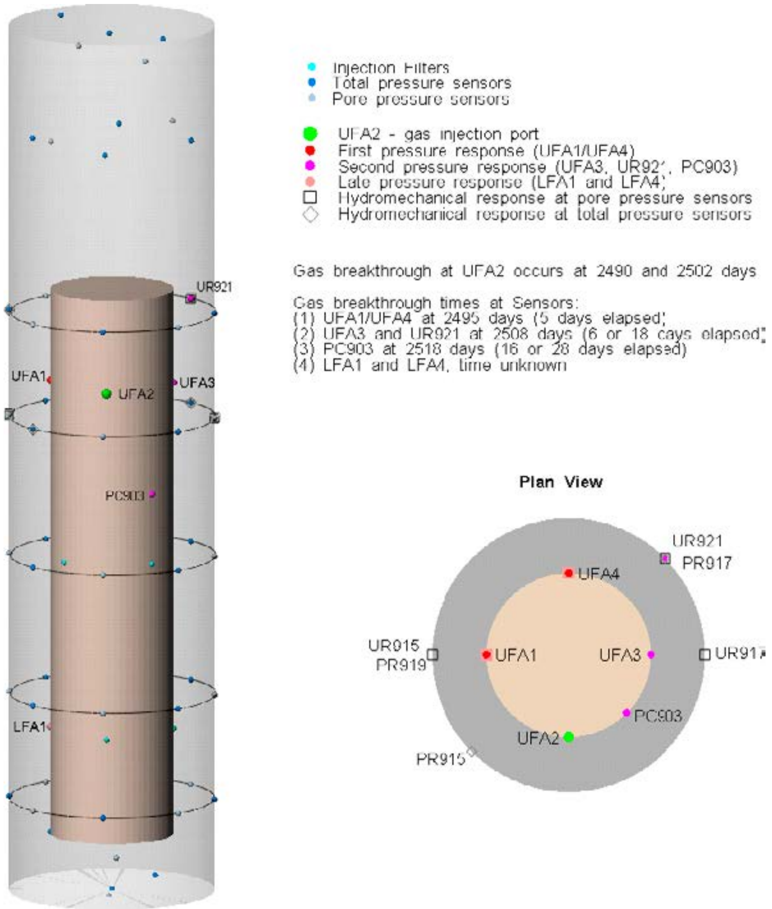


Figure 8-25. SKB 2010 Gas Injection Tests Showing Locations of Gas Injection (UFA2) and Gas Breakthrough.

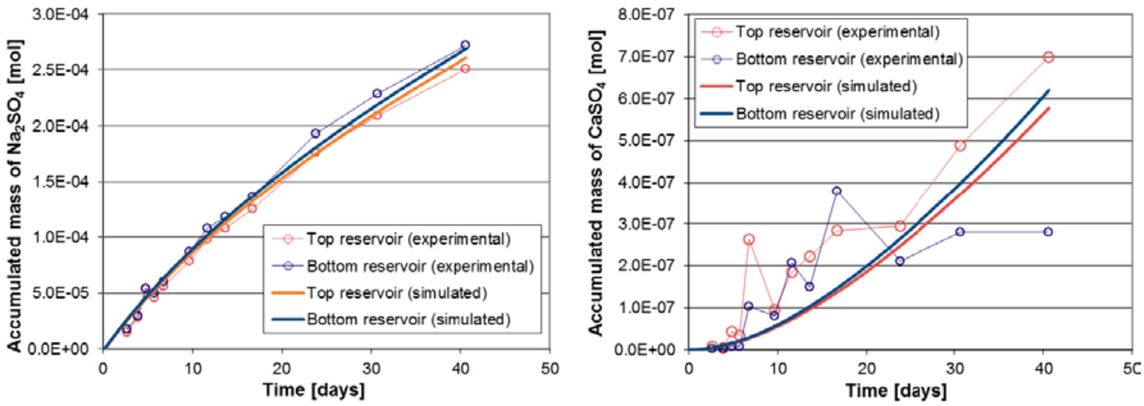


***Figure 8-26.** Comparison of simulated and experimental accumulated Na_2SO_4 mass (left) and $CaSO_4$ mass (right).*

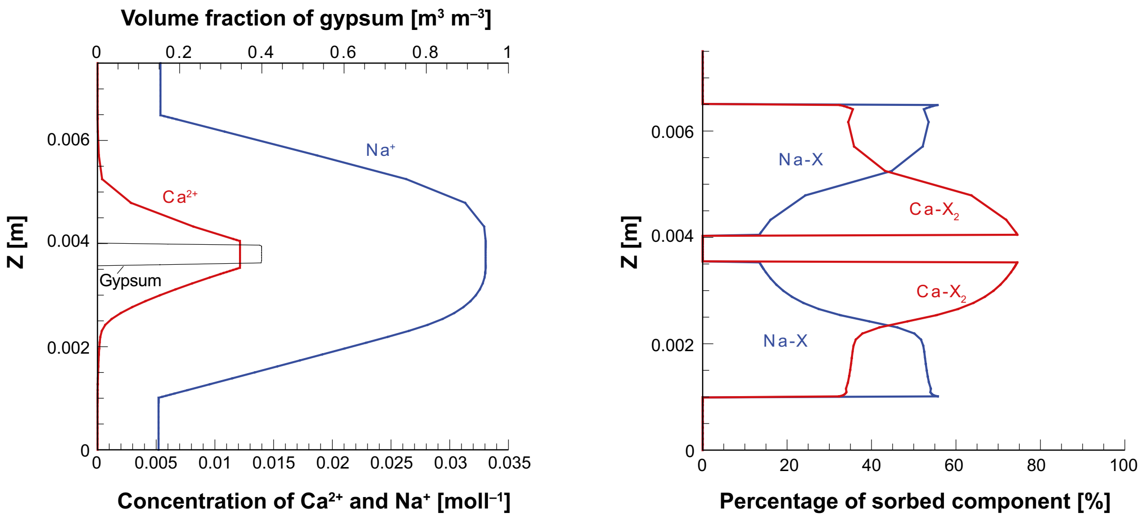


Figure 8-27. *Numerical simulation results at 40.6 days: left – profiles of aqueous Ca2+ and Na+ concentration and gypsum volume fraction; right – equivalent fractions of ion-exchanged species reported as percentages.*

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 the following four areas:

- 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 as joint projects together with SKB. 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 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.
- Long Term Test of Buffer Material.
- 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 the Posiva and the projects are described more detailed in other Chapters in this report. In addition Posiva and SKB are planning more extensive co-operation also in other areas, see Figure 8-28.

8.8 Nagra

8.8.1 Task Force on Engineered Barriers Systems

Nagra participates actively in both the THM- and the C-Group. A modelling group (Prof. Laloui and co-workers, EPF Lausanne) is involved in two benchmarks of the THM-Group, namely in the "Sensitivity Analyses" and in the "Homogenisation" task. This year the report on these tasks was completed. A Task Force meeting was organised and held in Switzerland in November 2013.

8.8.2 Alternative Buffer Materials

During this year Nagra and co-workers participated at the annual ABM meeting in Milos. Different groups are involved in the investigation of the ABM samples and the results were presented during that meeting. A new project in collaboration with SKB for the investigation of Fe-Bentonite has been bundled and started in March 2014.

8.8.3 Prototype Repository

Nagra joined the annual Prototype Repository project meeting.

Figure 8-28. *The president of SKB Christopher Eckerberg and the president of Posiva Reijo Sundell and development director at Posiva Tiina Jalonen signed the Letter of Intent in Autumn 2013. The aim is to develop the KBS-3 concept together and prepare for the disposal facility operation.*

8.9 Rawra

8.9.1 Task Force on Engineered Barrier Systems

Work on TF EBS has been realised by two contractors, Technical University of Liberec (THM) and UJV (chemistry).

Work by the TUL team

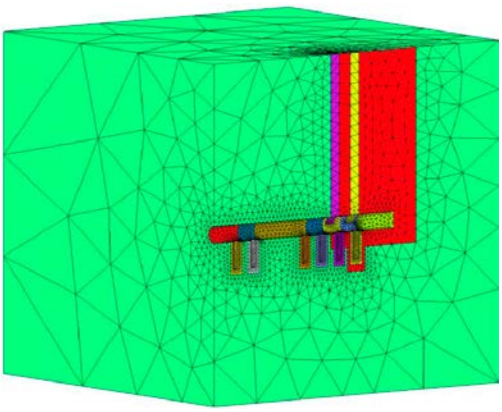
The TUL team worked on two tasks, Task 8 (BRIE) and the Prototype Repository. They continued to use the non-linear diffusion model within ANSYS software for water saturation and updated models to new data given to the teams. The variants of BRIE boreholes with one water-bearing fracture were solved. The team improved the concept of non-linear boundary condition (rock/bentonite flux) determined from solution of simpler larger-scale problems. The same model concept has been used for hydration of the Prototype Repository boreholes in 3D, using either prescribed pressure or flux distributed in a matrix based on diaper measurement of rock discharge, see Figure 8-29 right. Additionally the TUL team also solved the first phase of Prototype Repository task, inflow to excavation with larger-scale inhomogeneous continuum model, similar to the configuration used by the SKB team, by own FLOW123D software , see Figure 8-29 left. They also made a separate study of unsaturated water flow on rock and bentonite interface solving the Richards equation in FEFLOW software.

Work by the UJV team

The ÚJV contribution in EBS TF covered two main issues: evolution of porewater chemistry of the compacted bentonites (bentonites of Czech provenience) and erosion experiments focusing on erosion under saturation phase. In the following text the main results from more than 3 years of participation in the EBS TF project are summarised.

Porewater chemistry of compacted bentonites

Generally accepted approach for studying porewater chemistry evolution is a combination of experiments, followed by the geochemical modelling and its comparison to experimental results. A similar approach was used in our study. The equilibrium thermodynamic model was developed and tested. Model calculations were focused on both the initial porewater composition (bentonite in equilibrium with distilled water, see Table 8-1) and the porewater composition after equilibrium with the real groundwater. A simple sensitivity analysis showed that the most important parameter influencing the composition of compacted bentonite porewater is solid to liquid ratio (S:L). For further clarification of the real site conditions, we suggest to append the hydrochemistry data, especially the analysis of groundwater from the relevant depths (actual concept of deep geological repository considers depths > 500 m) and host rocks in the Czech Republic.



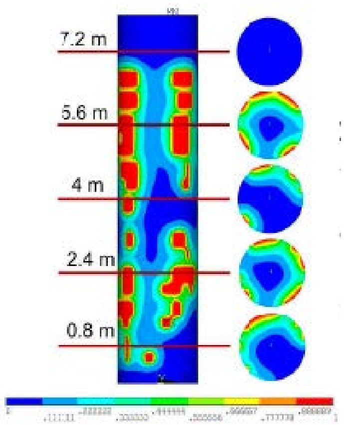


__Figure 8-29.__ Model of water inflow from rock to the Prototype Repository excavation (Left) and results of bentonite saturation in Nr.6 borehole calculated from diaper inflow measurement.

Table 8-1. Comparison of results: initial composition of pore water for compacted bentonites F02 and B75 (two solid to liquid ratios – S:L) and for another two well know bentonites MX-80 and FEBEX.

	UJV				B & B, 2003	Fer. et al., 2001
	F02	F02	B75	B75	MX-80	FEBEX
Dry density [kg/m^3]	1,600	1,600	1,600	1,600	1,600	1,600
Geochem. Porosity	0.208	0.020	0.208	0.015	0.020	0.220
S:L ratio [kg/dm^3]	7.7	80	7.7	106.7	80	7.1
log pCO_2 [bar]	–3.45	–3.87	–3.59	–4.57	–3.48	–3.50
pH	7.866	7.865	8.813	8.600	8.000	7.720
IS [mol/dm^3]	0.03	0.08	0.05	0.32	0.33	0.25
Concentration [mg/dm^3]						
Na	24.6	44.2	822.8	5,195.7	6,000.3	2,981.0
K	14.0	24.9	30.2	195.9	51.6	66.0
Mg	59.2	212.6	7.6	435.1	186.9	568.0
Ca	245.9	881.4	6.0	353.1	404.8	917.0
Sr	0.0	0.1	–	–	7.8	–
Cl	103.5	1,077.2	140.0	1,935.7	3,828.9	5,637.0
SO_4^{2-}	694.6	1,588.0	1,285.8	11,040.0	9072.0	3132.0
C_{inorg}	30.2	13.4	206.0	16.7	47.5	25.0
F	1.6	1.2	–	–	4.0	–
Si	2.8	2.8	3.1	2.8	5.1	16.0

Comm.: B & B, 2003 – Bradbury and Baeyens 2003, Fer. et al. 2001 – Fernández et al. 2001.

Bentonite erosion into the granite fracture

The conceptual model focused on the bentonite in saturation phase, where the mechanical and chemical erosion is expected. The aim of the study was to size up the amount of bentonite particles eroded from the swelling bentonite by the flowing water in the fracture and verify that erosion poses a significant risk to use the Ca-bentonite as the buffer.

The experimental results showed that the erosion rate at a given experimental arrangement reached from 0.4 to 55 kg/m^2/year at flow rates in the range of $5.37 \cdot 10^{-6} – 2.48 \cdot 10^{-4}$ m/s and fracture aperture in the range from 0.15 to 2 mm, see Figure 8-30. The erosion experiments did not show a clear trend between the erosion rate and width of aperture, which is probably caused by the small set of experiments.

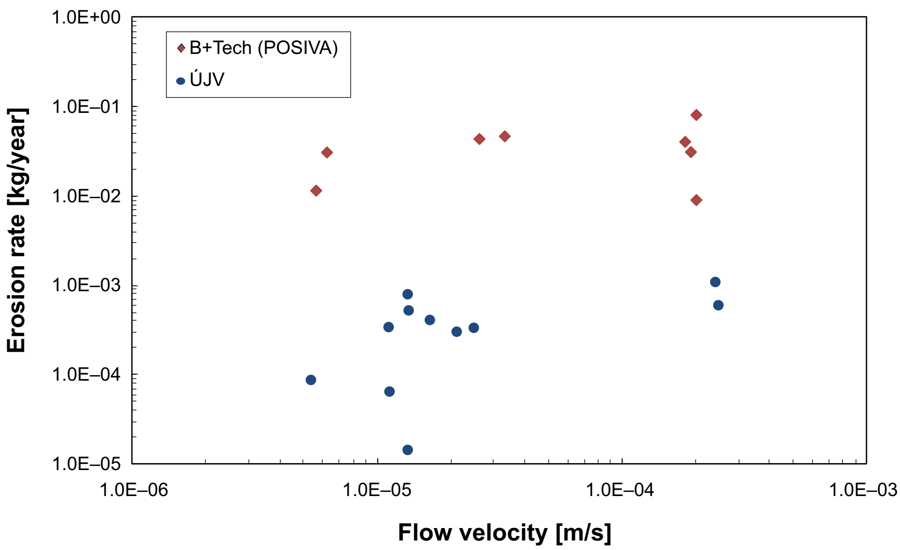


Figure 8-30. *Comparison of results: Erosion rate vs. flow velocity, blue points ÚJV results, red points POSIVA 2012-44 (Schatz et al. 2013).*

All experiments were carried out with distilled water which simulated groundwater with low ionic strength and therefore the extreme conditions with the highest rate of erosion. Mineral separation was observed (probably quartz and biotite) in experiments performed with small fracture aperture from 0.1 to 0.2 mm. This phenomenon may be particularly important mainly for the filtering effect, where the accumulations of small mineral grains can clog pores or fissures and thus prevent the bentonite erosion.

Generally, the chemical-mechanical erosion for Ca-bentonites is less significant than for Na-bentonites. However, it is necessary to consider the ion exchange between groundwater and bentonite, which can result in complete exchange of cations, and thus the selection of Ca- or Na-bentonite may not be crucial issue. Erosion experiments are continuing in the BELBaR project within Euratom FP7.

New benchmark no. 5

During the EBS TF meeting in London (May 2013) ÚJV presented the results from the diffusion experiments of various anions (iodide, chloride and selenate) through the compacted bentonites with quite attractive results. Considering the interest of partners in these results the chemistry group agreed on new benchmark no. 5 on a chemical workshop (November 2013). This benchmark will be available during the first half of 2014.

8.10 NDA

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

Through 2013, the NDA 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 taskforce, the LASGIT experiment, and the Prototype Repository experiment.

8.10.1 Task force on Engineered Barrier Systems (EBS)

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

In 2013, we continued to be members of the SKB EBS Task Force, attending the six monthly progress meetings and providing steer to the activities in which the task team is involved. As part of this work, AMEC undertook on our behalf modelling of bentonite resaturation using data supplied by SKB from Äspö (the BRIE experiment). This work includes sensitivity analysis and code comparisons using test cases. AMEC are also commencing modelling work aimed supporting the Prototype Repository Experiment.

8.10.2 Large scale gas injection test

As part of a wider programme of international research focussed on the processes and mechanisms governing gas flow in compact bentonite, RWMD 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:

(i) The minimum pressure gas will become mobile and enter the clay,

(ii) how much interstitial water, if any, is displaced as a direct consequence of gas flow either through visco-capillary processes or compression of the surrounding clay matrix, and

(iii) what is the nature of the observed coupling between gas flow, gas pressure, total stress and porewater pressure, and the impact this has on gas permeability.

Gas was found to migrate along pressure induced pathways, the number, distribution and aperture of which varied in time and space within the clay. Evidence of pathway self-sealing was also observed during gas flow, underlying the unstable nature of these features within compact bentonite. Important information was gathered on the response of the clay to cyclic gas flow events as well as examining the behaviour of the bentonite to changes in gas pressure gradient and flow rate. Additional insights into the processes and mechanisms governing initial hydration and swelling of the clay were also obtained as part of this study. 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 in the engineered barrier system.

8.10.3 Prototype repository

Throughout 2013, the NDA has actively contributed to the Prototype Repository Project by regularly attending progress meetings and providing direct technical input and steer to the project. The project is now in its final reporting stages (the last meeting was held in February 2014) and the NDA, together with other partners, has expressed very positive views of the outcomes of the project.

The input provided, particularly at the last meeting, included support to the interpretation of key research findings and to the identification of key areas of learning (for future experiments). From this point of view, a suggestion was provided to include in the reporting activities already planned specific documentation/sections aimed at describing lessons learned in the project. This is considered particularly helpful in the successful design, retrieval, analysis, interpretation, planning and management of future large scale experiments of a similar nature.

8.10.4 Secondment to the Äspö Hard Rock Laboratory

Between September 2013 and December 2013, the NDA RWMD seconded one of its employees (Dean Gentles, Engineering Manager) to the Äspö HRL to gain a better understanding of the work being carried out in the facility and how the learning from the ongoing experimental programmes could be transferred into the UK work programmes.

Whilst on secondment, Dean worked directly on the development of bentonite barriers in the KBS-3V disposal concept and on the Multi-Purpose Test (MPT) for the KBS-3H disposal, as well as being able to observe a number of other relevant activities. On return to the NDA, Dean shared his experience with colleagues and, looking forward, plans to influence future UK work programmes with the knowledge acquired during his secondment.

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