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# Äspö Hard Rock Laboratory Annual Report 2015

Svensk Kärnbränslehantering AB

SVENSK KÄRNBRÄNSLEHANTERING AB

SWEDISH NUCLEAR FUEL
AND WASTE MANAGEMENT CO

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

SVENSK KÄRNBRÄNSLEHANTERING

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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 2015 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 aim of project *DETUM-1 Large Fractures experiment* experiment is to further develop strategies and integrated investigation and modelling methodology for the identification and characterization of geological structures. The Large fractures experiment investigations include geological mapping, hydraulic testing and geophysical investigations using boreholes and tunnels. Work during 2015 has focused on analyzing and reporting results from the method specific investigations.

### *Natural barriers*

At Äspö HRL, experiments are performed under the conditions that are expected to prevail at repository depth. The experiments are related to the rock, its properties and in situ environmental conditions. The aim is to provide information about the long-term function of natural and repository barriers. Experiments are performed to develop and test methods and models for the description of groundwater flow, radionuclide migration, and chemical conditions at repository depth. The programme includes projects which aim to determine parameter values that are required as input to the conceptual and numerical models.

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

Important goals of the activities at Äspö HRL are the evaluation of the usefulness and reliability of different models and the development and testing of methods to determine parameter values required as input to the models. An important part of this work is performed in the *Task Force on Modelling of Groundwater Flow and Transport of Solutes*. During 2015, the focus within Task 7 has been on reporting, and optional publishing. The Task 8 work mainly contained modelling of BRIE with different levels of detailed data. Task 9 started up by modelling of WPDE 1 (Water Phase matrix Diffusion Experiments) and 2 of the REPRO experiment (Rock Matrix Retention Properties).

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. Work during 2015 has focused on analyzing and reporting the results from the experiment.

### *Engineered barriers*

At Äspö HRL, an important goal is to demonstrate technology for and the function of important parts of the repository system. This implies translation of current scientific knowledge and state-of-the-art technology into engineering practice applicable in an operational repository. It is important that development, testing and demonstration of methods and procedures are conducted under realistic conditions and at an appropriate scale. A number of large-scale field experiments and supporting activities are therefore carried out at Äspö HRL. The experiments focus on different aspects of engineering technology and performance testing.

The *Prototype Repository* is a demonstration of the integrated function of the repository and provides a full-scale reference for tests of predictive models concerning individual components as well as the complete repository system. The layout involves altogether six deposition holes, four in an inner section and two in an outer. The relative humidity, pore pressure, total pressure and temperature in different parts of the test area are monitored. The measured data indicate that the backfill in both sections of the tunnel is saturated and that there is different degree of saturation in the buffer in the deposition holes. The outer test section was retrieved during 2011 after approximately eight years of water uptake of the buffer and backfill. The laboratory examinations of the taken samples started during 2011 and was finalised during 2013. The reporting of the retrieval of the outer section started during 2013 and was finalized at the beginning of 2016. The monitoring of the inner section will be continued at least until 2020.

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

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 2015 (day 3620 – day 3985) the test programme of Lasgit entered a phase of prolonged "hibernation" with monitoring of the natural and artificial hydration of the bentonite buffer.

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. The first canister was retrieved and analysed in 2011. Two additional canisters were retrieved and analysed during 2015.

In the project *Concrete and Clay* the aim of the project is to increase our understanding of the processes related to degradation of low and intermediate level waste in a concrete matrix, the degradation of the concrete itself through reactions with the groundwater and the interactions between the concrete/groundwater and adjacent materials such as bentonite and the surrounding host rock. During the time period 2010–2014 a total of 9 packages comprising concrete cylinders or bentonite blocks each containing different types of waste form materials were deposited at different locations in the Äspö HRL. The four concrete specimens were prepared and deposited during 2010 and 2011. During 2014 the bentonite specimens comprising 150 bentonite blocks in 5 different packages were installed in TAS06. During 2015 the first concrete cylinder containing specimens of zink, aluminium, stainless steel and carbon steel was retrived and analysed.

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.

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 2015; one in Barcelona on May 18–20 and one in Lausanne on November 10–12.

The reference design considered by SKB for backfilling tunnels includes emplacement of pre-compacted blocks in the tunnel and bentonite pellets that fill up the space between the blocks and the tunnel walls. One of the main problems identified is how the water inflow to the tunnels should be handled during emplacement. Five test have been performed during 2015 in the project *Water handling during backfilling of deposition tunnels,* with the aim to investigate the water storing capacity of sieved pellets. One additional aim was to test the new glass fiber geotextile. One of the tests, no. 5, also included a test of temporary drainage equipment.

The project *System Design of Dome Plug for Deposition Tunnels* aims to ensure that the reference design of the KBS-3V deposition tunnel end plug works as intended. By testing the design in a full-scale demonstration it is to be proven that the method for plugging of a deposition tunnel is feasible and controllable. In 2012, the experiment tunnel (TAS01) was excavated and the accurate plug location was determined. The installation of the inner parts of the plug began in late 2012 and was completed in the beginning of 2013. On March 13th 2013, the casting of the concrete dome took place. The monitoring of the Domplu experiment started in September 2013 (month 0) when the bentonite seal had been artificially wetted by flooding of the filter during the summer. The experiment will be under continued observation until 2016. The test is part of the EU-project DOPAS, which receives funding from European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007–2013.

Several projects are ongoing with focus on *System design of buffer*. During 2015 a test was installed in the Äspö tunnel, testing one of two installation methods currently being investigated. The test comprises a total of 14 buffer blocks, 10 ring shaped blocks around the canister, the bottom block and three solid blocks on top of the canister each with dimensions according to the reference design.

The project *Tunnel Production* is a technology development project with aim to establish methods and concepts for excavation of deposition tunnels in the planned Final Repository for Spent Nuclear Fuel. This includes rock excavation methods, grouting and concepts for rock reinforcement.
A smooth floor is required in the deposition tunnels in the planned repository for spent nuclear fuel and during 2015 the Tunnel Production project initiated a full scale test in TAS04 to study the possibility to level the tunnel floor by means of wire sawing.

### *Mechanical and system engineering*

At Äspö HRL and the Canister Laboratory in Oskarshamn, methods and technologies for the final disposal of spent nuclear fuel are being developed. Established as well as new technology will be used in the Final Repository for Spent Nuclear Fuel. The approximately 200 technical systems, machines and vehicles that are needed in the final repository have been identified and listed in a database called FUMIS. Extensive work has been put into assessing the degree of development and prototyping needed, costs, schedule, deadlines etc. Several projects within mechanical and system engineering are ongoing, including the Deposition Machine, equipment for backfilling and equipment for buffer emplacement. There has been reduced activity at Äspö during 2015, as much focus has been on continuation and reporting of work from 2014.

### *Äspö facility*

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

In *the Bentonite Laboratory* different methods and techniques for installation of pellets and blocks in deposition tunnels are tested, and work on buffer and backfill is performed. A Bentonite press was delivered in December 2014, and has been used during 2015 to produce approx. 65 tonnes of pellets for several experiments at Äspö HRL.

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

*The operation of the facility* during 2015 has been functioning very well, with a very high degree of availability. During the year, a new software has been adopted for the HMS system to fit SKB's requirements on long time monitoring at Äspö and in Forsmark. Fire prevention has been improved through fitting vehicles with sprinkler systems, and equipment for measuring energy efficiency in areas of the facility has been installed.

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 2015, 4055 people visited the Äspö HRL and with the visitors at Clab and the Canister Laboratory included it resulted in a total of 6166 people. The total number of visitors to SKB's facilities in both Oskarshamn and Forsmark/Östhammar was 10 154 people. The unit also arranged a number of events and lectures during 2015.

### *Open research and technical development platform, Nova R&D*

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 R&D). Nova R&D 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 R&D 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 R&D provides access to the Äspö Hard Rock Laboratory and Bentonite Laboratory at Äspö and the Canister Laboratory in Oskarshamn.

### *International co-operation*

During 2015 eleven organisations from six countries in addition to SKB participated in the cooperation at Äspö HRL. Five of them; BMWi, RWM, NUMO, CRIEPI and JAEA formed together with SKB the Äspö International Joint Committee (IJC), which is responsible for the coordination of the experimental work arising from the international participation.

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

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

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

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

April 21st–23rd, 2015 SKB together with Posiva organised the Äspö HRL Symposium. The symposium covered research and development at SKB and Posiva with special focus on the activities at the Äspö HRL and the Canister Laboratory in Oskarshamn. In total over 60 persons from 17 organisations participated.

# 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 2015.

### *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. Studier genomförs i både laboratorier och fältexperiment, samt modelleringsarbete. Aktiviteterna levererar geovetenskaplig data till experiment och säkerställer hög kvalitet på experiment och mätningar inom geovetenskap.

I projektet *DETUM-1* genomförs experiment inom *Stora Sprickor* för att vidareutveckla strategier och integrera metoder för undersökning och modellering för indentifiering och karakterisering av geologiska strukturer. Undersökningarna inom projektet inkluderar geologisk kartläggning, hydraulisk testning och geofysiska undersökningar i borrhål och tunnlar. Under 2015 har arbetet fokuserat på analys och rapportering av resultat från metodspecifika undersökningar.

### *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. Experiment genomförs för att utveckla och testa metoder och modeller för grundvattenflöde, radionuklid-transport och kemiska förhållanden på förvarsdjup.

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

Aktiviteterna vid Äspölaboratoriet omfattar projekt med syfte att utvärdera användbarhet och tillförlitlighet hos olika beräkningsmodeller. I arbetet ingår även att utveckla och prova metoder för att bestämma parametervärden som krävs som indata till modellerna. En viktig del av detta arbete genomförs i ett internationellt samarbetsprojekt ”*Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes*”. Under 2015 har modelleringsarbetet inom Task 7 slutförts, och fokus har legat vid rapportering och publicering. Arbetet med Task 8 har mest inneburit modellering av *BRIE* med data i olika detaljnivå. Task 9 har startat upp med modellering av WPDE 1 (Water Phase matrix Diffusion Experiments) och 2 i projekt REPRO (Rock Matrix Retention Properties).

*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. Arbete under 2015 har fokuserat på analys och rapportering av resultat från försöket.

### *Tekniska barriärer*

Verksamheten vid Äspölaboratoriet har som mål att demonstrera KBS-3-systemets funktion. Detta innebär att vetenskapliga och teknologiska kunskaper används praktiskt i arbetet med att utveckla,

testa och demonstrera de metoder och tillvägagångssätt som kan komma att användas vid uppförandet av ett slutförvar. Det är viktigt att möjlighet ges att testa och demonstrera hur KBS-3-systemet kommer att utvecklas under realistiska förhållanden. Ett flertal projekt i full skala, liksom stödjande aktiviteter, pågår vid Äspölaboratoriet. Experimenten fokuserar på olika aspekter av ingenjörsteknik och funktionstester.

*I Prototypförvaret* pågår en demonstration av den integrerade funktionen hos förvarets barriärer. Prototypförvaret utgör dessutom en fullskalig referens för prediktiv modellering av slutförvaret och barriärernas utveckling. Prototypförvaret omfattar totalt sex deponeringshål, fyra i en inre tunnelsektion och två i en yttre. Mätningar av relativ fuktighet, portryck, totalt tryck och temperatur i olika delar av testområdet genomförs kontinuerligt. Genomförda mätningar indikerar att återfyllningen i båda sektionerna av tunneln är vattenmättade och att mättnadsgraden i bufferten varierar för de olika deponeringshålen. Den yttre sektionen bröts och kapslarna återtogs under 2011. Laboratoriestudier av tagna prover inleddes 2011 och avslutades 2013. Rapporteringen av återtaget av den yttre sektionen inleddes under 2013 och färdigställdes i början av 2016. Moniteringen av den inre sektionen kommer fortsätta till minst år 2020.

Ett forskningsprogram för ett *KBS-3-förvar med horisontell deponering* (KBS-3H) genomförs som ett samarbetsprojekt mellan SKB och Posiva. Nu pågår en fortsättningsfas av projektet med målsättningen att utveckla KBS-3H till en sådan nivå att en jämförelse mellan 3V/3H och förberedelser inför en PSAR är möjlig. Den nuvarande projektfasen är planerad till 2011–2016. Fasen täcker samtliga delar av KBS-3 metoden men fokuserar på KBS-3H specifika frågor. Två större aktiviteter initierades under 2011; ett systemtest (Multi Purpose Test, som även är del i EU-projektet LucoeX, vars finansiering stöds från Euratoms Seventh Framework Programme FP7/2007–2013) och konstruktion och förberedelser av en ny KBS-3H drift på −410 m nivå. Systemtestet installerades under 2013 och har sedan dess övervakats. Sensordata indikerar att bufferten har börjat vattenmättas, men är fortfarande i en tidig utvecklingsfas.

Syftet med ett *Gasinjekteringsförsök i stor skala* (Lasgit) är att studera gastransport i ett fullstort deponeringshål (KBS-3). Installationsfasen med deponering av kapsel och buffert avslutades under 2005. Vatten tillförs bufferten på artificiell väg och utvecklingen av vattenmättnadsgraden i bufferten mäts kontinuerligt. Under 2008 avslutades de preliminära hydrauliska testerna och gasinjekteringstesterna. Under 2015 inleddes en förlängd fas av vila med monitering av den naturliga och artificiella bevätningen av bentonitbufferten.

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. Ytterligare två kapslar återtogs och analyserades under 2015.

I *"Betong- och lerprojektet"* är syftet att öka förståelsen för processer i samband med nedbrytning av låg- och medelaktivt avfall i en betongmatris, nedbrytning av betongen självt genom reaktioner med grundvattnet och växelverkan mellan betong, mark och angränsande material som bentonit och den omgivande berggrunden. Fyra betong prover installerades under 2010 och 2011. Under 2014 installerades fem bentonitprover bestående av 150 bentonitblock fördelade i 5 paket. Under 2015 återtogs den första betongcylindern, innehållandes prover av zink, aluminium, rostfritt stål och kolstål.

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, ingjutning av bergbultar, bergförstärkning i form av sprutbetong och som betong för pluggar i deponeringstunnlarna.

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 2015;

ett i Barcelona under 18–20 maj och ett i Lausanne under 10–12 november. Det senare var ett gemensamt möte med *Task Force on Modelling of Groundwater Flow and Transport of Solutes.*

SKB:s referensdesign för återfyllnad av tunnlar inkluderar placering av förkompakterade block i tunnlar och bentonitpellets som fyllnad i utrymmet mellan block och tunnelvägg. Ett av de problemenområden som identifierats är hur vatteninflöde i tunnlar ska hanteras under installation. Fem försök har genomförts under 2015 i projektet *Hantering av vatteninflöde under återfyllnad av deponeringstunnlar*, vilket syftar till att undersöka vattenlagringsförmågan hos pellets. Ytterligare ett mål med försöken var att testa ny geotextil av glasfiber. Ett av försöken inkluderade även test av temporär dräneringsteknik.

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

Flera projekt pågår med fokus på *Systemkonstruktion av buffert*. Under 2015 har ett försök installerats i Äspötunneln för att testa en av de två installationsmetoder som utvärderas. Testet består av 14 buffertblock; 10 ringformade block runt kapsel, bottenblock och tre solida block ovanpå kapseln, samtliga med dimensioner som överensstämmer med referenskonceptet.

Projektet *Tunnelproduktion* är ett teknikutvecklingsprojekt med syfte att etablera metoder och koncept för tunnelproduktion för deponeringstunlar i det planerade slutförvaret. Detta inkluderar metoder för berguttag, injektering och koncept för bergförstärkning. Under 2015 initierades ett fullskaleförsök i TAS04 för att studera möjligheten att utjämna golv genom vajersågning.

### Maskin- och systemteknik

Vid Äspölaboratoriet och Kapsellaboratoriet i Oskarshamn utvecklas teknik och metoder för slutförvaring av använt kärnbränsle. Befintlig liksom nyutvecklad teknik kommer att användas. De omkring 200 tekniska system, maskiner och fordon som behövs har identifierats och har dokumenterats i en databas, FUMIS. Ett omfattande arbete har gjorts för att bedöma grad av nyutveckling, behov av prototypframtagning, kostnad, tidplaner etc. Flera utvecklingsprojekt inom maskin- och systemteknik pågår, bland annat deponeringsmaskin för vertikal deponering av kapsel, utrustning för återfyllnad och utrustning för buffertplacering. Under 2015 har färre aktiviteter genomförts på Äspö, då fokus legat på fortsättning och rapportering av aktiviteter från 2014.

### Äspölaboratoriet

I *Äspöanläggningen* ingår både det underjordiska berglaboratoriet och Bentonitlaboratoriet. En viktig del av verksamheten vid Äspöanläggningen är administration, drift och underhåll av instrument samt utveckling av undersökningsmetoder. Huvudmålet för driften av Äspöanläggningen är att garantera säkerheten för alla som arbetar i eller besöker anläggningen samt att driva anläggningen på ett miljömässigt korrekt sätt.

I *Bentonitlaboratoriet* provas olika metoder och tekniker för installation av pelletar och block i deponeringstunnlar och studier av erosion av buffert och återfyllningsmaterial utförs. Under 2014 har ca 50 ton bentonit blandats i Bentonitlaboratoriet, det mesta för användning i projekten *Alternative Buffer Protections* och *Concrete & Clay*. Under 2014 köptes även en press för tillverkning av extruderade bentonitpelletar, vilken under 2015 har använts för att producera 65 ton pellets till flera försök på Äspö.

Ett *Laboratorium för Materialstudier* finns på Äspö, med fokus på materialkemi för bentonitfrågor och kompetensutveckling. De största fokusområdena är metodutveckling för kvalitetskontroll av bentonit som ska användas som buffert- och återfyllnadsmaterial.

*Driften* av anläggningen under 2015 har fungerat mycket bra med en mycket hög tillgänglighet. Under 2015 har ny mjukvara tagits i bruk för HMS-systemet, för att uppnå SKB:s krav på långtidsmonitering på Äspö och i Forsmark. Brandskydd har förstärkt genom installation av sprinklersystem i fordon, och utrustning för att mäta energiförbrukning i olika anläggningsdelar har installerats.

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 2015 besöktes Äspölaboratoriet av 4055 personer. Enheten arrangerade ett flertal evenemang och föreläsningar 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 elva organisationer från sex länder deltagit i det internationella samarbetet vid Äspölaboratoriet under 2015. Fem av dem; BMWi, RWM, NUMO, CRIEPI och JAEA 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.

Ett Äspö HRL Symposium arrangerades av SKB och Posiva den 21–23 april, där forskning och framsteg inom de två organisationerna presenterades. Över sextio deltagare från sjutton organisationer närvarade.

# Contents

# 1 General

## 1.1 Background

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

The underground part of the laboratory consists of a main access tunnel from the Simpevarp peninsula to the southern part of the Äspö island where the tunnel continues in a spiral down to a depth of 460 m, see Figure 1-1. The total length of the tunnel is 3600 m where the main part of the tunnel has been excavated by conventional drill and blast technique and the last 400 m have been excavated by a tunnel boring machine (TBM) with a diameter of 5 m. The underground tunnel is connected to the ground surface through a hoist shaft and two ventilation shafts.

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

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

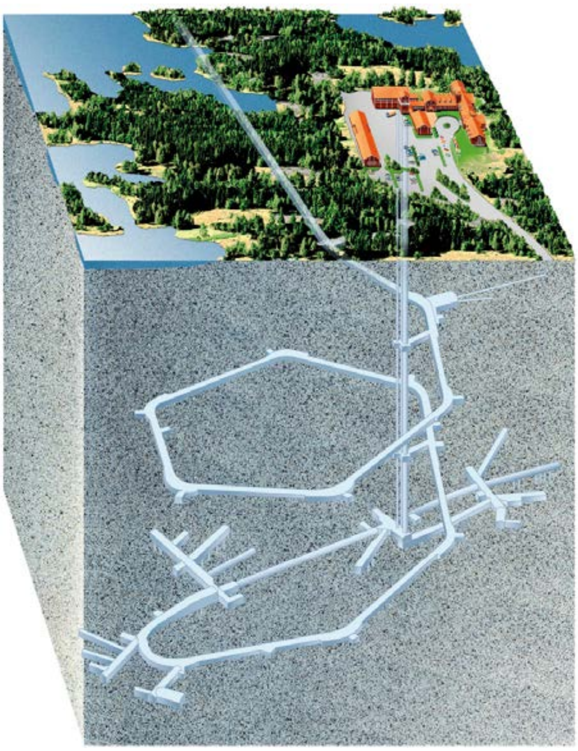


***Figure 1-1.*** *Overview of the Äspö HRL facilities, including the new areas produced in the tunnel expansion, and the Simpevarp peninsula.*

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

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

## 1.2 Goals

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

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

Goal number 1 was reached at an early stage and was preparatory to the site investigations which have been implemented successfully in Oskarshamn and Forsmark. Goal number 2 is not reached fully. The lessons learned from the detailed investigations during the construction phase are now used as a basis when planning for the coming detailed investigations in the spent fuel repository in Forsmark. Goal number 3 has been reached. Tasks related to goal number 4 will continue until about 2025 and any remaining tests will continue in Forsmark.

## 1.3 Organisation

Äspö HRL is the residence of the unit *Repository Technology* and the unit includes employees in Äspö, Stockholm and Forsmark. The main responsibilities of the unit are to:

- Develop, demonstrate and streamline repository technology for nuclear waste, including installation methods, transport- and handling techniques.
- Operate Äspö HRL as an attractive resource for experiments, demonstration tests and visitor activities.
- Actively work for a broadened use of Äspö HRL, with the aim to turn the facility over to future research- and development parties.

During 2015, the *Repository Technology (TD)* unit was organised in the following groups;

- *Geotechnical barriers and concrete techniques (TDG),* responsible for the development, testing and demonstration of techniques for installation of buffer, backfill and plugs in deposition tunnels, backfilling of the Final Repository for Spent Nuclear Fuel and plugging of investigation boreholes.
- *Mechanical and system engineering (TDM*), responsible for the development, testing and demonstration of equipment, machines and vehicles needed in the Final Repository for Spent Nuclear Fuel.
- *Project and experiment service (TDP),* responsible for the co-ordination of projects undertaken at the Äspö HRL, providing services (administration, design, installations, measurements, monitoring systems etc) to the experiments.

- *Facility operation (TDD),* responsible for the operation and maintenance of the Äspö HRL offices, workshops and underground facilities and for development, operation and maintenance of supervision systems.
- *Administration, quality and planning (TDA),* responsible for planning, reporting, QA, budgeting, environmental co-ordination and administration. The staffing of the Äspö reception and the SKB switchboard are also included in the function.
- *Rock Characterisation and Rock Engineering (TDU)*, responsible for development and management of investigation and evaluation methods, measurement systems with tools and field equipments.
- *Chemistry Laboratory (TDK),* responsible for taking water samples and to do chemical water analysis.

Each major research and development task ordered by SKB and 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.

## 1.4 International participation in Äspö HRL

During 2015 eleven organisations from six countries in addition to SKB participated in the cooperation at Äspö HRL. Five of them; BMWi, RWM, NUMO, CRIEPI and JAEA formed together with SKB the Äspö International Joint Committee (IJC), which is responsible for the coordination of the experimental work arising from the international participation. Several of the participating organisations take part in the two Äspö Task Forces on:

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

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

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

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

## 1.5 Allocation of experiment sites

The rock volume and the available underground excavations are allocated for the different experiments so that optimal conditions are obtained, see Figure 1-2.

## 1.6 Reporting

The plans for research and development of technique during the period 2014–2019 are presented in SKB's RD&D-Programme 2013 (SKB 2013). Detailed account of achievements to date for the Äspö HRL can be found in the Äspö HRL Annual Reports that are published in SKB's Technical Report series. This report describes the achievements during 2015.

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.

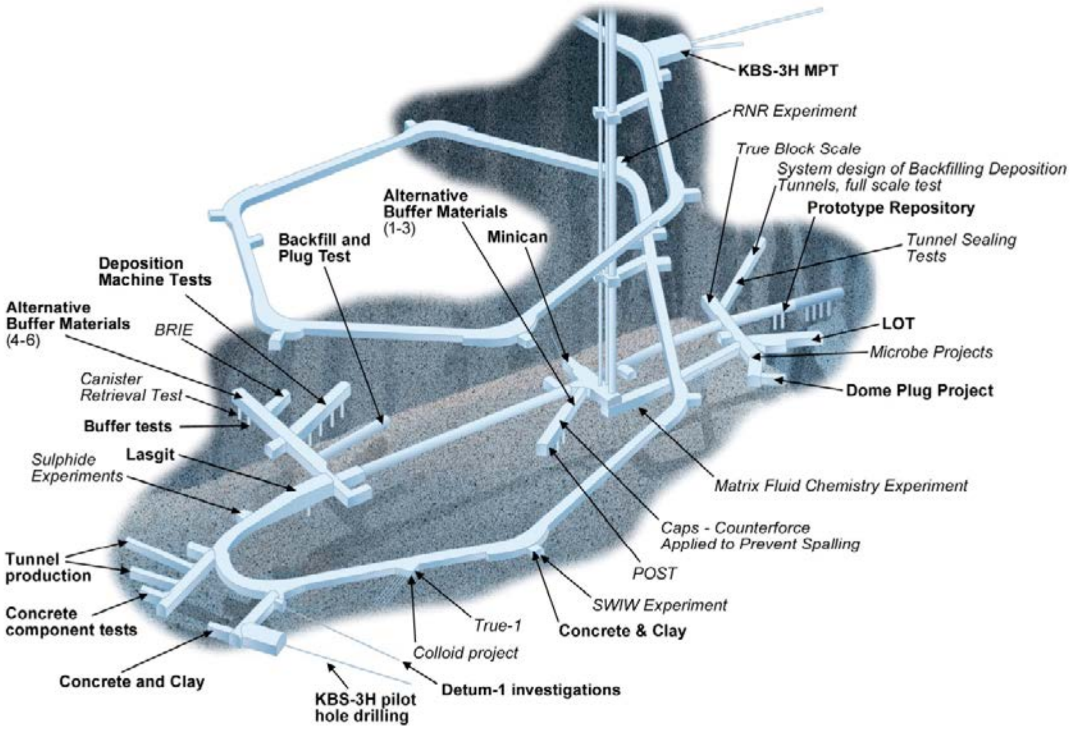



***Figure 1-2.*** *Allocation of experiment sites from −220 m to −460 m level. Ongoing experiments in bold text.*

## 1.7 Management system

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

## 1.8 Structure of this report

The achievements obtained at Äspö HRL during 2015 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 R&D.
- International co-operation.

# 2 Geoscience

## 2.1 General

Geoscientific research is a part of the activities at Äspö Hard Rock Laboratory as a complement and an extension of the stage goals 3 and 4 which were stipulated early in connection to construction of the Äspö HRL;

**Test models for description of the barrier functions at natural conditions –** Further develop and at repository depth test methods and models for description of groundwater flow, radionuclide migration and chemical conditions during operation of a repository as well after closure.

**Demonstrate technology for and function of important parts of the repository system –** In full scale test, investigate and demonstrate the different components of importance for the long-term safety of a final repository 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 rock mass properties.

## 2.2 Geoloscientific description of the rock mass at Äspö HRL

***Background***

An understanding of the rockmass att Äspö HRL regarding geology, hydrogeology and hydrogeochemistry, i.e. geometrical description of the fracturing of the rock mass, distribution of rock types, hydrogeological processes, hydrogeochemical parameters and the state rock stress, 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 based mainly on the data collected during the site investigations and the construction of the underground facitilty at Äspö and a second one in 2002 besed on additional data from experiments performed at the HRL.

Through the different experiments and projects undertaken in the tunnel since 2002, additional data is collected and understanding is gained for the local experimental volume. As such, this local knowledge constitutes a building block for integration in the larger scale site descriptive volume. With new experiments new local models are providing input to the gradual updating and refining of the site descriptive model.

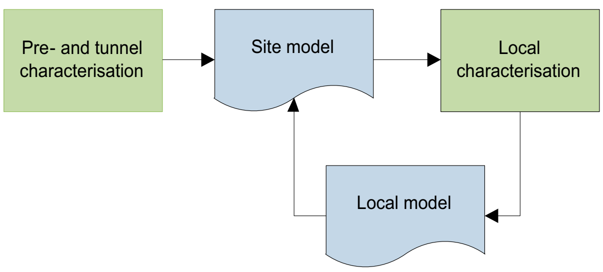



***Figure 2-1.*** *Evolution of local- and site descriptive model.*

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 Laxemar and Simpevarp, municipality of Oskarshamn and at Forsmark, municipality of Östhammar. The intention is to develop an integrated multidisciplinary descriptiption of the rock mass att Äspö HRL into a dynamic working tool suitable with short turn over times for predictions in support of the experiments in the laboratory as well as to test geological, hydrogeological and hydrogeochemical hypotheses in order to improve the conceptual understanding.

#### *Objectives*

The main objective is to establish and develop a multidisciplinary geoscientific model of the rock mass at Äspö HRL. This willinclude 3D geometrical model of the deformation zones, description of their geological, hydrogeological and hydrogeochemical properties, as well as 3D model describing the distribution and the properties (geological, hydrogeological, hydrogeochemical and mechanical) of the different rock types in the rock volume of the Äspö HRL.

#### *Results*

Strategies for this integrated multidiscilpinary modeling work and a work flow has been developed that presents a sequence of modeling steps that are designed to meet the modeling objectives under modeling constrains. This work flow represents the steps to realize model concepts for each discipline, (geology, hydrogeology and hydrogeochemistry), prerequisites – proceeding from data and expert knowledge to conceptual geoscientific models as well as geometrical and numerical presentations.

## 2.3 Geology

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 geometrical 3D modelling of deformation zones and special distribution of different rock types, including description of their properties.

#### *Objectives*

The main objectives of the geological activities are to:

- Maintain and develop the geometrical 3D model describing the deformation zones, including their properties and the distribution of the different rock types in rock mass at the Äspö HRL.
- Maintain and develop the geological conceptual understanding of the site.
- Provide geological support to projects and experiments at Äspö HRL.
- Provide hydrogeological expertise to SKB at large.

#### *Results*

Geological support was largely provided the “Large fractures” project including geological characterisation and 3D modelling integrated with the hydrogeological modelling (see Section 2.6). Furthermore, strategies and work flow regarding the integrated multidisciplinary modeling of the Äspö HRL was developed.

## 2.4 Hydrogeology

The basic framework and motivation for the hydrogeological work is as given in Section 2.2 Background. A central component in this work is the hydrogeological monitoring system which is decribed in Section 2.4.1.

### *Objectives*

The major aims of the hydrogeological activities are to:

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

### *Experimental concept*

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

### *Results*

Hydrogeological resources were largely provided to three major projects;

i. the Large fractures project with hydrogeological characterisation, modelling and forecasting. The project developed strategy, integrated investigations methodology and modelling methodology for determination of fracture size,

ii. the Modern2020 project with the aim to provide the means for developing and implementing an effective and efficient nuclear waste repository operational monitoring programme (www.modern2020.eu) and

iii. the Detailed investigation methodology project for developing hydrogeological methodology and instrumentation required for the construction of the nuclear waste repository in Forsmark.

A project was also undertaken in the Äspötunnel to investigate energy losses caused by to non-Darcy flow during well testing at large depths, 400 m below ground.

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

## 2.4.1 Hydro Monitoring Programme

### *Background*

The hydro monitoring programme constitutes a cornerstone for the hydrogeological research and a support to the experiments undertaken in the Äspö HRL. Monitoring was also required by the water rights court, when granting the permission to execute the construction works for the tunnel. A staged approach of monitoring has been adopted according to Figure 2-2 (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 base-line. The monitoring system is also utilised for characterisation during construction and to develop site descriptive models.

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

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

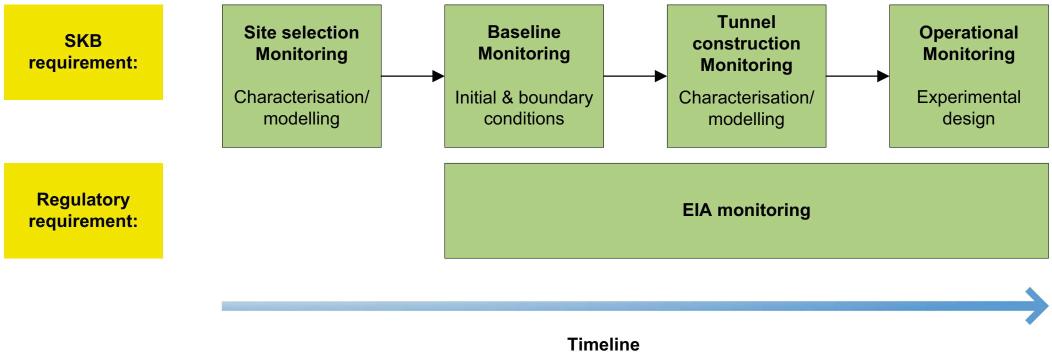



***Figure 2-2.** The staged approach of monitoring at Äspö.*

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 relies on a relatively large number of measuring points of various hydrogeological variables (about 1500).

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

### Results

The monitoring system is continuously maintained and data collected. The hydrogeological monitoring system has functioned well and the monitoring points in the tunnels have been maintained. The monitoring system has provided continuous support for the experiments and projects in their planning and execution and for the tunnel activites operations.

Upgrading the hydro monitoring system software to 64-bit windows operating system has been implemented, first at Äspö and later at Forsmark. The previous 32-bit system was simultaneously phased out. The upgrade comprises a switch to a database platform, enhanced access to the system through the world wide web and additional functionality for system administrators as well as for end users. The system that was phased out was originally commissioned in 1997 and has been operating reliably and well for 18 years, until 2015. Figure 2-3 is a sample screen dump which the end user is interfacing with when working with the Hydro Monitoring System.

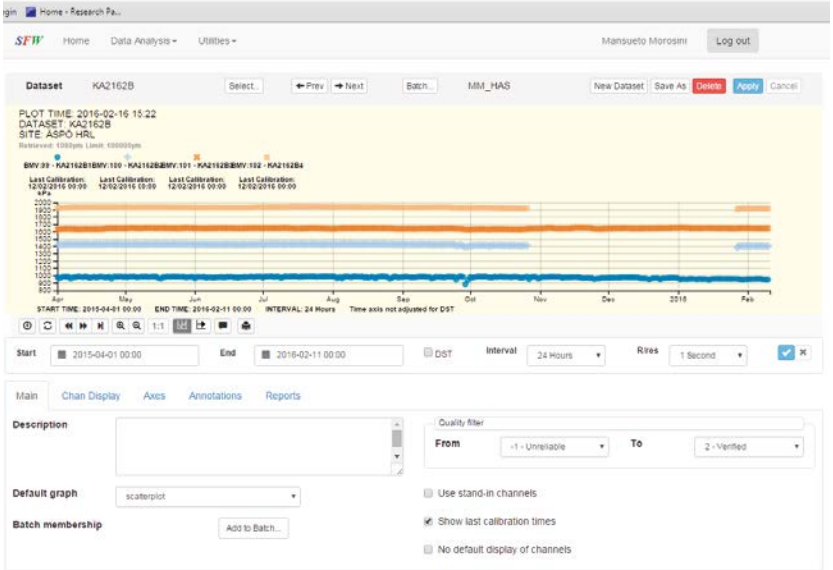



***Figure 2-3.*** *Screen dump of the new web based end user interface of the Hydro Monitoring System, for plotting of timeseries data.*

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

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

## 2.5 Hydrogeochemistry

The Äspö area is equipped with numerous sampling spots specially selected for the characterisation of the local hydrogeological system, including three main aqueous environments denoted as:

1. the surface environment: precipitation, stream, lake and sea water (i.e., surface water),
2. the near surface environment: regolith aquifer (i.e., near surface water),
3. the deep environment: water-bearing fracture network (i.e., groundwater).

The chemical and isotopic compositions of these different waters are determined on regular basis, as part of the hydrogeochemical monitoring program. Hydrogeochemical data is also collected from deep boreholes drilled along the Äspö HRL, in the framework of specific research and development projects carried out by the Swedish nuclear fuel and waste management company and its international partners.

### 2.5.1 Hydrogeochemical monitoring program

#### *Background*

The monitoring program is designed as monthly to biannual sampling campaigns depending on the type of aqueous environment. Surface waters are collected from permanent meteorological stations, and temporary stream, lake and sea stations. Near surface waters are collected, through pumping, in shallow boreholes – also named soil tubes in the SKB literature – reaching the bottom of the regolith aquifer. Ground waters are collected in packed-off sections of percussion and core-drilled boreholes, either by pumping (subvertical surface boreholes) or by artificial drainage (subhorizontal tunnel boreholes). Analyses take place at Äspö chemical laboratory as well as in external laboratories.

#### *Objectives*

The hydrogeochemical monitoring program aims to provide primary data for the long-term ongoing SKB research & development program and experiments in the tunnel at Äspö. This program maintains the continuity of hydrogeochemical time series started, for some of them, since the beginning of the excavation of the Äspö Hard Rock Laboratory in 1990. These time series allow a continuous improvement of the site model, which, in turn, aims to gain knowledge and ultimately predict the influence of an underground facility and its activities on the hydrogeological system. Additionally, the monitoring program provides data for external research organisations, through Nova R&D.

#### *Results*

During the year 2015, sampling and analyses of surface waters have been performed at different time intervals: once a month to six times a year for stream waters and four times a year for sea water. In a similar way, near surface waters have been sampled and analysed six times a year. By contrast, sampling campaigns have been carried out twice for groundwaters, one completed in May and the other in November, mainly from tunnel boreholes. All analytical data are quality assured and stored in SKB database to provide background information for modelling.

### 2.5.2 Research and development project

#### *Background*

One main research and development project, testing the sampling method for determination of dissolved gases and their isotopic signature, has been in focus during the year 2015. The current amount of dissolved gas data available in SKB database is relatively limited and of varying quality.

#### *Objectives*

Two main objectives have been in focus within this project:

- Development of new methods for gas sampling in DETUM (Methods & Tools)
- Sampling and analysis of gas needed for geochemical interpretation, such as for the understanding of the redox and microbial processes resulting in producing sulphide in groundwater in few boreholes in the Äspö Hard Rock Laboratory.

#### *Results*

The gas samplers have been applied to two borehole sections. The sampling method performed well for Ar, $CH_4$ and He gases (i.e., good reproducibility of the results). $H_2$ gas displayed a high sensitivity to pressure and sampling flow rate. The samples of gas extracted from the water standing in the borehole were systematically overrepresented with $N_2$ in the sampled borehole sections and were overrepresented with $O_2$ and $CO_2$ in one of the two borehole sections. On broader terms, the preliminary results suggest a large difference of concentration and composition of dissolved gases in the groundwater in the Äspö area, in line with the previous characterisation of the existing but limited dissolved gas data.

### 2.5.3 Review of methodology for hydrochemistry

#### *Background*

Many of the method descriptions used when sampling different types of waters, needed a review and to be updated. There were for example differences in performance between the organisations at Äspö HRL and Forsmark, deficiencies in the methodology documentation and difficulties in data management.

#### *Objectives*

The goal of this work was to:

- provide a basis for updating method descriptions,
- update existing and develop new methodologies,
- in cooperation with the FI develop procedures and systems for effective quality control and data storage,
- clarify the organization and structure of the different parts of the hydrochemistry.

The interface to the chemistry laboratory and its accredited activities should also be considered.

#### *Experimental concept*

The work was performed like a small project with a working group consisting of different types of competencies in the hydrochemistry area.

#### *Results*

Several method descriptions were updated and one completely new method description for sampling near surface groundwaters was produced. All of them will be approved in 2016.

## 2.6 DETUM-1 Large Fractures

#### *Background*

The Large fractures experiment is one part of DETUM-1 handling the SKB investigation program for the Final Repository for Spent Nuclear Fuel (see SKB 2010). The aim of the investigation program is to provide a basis for adaptation of the repository to site-specific conditions in order to meet the design criterias in the light of long-term safety considerations. Furthermore, investigations should provide input for engineering decisions, such as grouting and reinforcement. They are also performed to update site models, which will in turn form the basis for long-term safety assessments. According to the KBS-3 method, the canister and the bentonite should be placed in 1.75 m diameter deposition holes drilled to a depth of approximately 8 meters in the floor of the deposition tunnels. The important geoscientific issue treated in the Large fractures experiment is the location of fractures and deformation zones with shearing potential, as they are not allowed at a canister position. With regard to size of the fracture, a canister should not be localized where an intersecting fracture has a diameter exceeding approximately 200 m (e.g. Fälth 2015).

#### *Objectives*

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

#### *Experimental concept*

The Large fractures experiment investigations include geological mapping, hydraulic testing and geophysical investigations using boreholes and tunnels (e.g. groundpenetrating radar, seismics, resistivity and mise à la masse). This is followed by an integrated interpretation using cross-hole/tunnel correlation and geophysical techniques aiming at an increased confidence in the location, orientation and size of the larger fractures and deformation zones. The experiment is related to the different steps included in the SKB investigation program for the repository (SKB 2010) with focus on investigations from deposition tunnels (Measurement Campaign 1) and probe holes for deposition tunnels (Measurement Campaign 2, see Figure 2-4 and Fransson et al. 2014).

#### *Results*

Work during 2015 has focused on analyzing and reporting results from the method specific investigations. Further the integrated interpretation of the results has continued.

The integrated modelling methodology developed within the project includes an FPI-catalogue where identified FPIs are compiled and their trace(s) described. A Critical Structure Identification Matrix including FPIs and investigation methods was developed to organize data and interpretations and allow work to be performed in parallel for different disciplines. FPIs and geophysical anomalies were compiled in a rock modelling and visualization tool (RVS) as a basis for discussions and integrated interpretation. Additional information from the other investigation methods was also added in the FPI-catalogue ending up with a conclusion on the potential extension of the FPIs into the rock mass and between tunnels.

Focus in the current work has been on exemplifying the methodology for a potentially large fracture and a fracture that has no indications of being large. A complex deformation zone (presence of geological proxies for size and indication of existence using several of the utilized investigation methods) results in a high confidence structure. Fracture aperture, shear displacement, deformation zone thickness and conductivity/transmissivity are suggested proxies for size (Cosgrove et al. 2006).

Geophysical investigations of basic structures (e.g. single fractures with absent/limited occurrence of geological proxies for size) may not necessarily add substantial knowledge. One example that may result in a fracture assumed to be large without being so is that some of the anomalies interpreted from geophysics have shown not having any obvious geological explanations. Other interesting examples from the site investigations are sub-horizontal structures (potential EFPCs) indicated using seismics, se Figure 2-5 and observations related to fracture sets of potentially limited size.

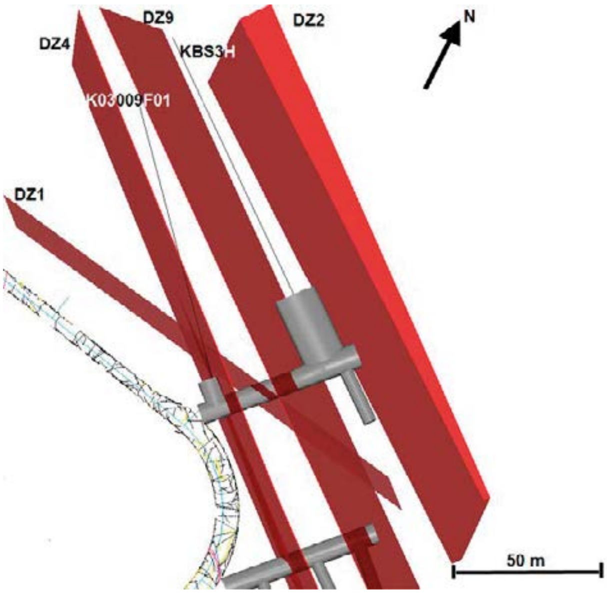



*Figure 2-4. The focus in Measurement Campaign 1 is on the volume between two short tunnels (lower part of the drawing). The focus in Measurement Campaign 2 is on the volume between two boreholes (upper part of drawing). Included in the figure are a number of preliminary (in terms of location and size) deformation zones.*

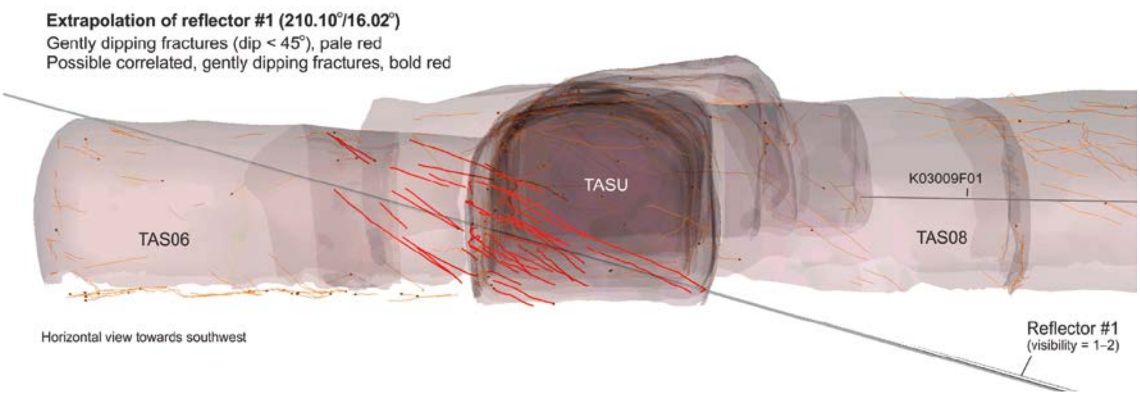



*Figure 2-5. Example of a fracture swarm being a potential origin of an anomaly using seismics. Horizontal view along tunnel TASU (222°) showing the extrapolated surface of reflector #1 relative to the traces of gently dipping (≤ 45°) fractures (thin pale red lines) that are mapped in TASU, TAS06 and TAS08. A swarm of gently dipping fractures (bold dark red lines) is inferred to coincide geometrically with the extrapolated reflector #1.*

# 3 Natural barriers

## 3.1 General

At Äspö HRL, experiments are performed under the conditions that are expected to prevail at repository depth. The experiments are related to the rock, its properties and in situ environmental conditions. The aim is to provide information about the long-term function of natural and repository barriers. Experiments are performed to develop and test methods and models for the description of groundwater flow, radionuclide migration, and chemical conditions at repository depth. The programme includes projects which aim to determine parameter values that are required as input to the conceptual and numerical models.

## 3.2 The integrated sulphide project

***Background***

In the construction of 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 observed (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.

As these diverse questions remained, the Intergrated sulphide project was initiated. It is a collaboration project between Posiva and SKB and consists of eight subprojects all with the purpose to answer questions related to sulphide levels a final repository.

***Objectives***

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

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

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

**WP1 – Sulphide concentrations and processes in the geosphere**

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

Sub activity 2: Transport and origin of gases that can be used by sulfate-reducing bacteria.

a) Development and testing of gas samplers.

b) Dry drillhole in ONKALO.

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

**WP2 – Sulphide concentrations and processes in bentonite**

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

Sub activity 2: Threshold buffer density.

Sub activity 3: FATSU.

**WP3 – Integration with the safety case**

Sub activity 1: Modelling.

### *Results*

**WP1 the geosphere:**

Subactivity 1: The investigated materials from drillhole sections release $H_2$ and organics respectively that can provide enough electron donors to explain the observed sulphide production by SRB. Aluminum releases large amounts of $H_2$ compared to stainless steel (Figure 3-1).

One of the main conclusions is that aluminum should not be used in drillholes.

Subactivity 2a: The new samplers functioned well, but it was clearly seen that also the sampling technique itself had great impact on the quality of the sample. Of particular importance was to have a large enough back-pressure in order to not lose gases such as $H_2$. The amount of purged volume played an important role as well and as stated in the previous subactivity, the material of the pulling rod. The amount of $H_2$ was significantly higher in those with sections with Al compared to those made of steel (Figure 3-2).

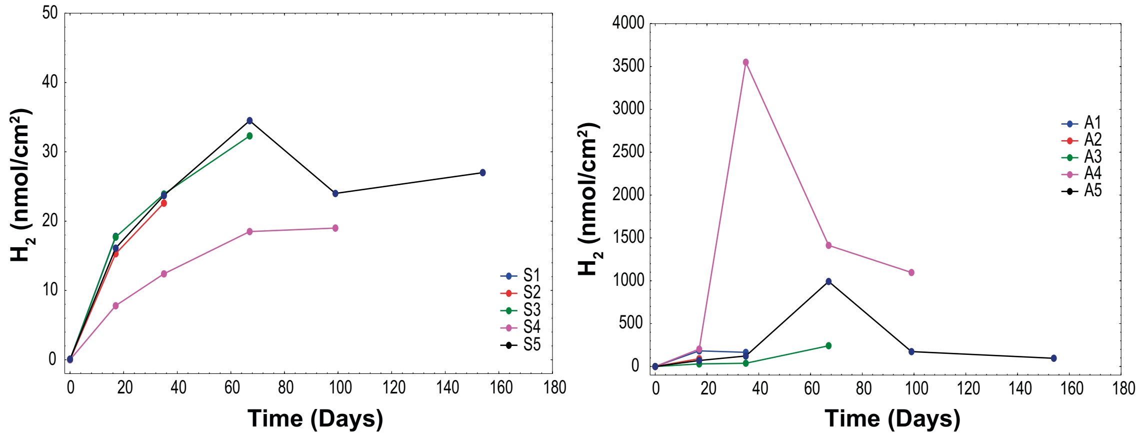



*Figure 3-1. Stainless steel and aluminium leached in groundwater.*

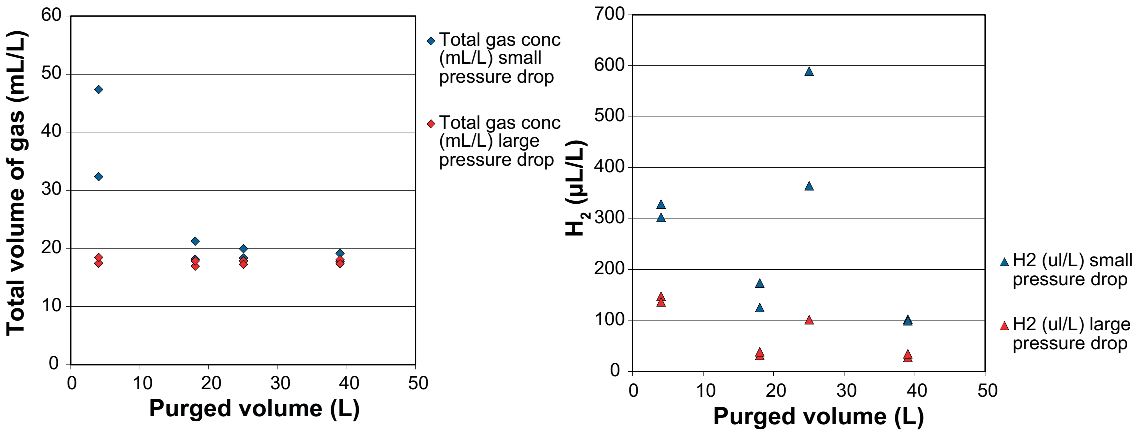



*Figure 3-2. Impacts of back-pressure and purged volume.*

**WP2: Buffer and back-fill:**

No sulphide could be leached out from the clay and upon addition of sulphide the sulphide was adsorbed by the clay to a certain extent before a break-through could be observed (Figure 3-3). This was most clear for MX80.

The project has confirmed that there is a sharp cut-off density for when sulphate reducers are active and when they are not (Bengtsson et al. 2015). The threshold buffer densities vary significantly with the type of clay. This is particularly obvious for Asha, which has much lower cut-off density than MX80 and Calcigel. More studies to confirm the observations are now planned for the next year.

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

### *Background*

The work within SKB Task Force on modelling of groundwater flow and transport of solutes (TF GWFTS) constitutes an important part of the international co-operation within the Äspö HRL. The group was initiated by SKB in 1992. A Task Force delegate represents each participating organisation and the modeling work is performed by modelling groups. The Task Force meets regularly about once to twice a year. Relevant experiments are utilised as topics for the modelling tasks, and the modelling can in turn potentially support the design, performance, and interpretation of the experiments.

The modeling tasks so far, and their status are as follow:

- Task 1: Long term pumping and tracer experiments (completed).
- Task 2: Scooping calculations for some of the planned detailed scale experiments at the Äspö site (completed).
- Task 3: The hydraulic impact of the Äspö tunnel excavation (completed).
- Task 4: The Tracer Retention and Understanding Experiment, 1st stage (completed).
- Task 5: Coupling between hydrochemistry and hydrogeology (completed).
- Task 6: Performance assessment modelling using site characterisation data (completed).
- Task 7: Reduction of Performance Assessment uncertainty through modelling of hydraulic tests at Olkiluoto, Finland (final reporting ongoing).
- Task 8: The interface between the natural and the engineered barriers (reporting ongoing).
- Task 9: Modelling of the field experiments REPRO and LTDE-SD (ongoing).

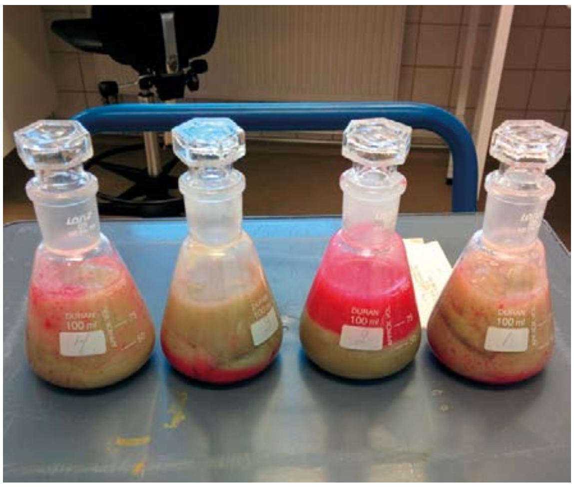


***Figure 3-3.** Sulphide was added to give 0, 0.2, 1.0 and 2.0 mg/L, but no sulphide was detected in the supernatant.*

### *Objectives*

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

Task 7 was addressing hydraulic tests performed at the Olkiluoto Island in Finland. 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 is addressing the processes at the interface between the rock and the bentonite in deposition holes. Task 8 has continued in terms of modelling of the experiment BRIE (Bentonite Rock Interaction Experiment) project.

The main objective of Task 9, modelling of the field experiments REPRO and LTDE-SD, is to increase the realism in solute transport modelling. The task started up in 2015 by modelling of some of the experiments included in REPRO performed in Olkiluoto, Finland.

### *Results*

During 2015, the focus within Task 7 has been on reporting, and optional publishing. The Task 8 work mainly contained modelling of BRIE with different levels of detailed data. The BRIE project 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 Task 8 modellers have been updating their modelling reprts based on review comments. Task 9 started up by modelling of WPDE 1 and 2 of the REPRO experiment.

The 33rd international Task Force meeting was held in Kalmar, in October. The presentations were mainly addressing modelling results on sub-tasks 8D (modelling of BRIE with more and updated data), 8E (modelling of Prototype), and 8F (updating models based on new experimatal data, e.g. pictures of wetting patterns on the surfaces of retrieved bentonite blocks). In Task 9 that is addressing both SKB's LTDE-SD and Posiva's experiment REPRO, preliminary results of sub-task 9A were presented, i.e. modelling of WPDE 1 and 2.

A workshop for mainly Task 9 was held in April where modelling approaches and plans for the future modelling were presented and discussed. The venue took place in Helsinki, Finland.

Minutes of TF meetings 32 (December, 2014) and 33 have been distributed to the Task Force together with presentation material. The description and the status of the specific modelling sub-tasks within Task 8 and 9 are given in Table 3-1.

**Table 3-1. Descriptions and status (within brackets) of the specific sub-tasks in Task 8 and 9.**

| | |
|---|---|
| **8** | **Interaction between engineered and natural barriers** |
| 8A | Initial scoping calculation (reporting ongoing) |
| 8B | Scoping calculations (reporting ongoing) |
| 8C | Final results (reporting ongoing) |
| 8D | Updated results (presented at Task Force meeting 33) |
| 8E | Updated results (presented at Task Force meeting 33) |
| 8F | Revisit to models with more field data (presented at Task Force meeting 33) |
| **9** | **Interaction between engineered and natural barriers** |
| 9A | Modelling of REPRO WPDE 1 and 2, preliminary results (presented at Task Force meeting 33) |
| 9B | Modelling of LTDE-SD (discussions at Task Force meeting 33) |

The Task Force on Engineered Barriers is presented in Section 4.8.

## 3.4 BRIE – Bentonite Rock Interaction Experiment

### *Background*

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

### *Objectives*

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

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

### *Experimental concept*

The experiment was subdivided into two main parts: Part I describing the selection and characterization of a test site and two central boreholes and Part II handling the installation and extraction of the bentonite buffer. The characterisation aim at a deterministic description of the fracture network at a small scale (≈10 m). Focus is on the most important water-bearing fractures. The experiment and the site is further described in Fransson et al. (2012, 2014) and Holton et al. (2012). Results and modelling related to the experiment is found in Dessirier et al. (2014, 2015) and Åkesson et al. (2014).

### *Results*

Work during 2015 has focused on analyzing and reporting the results from the experiment. Main modelling has been on-going within Task 8, see some references above. One additional issue that has been performed in relation to the experimental work in BRIE (with funding from Formas and SKB) is a continuation of the hydromechanical characterization of fractures, see Fransson et al. (2012) and Thörn (2015). The additional work included geological tunnel mapping focusing on kinematic indicators to get an input regarding what fractures have deformed (sheared) historically. Numerical modelling was performed to see if differing (relevant) stress regimes would lead to local deformation within the main water-bearing fractures. Preliminary results indicate a local deformation that may influence flow. Possibly this is one explanation for the high water content (blue) between 72 and 144 degrees along the upper part of the wetted trace, see Figure 3-4. This will be further investigated.

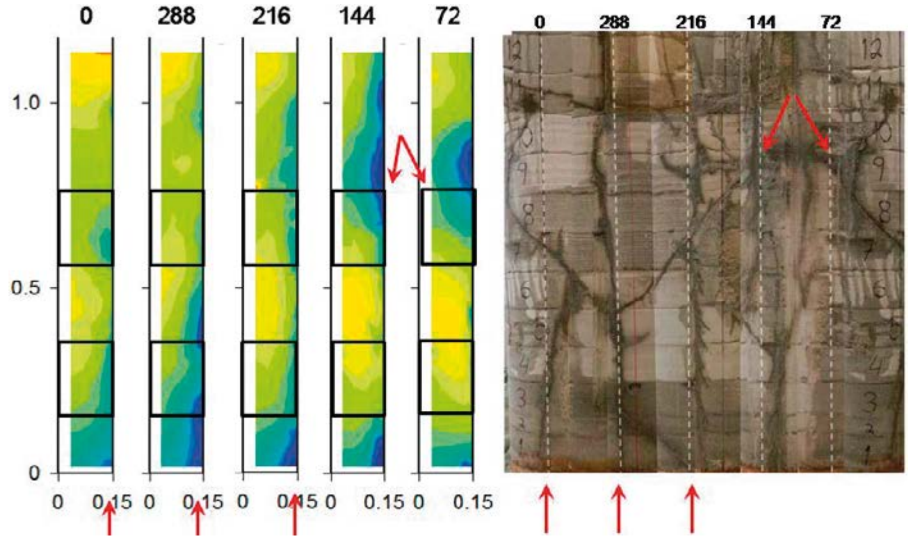



***Figure 3-4.** Comparison of water content plots (blue high water content and orange low) for five different orientations with markings on parcel surface for Hole 18 (the lowermost meter).*

# 4 Engineered barriers

## 4.1 General

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

It is important that development, testing and demonstration of methods and procedures, as well as testing and demonstration of repository system performance, are conducted under realistic conditions and at appropriate scale. A number of large-scale field experiments and supporting activities are therefore conducted at Äspö HRL. The experiments focus on different aspects of engineering technology and performance testing and are in line with what is adressed in SKB's RD&D programme.

During 2015 following experiments and projects within the Engineered Barriers were conducted:

- Prototype Repository
- 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
- Water handling during backfilling of deposition tunnels
- System Design of Plug of Deposition Tunnels
- System design of buffer
- Tunnel production.

## 4.2 Prototype Repository

### *Background*

Many aspects of the KBS-3 repository concept have been tested in a number of in situ and laboratory tests. Models have been developed that are able to describe and predict the behaviour of both individual components of the repository, and the entire system. However, processes have not been studied in the complete sequence, as they will occur in connection to repository construction and operation. In addition, it is needed to demonstrate that it is possible to understand the processes that take place in the engineered barriers and the surrounding host rock.

The Prototype Repository provides a demonstration of the integrated function of the repository and provides a full-scale reference for test of predictive models concerning individual components as well as the complete repository system. The Prototype Repository should demonstrate that the important processes that take place in the engineered barriers and the host rock are sufficiently well understood.

The installation of the Prototype Repository has been co-funded by the European Commission with SKB as co-ordinator. The EC project started in September 2000 and ended in February 2004. The continuing operation of the Prototype Repository is funded by SKB. The retrieval of the outer section, which started in 2011 and was finalized at the end of 2013, was made in cooperation with Posiva. Furthermore, the following organisations were participating and financing the work with the dismantling; NWMO (Canada), ANDRA (France), BMWi (Germany), NDA (United Kingdom), NAGRA (Switzerland) and NUMO (Japan). The reporting of the retrieval of the outer section started during 2013 and was finalized during 2016.

### *Objectives*

The main objectives for the Prototype Repository are to:

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

### *Experimental concept*

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

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

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

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

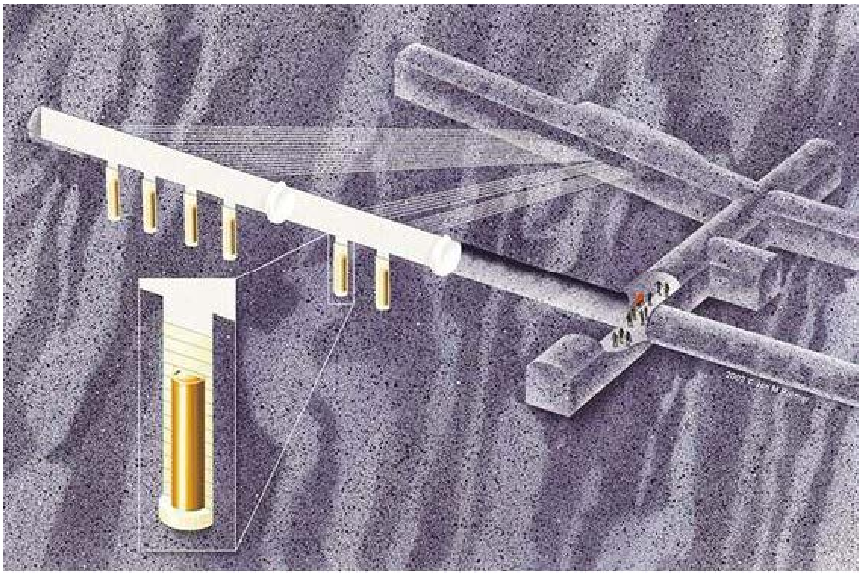


***Figure 4-1.*** *Schematic view of the layout of the Prototype Repository (not to scale).*

### Results

The installation of the inner section (section I with deposition holes #1, #2, #3 and #4) was done during summer and autumn 2001. The heating of the canister in deposition hole 1 started at 17th September. This date is also marked as start date. The backfilling was finished in the end of November and the plug was cast at in the middle of December. The installation of the outer section (Section II with deposition hole #5 and #6) was done during spring and summer 2003. The heating of the canister in hole 5 started at 8th of May. This date is also marked as start date for Section II. The backfilling was finished in the end of June and the plug was cast at in September. The interface between the rock and the outer plug was grouted at the beginning of October 2004.

At the beginning of November 2004 the drainage of the inner part of Section I and the drainage through the outer plug were closed. This affected the pressure (both total and pore pressure) in the backfill and the buffer in the two sections dramatically. Example of data from the measurements in the backfill of the total pressure is shown in Figure 4-2. The maximum pressures were recorded around 1st January 2004. At that date the heating in canister 2 failed. It was then decided to turn off the power to all of the six canisters. Four days later, also damages on canister 6 were observed. The drainage of the tunnel was then opened again. During the next week further investigations on the canisters were done. The measurements showed that the heaters in canister 2 were so damaged that no power could be applied to this canister. The power to the rest of the canisters was applied 15th of November 2004 again. The drainage of the tunnel was kept open. At the beginning of August 2005 another failure of canister 6 was observed. The power to this canister was switched off until beginning of October 2005 when the power was switched on again. During 2008 new problems were observed with the heaters in canister 6, resulting in that the power was reduced to 1160 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 1000 transducers were installed in the rock, buffer and backfill (Collin and Börgesson 2001, Börgesson and Sandén 2002, Rhén et al. 2003). The transducers measure the temperature, the pore pressure and the total pressure in different part of the test area. The water saturation process is recorded by measuring the relative humidity in the pore system of the backfill and the buffer, which can be converted to total suction.

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

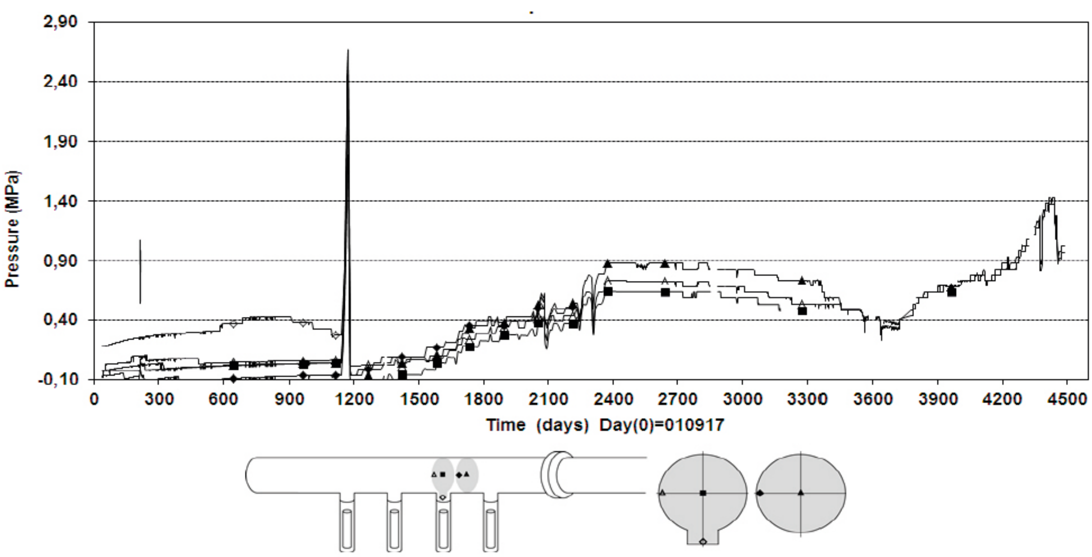



***Figure 4-2.*** *Examples of measured total pressure in the backfill around deposition hole 3 (17th September 2001 to 1st January 2014) (Goudarzi 2015).*

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

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

Equipment for taking gas and water samples both in buffer and backfill have been installed (Puigdomenech and Sandén 2001). A report where analyses of micro-organisms, gases and chemistry in buffer and backfill during 2004–2007 are described has been published (Eriksson 2008). New gas and water samples have been taken and analysed during 2009–2010 (Lydmark 2010).

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

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

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

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

**Hydration of the backfill in Section I**

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

**Opening and retrieval of Section II.**

The aim of the retrival of the outer section of the Prototype Repository was in particular to capture the following processes and phenomena:

- Temperature evolution in canister, buffer, backfill and rock.
- Copper corrosion.
- Hydraulic conductivity and hydraulic head of the near-field rock.
- Stresses and displacements in the near-field rock.
- Coupled hydraulic and stress regimes in the rock.
- Wetting of buffer and backfill.
- Evolution of pore pressure in buffer, backfill and rock.
- Evolution of swelling pressure and displacement in buffer and backfill.
- Deformation and displacement of canisters.
- Gas accumulation and composition in the buffer and backfill.
- Chemical composition of the backfill and buffer pore waters and the water in the near-field rock.
- Salt accumulation in the buffer.
- Mineral alteration in the buffer.
- Bacterial growth and migration in the buffer.
- Cellulose alteration in high pH environment.
- Strains and deformations in plug during curing.

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

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

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

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

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

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

The work with the exvation of the outer section has been reported in a summary report (Svemar et al. 2016).

## 4.3 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, see Figure 4-3.

In 2001 SKB published a RD&D programme (SKB 2001) for the KBS-3H alternative with four phases. The current joint (SKB/Posiva) project phase, KBS-3H System Design, was initiated in 2011 and it will be concluded end 2016. All development steps have been made in close cooperation between SKB and Posiva. The current project phase 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 long-term safety evaluation. The safety evaluation will be done for Olkiluoto site only. The work for Olkiluoto is deemed to provide results that will indicate if KBS-3H is also applicable to Forsmark site. This work will be based on earlier safety assessment work and will make use of Posiva's safety case "TURVA-2012" for KBS-3V (produced by SAFCA) for Olkiluoto and SR-Site for Forsmark. This is expected to be achieved by the end of 2016.

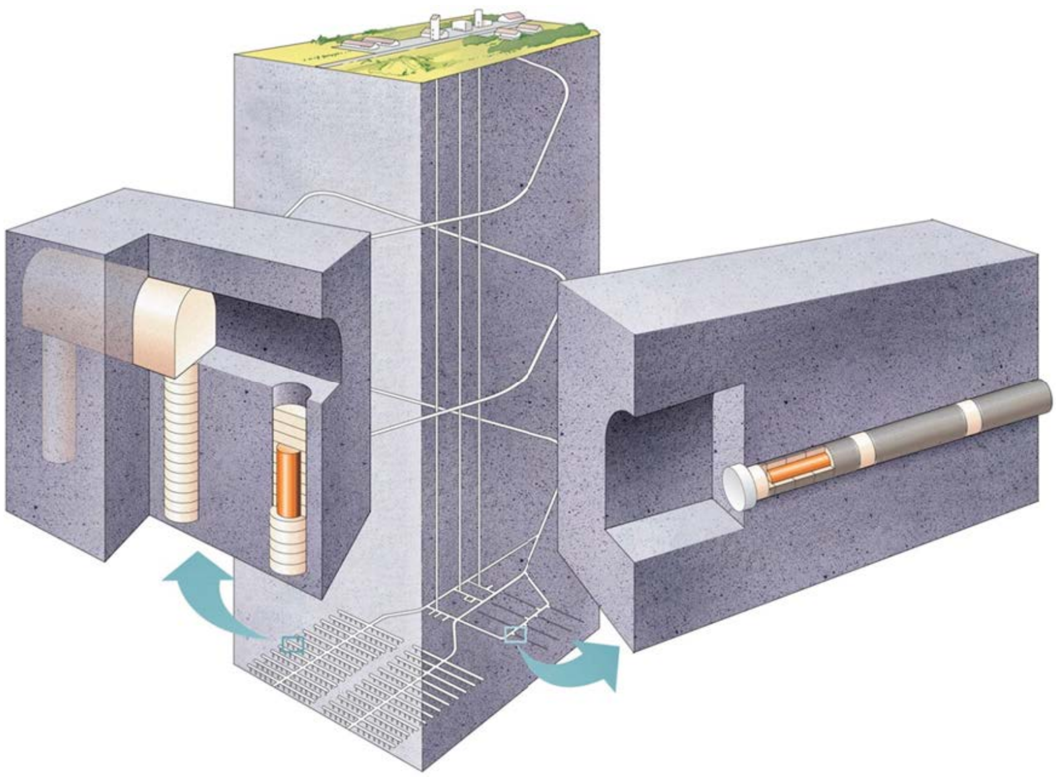


*Figure 4-3. Schematic drawing of the KBS-3V reference design (left) and KBS-3H (right).*

### Design of KBS-3H in short

The DAWE (Drainage, Artificial Watering and air Evacuation) design alternative has been chosen as the reference design for the KBS-3H concept. Consequently, the deposition drift is divided into two compartments with an approximate length of 150 m each.

In the KBS-3H concept, the canisters are placed in long horizontal deposition drifts, see Figure 4-4. Unlike the KBS-3V concept (reference design), the KBS-3H concept utilises a prefabricated installation package called Supercontainer that is assembled in an industrial process at the canister reloading station before disposal, thus reducing the risk of human error. The Supercontainer consists of a perforated protective shell made of metal with bentonite buffer and copper canister installed inside the buffer. Several Supercontainers are installed into each deposition drift. The drifts are almost horizontal, and their maximum length is 300 metres. The drifts have a diameter of c 1850 mm, and they have a slight upward inclination (c 2°), which is why water is removed from the drifts by gravity along the bottom of the deposition drift during installation. The Supercontainers and the bentonite blocks installed in the drift stand on parking feet between which the inflow water can flow out of the drift. The average gap between the Supercontainer and the drift wall is 44.5 mm (top 37.6 mm, bottom 51.4 mm).

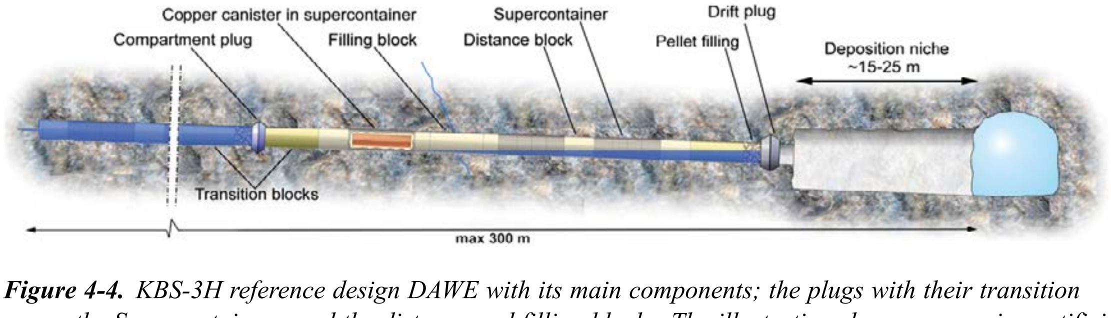



*Figure 4-4. KBS-3H reference design DAWE with its main components; the plugs with their transition zones, the Supercontainers, and the distance and filling blocks. The illustration shows an ongoing artificial water filling procedure of the second compartment.*

### *Differences between KBS-3V and KBS-3H*

The main differences between the two concepts: the horizontal and the vertical emplacement can be divided in the following aspects when comparing the two options from the angle of KBS-3H:

- Cost aspect
  - Less costly mainly due to lower volumes of excavation and backfilling
- Environmental aspect
  - Less excavation (no deposition tunnels)
  - The volume to be backfilled much smaller
  - Smaller clay production facility needed
- Operational safety
  - No risk of canister falling during installation
  - Risk of fire is smaller due to less amount of vehicles and machines which form the most significant fire load
- Occupational safety
  - Less traffic in the repository
  - The number of work phases smaller
  - Less tunnel reinforcement needed during installation phase (reinforcement structures need to be dismantled before deposition)
  - Less explosives will be stored underground since mechanical excavation used for drifts
  - Less risks for being exposed to radiation
- Long-term safety
  - The most important of all aspects
  - Currently disadvantageous for 3H due to the issue of chemical erosion entailing the so-called “domino effect”
  - The definition of initial state better due to artificial wetting.

### *Experimental concept*

#### Demonstrations at Äspö HRL

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

a) The design solution meets the requirement specification.

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

These steps are carried out at the Äspö HRL and at Posiva’s Underground research facility ONKALO. The work is part of the Demonstration sub-project focusing on verifying the functionality of equipment, methods and components developed within the KBS-3H project.

The sub-project also includes an activity at ONKALO, the drilling of a straight 300 m long pilot hole described in the Section “Demonstration of a 300 m long straight pilot hole ONK-PH28” below.

#### The Multi Purpose Test (MPT)

The MPT is basically a down-scaled (length-wise and temporal) non-heated installation of the reference design, DAWE, and includes the main KBS-3H components in full scale, see Figure 4-5. It is installed at the −220 m level which implies that the hydraulic boundary conditions differ from those foreseen at a typical repository depth.

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

The MPT has been set up with two main objectives:

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

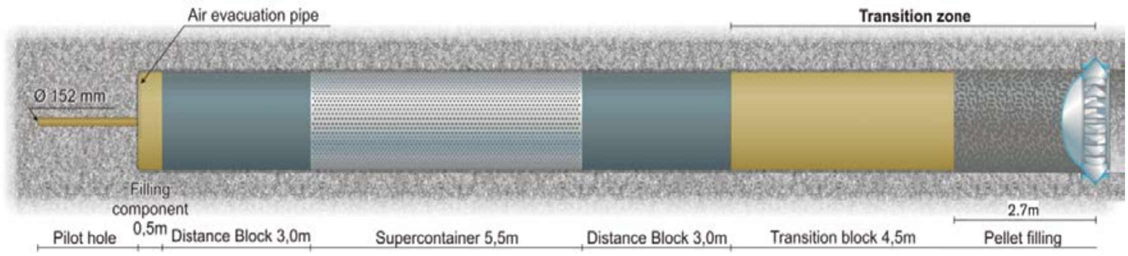



***Figure 4-5.*** *Schematic illustration of the MPT layout.*

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.

The MPT has also been a part of the EU-project LucoeX and it has been granted funding from the European Atomic Energy Community's (Euratom) Seventh Framework Programme. The LucoeX project was concluded at the end of August in 2015. The deliverables of the MPT are accessible on the website www.lucoex/deliverables.eu under Work Package 4.

Five reports covering the MPT have been prepared during 2015:

- Preparations, assembly and installation of MPT (Kronberg 2015)
- Final report of the WP4 (Kronberg and Gugala 2015)
- Steered core drilling of two boreholes at Äspö (Nilsson 2015)
- Initial data report for MPT (Pintado et al. 2015)
- Comparison between uni-axial and isostatic compaction methods for the production of bentonite components (Haapala et al. 2015).

**Monitoring of Multi Purpose Test (MPT)**

The MPT test has been instrumented with 227 sensors. The monitoring phase has been ongoing since Dec. 7, 2013. The monitoring phase will continue until the dismantling of the MPT, which has been decided to take place beyond the current project phase i.e. after 2016 based on the dismantling criteria, which remain to be finalized by SKB and Posiva.

Maintenance visit was made in March 2015 and the functioning of sensors and the PC operation system were checked. Work on updating the initial data report for MPT (Pintado et al. 2015) has been initiated and the scope is the same but the updated version should include all data till the end of 2015. The data reported in the earlier version included time period between Dec. 7, 2013 and June 10, 2014.

**Characterisation of boreholes K08028F01 and K03009F01**

All characterisation reports related to K08028F01 and K03009F01 have been compiled in cooperation with DETUM-project and are currently ready to be subjected to quality review. The characterisations include the following reports:

- Drilling of boreholes
- Borehole radar (Ramac system), Borehole Image Processing System (BIPS) imaging
- Posiva difference flow logging (PFL)
- Boremap logging of the drillcore
- Borehole geophysics
- Cross-hole interference tests
- Compilation of hydrogeochemical data
- Single hole interpretation (SHI).

**Demonstration of a 300 m long straight pilot hole ONK-PH28**

The successful drilling of borehole K08028F01 at Äspö meeting the strict KBS-3H requirements for the straightness was followed by a 300 m steered core drilling at ONKALO where a need for a 300 m long hole at ONKALO was raised by Posiva. Common interest between Posiva and the KBS-3H project was evident and a joint enterprise was established.

For the KBS-3H project drilling a 300 m straight pilot meeting the strict straightness criteria has been one of the technical challenges from the very start of the project. One of the most important goals of drilling ONK-PH28 was therefore to solve this issue by demonstrating that it is viable with the enhanced methodology developed at Äspö where it was applied in the 94 m long borehole K08028F01. In a later phase this borehole is planned to be reamed to the full drift size followed by post-grouting demonstration with Mega Packer equipment at the repository depth in, see the Section "Excavation of the 3H drift at Äspö HRL (future activity)" below. It was also deemed important for the KBS-3H project to assess the transferability of results and experiences between sites.

The pre-requisites for performance of borehole ONK-PH28 was that it should be drilled according to the KBS-3H project's borehole requirements as well as in compliance with Posiva's requirements for the pilot borehole to stay within the tunnel profile with a 0.5 m margin, and with the tunnel profile in this case corresponding to a theoretical KBS-3V deposition tunnel placed inside the actual planned tunnel as described below.

The drilling of ONK-PH28 entailed engaging contractors for core drilling, for deviation measurements / steerings and for leading the activity functions including aspects related to steering strategy. The borehole ONK-PH28 serves as the pilot hole of the c 300 m long tunnel that will be excavated in a later stage after all borehole characterization measurements have been carried out, see Figure 4-6.

The borehole was core drilled with 76 mm bit size. The length was c 300 m with the assigned strike- and dip values 313.4° and 2°, respectively. In total 25 steerings were made using the DeviDrill™ system to steer the borehole to the selected target. The borehole trajectory was controlled by surveying tools DeviTool™ (Pee Wee) and ReflexGyro. The drill rig used in this work was Atlas Copco B20 APC drill rig, see Figure 4-7.

The overall results pertaining to the straightness of the borehole is shown in Figure 4-8. All measured data were included for the final calculation of inclination, but for azimuth only gyro measurement was used, and furthermore, due to the risk of having the gyro instrument slightly displaced from its correct position in measurements into the borehole, only the gyro measurements out of the borehole were approved.

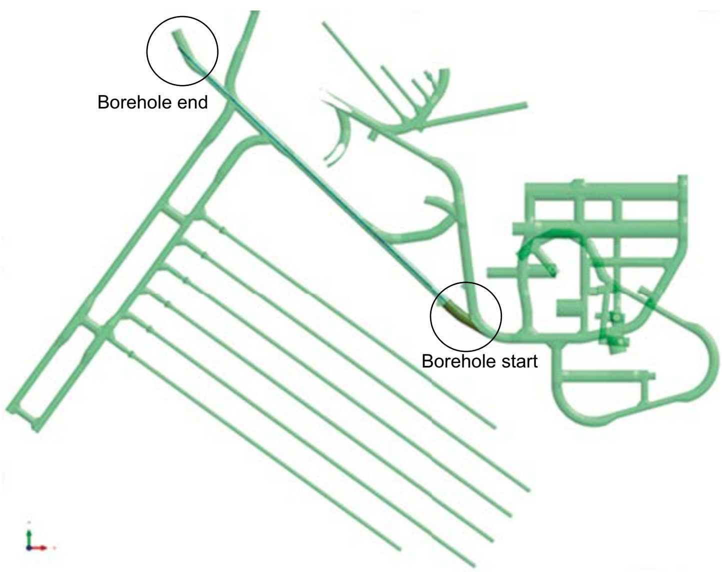



*Figure 4-6. General location of the KBS-3H pilot hole ONK-PH28 in ONKALO at the -437 m level. Start and end locations marked by black circles.*


***Figure 4-7.*** *The Atlas Copco B20 APC drill rig at the ONK-PH 28 drill site. The powerful drill rig stands on a solid concrete platform surrounded by hard-packed gravel. To the left the electrically powered hydraulic unit is shown.*

The strategy discussions prior to drilling pointed out that the decided borehole direction in relation to the schistosity (150/40) in ONKALO could lead to a borehole deviation caused by the rock structures. This turned out to be a correct prediction. The schistosity together with the initial borehole direction turned the borehole downwards. Only after the initial six steerings the deviation measurements indicated that the borehole had stopped declining at the borehole length c 50 m, see Figure 4-8. It should be noted that although declining from its original trajectory it still has a positive inclination in line with the requirements stating that the drift inclination shall be between 2° ± 1°.

In the borehole section 100–160 m the steerings were mainly aiming at smoothening out the rise upwards. At 200 m length the borehole position was very close to the target line. From 200 m, the increased sections of alterations between soft and hard rock, together with the desire to move the borehole more to the right from the preliminary target, complicated the continued execution of steering. Steering to the right was easy to achieve, but in order to level it out, high settings were demanded, together with a precise direction before it was safe to finalize the borehole with conventional drilling from 250 m. When the (x, y, z)-coordinates were calculated later, the deviation of the hole at the borehole end (300 m) turned out to be c 34 cm downwards and 90 cm to the right, see Figure 4-8.

In a later stage the coordinates of the borehole based on the deviation measurements will be compared with the geodetic measurements during excavation of the tunnel i.e. after each blasting round to confirm the results of the deviation measurements. The excavation of the tunnel is planned to be started in March 2016.

Based on the experiences from the steered drilling of ONK-PH28 the six technical items listed below are deemed as having been of special importance for the successful outcome of the drilling of a straight borehole: Platform, Drill rig, Starting orientation, Drilling equipment (hard and soft drill bits), Steering and Insertion rig for deviation measurements.


***Figure 4-8.*** *Final distance of borehole ONK-PH28 from an imagined straight borehole trajectory is presented, where the vertical distance is green, the horizontal distance red, and the total distance blue.*

**Excavation of the 3H drift at Äspö HRL (future activity)**

A new full scale KBS-3H test site has been planned and prepared earlier at the −410 m level of the Äspö HRL, and hence being more representative of a typical repository depth. Pilot borehole drilling techniques over a 100 m length scale have been demonstrated to meet the geometrical requirements for the straightness of the pilot hole.

The demonstration of reaming the drilled pilot borehole K08028F01 for the KBS-3H experimental drift to full-size drift diameter (1.850 m diameter) over a 100 m length scale remains to be accomplished and it is currently planned to be conducted in 2016. The excavation of the drift is planned to be followed by the demonstration of the performance of the post-grouting equipment, Mega-Packer, at the repository depth.

**Heater test (future activity)**

The issue of possible cracking of bentonite in the Supercontainer due to a hot canister before installation remains to be checked for KBS-3H and a test is planned to be conducted in 2016 given that the resources are available. The work has so far proceeded with pre-modellings of the heater test.

## 4.4 Large Scale Gas Injection Test

### *Background*

The large-scale gas injection test (Lasgit) is a full-scale in situ test designed to answer specific questions regarding the movement of gas through bentonite in a mock deposition hole located at 420 m depth in the Äspö Hard Rock Laboratory (HRL).

The multiple barrier concept is the cornerstone of all proposed schemes for the underground disposal of radioactive wastes. Based on the principle that uncertainties in performance can be minimised by conservatism in design, the concept invokes a series of barriers, both engineered and natural, between the waste and the surface environment. Each successive barrier represents an additional impediment to the movement of radionuclides. In the KBS-3 concept, the bentonite buffer serves as a diffusion barrier between the canister and the groundwater in the rock. An important performance requirement of the buffer material is that it should not cause any harm to the other barrier components. Gas build-up from, for example, corrosion of the iron insert, could potentially affect the buffer performance in three ways:

- Permanent pathways in the buffer could form at gas breakthrough. This could potentially lead to a loss of the diffusion barrier.
- If gas cannot escape through the buffer, the increase in pressure could lead to mechanical damage of other barrier components.
- The gas could de-hydrate the buffer.

Knowledge pertaining to the movement of gas in initially water saturated buffer bentonite is largely based on small-scale laboratory studies. While significant improvements in our understanding of the gas-buffer system have taken place, laboratory work highlighted a number of uncertainties, notably the sensitivity of the gas migration process to experimental boundary conditions and possible scale dependency of the measured responses. These issues are best addressed by undertaking large scale gas injection tests. Additionally, a full-scale experiment designed to identify gas pathway formation is suited to study the hydration of the bentonite buffer over a 10+ year time-scale.

The experiment has been in continuous operation since February 2005. The first two years (Stage 1, up to day 843) focused on the artificial hydration of the bentonite buffer. This was followed by a year-long programme of hydraulic and gas injection testing in filter FL903 (Stage 2, day 843 to 1110). A further year of artificial hydration occurred (Stage 3, day 1110 to 1385), followed by a more complex programme of gas injection testing in filter FL903 (Stage 4, day 1430–2064). In late 2010 attention moved from the lower array filter (FL903) to the upper array (FU910). Stage 5 started on day 2073 and was completed on day 2725. Focus then returned to the lower array (FL903) in late 2012 and involved a gas injection test throughout 2013. In 2014, the focus of the experiment was to determine the hydraulic properties of the bentonite buffer at all measurable locations by means of two-stage hydraulic head tests. In 2015, the experiment returned to a period of prolonged natural and artificial hydration.

### *Objectives*

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

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

### *Experimental concept*

Lasgit is a full-scale demonstration project conducted in the assembly hall area in Äspö HRL at a depth of −420 m. 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 5000 tonnes of force.

In the field laboratory (Figure 4-9) instruments continually monitor variations in the total stress and porewater pressure at the borehole wall, the temperature, any upward displacement of the lid and the restraining forces on the rock anchors. The experiment is a “mock-up test” which does not use any radioactive materials.

Lasgit has consisted of four operational phases; the installation phase, the hydration phase, the gas injection phase, the homogenisation phase. The installation phase was undertaken from 2003 to early 2005 and consisted of the design, construction and emplacement of the infrastructure necessary to perform the Lasgit experiment.

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

***Figure 4-9.** Photo of the laboratory area for the large-scale gas injection test 420 m below ground at Äspö HRL.*

### *Results*

During 2015 (day 3620 – day 3985) the test programme of Lasgit entered a phase of prolonged "hibernation" with monitoring of the natural and artificial hydration of the bentonite buffer. The four syringe pumps have been arranged so that one each studies the artificial hydration mats, the lower canister filters, the mid-plane canister filters and the upper canister filters.

Figure 4-10 shows the complete history of the Lasgit experiment and shows that stress is continuing to increase in the deposition hole. Pore pressure within the bentonite buffer is now increasing and should equilibrate with the pore water within the host rock within 3 to 5 years. The reduction in pore pressure of the host rock as a result of draw-down from the tunnel excavation has appeared to have reached a plateau.

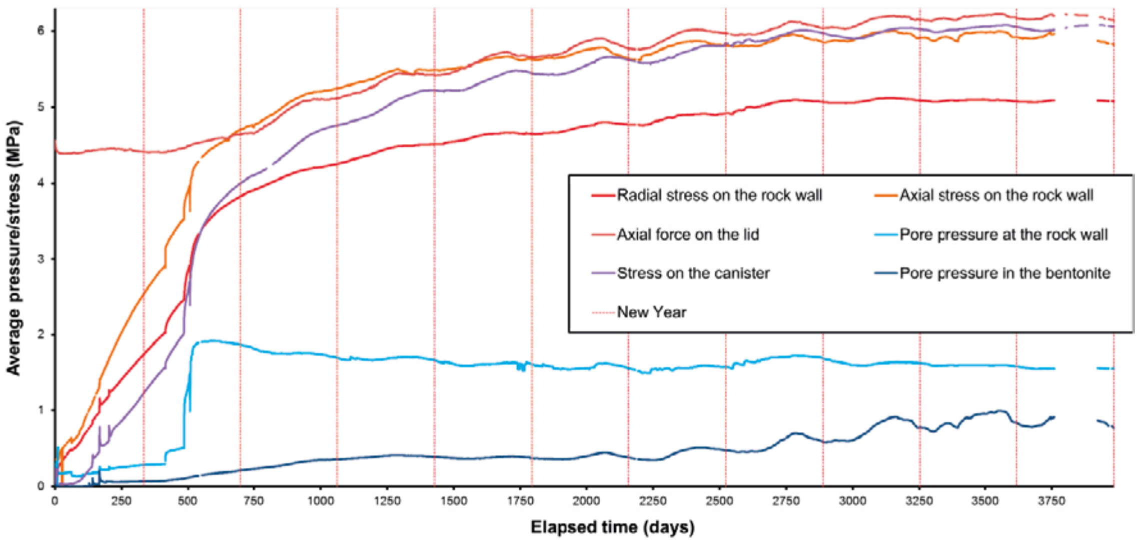



***Figure 4-10.** Average pore water pressure and stress readings during the complete 10-year history of Lasgit. As can be seen pore water pressure readings at the deposition hole wall has been decaying since day 500 due to the draw-down of the Äspö HRL due to pumping of the galleries. It can be clearly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

Lasgit celebrated 10 years of continuous operation in February 2015. As can be seen in Figure 4-10, the data logging computer failed midway through the year after 10 years of faultless operation. This episode took time to rectify, with a replacement computer being commissioned in November.

Results from the Lasgit experiment have been reported in the peer-reviewed literature (Bennett et al. 2015) and at an international conference (Graham et al. 2015) during 2015.

## 4.5 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 products 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 assembly 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 4-11), 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.

Cast iron and copper corrosion coupons are mounted inside the support cages of each experiment and corrosion behaviour is monitored electrochemically. Cast iron and copper weight loss specimens are also present. Each support cage contains a 'sandwich type' copper-cast iron specimen to investigate oxide jacking effects and galvanic corrosion. U-bend and wedge open loading stress corrosion specimens are mounted in one of the boreholes in direct contact with the groundwater, to assess the possible risk of stress corrosion cracking of copper. In addition, two of the canisters will be monitored using strain gauges to detect any expansion in the copper shell. The redox potential, $E_h$, is being monitored using a combination of metal oxide, platinum and gold electrodes.

The boreholes are located in a region with many fractures, leading to a plentiful supply of 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 regularly 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).

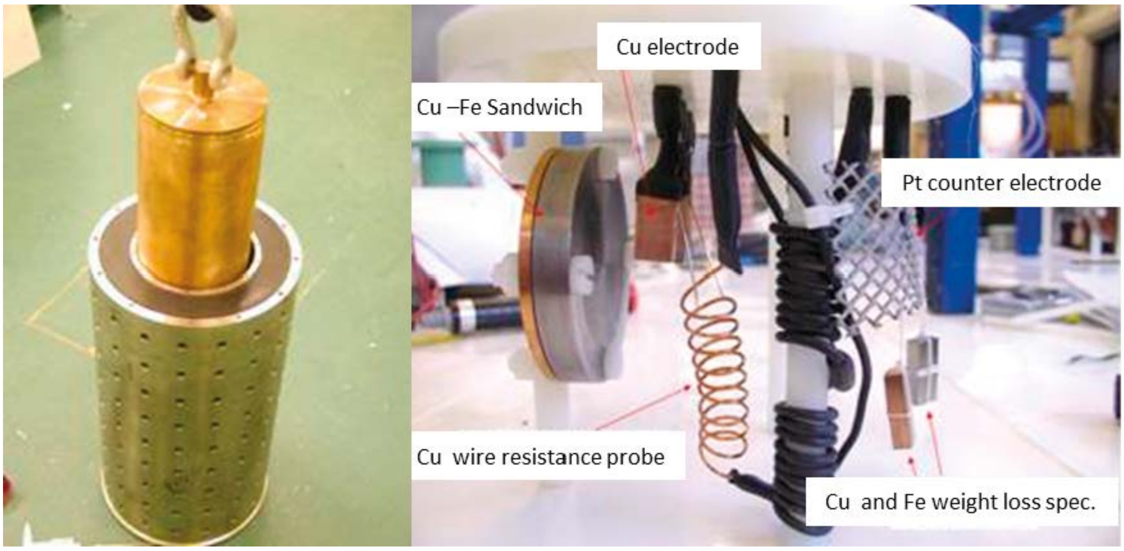



***Figure 4-11.*** *Model canister being lowered into support cage containing bentonite pellets in annulus (left). Test electrodes inside support cage around model canister experiments (right).*

### *Results*

In October 2015, a team composed of staff from from SKB, Swerea-KIMAB and Microbial Analytics AB, retrieved two experimental packages in the MiniCan series.

The MiniCan series was installed late in 2006 and the first package of five was retrieved and analysed in 2011. In that package the bentonite clay surrounding the copper-cast iron canister had a density much lower than that specified in the KBS-3 concept. The microbial activity, especially the metabolism of sulfate reducing bacteria (SRB), seemed to have reached levels never before observed in a KBS-3 like field test. When the package was dismantled, it became clear that the SRB had occupied a water filled void in between the copper canister and the bentonite clay. This void was included in the design of the experiment in order to place various electrodes for electrochemical monitoring of the system. Electrodes and weight-loss specimens made of cast iron had been completely corroded and converted into iron sulphides. As a consequence, all other surfaces inside the package were also covered with an iron-sulphide deposit, which in turned caused severe disturbance of the electrochemical measurements.

In order to better understand what determines the microbial activity, the two packages retrieved this year were one with highly compacted bentonite clay, and one package which contained no bentonite clay at all. When dismantling the two packages it became clear that the presence and density of the clay is of great importance for the corrosion of iron. In the package without bentonite clay the corrosion of iron was visually very similar to that observed earlier in the package with low density bentonite. On the contrary, the iron components in the package with highly compacted clay had retained their original shape and sharp edges, even a weak metallic shine could still be observed.

The analysis program that now follows is very ambitious. Microbiological sampling was made from various surfaces in the experiment, DNA has been extracted, the copper shell has been sliced into a number of test specimens for both spectroscopic and microscopic examination of the surface. The goal is that the final report will be out by summer 2016 and the plan is to present some of the results at a conference in Toronto in May.

During 2015 SKB published the last planned progress report from MiniCan (Smart et al. 2015), which containes data until 2013. The monitoring of the remaining experiments 1 and 2 will continue, but no annual progress report will be published. Instead, the data from the measurements (ground water chemistry, electrochemical methods, microorganisms etc) will be published together with the post test analysis of these experiments when they have been retrieved. During 2015 Nick Smart and co-workers at Amec Foster Wheeler, also did further metallographic investigations of SCC (stress corrosion cracking) specimens from the retrieved MiniCan 3 (Aggarwal et al. 2015).

***Figure 4-12.*** *Ground water filled container docked to the borehole of MiniCan 4. The experimental package was taken out and placed in a transport flask under nitrogen saturated water in order to avoid exposure to the atmosphere.*

***Figure 4-13.*** *Transport flask being lifted out of the container.*

***Figure 4-14.*** *Claes Taxén from Swerea-KIMAB controlling the potential of reference electrode.*

***Figure 4-15.*** *Sampling for microorganisms.*

***Figure 4-16.*** *Canister of MiniCan 4 sees daylight after nearly nine years in the borehole.*

***Figure 4-17.*** *Canister before being sliced for preparation of metallographic examination.*

## 4.6 Concrete and Clay

### *Background*

In the present and future repositories for low-and intermediate level waste, SFL and SFR, interaction will occur between the many different types of wasteform materials deposited there and the barrier materials, mainly comprising different forms of cementitious materials but also bentonite clay. These interactions will affect the barriers chemical, physical and mechanical properties and their ability to prevent the release of radio nuclides.

The project Concrete and Clay was initiated in 2009 with the aim of increasing the level of knowledge 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.

### *Objectives*

The objective of this project is to increase the understanding of the processes occurring in repositories for low- and intermediate level waste. Three main fields of interest have been identified:

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

### *Experimental concept*

The experiments comprise a total of 12 concrete cylinders containing materials representative for low- and intermediate level waste which are deposited in four different deposition holes in NASA0507A and NASA2861A respectively. Further also a total of 150 bentonite blocks in 5 different packages are deposited in TAS06. In each bentonite block (Ø 270 mm and height 100 mm) 4 different material specimens have been placed.

As a complement to the large scale experiments, also reference experiments have been prepared. These comprise different types of waste form materials which are placed in steel containers filled with a mixture of Äspö ground water and hardened and crushed cement paste. The objective of these experiments is to serve as a guide for the decision on when to retrieve the large scale experiments in the bedrock.

The project is expected to run for up to 30 years and some of the experiments deposited in 2010 have now been retrieved. Experiments will continue to be retrieved at regular intervals and the last will be left for the entire 30 year period or until the closure of the Äspö HRL.

### *Results*

#### Installation of the experiments

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

During 2014 the bentonite experiments were prepared. A total of 150 bentonite blocks, each also containing 4 different material specimens, were manufactured from MX-80, Asha, Febex and Ibeco RWC. The experiments are now deposited in 5 different deposition holes in TAS06.

The preparation of the specimens and the installation procedure is described in Mårtensson (2015).

#### Retrieval and Analysis of a concrete cylinder with metal specimens

During 2015 the first concrete cylinder containing specimens of zink, aluminium, stainless steel and carbon steel was retrieved and analysed. The process of retrieving the concrete cylinder was very smooth and required in all less than one day's work, Figure 4-18 to 4-20.

The analyses (Kalinowski 2015) focused on studies of corrosion of aluminium and zinc and the composition and distribution of the corrosion products in the concrete adjacent to the metal specimens.

The analyses of the level of humidity in the concrete cylinders showed RF values between 82 and 97 % indicating that sufficient water had been available for the corrosion process.

Visual inspections of the surface of the metal specimens showed obvious signs of corrosion of the Zn and Al specimens, Figure 4-21 left image, whereas the different steel specimens were virtually unaffected.

***Figure 4-18.** The lid is removed from the deposition hole.*


***Figure 4-19.*** *After removing the topmost layer of sand and the bentonite used to seal the deposition hole from intruding surface water the concrete cylinder is exposed. Please note that the sand-filled slit is saturated with ground water. The right figure shows the label of the concrete cylinder ensuring that the correct concrete cylinder is retrieved.*

***Figure 4-20.*** *The concrete cylinder was cut into four different pieces, each containing only one type of metal specimens, packed and shipped to CBI for analysis.*

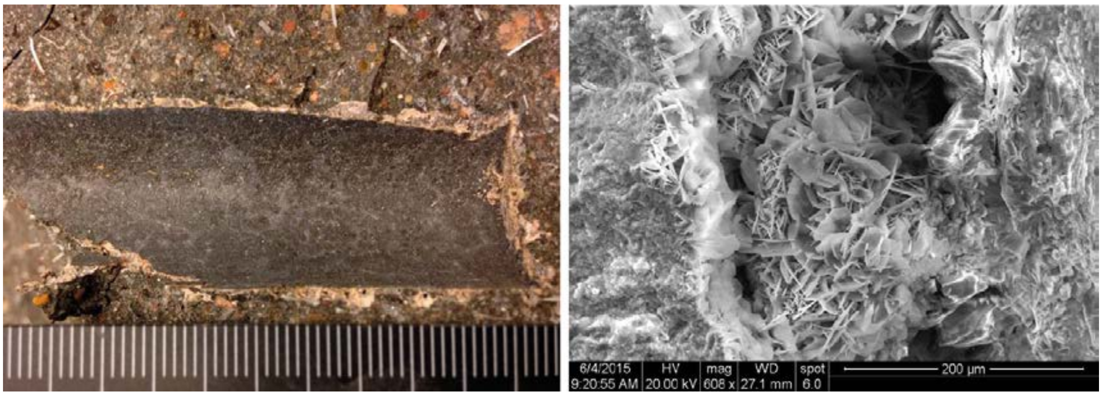



***Figure 4-21.*** *The surface of an aluminium rod with a thin crust of whitish corrosion products extruding into the concrete, left image. A small pore just at the interface between the aluminium rod and the concrete. The pore, which is now partially filled with secondary minerals, was probably formed during the casting of the specimen when hydrogen was evolved through a reaction between the Al rod and the yet wet concrete, right image, from Kalinowski (2015).*

Microscopical investigations of the cross section showed that the thickness of the layer of corrosion products on Zn and Al were on an average 100 µm and 150 µm respectively but areas with thicker outgrowths were also found. SEM studies also revealed the presence of small pores or voids just at the interface between the concrete and the Al and Zn specimens, Figure 4-21 right image. These pores, now partially filled with secondary minerals, were probably formed during the casting of the specimen when hydrogen was evolved through a reaction between the yet wet concrete and the metal specimen. No pores were found in the concrete adjacent to the steel specimens.

EDS analyses showed that corrosion products had diffused into the concrete. For Al and Zn increased levels were found up to 300 µm and about 1200 µm respectively from the metal surface whereas for steel and stainless steel the levels did not reach above the background level.

The results from this study suggests that the corrosion rate of Al and Zn is considerably lower than 1 mm/year which is the currently assumed corrosion rate for these metals, see Table 6-3 in SKB (2015). More detailed investigations are therefore planned in order to gain further insight in the corrosion process of these metals under repository-like conditions.

## 4.7 Low pH-programme

### *Background*

The purpose of the Low-pH programme is to develop cementitious low-pH products that can easily be produced for use 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 original 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 monolith was also cast in the same low-pH concrete and at the same time, to be able to investigate long term properties of this material. A new project which aims to further develop recipes for cementitious low-pH materials started at 2014. Developed recipes in this project will be tested at Äspö HRL during 2016–2017.

### *Objectives*

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

### *Experimental concept*

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

During 2009 field tests also started on corrosion behaviour of steel in low-pH concrete. 24 samples were prepared and placed in an open container in a niche at Äspö HRL. Each specimen contained three steel bars. Each steel bar, with a diameter of 20 mm and a length of 200 mm, was carefully cleaned and weighed with an accuracy of 1/1000 gram. The specimens were then placed for field exposure in an open container in niche NASA2715 at the Äspö HRL.

The development of the rock bolt grout and shotcrete for rock support and the results of corrosion tests after one year of exposure are reported in a SKB report (Bodén and Pettersson 2011).

A monolith has been cast using the same low-pH concrete as in the Domplu-test (system design of dome plug for deposition tunnels, see Section 4.10) and in the same area as the plug, Figure 4-23.

The programme will follow the evolution of the low-pH concrete and changes in material properties by taking core samples from the monolith, during three years and even further if it shows to be of advantage for better understanding of these materials.

### *Results*

During 2013, three rock bolts, two horizontally and one vertically emplaced, were over-cored and investigated, see Figure 4-22. Over-coring of the vertically emplaced bolts showed to be extremely demanding and time consuming. Therefore it was decided to settle for over-coring for only one of the vertical bolts.

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

Concrete cores have been taken from the monolith, casted with the same material as the Domplu, after 28 days, 90 days, 120 days, and 180 days hardening in the Äspö HRL. These cores have been investigated with regard to their strength. Even the modulus of elasticity has been determined in some cases. The results have been published in a SKB report (Mathern and Magnusson 2015). The testing programme has continued with investigations after one year of exposure which will be reported in the Domplu project. Thereafter the low-pH programme has continued to take out cores and investigate them. Cores have been taken out and been investigated after 2 years, see Figure 4-24. The program will continue to investigate cores after 3 years of exposure. The exposure and investigations may continue even for a longer period of time, if the results are jugded to be of interest. Results of these investigations will be published later together with results from other ongoing long term investigations on low-pH-materials, i.e. creep investigations.

***Figure 4-22.*** *Overcoring of bolts for investigation.*


***Figure 4-23.** Concrete monolith.*


***Figure 4-24.** Cores being taken out of the monolith.*

## 4.8 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 expanded 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 clarify 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 ones.

### *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), RAWRA (Czech Republic), RWM (England) and DOE/UFC (USA). All together approximately 10 modelling teams are participating in phase 2.

**Geochemistry**

The present phase includes the following tasks:

1. Diffusion of NaCl in Na-montmorillonite and $CaCl_2$ in Ca-montmorillonite (ClayTechnology)
2. Gypsum dissolution and diffusion in Na- and Ca-montmorillonite (Clay Technology)
3. Ca/Na-exchange in montmorillonite (Clay Technology)
4. Core infiltration test on material from parcel A2 in the LOT-experiment (UniBern)
5. Anion of selected anions through compacted bentonite (ÚJV Rez).

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

### *Results*

Two Task Force meetings have been held during 2015; one in Barcelona on May 18–20 and one in Lausanne on November 10–12. 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.

An additional phase of this task implies code validation with well-defined tasks and parameter values. An updated task description was distributed in December 2015. The current description of the code comparison is divided in the following stages with increasing complexity of the coupled simulation.

1. Thermo-hydraulic calculation neglecting vapour diffusion
2. Thermo-hydraulic calculation considering vapour diffusion
   a. Richard's approximation, constant fluid properties
   b. Richard's approximation, temperature dependent fluid properties
   c. Two-phase flow, constant fluid properties.
3. Thermo-hydro-mechanical calculation
   a. Elastic material behaviour
   b. Elastic material behaviour + linear swelling of bentonite.

Seven modelling teams have presented results within this task during 2015:

- SKB-1/ClayTech has used the code COMSOL Multiphysics and has presented results for Stage 2a, 2b and 2c. This work has resulted in the successful implementation of vapour diffusion into the COMSOL code.
- RAWRA/TUL has used the code ISERIT and has presented results for Stage 1.
- RWM/Amec has used the code TOUGH2 and has presented results for Stage 2c.
- CRIEPI has used the code LOSTUF and has presented results for Stage 3.
- NAGRA/EPFL has used the code Lagamine and has presented results for Stage 1, 2a, 2b and 3.
- The CodeBright Consortium at UPC (Polytechnic University of Catalonia) contributed with model results for Stage 3.
- BMWi/BGR has used the code OGS and has presented results for all stages. BMWi/BGR also defines the tasks and performs the compilation and comparisons of model results from the different teams. The presented results showed an excellent agreement in the thermal evolution in the buffer for all stages. The hydraulic evolution of the buffer for Stage 1, 2a and 2b also showed a good agreement. Results of Stage 2c showed some deviations in the saturation evolution and further analysis of this was required. For the mechanical process in Stage 3, an alternative effective stress principle was proposed, which was included in the updated task description.

*Task 8: hydraulic interaction rock/bentonite*

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

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

The task concerns modelling of an Äspö test in a project called Brie (Buffer-rock interaction experiment), which was installed in 2012. This task is divided into several subtasks (T8a–T8f). The project is described in more detail in Chapter 3.

Data deliveries (No 16–20), e.g. with water contents, densities and a visualization of these, were distributed between February and June 2015. A Framework for Comparative Analyses and Conceptual Uncertainty Evaluation was distributed in November 2015. This included a questionnaire with 24 items, which the modelling teams were asked to respond to in December 2015.

Four modelling teams have been working with this task during 2015:

- SKB-1/ClayTech has primarily used Code_Bright for this task, and has focused on Task 8f in which data from the dismantling of BRIE has been used to refine the models. A relative permeability relation for rock was evaluated from measurements of vapour permeability performed on granite samples found in the building material engineering literature. COMSOL Multiphysics was used for analysing this relation for the near-field rock around the BRIE parcels.
- BMWi/GRS has used the CODE VIPER for Task 8f, and has mainly focused on the upper dry section of Hole 17.
- RAWRA/TUL has used the diffusion model in Code Ansys for this task and has presented model results for both bentonite parcels and also comparisons with experimental data.
- RWM/Amec has used ConnectFlow for this task, and has focused on Task 8f.

*Homogenisation*

This is a task related to erosion and loss of buffer and backfill and subsequent homogenisation afterwards but can also refer to homogenisation in general. The general understanding of bentonite is that it has excellent swelling properties but the homogenisation is not complete due to friction, hysteresis effects and anisotropic stress distributions. The task involves two subtasks.

- In subtask 1 a number of laboratory swelling tests that have been made are modelled and used for checking/calibrating the mechanical model.
- In subtask 2 a large laboratory scale test that simulates bentonite lost in a deposition hole was started three years ago. This scale test was dismantled and sampled in August 2015 and the results were subsequently distributed to the Task Force.

A compilation of all available test results was distributed in April 2015. Data from dismantling of SH1 used in Task 2 was distributed in November 2015. Four teams have been working with this task during 2015:

- SKB-1/ClayTech presented a model for non-isotropic hydro-mechanical problems which was based on the description that the swelling pressure for a specific void ratio is restricted by two bounding lines. Stress/strain relations for saturated conditions were derived by defining a clay potential (the sum of suction and stress) as a function of the void ratio and the strain history (thereby incorporating a path dependence). These relations were solved using the MathCad software for three different 1D homogenization problems corresponding to the analysed experiments in Task 1: i.e. axial, radial (outward) and spherical swelling.
- SKB-2/ClayTech has used a Plastic Cap model and a Drucker-Prager model implemented in Abaqus, and presented modeling results for SH1 in Task 2 and a comparison with measured results.
- Posiva/B+Tech has used the BExM implemented in Code_Bright and presented results for the isotropic swelling test included in Task 1.
- Posiva/UCLM has used the BExM, with plastic free swelling mechanism, implemented in COMSOL Multiphysics, and presented results for the isotropic swelling test included in Task 1.

*Prototype Repository*

This task is to model one of the two outer deposition holes in the Prototype Repository in Äspö HRL. A prediction of the state of the outer section of the Prototype Repository (mainly in the buffer in the deposition holes) and capturing the THM processes during operation are the main goals of the assignment. Three steps for solution strategy have been proposed:

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

Four modeling teams have been working with this task during 2015:

- SKB-1/ClayTech has used Code_Bright for this task, and has focused on task PR-3. Friction between the buffer and the deposition hole wall is of major interest in this task. However, the used code can only represent friction in plane and axisymmetric geometries. Therefore the current analysis has focused on the conditions and processes recorded in Canister Retrieval Test.
- BMWi/GRS has used code $d^3f$ and has focused on task PR-1.
- RAWRA/TUL has used the diffusion model of Ansys for this task and has modelled the bentonite hydration of DH5 and DH6.
- CRIEPI has used the code LOSTUF and presented results from both PR-1 and PR-2.

*Proposals of new tasks*

Proposals for four new tasks were distributed in July 2015 and subsequently presented and discussed at the November meeting. These concerned the following four topics:

- Water transport in pellets-filled slots
- Febex in situ test
- Homogenization of unsaturated barriers
- Gas transport in bentonite.

**Geochemistry**

At the spring meeting in Barcelona, Urs Mäder started the chemistry session by giving an overview of the benchmarks, as well as discussing different concepts adopted for modelling them. Radek Cervinka presented an update on modelling of Benchmark 1 using the code GoldSim with module EVALDIFF. Andreas Jenni gave an update on reactive transport modelling in bentonite using the code CrunchFlowMC, which was used for modelling the "uphill" diffusion phenomena. Martin Birgersson presented a review of model-discriminating experiments, performed within the context of the EBS Task Force. Paul Wersin gave a talk on the role of iron and redox chemistry in bentonite with respect to buffer performance. Magnus Hedström presented a set of suggestions for new benchmarks for the next phase of the chemistry part of the Task Force. This list of proposals was the outcome of a meeting held in March 2015 at Clay Technology with representatives of SKB (Peter Wikberg, Anders Sjöland), BMG (Michael Ochs), and Clay Technology (Ola Karnland, Magnus Hedström, Martin Birgersson). The suggested tests – which include both existing experiments and experiments to be performed – are focused on processes of importance for the KBS-3 concept. Martin Birgersson presented the plans for a cooperation between Amec Foster Wheeler and Clay Technology with the aim of implementing a new transport tool for diffusion in bentonite at the request of RWM. The tool will be based on ion equilibrium and transport in interlayer pores. The chemistry session was closed by a discussion on choosing new benchmark data sets.

At the fall meeting in Lausanne, Urs Mäder started the chemistry session by giving an overview of the "issues" of concern, with focus on choosing new tasks for the EBS Task Force. He also gave an overview of recent tool development activity. Eva Hofmanová presented additional experiments, complementing Benchmarks 1 and 5. In one type of experiment she demonstrated that the diffusion behaviour is basically identical regardless of whether it is performed with constant or variable ionic strength across the clay. In another type of tests it was shown that the diffusion behaviour of ions change depending on the Ca/Na ratio in the clay, although the ionic strength is the same. Both of these findings are consistent with the notion that diffusion in compacted bentonite is governed mainly by the properties of interlayer pores. Andrew Hoch presented an update on the ongoing work on implementing a model for solute transport in bentonite using the "interlayer-only" concept. Andreas Jenni and Ángel Yustres presented ongoing work on coupling pore water composition to swelling pressure using a dual-porosity approach. In conjunction with this presentation Ola Karnland gave a short reply, showing results of free swelling tests on fully saturated samples with circulating test solutions. Peter Alt-Epping presented reactive transport simulations in bentonite backfill, with focus on sulphide. He also gave a new proposal for a future benchmark calculation, involving a rock component, a EDZ component, and a bentonite backfill component. Magnus Hedström gave an overview of the performed molecular dynamics simulations performed within the EBS Task force, and related the results to macroscopic models. He concluded that using the Donnan potential is the optimal first order approximation to electrostatics in compacted bentonite and that the use of activity coefficients as a mean to go beyond electrostatics is meaningful. He also showed that fully atomistic MD simulations of osmotic pressure now are possible. Martin Birgersson revisited modelling work made on the "uphill" and "counter ion diffusion" experiments – experiments which now are suggested as new benchmarks. The chemistry session was concluded with Urs Mäder presenting the full set of suggested new tasks/benchmarks for the chemistry part of the EBS Task Force. In total there are 10 different suggestions, ranging from already performed small-scale tests, to larger scale tests with explicit mechanical couplings. No decisions were made on which of the suggestions should be chosen.

## 4.9 Water handling during backfilling of deposition tunnels

***Background***

The reference design considered by SKB for backfilling tunnels includes emplacement of pre-compacted blocks in the tunnel and bentonite pellets that fill up the space between the blocks and the tunnel walls. Pellets will also be placed on the tunnel floor in order to even out the rough rock surface and by that provide a suitable surface on which the backfill blocks can be stacked. The installation of such a backfill system includes advanced technical solutions for automation of block manufacturing, block transports, stacking of blocks, emplacement of pellets, etc.

One of the main problems identified is how the water inflow to the tunnels should be handled during emplacement. Depending on flow rates and how the inflow points are distributed in the tunnels the inflowing water may affect the stability of the backfill installation and also cause erosion of the backfill. The Forsmark site is assessed to be rather dry, but preliminary studies show that about 45 of in total 207 planned deposition tunnels will have an inflow of more than 10 l/min and 13 tunnels will have inflows of more than 30 liters per minute (Joyce et al. 2013). Since it is desirable that no deposition tunnels should be abandoned, it will be necessary to develop methods and techniques to handle these expected water inflows. The deposition tunnels in the current reference design have an inclination upward, towards tunnel face, of 1 degree to enable drainage of inflowing water away from the backfilling works as long as possible.

Tests with bentonite pellets have been performed in different scales and they have shown that the inflowing water can, to a large extent, be stored in the macro voids between the bentonite pellets, in the pellet filled gap between backfill blocks and rock. The water storing in the pellet filling is probably enough for the main part of the tunnels but it will be necessary to have other techniques and methods for tunnels with very high inflow rates (Sandén and Börgesson 2014).

Two methods handle inflowing water have been tested in the Bentonite Laboratory at Äspö:

1. **Geotextile**. Geotextile can be used as a distributor of inflowing water. The geotextile is fastened on the rock wall over either a point inflow or over a water bearing fracture zone and distributes the inflowing water over a larger area. The idea is to improve the water storing capacity of the pellet filling with this technique.
2. **Temporary drainage**. If the inflow rate is between 0.5 to 1.0 l/min it could be necessary to also use a temporary drainage system in combination with the geotextile. The suggested technique implies that the geotextile is connected to a steel tube so that the inflowing water can be drained away while the pellet filling is installed. The drainage pipe should be removed after having fulfilled the drainage. The idea with this technique is that this will delay the time for inflowing water to reach the backfill front.

### *Objectives*

Tests have earlier been performed within the project "System design of backfill" with the aim to investigate if geotextile can be used as a water distributor during backfill installation. Four tests were performed in the steel tunnel (half scale tests in the Bentonite Laboratory) and one full scale test was performed underground at the Äspö HRL. After evaluation of these tests there were some remaining questions e.g. how the results were influenced of fines present in the pellet filling.

In this project, KBP1011, five additional tests have been performed in the steel tunnel. The new tests were performed with the aim to investigate the water storing capacity of sieved pellets i.e. all fines were removed before installation, and also to determine the limits regarding which water inflow rate that can be handled with this technique. One additional aim was to test the new glass fiber geotextile. One of the tests, no. 5, also included a test of temporary drainage equipment.

### *Experimental concept*

#### General

In short, the experimental concept was to record the effect of the geotextile on wetting pattern in the pellet filling, and time to outflow through the backfill front, for different water inflows.

For one of the tests, a system for temporary drainage was applied and the outflow through the drainage system was compared to the measured inflow into the tunnel and thereby judging on the effectiveness of the drainage system.

#### Test setup

The test setup, see Figure 4-25, was in the steel tunnel in the Bentonite Laboratory. The tunnel is in half scale compared to the planned deposition tunnels. The nominal cross section area of the tunnel is 7.1 $m^2$ and the length is 6 m. The usable length for the tests has been 4 m. Figure 4-25 also shows the geometry in which bentonite blocks and pellets were installed. The tunnel walls are not able to withstand the full swelling pressure of a completely backfilled tunnel and therefore, instead of backfilling the centre of the tunnel, there was a wooden framework designed to deform and fail mechanically if the swelling pressures becomes too high. Since the blocks are assessed to be of less importance for the test results, this solution also saved time and money. The wooden frame was covered with a bentonite geotextile mat to prevent movement of any water that has managed to penetrate both the pellet and the block materials. Two different block stacking patterns have been used in the test series, Figure 4-25 shows the pattern used in tests 1–3. The reason for this was lack of backfill block of the same size. The remaining gaps between the blocks and the wall and ceiling were filled with pellets.

A water inlet, simulating the water inflow point in a deposition tunnel, was positioned on the middle of the left wall, 1.8 m from the tunnel back end.

In conjunction with steel tunnel Test 5, a new functional test of the temporary drainage equipment was made. In this test the water inflow rate was set to 1 l/min. Water collectors (see Figure 4-28) and drainage tubes were mounted on both sides of the tunnel, see drawing provided in Figure 4-29 (note that the drawing only shows one water collector) and photo in Figure 4-30. The drainage period lasted for 43 h and after that, the valves mounted at the ends of the drainage tubes were closed and the inflowing water could instead fill up the pellet filling. This test is assessed to well simulate a real situation that could occur during backfilling of a deposition tunnel.

#### Test matrix

The test series consisted of five tests, see Table 4-1.

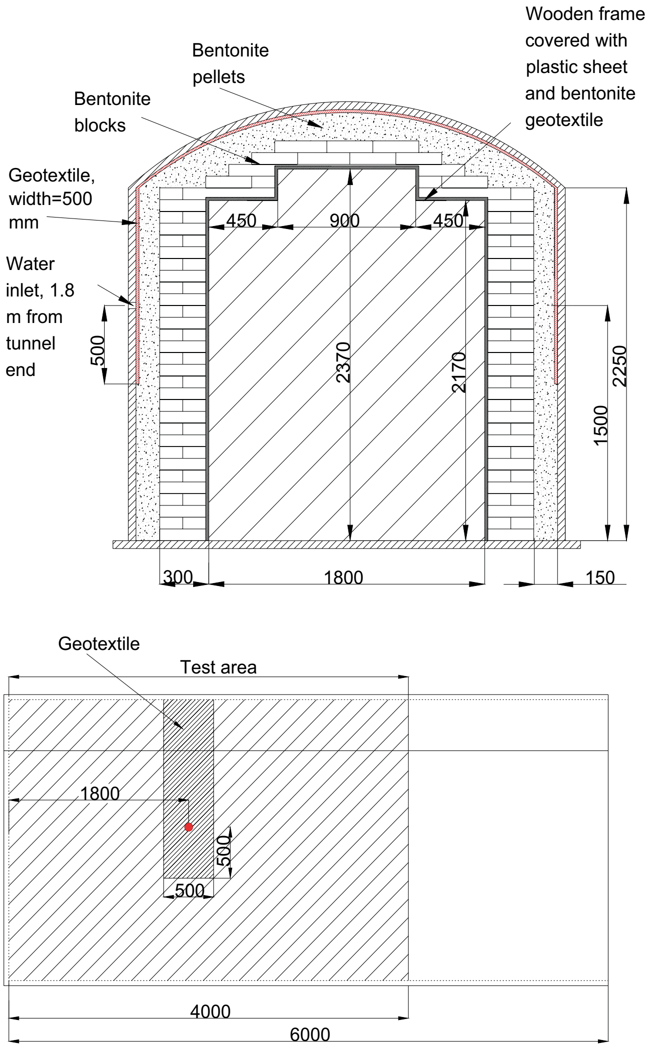



***Figure 4-25.*** *Schematic of the ½-scale test tunnel. Upper: Cross-section showing the central mould of wood, the block stack and the pellets. Lower: Steel tunnel from the long side showing the position of the geotextile. The backfill front can be seen on the right side.*

***Figure 4-26.*** *Photo showing Test 3 after installation of backfill including the concluding vertical pellet wall.*

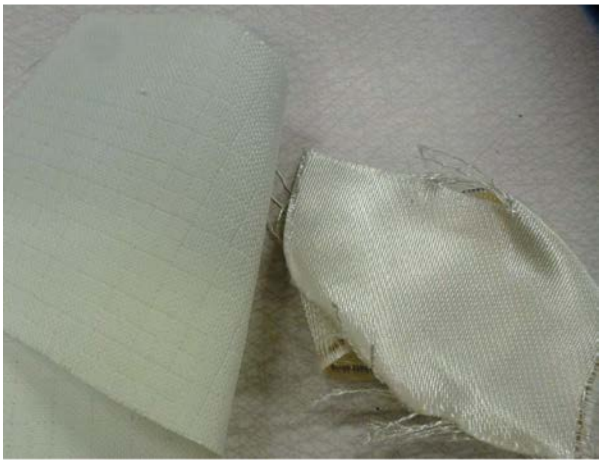


*Figure 4-27. Samples of glass fiber based geotextiles. The one to the right was judged to be most feasible as water distributor in the steel tunnel tests.*

*Figure 4-28. Mounting of water collector prototype in the steel tunnel.*

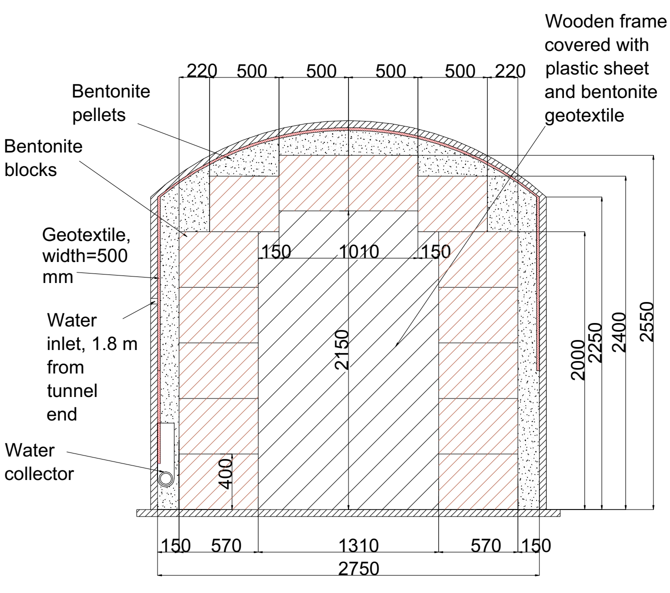



*Figure 4-29. Schematic drawing of the block pattern used in Test 4 and 5 including one water collector (used only in test 5).*

*Figure 4-30. Photo showing the backfill front in Test 5 after having finished the installation. The two drainage pipes can be seen on each wall leading out from the tunnel.*

**Table 4-1. Test matrix for the steel tunnel tests.**

| Test | Pellet material | Flow rate [l/min] | Geotextile | Comments |
|---|---|---|---|---|
| Test 1. | Asha | 0.25 | No | Reference test. |
| Test 2. | Asha | 0.25 | Yes | Repeating 2012 test with glass fiber geotextile. |
| Test 3. | Asha | 0.50 | Yes | Repeating 2012 test with glass fiber geotextile. |
| Test 4. | Asha | 0.50 | Yes | Repetition of test 3, but performed using full scale backfill blocks. |
| Test 5. | Asha | 1.00 | Yes | Extreme case. Including equipment for temporary drainage. |

### *Results*

The results concerning water storage capacity are graphically presented in Figure 4-31 that shows contour plots of the wetting pattern seen on the surface closest to the developed walls and roof for all five tests performed in the steel tunnel. The darker rectangular areas indicate the position of the geotextile and the stars indicate the position of the inflow point. The white areas shows where no samples were taken due to bentonite collapse (bentonite fell down on floor).

The first test in this test series was a reference tests, performed with an inflow rate of 0.25 l/min and without any geotextile installed. In this test 525 litres were stored before outflow occurred. The second test was performed with the same inflow rate (was later adjusted to 0.2 l/min depending on leakages from the steel tunnel) but with geotextile installed. In this test, the water storage increased to 1955 l/min before breakthrough at the front. This large difference in water storing capacity is very evidently shown in the contour plots for these two tests, Figure 4-31.

Test 3 and Test 4 were both performed with an inflow rate of 0.5 l/min and with geotextiles mounted on the “rock” walls. The rather early water breakthrough in Test 3, after 32 hours test duration, was believed to depend on the low block quality and therefore it was decided to repeat this test but instead using backfill blocks of high quality. In Test 4 the water breakthrough occurred after 38 hours test. During this time, 1140 litres of inflowing water were stored in the pellet filling.

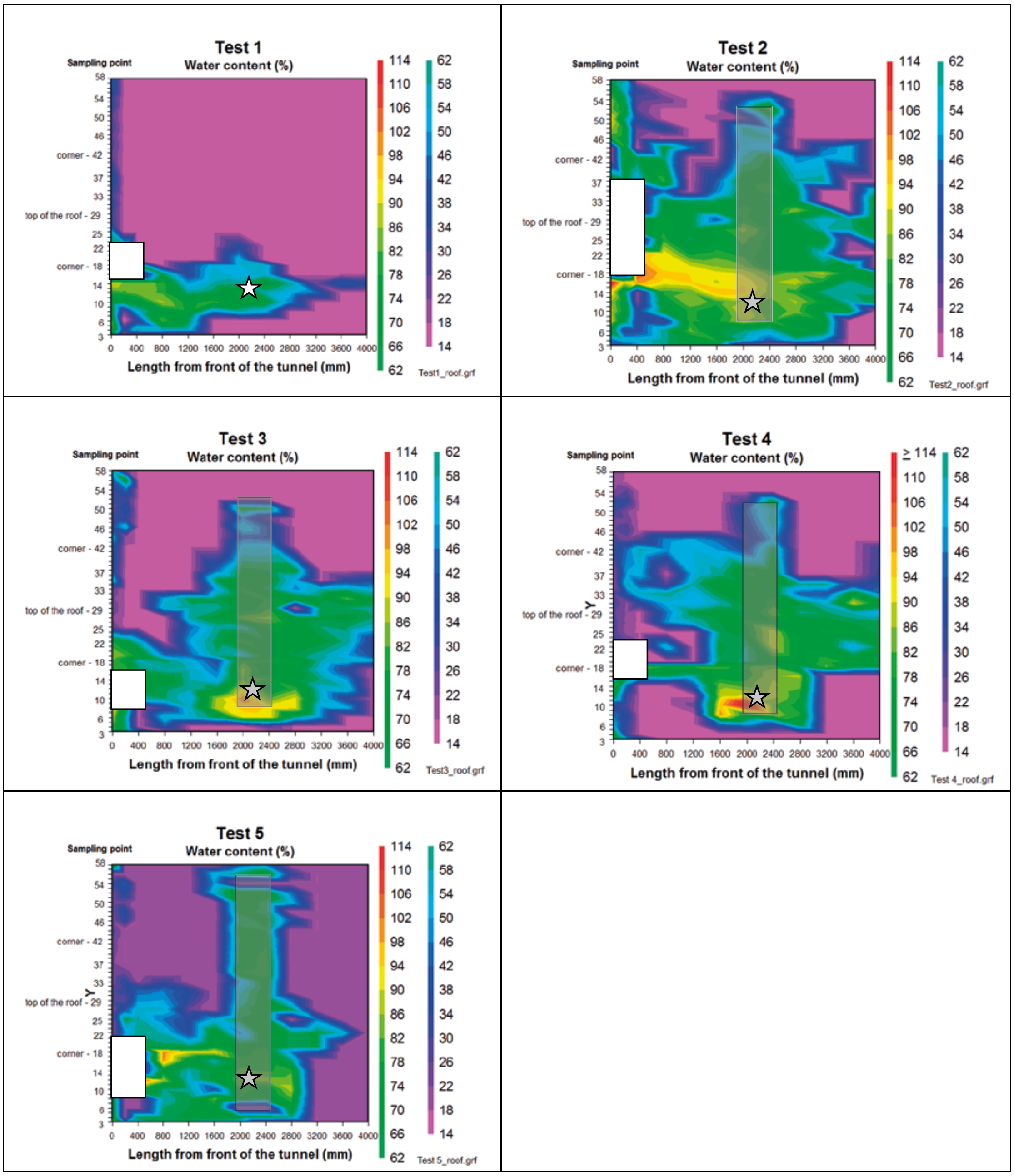



***Figure 4-31.*** *Contour plots showing the wetting pattern seen on the surface closest to the developed walls and roof for all five tests performed in the steel tunnel. The white boxes shows the areas where no samples could be taken due to material loss after the breakthrough. The darker rectangular areas indicate the position of the geotextile and the stars indicate the position of the inflow point.*

The last test, Test 5, was performed with an inflow rate of 1 l/min and with geotextile mounted on the "rock" wall. This test also included a function test of equipment for temporary drainage. The drainage phase did last for 43 hours and during this time approximately 2000–2250 litres were drained away. It is estimated that 300–600 litres of water were stored in the pellet filling during the drainage phase, i.e. most but not all of the inflowing water was drained out. When the valves to the drainage pipes were closed, all inflowing water was stored in the pellet filling. At this high inflow rate it took about seven hours before a breakthrough occurred in the backfill front. During these seven hours, 420 litres were stored in the pellet filling.

The tests have shown that the use of geotextile as a water distributor in order to increase the water storing capacity of a pellet filling, works well. It seems, however, as if the effect is depending on the inflow rate. At low inflow rates, < 0.25 l/min, the effect is strong, but when the inflow rate increases, the effect of using geotextile seems to decrease. The contour plots provided in Figure 4-31 shows clearly the effect of geotextile on the wetting pattern. Water has followed the geotextile from one side, up over the crown and down on the other side. At high inflow rates, the wetted parts on the other side seem to be limited to the surface below or close to the geotextile. In the performed tests, geotextile sheets with a width of 0.5 meter have been used in order to have a certain security distance to the backfill front. In a full scale installation it will of course be possible to increase the width of the geotextile in order to further increase the water storage capacity.

The performed tests have shown that the suggested design for a temporary drainage of a water bearing fracture zone works very well. In both tests there has been a short delay before water starts to flow out through the drainage pipe. This depends probably on the fact that the pellets closest to the inflow point is wetted in the beginning of the test, but as the wetting proceeds, the bentonite swells and seal and the flow resistance increase which means that it is easier for the water to flow through the geotextile into the water collector and further out through the drainage pipe.

## 4.10 System design of plug of deposition tunnel

### *Background*

The reference conceptual design of a KBS-3V deposition tunnel end plug consists of an arched concrete dome, a bentonite seal, a filter zone and material delimiters between each layer. Furthermore, a backfill transition zone has been introduced to moderate the swelling pressure from the backfilling in the tunnel, with the purpose of attaining a predetermined load from swelling pressure on the plug system.

In the Spent Fuel Repository, plugs will be cast 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 has been developed to meet the requirements of the design (Vogt et al. 2009).

Additional input to the system design 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 a total pressure of 7 MPa. However, reassessment of the system during testing has reduced the applied water pressure to 4 MPa due to experimentally related water escape problems, as later presented in section Results below. A load case with a water pressure equal to 4 MPa is a realistic case for groundwater pressure in the repository. At the end of the measurements, i.e. just before dismantling the Domplu, the plan is to perform a load test close to the design load of 7 MPa of total pressure.

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

### Experimental concept

The experimental site for the Domplu-test is located at Äspö HRL −450 m level, which is a representative depth for the deposition area in a repository. 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 remaining sensors are monitoring water pressure, total pressure, relative humidity and displacements of the bentonite seal, filter and the backfill zone.

As stated above, a key objective is to monitor the water leakage past the plug over time (about 36 months). For this purpose, a measurement system for leakage control has been developed and the water is dammed up and protected from evaporation behind a plastic cover just downstream of the weir. Effluent water is directed by gravity to a pendent scale for on-line registration of the flow rate. The experiment is pressurised artificially by pumping water into the backfill behind the plug, see Figure 4-32. The experimental set-up and pressurisation by water is targeted to reflect the 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 smooth excavation resulting in a discontinuous 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 theoretical cross sectional area of 18.9 $m^2$.

The plug slot, 8.8 meters in diameter, was excavated to obtain smooth surfaces using wire sawing in an octagonal pattern. The wire sawing method is assumed to minimise risk of a continuous EDZ over the plug and it provides smooth rock surfaces for the concrete dome. The performance and results of wire sawing are presented in detail by Grahm and Karlzén (2015). In Figure 4-33, a model composed of data from the 16 laser scanned slot surfaces has been incorporated in the model of experiment tunnel TAS01. The remaining half-pipe boreholes as seen in Figure 4-33 were filled by mortar before casting of the dome.

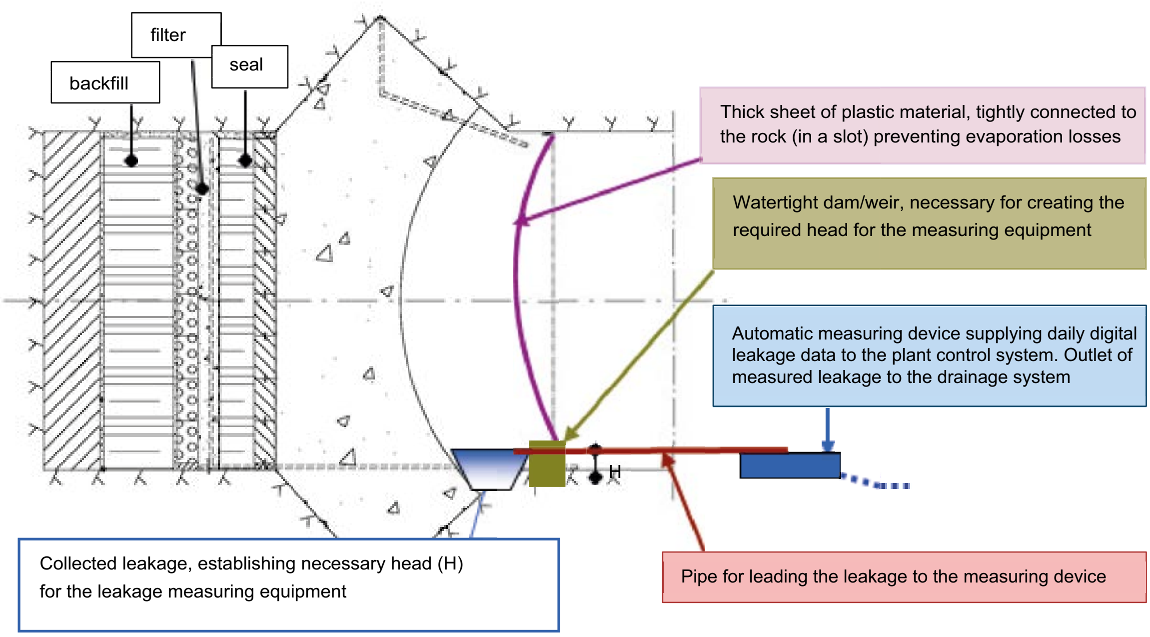



***Figure 4-32.*** *Layout of the full-scale experimental set-up Domplu.*

***Figure 4-33.*** *Illustrative model structured of data from laser scanning of TAS01 as well as of the excavated slot abutment (seen from above).*

The installation of the inner plug components began in late 2012 and was completed in the beginning of 2013 see Figure 4-34 and Figure 4-35. Domplu was designed with 45 sensors in the backfill and seal layer and another 56 sensors within the concrete dome. The sensors in the backfill and seal layers are fed through pipes in the rock to the adjacent tunnel, a distance of about 21 meters. Cables from sensors within the concrete dome are joined together and fed out as one bundle through the front face of the concrete dome. The properties being measured by the array of sensors include temperature, relative humidity, strain, displacement, pore pressure and total pressure. All data results are summarised and evaluated by Grahm et al. (2015).

On March 13, 2013 the casting of the concrete dome took place (Figure 4-36). The use of the B200 concrete was successful for the 94 $m^3$ structure. Dismantling of the formwork began three weeks after casting. The dome structure is seen in Figure 4-37. About 100 days subsequent to casting to await the early concrete shrinkage, in June 2013, contact grouting was performed over three sections of the dome to close any gaps in the concrete – rock interface. A cooling system was used to to compress the structure and thus get a better effect of contact grouting when the dome expands after completion of cooling. The resulting pre-stress in the concrete dome after cooling was however lower than expected (53 % of theory). According to Grahm et al. (2015) this is probably due to the fact that the measured concrete shrinkage was lower than expected in combination with the dome not fully releasing from the rock. This experience should be studied further during the detailed design phase.

The monitoring of Domplu started in September 2013 (month 0) when the bentonite seal had been artificially wetted by controlled flooding of the filter during the summer. When the drainage valves to the filter were closed, pressurisation of the experiment began by the natural groundwater inflow, corresponding to about 100 kPa per week (month 1–2). From December 2013 (month 3), the pressurisation system is operational, pumping in water for a faster pressure increase rate of about 250 kPa per week. In February 2014 (month 5), the water pressure reached 4 MPa and has been maintained at that level since then.

The plug was almost watertight up to about 3 MPa. When exceeding just over 3 MPa, the measured leakage past the plug increased somewhat. In addition, two experiment-related water escapes were observed. One water escape was via the cable bundle from sensors within the concrete dome. The other water escape route was a rock fracture ending in the main tunnel, 14 metres in front of the plug. The flow rate of the two water escapes was subsequently measured manually, supplementing the on-line recording of leakage past the plug collected in the weir, see Figure 4-38.

***Figure 4-34.** Detail photo showing (from left) delimiter of leca-beams, gravel filter with drainage (air) pipe, delimiter of geotextile, bentonite seal of MX-80 (blocks and pellets) and delimiter of concrete beams. All sensor cables are led in steel tubes.*

***Figure 4-35.** Installation of concrete beams, bentonite seal, gravel filter and sensors.*

***Figure 4-36.*** *Concrete is pumped in behind the formwork for casting of the concrete dome structure.*

***Figure 4-37.*** *The hardened concrete dome structure after removal of formwork. The steel beams in front of the dome are used for displacement sensors.*

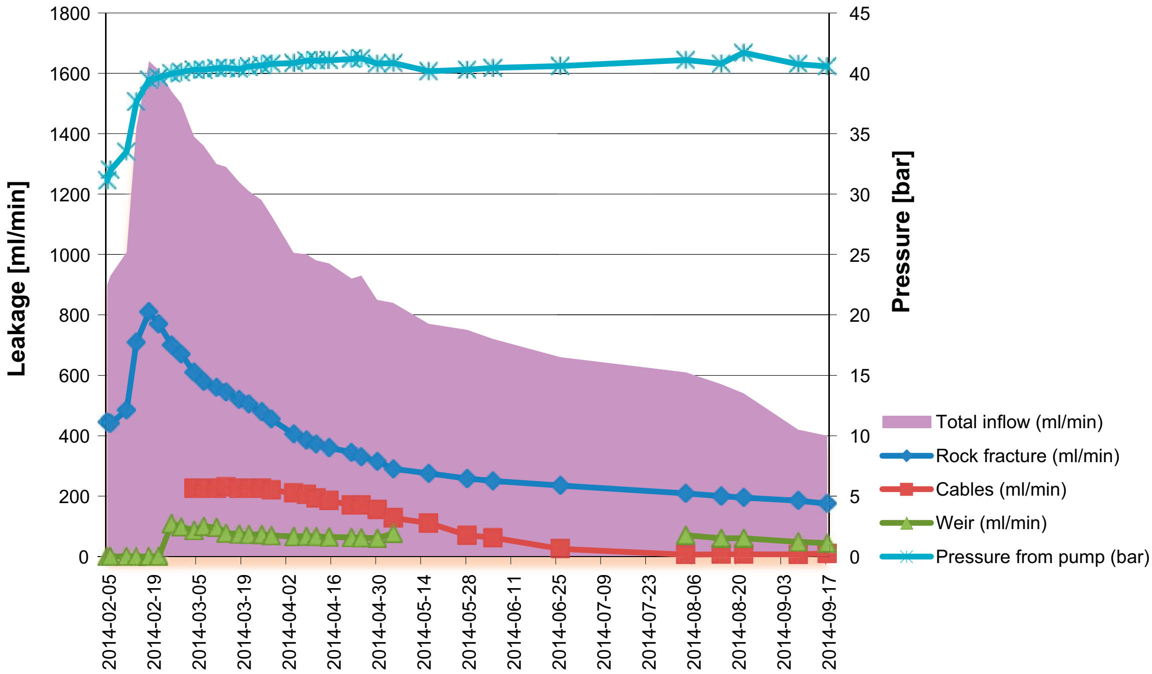



***Figure 4-38.*** *Measurements of leakage together with total water injection flow needed to keep the water pressure stable near at 4 MPa (about 40 bar).*

As seen in Figure 4-38, initially about 1600 ml/min injection water was needed to keep the 4.0 MPa water pressure in the filter. After eight months of plug system operation, just about 400 ml/min was needed to maintain the same pressure. This is probably due to effects of the swelling bentonite clay as well as of mineralogical clogging of fractures.

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

Since February 2014 (month 5), the water pressure has been fixed at about 4.0 MPa and the leakage rate collected in the weir during the follow up until the first data freeze (month 12) has been steadily reduced. On September 30, 2014, the recorded leakage rate was about 2.6 litres per hour (0.043 l/min). This is well below the proposed design criteria of a leakage rate past the deposition tunnel plug below 0.1 l/min. Moreover, based on the appearance of the measured leakage it is believed to decrease further since the swelling pressure of bentonite seal will continue increasing for a couple of years. The trend of the leakage rate based on data from on-line recording is shown by Figure 4-39.

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

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

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

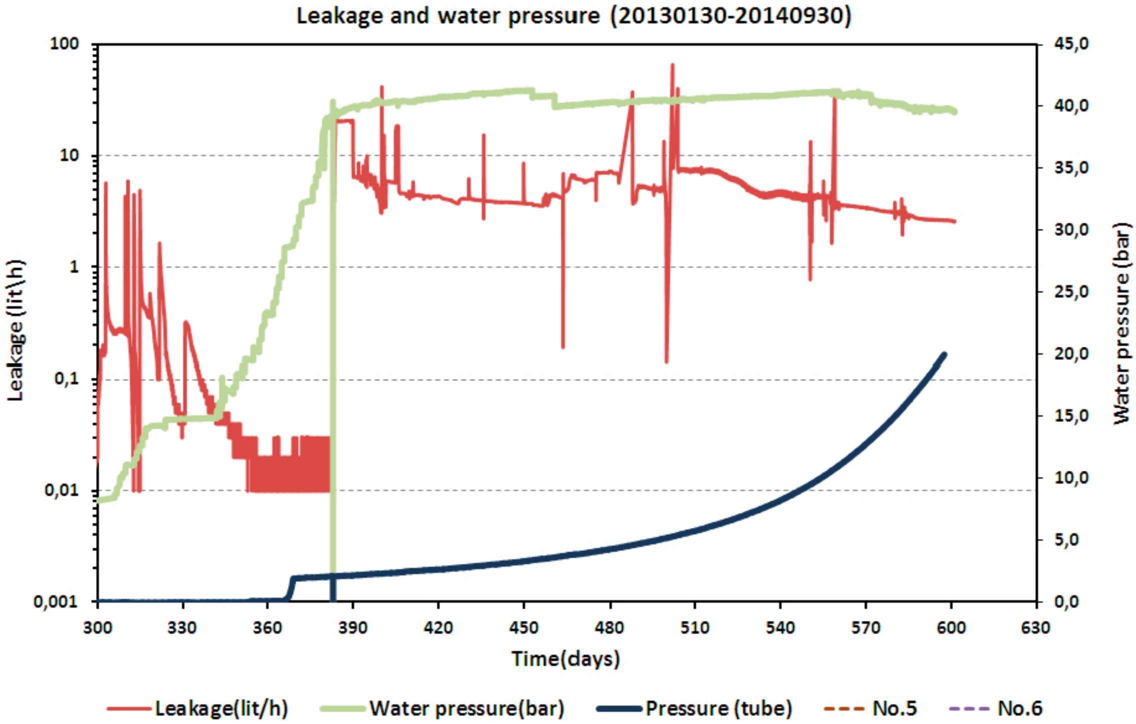



***Figure 4-39.*** *Measured leakage from the weir and the applied water pressure.*

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

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

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

**DOPAS (Full scale Demonstration of Plugs and Seals)**

The Domplu test is part of the EU-project DOPAS, which receives funding from the European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2011–2013, under Grant Agreement No. 323273 for the DOPAS project. DOPAS aims to improve the adequacy and consistency regarding industrial feasibility of plugs and seals, the measurement of their characteristics, the control of their behavior over time in repository conditions and also their hydraulic performance acceptable with respect to the safety objectives. DOPAS is carried out in a consortium of 14 organisations representing waste management organisations, research organisations, academia and consulting organisations.

## 4.11 System design of buffer

### *Background*

Based on the knowledge of the early THM processes, which were partly built up based on results from activities described in previous reports, two installation methods are currently being investigated.

1. In relatively dry deposition holes buffer blocks and pellets are installed simultaneously. The low inflow coming from the rock to the buffer before it gets support from the backfill is absorbed by the buffer pellets and blocks. This leads to a certain acceptable heaving of the buffer.
2. For deposition with slightly higher water inflow an enhanced buffer protection is used. This installation method is beset with practical disadvantages as water pumps etc but this is expected to be needed for a small percentage of the deposition holes in Forsmark.

These installation methods are currently being developed by SKB and an installation test of method 1 was run during 2015.

### *Experimental concept*

The test comprises a total of 14 buffer blocks, 10 ring shaped blocks around the canister, the bottom block and three solid blocks on top of the canister each with dimensions according to the reference design. Furthermore, two solid blocks of concrete were placed on top of the buffer blocks to simulate the wheight of the backfill blocks in the top of the deposition hole. The numbering / naming of the blocks are shown in Figure 4-40. The outer gap was filled with bentonite pellets. The test was conducted with a full scale canister with a power of 1700 W.

About a hundred sensors were installed in the experiment in the buffer, the canister and the rock. Every other buffer block in the test was instrumented. The Sensors were placed in four orthogonal directions in the blocks, A (0°), B (90°), C (180°) and D (270°). In Figure 4-41 fotos form the installation are shown.

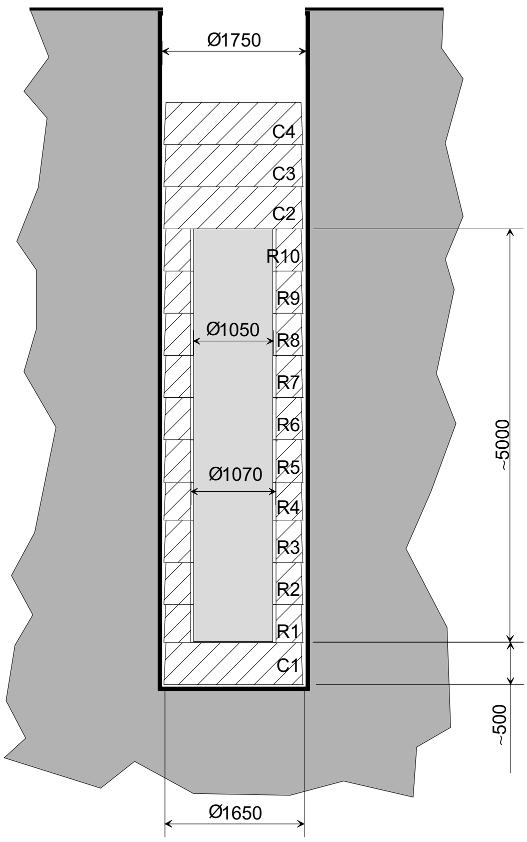



***Figure 4-40.*** *Test layout.*

*Figure 4-41. Fotos from the installation. Uppder left: installation of sensors in buffer blocks, lower left: Top buffer ring. Right: installation of canister.*

### Results

In Figure 4-42 preliminary results on the temperature evolution is shown and in Figure 4-43 preliminary results considering the heaving of the buffer is shown. The test will be dismantled in the beginning of 2016. A preliminary conclusion is that the heaving of the buffer stack is acceptable for the tested water inflow.

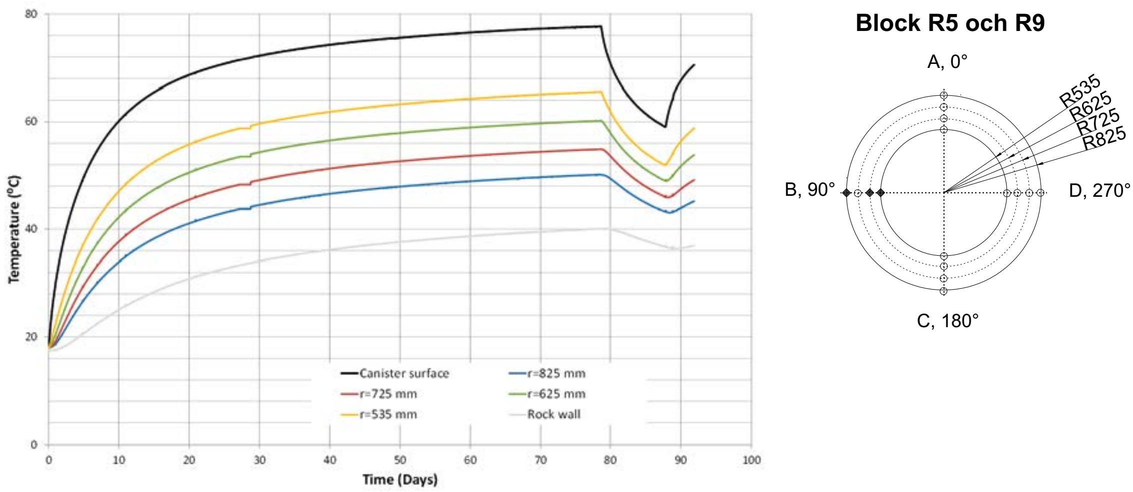



*Figure 4-42. Preliminary results considering the temperature evolution in ring shaped block no5.*

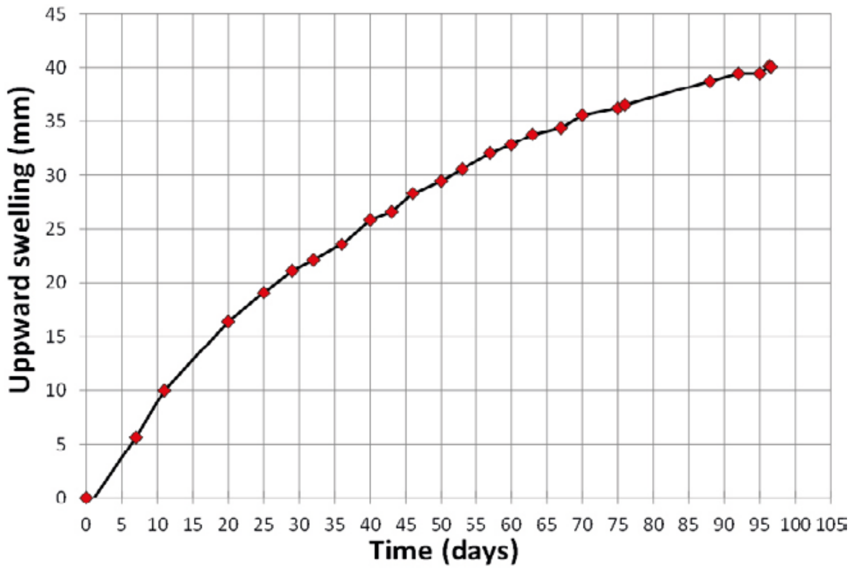



***Figure 4-43.*** *Preliminary results considering the heaving of the buffer.*

## 4.12 Tunnel production

### *Background*

Tunnel production is a development project with the aim to establish methods and concepts for excavation of deposition tunnels in the planned repository for spent nuclear fuel. This includes rock excavation methods, grouting and concepts for rock reinforcement.

### *Experimental concept*

As a part of the tunnel production project, SKB and Forcit Sweden AB conducted a joint project to study blast induced fractures from string emulsion. The purpose of the joint project is to study blast fractures from controlled string emulsion and to correlate the results to charge concentrations, evaluated from the charging and drilling logs. The data set could be used to update the blast damage tables for string emulsion used in the industry today. This will be an important design tool for SKB in order to predict, control and understand the influence of the excavation method on the rock mass. The project is partly financed by the Swedish Rock Engineering Research Foundation, BeFo, and is conducted in two steps. The field work in the first project step was completed at Äspö HRL during 2014 and the report was completed in 2015 (Ittner and Bouvin 2015). A new project phase is planned for 2016, where the project will conduct a similar study at another tunnel site.

A smooth floor is planned for the deposition tunnels in the planned repository for spent nuclear fuel and during 2015 the Tunnel Production project initiated a full scale test in TAS04 to study the possibility to level the tunnel floor by means of wire sawing.

The concept for the test was to excavate sawed slots close to the tunnel walls and face and then level the floor by wire sawing. The wire is pulled through the slots towards the tunnel entrance. Figure 4-44 to Figure 4-46 depicts the ongoing work.

### *Results*

The concept to level the floor by means of wire sawing will be evaluated in terms of production times, cost efficiency and quality of the results. The tested concept is one of several that will be evaluated in the Tunnel Production project.

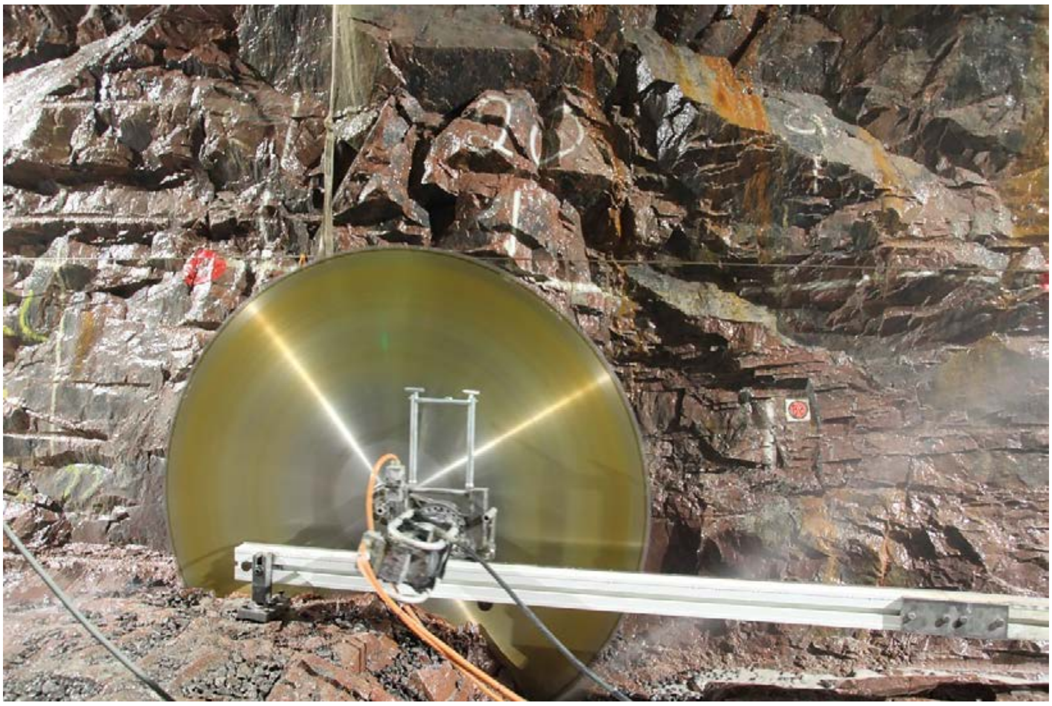


*Figure 4-44.* *Sawing of the slots on sides. Two parallel cuts are made on each side and the rock between them are removed (Photo by Rickard Enér).*

*Figure 4-45.* *Completed slot next to the tunnel face. Parts of the slots were excavated by seam drilling, see upper part of the photo (Photo by Rickard Enér).*

***Figure 4-46.** Ongoing wire sawing in TAS04 (Photo by Rickard Enér).*

# 5 Mechanical- and system engineering

## 5.1 General

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

Assessment has been made of when the production of machines must begin and when they need to be completed, as well as whether production of prototypes is necessary. The number of objects and affiliated information are due to change since the specifications are working documents. Several projects within mechanical- and system engineering are ongoing. There has been reduced activity at Äspö during 2015, as much focus has been on continuation and reporting of work from 2014. Some of the different projects are described in the text below.

## 5.2 Technical Development at Äspö HRL

### 5.2.1 Mission control system

#### *Objectives*

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


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

### *Background*

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

### *Experimental concept*

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

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

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

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

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

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

### *Results*

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

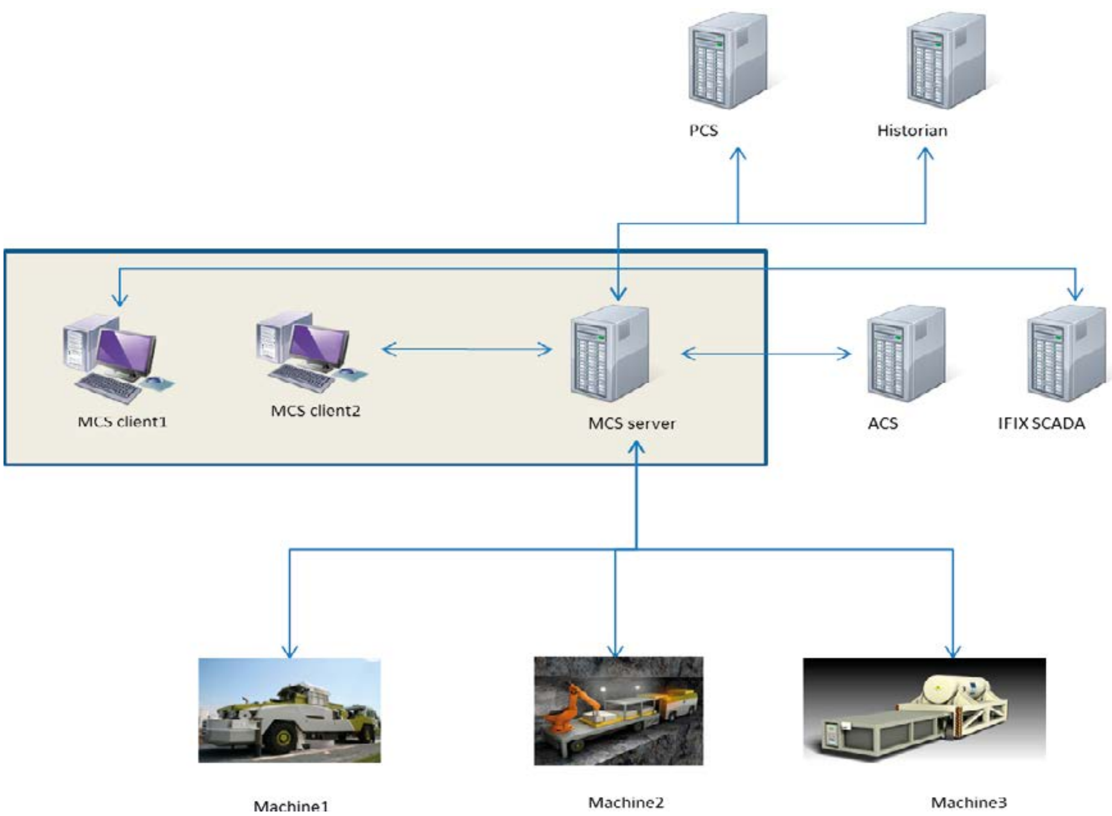



***Figure 5-2.*** *Mission Control System overview.*

### 5.2.2 Transport system for buffer and backfill material

#### Objectives

The objective is to develop a concept a concept for an autonomous and remotely operated transport system for buffer and backfill material from the production premises to the deposition tunnels.

#### Background

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

#### Experimental concept

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

#### Results

Testing of the system, with the available machines; the deposition machine, the MPT and the backfill machine, was performed during 2014. Follow up and reporting of these activities has continued during 2015.

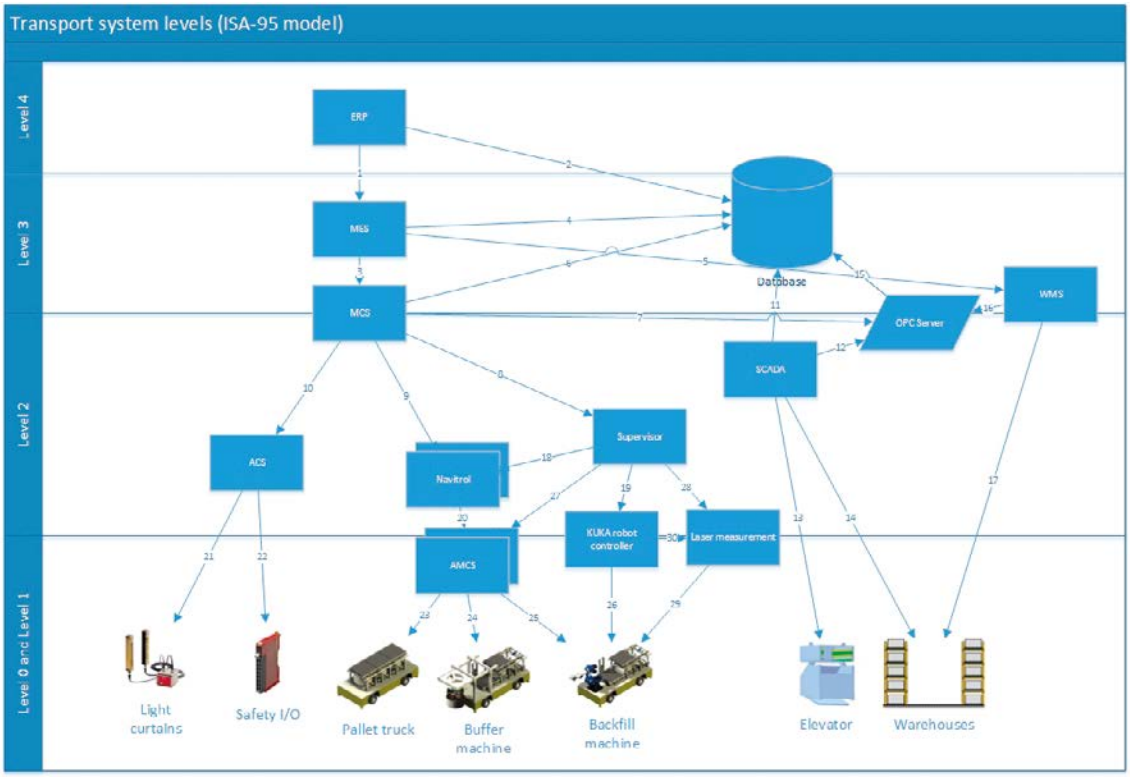



*Figure 5-3. Transport system levels and subsystems.*

### 5.2.3 Equipment for backfilling

***Background***

After deposition of canisters in the future Final Repository for Spent Nuclear Fuel, the tunnels will be filled with backfill material to seal the deposition tunnel. In order to perform this, and meet the requirements, a concept with a robot on a mobile platform has been developed.

Robot handling of these large amounts of material has the advantages of good capacity and excellent precision which is basic conditions to achieve excellent quality of the backfill in the repository.

***Objectives***

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

***Experimental concept***

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

***Results***

The system was a major component in the Åskar underground test of backfill installation during 2014.

### 5.2.4 Buffer emplacement

***Background***

The buffer consists of blocks and rings, as well as pellets, of bentonite. Equipment is needed to place the buffer in the deposition hole with a large degree of precision, to form a straight hole that the canister can be placed in. The steering gear of the tool for lift and location of the buffer was tested during 2012. The tool works with vacuum to hold the buffer blocks and has shown good function in laboratory tests (see Figure 5-5).

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

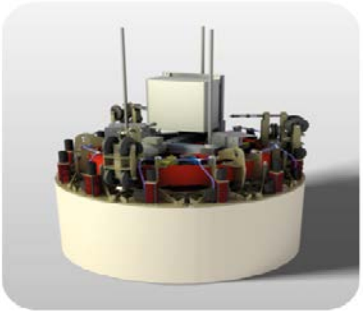


*Figure 5-5. Lifting tool for buffer emplacement.*

#### 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

During 2014, the development of a concept for a carrier of the lifting tool used for emplacement of blocks and rings and a concept for installation of pellets was carried out, and prototypes were constructed. Testing of the prototypes is ongoing.

### 5.2.5 Multipurpose vehicle

#### Background

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

#### Objectives

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

#### Experimental concept

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

#### Results

This vehicle was used for heavy load transports in the ramp att Äspö HRL during 2014. During 2015 the vehicle has been used at the Barsebäck nuclear power plant in Skåne, Sweden.


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

# 6 Äspö facility

## 6.1 General

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

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

Äspö HRL is the residence of the unit *Repository Technology* but the unit includes employees in both Äspö, Stockholm and Forsmark. The main responsibilities of the unit are to:

- Develop, demonstrate and streamline repository technology for nuclear waste, including installation methods, transport- and handling techniques.
- Develop, administer and operate Äspö HRL as an attractive resource for experiments, demonstration tests and visitor activities.
- Actively work for a broadened use of Äspö HRL, with the aim to turn the facility over to future research- and development parties.

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

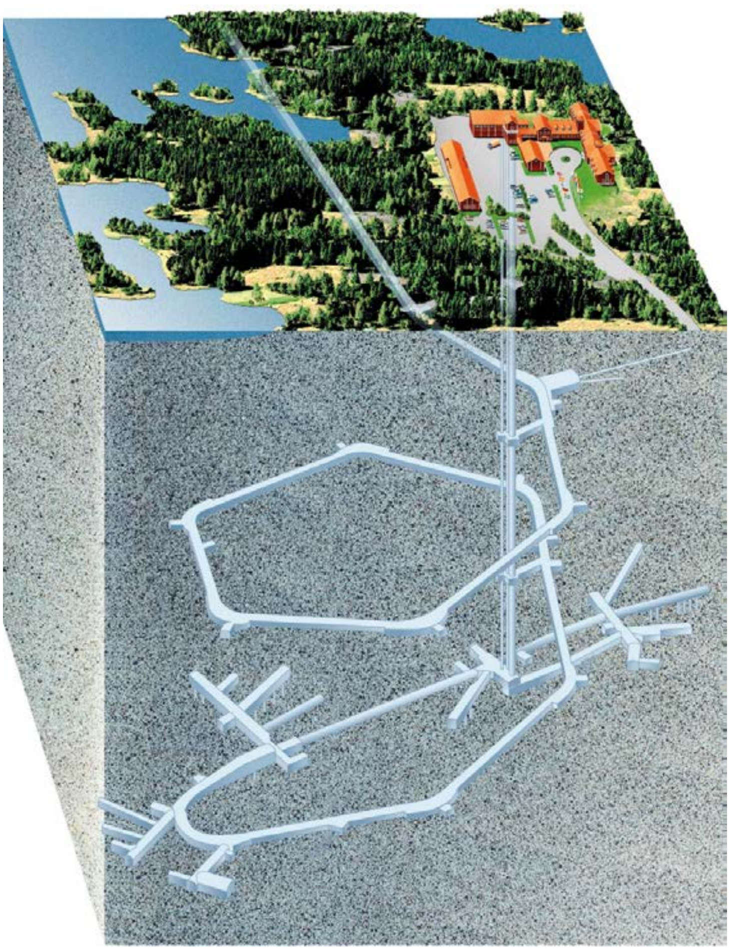


***Figure 6-1.*** *The Äspö HRL tunnel system below the island of Äspö.*

Each major research and development task ordered by SKB and 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.

## 6.2 Bentonite Laboratory

### *Background and objectives*

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

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

Other equipment in the laboratory includes an Eirich bentonite mixer with a load capacity of 1000 kg to allow mixing of bentonite with desired water ratio.

During 2014 a press for fabrication of extruded pellets was bought, and was delivered during December 2014. The press is a KAHL model, and is combined with a Baron CXL 4500 transporter and a CZ Multiscreen. Beginning in January 2015, the press was tested with several types of bentonite. The press produces extruded pellets with a diameter of 6 mm and a length of 20 mm. The production capacity is approx. 700 kg/h. A self cleaning filter system ensures a good working environment with low dust emissions. The entire press equipment has received a CE marking.

The press has been used during 2015 to produce approx. 65 tonnes of pellets. These have been used in the projects described in Section 4.9 (which was performed in the Bentonite Laboratory) and 4.11.

## 6.3 Material Science Laboratory

### *Background*

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

### *Objectives*

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

### *Results*

A number of methods and equipments have been implemented and developed. Wet chemical methods such as cation exchange capacity (CEC) and exchangeable cations (EC) have been implemented. Also diffraction and spectroscopic methods have been implemented, such as X-ray diffraction (XRD) for the determination of crystalline solids, X-ray fluorescence (XRF) spectroscopy for elemental compositon, Fourier Transformed IR (FT IR) spectroscopy for detailed analysis of the clay mineral structure and amorphous material, UV/Vis for the CEC method, and μ-Raman spectroscopy for analysis of corrosion products, accessory minerals and precipitates with a very high spatial resolution in a non-destructive manner. A total of nine cells for swelling pressure and hydraulic conductivity have been implemented during 2015 (Figure 6-2). A number of measurements have been performed on new bentonites and also on old ones to get statistical information about the method and the variation of clay shipments.

## 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.

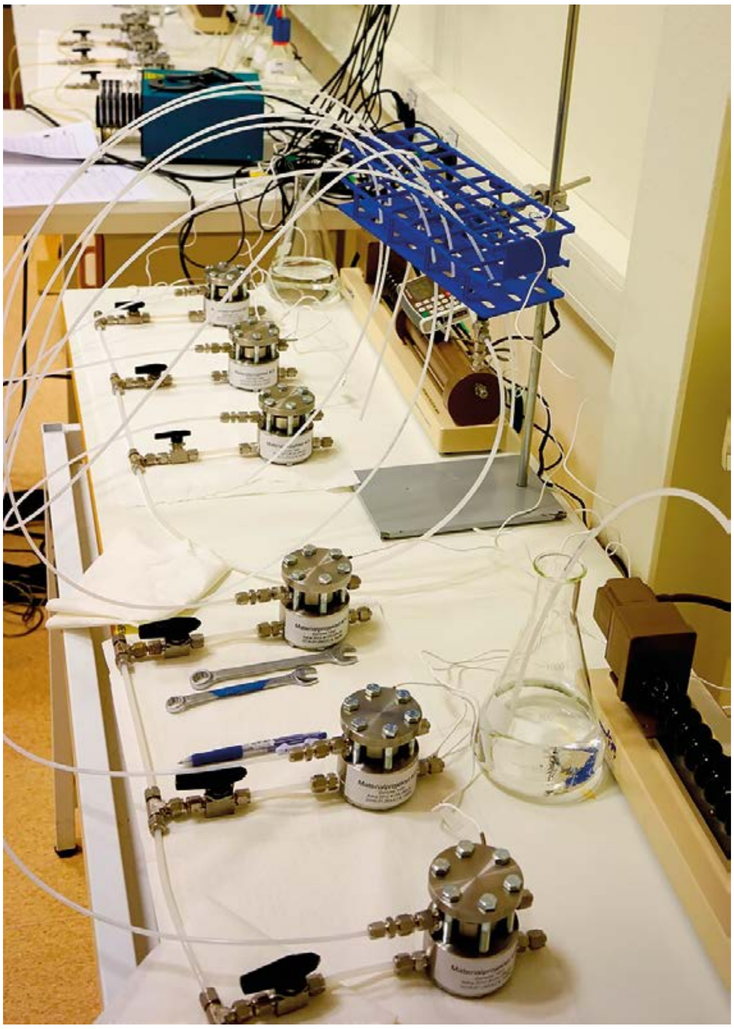


***Figure 6-2.*** *Nine oedometer cells for measurement of swelling pressure and hydraulic conductivity of compacted bentonite.*

***Results***

The facility has had a stable operation during 2015, with almost 100 % accessibility.

In the spring of 2015, the Hydro Monitoring System (HMS) switched to a newly developed web based (within SKB's network) software. The new system is interactive and allows for functions such as real time zooming. The system is developed specially to fit SKB's requirements on long time monitoring at Äspö and in Forsmark. The development has been performed by AIS (Applied Industrial System) in London, England, and has been constructed around an existing platform (SWF) with the SKB software adaptation added on. The system is also constructed to meet all SKB's demands from a security perspective on both software and hardware.

Fire prevention has been improved during 2015 by fitting all SKB vehicles, and those of external parties contracted for over a year, with sprinklers. Monthly checks were also carried out on all vehicles brought into the facility, to prevent any risks regarding fire. For several years, the synthetic fuel Ecopar has been used for vehicles driving in the tunnel.

Extensive ventilation work has been performed at the −220 m level in the Äspö tunnel, as old ventilation channels have been replaced with new ones.

Work with energy efficiency is ongoing in the facility. Equipment for measuring energy use in individual facility sections has been installed to allow localisation of areas or equipment with high energy use that can be targets for upcoming energy efficiency campaigns.

## 6.5 Communication Oskarshamn

***General***

SKB operates three main facilities in the municipality of Oskarshamn: Äspö HRL, the Central interim storage facility for spent nuclear fuel (Clab) and the Canister Laboratory. The main goal for the Communication unit in Oskarshamn is to create public acceptance for SKB, which is done in co-operation with other departments at SKB. The goal will be achieved by presenting information about SKB's facilities and RD&D work e.g. at Äspö HRL. Furthermore the unit 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 2015, one person retired and at the end of the year Communication Oskarshamn consisted of nine persons.

***Special events and activities***

During 2015, 4055 people visited the Äspö HRL and with the visitors at Clab and the Canister Laboratory included it resulted in a total of 6166 people. The total number of visitors to SKB's facilities in both Oskarshamn and Forsmark/Östhammar was 10 154 people. The visitors represented the general public, teachers, students, professionals, politicians, journalists and visitors from foreign countries. The total number of foreign visitors to the Äspö HRL was 622. The special summer arrangement "Urberg 500" was arranged during six weeks and 957 persons took the opportunity to visit the underground laboratory. Tours for the general public also took place some Saturdays during the year.

During 2015 the unit's school information officer went to schools and high schools within the municipality of Oskarshamn to inform about SKB's work. About 30 female students from the scientific and technical programs at the high school in Oskarshamn participated in "Tjejresan", an initiative aiming to show the opportunities for a career within the technical field. Fieldtrips and meetings with employees are ways to increase the female student's interest for a subject area otherwise highly dominated by men. Furthermore, the school information officer was part of "Innovation Camp" for second year students at the high school, arranged by Ung Företagsamhet (Young Enterprise).

All 9th grade students in Oskarshamn are offered a day with lego robot programming and a visit to the Äspö HRL or the Canister Laboratory. 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.

On April 11, the unit highlighted that Clab had been in operation for 30 years. Open tours to the facility with lectures about Clab and the planned Encapsulation plant were arranged.

The unit was a part of the national event Geologins Dag (The Geological Day) which was arranged on September 12. The unit arranged a geological walk through the "stone city" Oskarshamn. At this occasion, Äspö Miljöforskningsstiftelse handed out awards to two persons that have contributed to increase the public knowledge and awareness about the Baltic Sea and fish preservation. During the year, the unit was also part of Turista Hemma, an event arranged by the Tourist Office in Oskarshamn.

Every year the unit arranges lectures with different themes related to SKB's work. During 2015, two lectures were arranged, one on radiation and one on the review process.

SKB was involved in an activity called "Oskarshamn moves in" at the Linnaeus University in both Växjö and Kalmar. Companies and organizations from the municipality of Oskarshamn arranged an exhibition at the campuses and offered work opportunities, internships, lectures, study visits and so on.

On the 21st of November, almost 100 competitors participated in "the Äspö Running Competition".

***Figure 6-3.*** *Open tour of Clab, highlighting 30 years of operation.*


***Figure 6-4.*** *Runners participating in the Äspö Race, starting at the bottom of the Äspö tunnel.*

During 2015, 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.

# 7 Open research and technical development platform, Nova R&D

## 7.1 General

Äspö Hard Rock Laboratory is a world unique underground research laboratory, which is also open for more general research. Nova R&D is the organisation, which implements this policy and facilitates external access for research and development projects to the SKB facilities, data and competence in Oskarshamn (Figure 7-1). The aim of Nova R&D is to create local and regional spin-off effects in favour for the society and business development.

This chapter describes the major progress during the year 2015 for the research platform Nova R&D. The description of each project is made in terms of the aim, status and spin-off effects.

## 7.2 Mission, focus and status

Nova Centre for University Studies, Research and Development (www.novaoskarshamn.se) in Oskarshamn gives university courses, conducts research and performs business development in the municipality of Oskarshamn. Nova is contributing to the long-term growth in the region by creating networks between academia, business and society.

The Nova R&D mission is:

- Initiate new research projects
- Support on-going research projects
- Identify spin-off effects.

Nova R&D is supported and funded by the Municipality of Oskarshamn and SKB. Nova R&D provides access to the following SKB facilities:

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

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

The Nova R&D research platform is used for (see, Figure 7-2):

- Geotechnology used in infrastructure projects such as underground construction of e.g. tunnels
- Geothermal research for energy production from deep (1–7 km) boreholes
- Geosphere projects with an environmental and fundamental natural science focus
- Demonstration, education and public relations that are an important part of the Nova R&D activities. The aim is to inform about the unique technology and know-how in e.g. nuclear technology and to attract new research projects to the open research platform Nova R&D.

During the year 2015 about 160 researchers where using the Nova R&D research platform for various geotechnical, geothermal and geosphere research projects. The total value of the research projects is about 55 million SEK. The annual research volume is 34 on-going research projects, 46 peer review publications (of which two in the Nature series) and four theses.

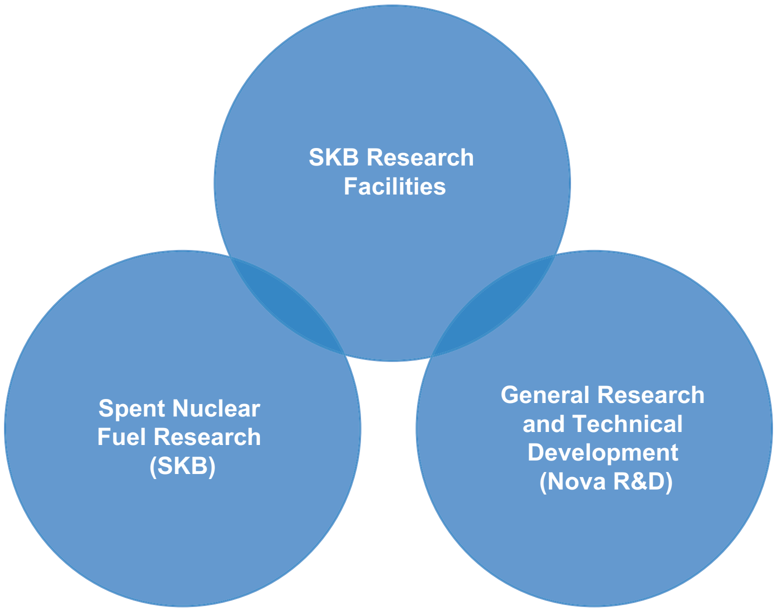



***Figure 7-1.*** *Nova R&D provides access to the SKB facilities and data for universities and companies for general research and technical development. The nuclear waste management research is handled by SKB.*

The highlight of the year was the establishment of the TRUST project, which is the largest infrastructure research project in Sweden and the establishment of geothermal research with the aim to extract heat from large depths. A geothermal workshop was held at Äspö HRL in November, 2015 with 36 participants from Sweden, Finland and Germany discussing future geothermal activities at Äspö HRL.

During year 2015 several new research projects with a more technical focus were established. This is in accordance with the Nova R&D steering group decision to have a more technical orientation in order to increase the possibilities for spin-offs in form of business development.

The EU project BRILLIANT was established to facilitate demonstration of nuclear technology for Baltic countries. The annual international training course in Geological Storage was performed including more than 40 students from 15 different countries.

Several Swedish universities submitted, in the autumn of 2015, two joint applications to the Swedish Research Council (Vetenskapsrådet) to establish Äspö-HRL as a national/international research infrastructure with the name National Geosphere Laboratory (NGL). If listed the final application will be submitted in 2017. Nova R&D can be regarded as a rehearsal for establishing NGL at Äspö HRL.

Further details concerning the research, demonstration, education and information projects are described in the chapters below.

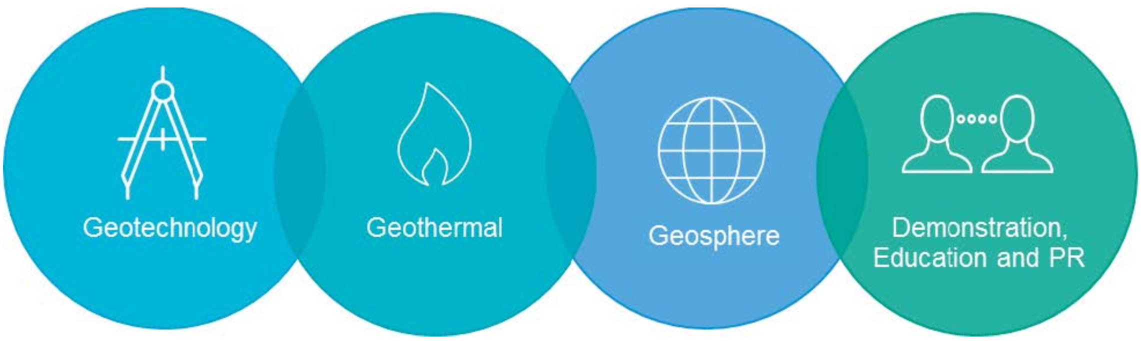



***Figure 7-2.*** *The focus areas within Nova R&D.*

## 7.3 Geotechnology

The aim of the geotechnology projects as described below are to improve methods, tools and understanding of importance for underground construction work. The ultimate goal is to be able to construct better, safer and more efficient under ground constructions.

### 7.3.1 Transparent Underground Structure – Management (TRUST 1)

Project Leader: **Maria Ask, Luleå University of Technology**

#### *Aim of the project*

The aim of TRUST is to improve methods and tools for planning, design and construction of underground facilities. Better quality and improved productivity will be the result of clarifying, considering and adapting to geological, technical, environmental, as well as economical uncertainties and risks. Scientists from the Swedish Universities of the Built Environment (SBU, i.e. Chalmers University of Technology, Royal Institute of Technology, Luleå University of Technology and Lund University), Uppsala University, the Geological Survey of Sweden and private companies collaborate closely within TRUST. There are four major themes. Theme 1, *Management*, is responsible for coordination and dissemination of the different subprojects in the themes and providing guidelines for innovation and implementation of the research result. Theme 2, *Holistic survey methods*, contains projects covering different site investigation methods in order to characterize the engineering geological properties of the rock mass, whereas Theme 3, *Smart underground construction*, uses the information in order to optimize adapt and control the different operations in the construction phase. Theme 4, *Information models, data structures and visualization*, integrates the information and provides the backbone for coordination between different actors and between planning, construction, operation and maintenance of underground facilities.

We want to coordinate the different research projects in joint case studies, of which the shallower parts of the Äspö HRL is the first joint case study. The planned activities are:

1. Collecting geophysical data in the ramp/new tunnel and on the surface, using electrical-, multi-component reflection seismic-, and electromagnetic methods.
2. Collecting data on the water chemistry. These activities are already described in an ongoing Nova R&D project from 2014-01-17, by Lars O. Ericsson, Chalmers.
3. Conducting grout-tests using the real-time grout-control method in the ramp/new tunnel.
4. In case of a new tunnel, and if project 3.1 is approved, collect Measure-While-Drilling data from drill rigs and conduct engineering geology mapping of tunnel face.
5. Access to the databases for relevant data (e.g. geophysic-, geologic-, structural geologic-, hydro-geochemic-, and rock mechanic data).

#### *Status of the project*

Planning for coordinated field activities of TRUST subprojects have been ongoing in 2015, and during TRUST workshop #5 on 3–4 February 2015 in Uppsala. Field measurements were conducted in April and May 2015. TRUST 1 supported these activities through funding of travelcosts through the Nova R&D grant. Initial results were presented at TRUST workshop #6 on 25–26 August 2015 in Gothenburg. In addition, TRUST 1 has funded a short movie about the campaigns that has been published o the TRUST website and online (https://youtu.be/vHQunJpT5rY). In addition, a MSc thesis on implementation of R&D projects between industry and academia was conducted at LTU (Pauldén and Stureson 2015) has been completed.

#### *Spin-off*

During the spring 2015, TRUST participated in the ERUF proposal by writing letter of support, "*Stödbrev till ERUF ansökan om vidareutveckling av Äspö-laboratoriet*, dated 2015-05-15.

### 7.3.2 Geoelectrical and seismic tomography along access tunnel to Äspö Laboratory (TRUST 2.1 and 4.2)

Project Leader: **Torleif Dahlin, Lund University**

#### *Aim of the project*

This project is an extension of the Geoinfra-TRUST project. The aim is to evaluate the capability of combined surveying with geoelectrical and seismic tomography across a water body for mapping depth to bedrock, and structres and properties in the rock of relevance to underground construction. The geoelectrical surveying is done as DCIP (combined Direct Current resistivity and time-domain Induced Polarisation) tomography. The objective is thereby to test and evaluate the methods' abilities and limitations for mapping rock properties in terms that are relevant for optimising underground construction. The SICADA database is the reference for evaluating the geophysical results.

#### *Status of the project*

A continuous survey across land and water with land-based and underwater sensors linked together was made with a continuous layout in order to create a continuous uninterrupted data profile along the access tunnel (Figure 7-3). The sensor positions for the resistivity-IP electrodes and the hydrophones used in the seismic survey were co-located in order to provide optimal conditions for joint inversion. A tailor made underwater electrode cable with 5 m take-out separation was used in combination with hydrophone strings with the same sensor interval. The electrode layout was extended on land using stainless steel plate electrodes that were buried or attached to the rock using a conductive gel depending on their position. The survey was carried out in parallel and collaboration with the TRUST 2.2 team from Uppsala University during one week in April 2015. They measured simultaneously with land based geophones in order to extend the seimics line outside the water body, and used our survey boat for offshore RMT electromagnetics.

The resistivity and seismics refraction data have been evaluated separately using the Res2dinv, Rayfract and BERT/GIMLi inversion software packages. Preliminary interpretation is that the low resistive zone in the right part of the resistivity section (Figure 7-4) corresponds to the NE-1 zone, although it is expected to have a steeper dip than indicated here. The apparent dip could be due to 3D effects. The large low resistive and low velocity zone in the left side of the midpoint in the diagrams is interpreted as a deep sediment filled valley that was previously unknown. It may possibly be interpreted as an erosion valley or a graben structure between the documented faults NE-3 and NE-4 or EW-7. Because of the very large contrast in physical properties at the site in combination with signal noise and signal attenution the evaluation of data is complicated, and joint inversion is expected to be a valuable tool for refined data interpretation.

Work on combined evaluation of the data with so called joint inversion of our data is in progress. Preparations are being made for evaluation of combined seismics with TRUST 2.2. Furthermore digital filtering of the geoelectrical data is underway for analysis of the IP contents, which is necessary due to electrical noise from the nuclear power plant with associated transformer stations, high tension power cables, etc. The results are evaluated against the available documentation in the SICADA database.

#### *Spin-off*

The methodology that was developed at Äspö and the purchased equipment was also used for similar tests in Stockholm in collaboration with the Swedish Transport Administration (Trafikverket) later in 2015. Test measurements were made both in Lake Mälaren and in Saltsjön. The results from these tests are presented in an MSc thesis by Elisabeth Lindvall and Erik Warberg which will be presented in February 2016.

#### *Literature*

Abstracts with results from the test at Äspö have been submitted to SAGEEP 2015 and NGM 2015. An extended abstract will be published for the latter, and a journal article manuscript is in progress.

*Figure 7-3. Field surveying across the water body between Äspö and Ävrö in progress (photo: Torleif Dahlin).*

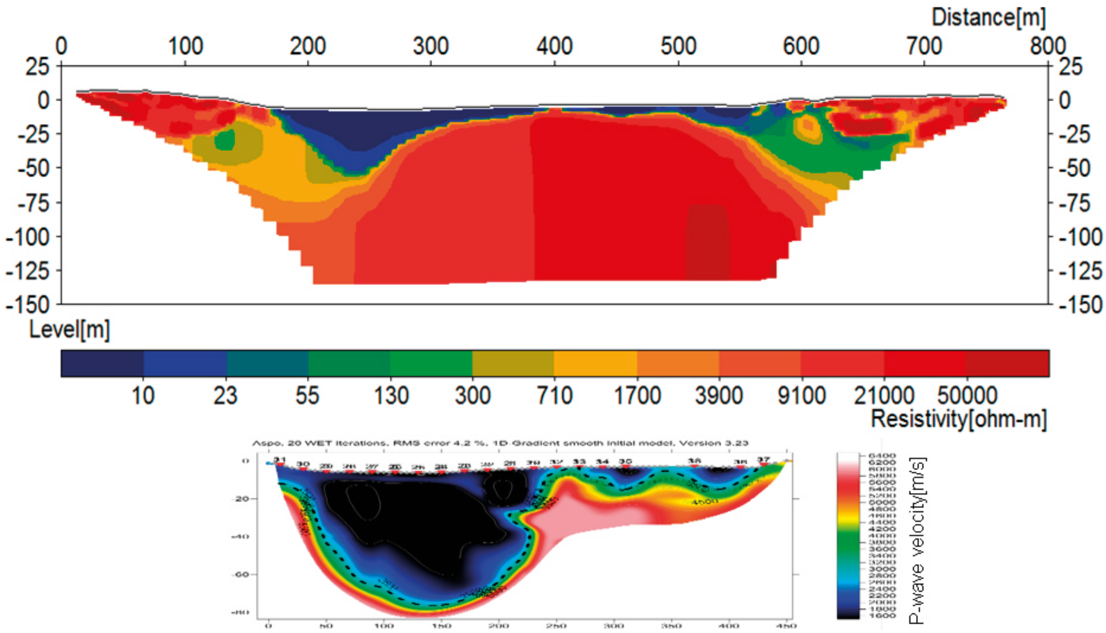



***Figure 7-4.** Preliminary tomography model results from separate inversion of resistivity (Res2dinvx64) and seismic refraction tomography (Rayfract) data. Observe difference in vertical scale.*

### 7.3.3 Multicomponent seismics and electromagnetics-Äspö (Trust 2.2)

Project leader: **Alireza Malehmir, Uppsala University**
Project members: **Bojan Brodic and Shunguo Wang, Uppsala University**
Project members: **Mehrdad Bastani, Geological Survey of Sweden**

#### *Aim of the project*

In order to evaluate the performance of some of the equipment and methods developed within the Trust 2.2 GeoInfra-Formas project, senior researchers and PhD students from Geophysics Program of Uppsala University and Geophysical Survey of Sweden (SGU) acquired unique state-of-the-art seismic and boat-towed RMT data using a combination of surface-lake-tunnel recording approach. Major fracture systems intersected in the main access tunnel and near surface geology were the main targets of the study. In addtion to this, we also aimed at evaluating the influence of noise in our equipment partciulary the seismic landstreamer system. With these objectives, more than 413 receivers out of which 80 were from the newly developed three-component seismic landstreamer (Figure 7-5; Brodic et al. 2015) were deployed in the tunnel at 2–4 m intervals. Wireless seismic recorders for a total number of 75 (10–20 m apart) were placed on the surface and a Bobcat-mounted drop hammer was used to generate seismic signal. Simultaneous recording of these signals were possible since they were synchronized using accurate GPS time. In addition to this, boat-towed RMT data (Bastani et al. 2015) were acquired on the lake over the southern part of the tunnel (Figure 7-6) for high-resolution imaging of electrical resistivity of the near surface structures. In 3 hours more than 5 km of boat-towed RMT data were acquired. Additional RMT data were also acquired on the surface above the main tunnel to check the possibility of detecting some of the major fracture systems near the surface.

The whole measurements took place during April 2015 for one week including mobilization and demobilization from the site and involved 8 persons.

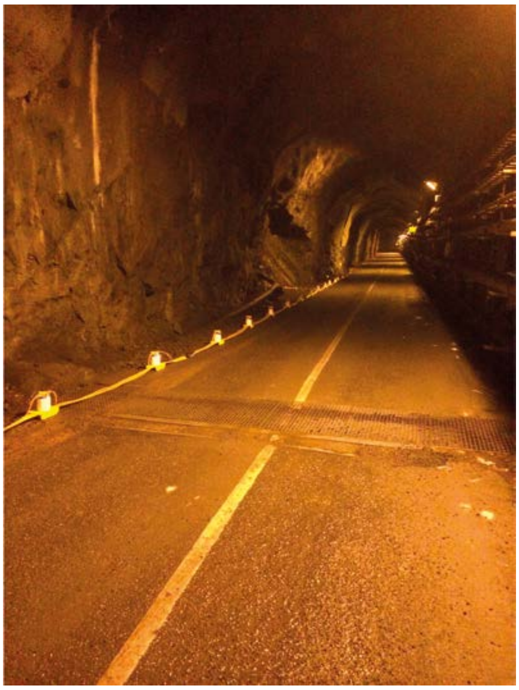


***Figure 7-5.*** *A segment of the seismic landstreamer placed on the tunnel floor in the proximity of the NE1 fracture system. The streamer uses digital-3C sensors and proved in this experiment to be free of electrical noise when compared with planted geophones on its either side in the tunnel.*

*Figure 7-6. Boat-towed RMT data acquisition over the southern part of the Äspö tunnel. The system was recently modified to make the acquisition faster and more reliable using a DGPS mounted recording system. In less than 3 hours more than 5 km/line RMT data were colleceted.*

#### *Status of the project*

Although preliminary, traveltime tomography of the first breaks and some analysis of the RMT data have been carried out. Strong electrical noise from the power lines passing on the side of the tunnel is evident in the data from the geophone-based sensors while the streamer is free of such a noise contamination. Nevertheless comparison with the existing data from SKB shows some of the major fracture systems have been delineated between the surface and the tunnel (Figure 7-7) and that we are able to provide an estimate of their dynamic Poisson's ratio thanks to the new landstreamer system and strong mode-converted seismic signal from the fracture systems. RMT data suggest a thicker package of lake sediments (major conductivity zone) in the southern part of the study area. However, this requires further analysis and possibly additional data acquisition over the lake using controlled-source low frequecncy radio magnetotelluric method. Joint interpretations and inversion of various datasets such as those acquired by Trust 2.1 and 4.2 (ERT and lake seismics), 2.4 (hydrogeological observations), 3.3 (real time grouting) and 4.1 (GeoBIM) and and in collaboration with them is also considerd and currently in parts on-going.

#### *Spin-off*

We are likely to use the tunnel-surface measurments in various other projects. Detailed planning and new developments are required given some of the complexities in tunnel measurments (e.g., no GPS time and issues with the geodetic surveying). A technical article about our developments and Äspö expriment was published in NyTeknik (Januray 2016): http://www.nyteknik.se/tekniknyheter/article3957042.ece

### 7.3.4 Development of standards for functional requirements at underground facilities with respect to the chemical environment (TRUST 2.4)

Project Leader: **Lars O. Ericsson, Chalmers University of Technology**

#### *Aim of the project*

The general objective of the project is:

- to further develop standards to meet functional requirements at underground facilities with respect to the chemical environment in terms of groundwater chemistry and vault atmosphere composition.

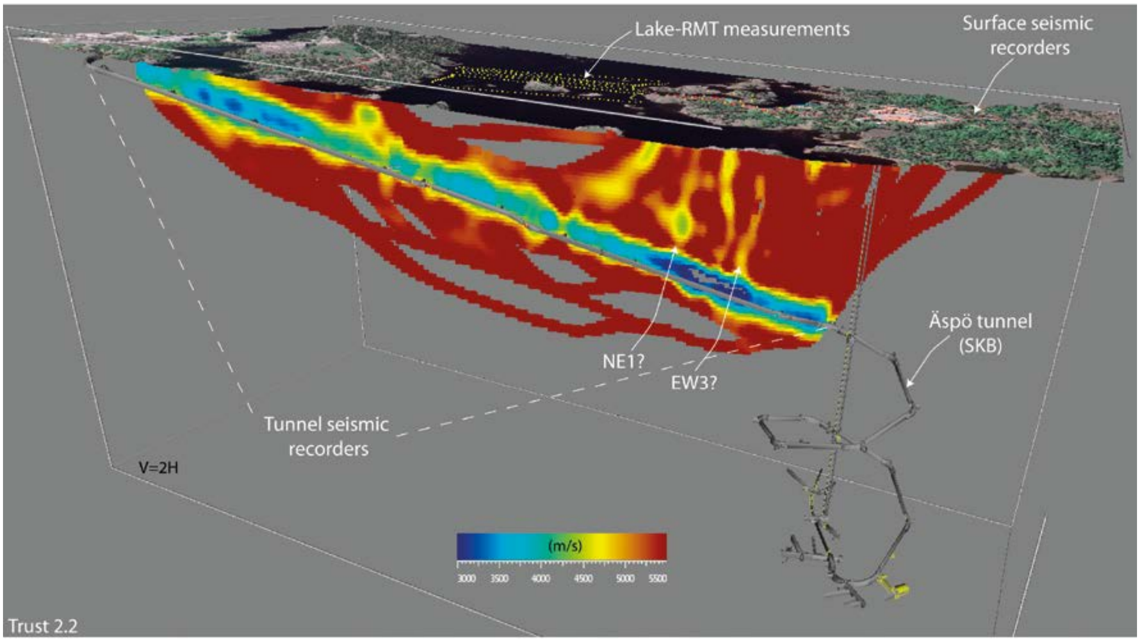



***Figure 7-7.** 3D visualization of the prelimienary tomography results with the tunnel model (provided kindly by SKB) showing possible delineation of some of the major fracture systems intersected by the tunnel. On the surface, RMT measurement points and wireless seismic recorders are notable.*

The project is run by means of integrated activities and studies on underground hydrochemistry, cement-based materials and corrosion processes.

The project is also expected:

- to provide a basis for improving the content of environmental impact assessments in conjunction with underground projects.

Furthermore the project aims:

- to provide a basis for constructing safer tunnels with cost-effective maintenance.

### Status of the project

This project comprises three sub-projects interacting with each other:

- Prediction of underground hydrochemistry due to excavation.
- Hydrochemical effects on resistance of shotcrete and injection grout to leaching and chemical degradation.
- Hydrochemical effects on the corrosion rate of rock bolts.

The Division of GeoEngineering, Chalmers University of Technology (Chalmers) represents the hydrogeological knowledge. The Swedish Cement and Concrete Research Institute (CBI) is mainly responsible for activities regarding cementitious materials and concrete issues. Swerea/KIMAB (KIMAB) covers subjects related to corrosion processes. Partners in the project are the Swedish Geological Survey (SGU) and Nordic Construction Company AB (NCC).

Funding for the project has been received by Formas within the so called GEOINFRA call, and the R&D activities are included in the TRUST cooperative program as sub-task No. 2.4. Other financiers are BeFo, Energiforsk (Elforsk), SKB, SBUF and Cementa as well as contributions in kind from Swerea/KIMAB, CBI/SP, NCC, Besab, Nova R&D/Oskarshamn, The Swedish Transport Administration, Thomas Concrete Group and SGU.

In 2015, Chalmers carried out modeling for prediction of water chemical changes in an underground construction environment based on data from the Hallandsås tunnel project. The modeling was done in order to test a proposed methodology from Fredrik Mossmark's doctoral thesis, which was completed in 2014 (Mossmark 2014). Results and conclusions from the modeling were presented in a conference paper, in a Chalmers report and at an international conference in the United States.

CBI has conducted laboratory experiments in which cementitious materials with various recipes were subjected to water with different concentrations of sulphate. KIMAB also performed laboratory tests of steel corrosion with water of different compositions. The chloride and sulphate concentrations were varied in synthetic waters and tests were also performed in original groundwater from rocks. These experiments were conducted with both stationary and flowing water on reinforcing bolts and the results illustrate the corrosion protective importance of calcium and bicarbonate in groundwater. Currently detailed planning is ongoing of in situ tests at the Äspö HRL. The tests are intended to commence in the spring of 2016. The field investigation focuses on the degradation of shotcrete and on corrosion of various carbon steel qualities.

#### *Spin-off*

Constructions in underground space represent major interventions in the surrounding environments. This concerns mainly the hydrology but also other aspects such as the release of ion species from the host rock during and after excavation. During and after constructions, which go hand in hand with the excavations, further factors needs to be considered, which concerns mainly the new construction materials brought into the underground space:

- Functionality of the new materials
- Interaction of the new materials with subsurface water
- Durability of the new materials.

All three factors are strongly influenced by the underground environment with the underground water constituting the transport media between the environment and the materials. The construction materials are mostly either cementitious or reinforcement for shotcrete and concrete parts (either as mesh, bars or fibers) as well as steel for rock bolts.

The Swedish Transport Administration (Trafikverket) publishes technical requirements that regulate and give advices concerning construction and dimensioning of a tunnel in a road and railroad environment. The technical requirements contain exposure and corrosivity classes for describing the type of environment concrete and steel are exposed to. This project, partly funded by Nova, proposes a further development of these standards.

### 7.3.5 Developing and implementation of Real Time Grouting Control Method (RTGCM) for rational tunnelling – with focus on grout penetration ability and real spread (TRUST 3.3)

Project Leader: **Almir Draganovic, KTH**

#### *Aim of the project:*

Aim of the project is verification of grout spread in rock fracture estimated with RTGC method in field (Figure 7-8). The idea is to find a conductive fracture in a tunnel. Drill a "grouting" and a number of "observations" bore holes to cross this fracture. Grout the fracture and observe and measure the time that grout penetrate from the grouting bore hole to observation bore holes and to the tunnel wall. The penetration of the grout is also calculated based on RTGC method and these two results will be compared and validated.

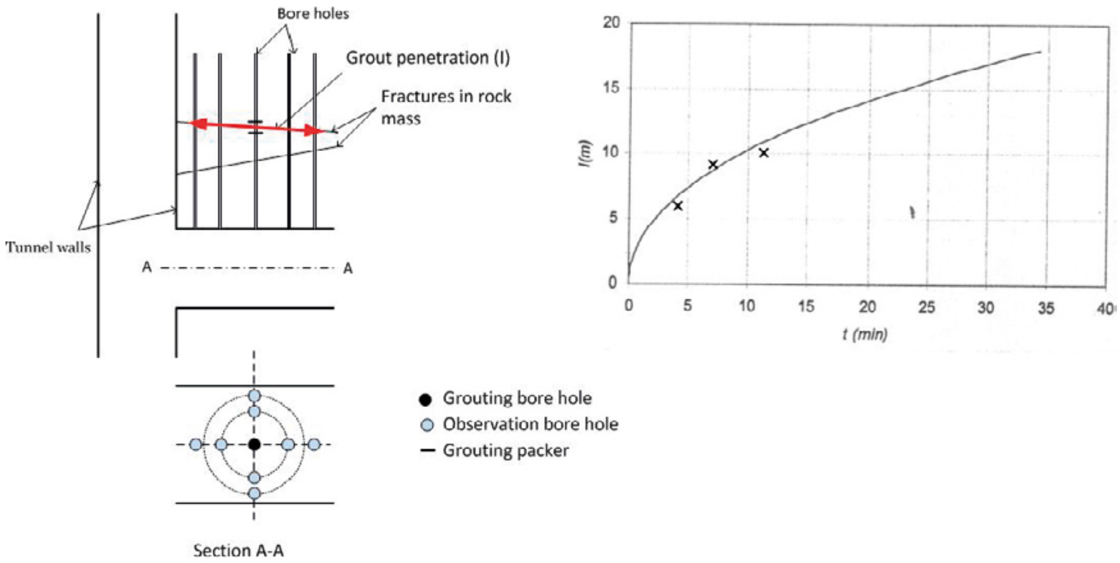



*Figure 7-8. Illustration of verification of RTGCM in field.*

### Status of the project

Nacka mine and Äspö HRL were places where field trials have been conducted. One of the problems with searching the fractures in Nacka mine was related to the relatively limited number of places because of old drill holes from the testing of Atlas Copco drill rigs. Problems with selection of fractures in the Äspö HRL were related to finding places that are not previously injected, which is not shotcrete, and that is not too deep. In the end, five places with fractures were chosen in Nacka mine and five places in the Äspö HRL for the field test.

Transmissivity measurements in Nacka showed in principle a flow of around 0.1 to 0.2 l / min corresponding to a $b_{hyd}$ between 25 and 31 microns. Average values of the physical fracture and $b_{hyd}$ are similar in magnitude in low range. This means that these fractures cannot be easily injected with cement based grouts. Further, the water flow was not observed on the tunnel walls.

Transmissivity measurements of 31 sections in Äspö HRL (Figure 7-9) showed principally the same results.

Only in three bore holes sections a flow of a substantial size were measured. In BH12 section 3 and 4 measured flow was about 0.35 l / min and in section 5 BH9 about 0.8 l / min. In the first case it corresponds to a $b_{hyd}$ of 37 µm or to the mean value of the physical aperture of about 40–45 µm. It is relatively small fractures for grouting with cement based grout.


*Figure 7-9. Transmissivity measurements in filed (Äspölaboratoriet).*

Based on these transmissivity measurements in Äspö HRL (31 sections) and also measurements performed in Nacka main (36 sections) (totally 77 sections), fractures in rock are not conductive in a degree as we expected. All fractures selected for the test in Äspö HRL prolong also through whole tunnel roof. They are long and therefore it was expected that they prolong also into the tunnel wall at least 5 m. The fractures were observed in the bore core and also observed with bore-hole camera. It shows that even if fractures exist in the rock mass the majority of them are not conductive.

Unfortunately after 77 tested bore holes sections in this project none of them were suitable to perform grouting test.

### 7.3.6 GeoBIM – Development of methods for efficient interpretation of geotechnical data (TRUST 4.1)

Project Leader: **Mats Svensson, Tyréns AB**

#### *Aim of the project*

The GeoBIM project is developing the GeoBIM concept 2013–2016, a cooperation between Tyréns and the department of Soil and Rock Mechanics at Royal Institute of Technology in Stockholm (KTH). The project is run under the TRUST umbrella (www.trust-geoinfra.se).

The GeoBIM concept consists of the five elements – Data storage (incl input/output), Modelling, Design work, Visualization, Uncertainty model. See also Figure 7-10. If the concept is well developed, it is rather a communication tool for explaining geotechnical data and models than a pure engineering tool.

The GeoBIM project aims at developing a database that can handle all data types and data formats used in a large infrastructure project, to organise the data preparing for an underground geotechnial BIM methodology, the GeoBIM concept. Today no single database or software can handle those approximately 150 methods/data formats. For modelling or visualizing the data or models, the situation is the same. Another aim is to develop tools, algorithms or methodology to keep control of the uncertainties of the various data or interpreted models.

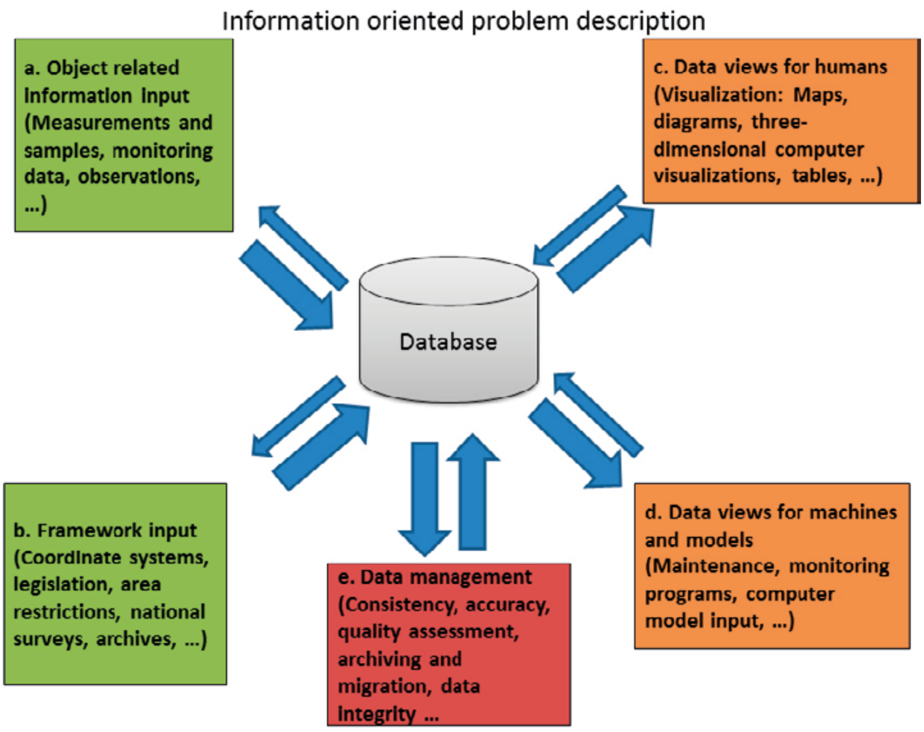



***Figure 7-10.*** *Principle of the GeoBIM database. Import of data from the left (green) and Export of data to the right (orange). The red box illustrates an uncertainty model tool connected to the GeoBIM concept.*

#### *Status of the project*

During 2015 the GeoBIM database has been delivered and pilot tested in a number of infrastructure projects – ESS, Lund and the Varberg railway tunnel. At the same time, the tool TYREngine for real time visualizing geotechnical data and interpreted models exported from the GeoBIM database has been successfully evaluated, see Figure 7-11. During late 2015 the GeoBIM concept was accepted by Trafikverket for being used in the East link high speed train project.

During the TRUST Äspö field campaign in the spring 2015 a large number of data was collected by the other TRUST sub projetcs, 2.1 and 2.2. At the same time the GeoBIM project (4.1) was digging deep in the SKB SICADA database to get hold of the existing reference data available in the area. The most current 3D model of the Äspö underground facility was also collected. At the moment the raw field data and the SICADA data is imported into the GeoBIM databse and work is going on using various softwares for doing joint interpretations and visualizations of all data and interpreted models together with the underground facility. This work is planned to be finished June 2016.

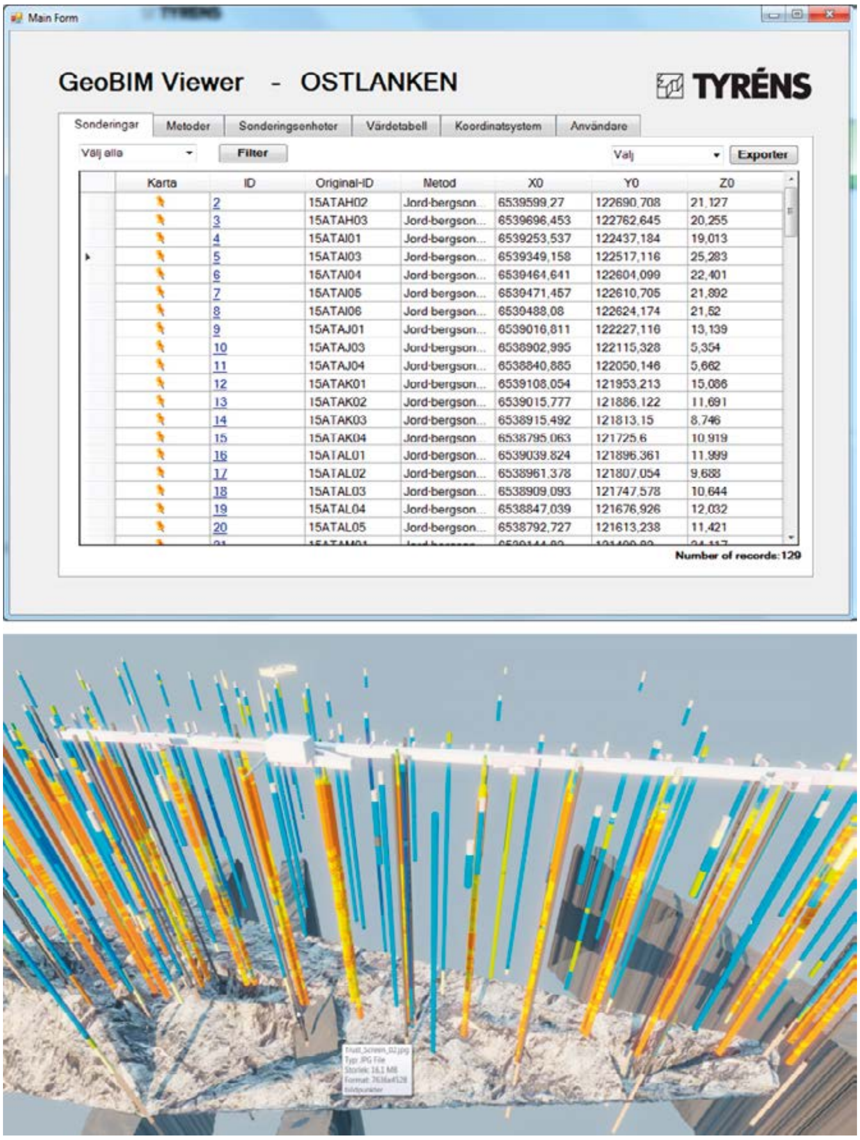



***Figure 7-11.** The GeoBIM database viewer and a screen dump showing a scene from the visualization tool TYREngine while flying through the ESS underground.*

### *Spin-off*

In order to implement all the achievements within the TRUST project the GeoBIM project acts as a hub for spreading the word in the industry. Among a large number of activities, a number of films have been produced, for example presenting the Äspö field campaign during spring 2015. All the films can bee seen at www.trust-geoinfra.se, also updated by the GeoBIM project. Presentations were held at the Swedish foundation 2014 and 2015 and also GeoBIM articles in the magazine Bygg och Teknik, January 2015 and 2016, have been presented.

## 7.3.7 Geophysical detection of EDZ/HDZ around tunnels

Project 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 utilized in optimizing cut-off design.

### *Status of the project*

When performing 2D resistivity profiling, the multi-gradient array was found to be suitable, with electrode spacings on the order of 1.5 the expected HDZ thickness being optimal. The lower frequency GPR antenna (centered around ~1500 MHz) was found to be most useful in identifying individual fractures, whereas the higher frequency antenna (centered around ~2500 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 Figure 7-12 and Figure 7-13, respectively, with borehole camera observations of fracture quality overlaid.

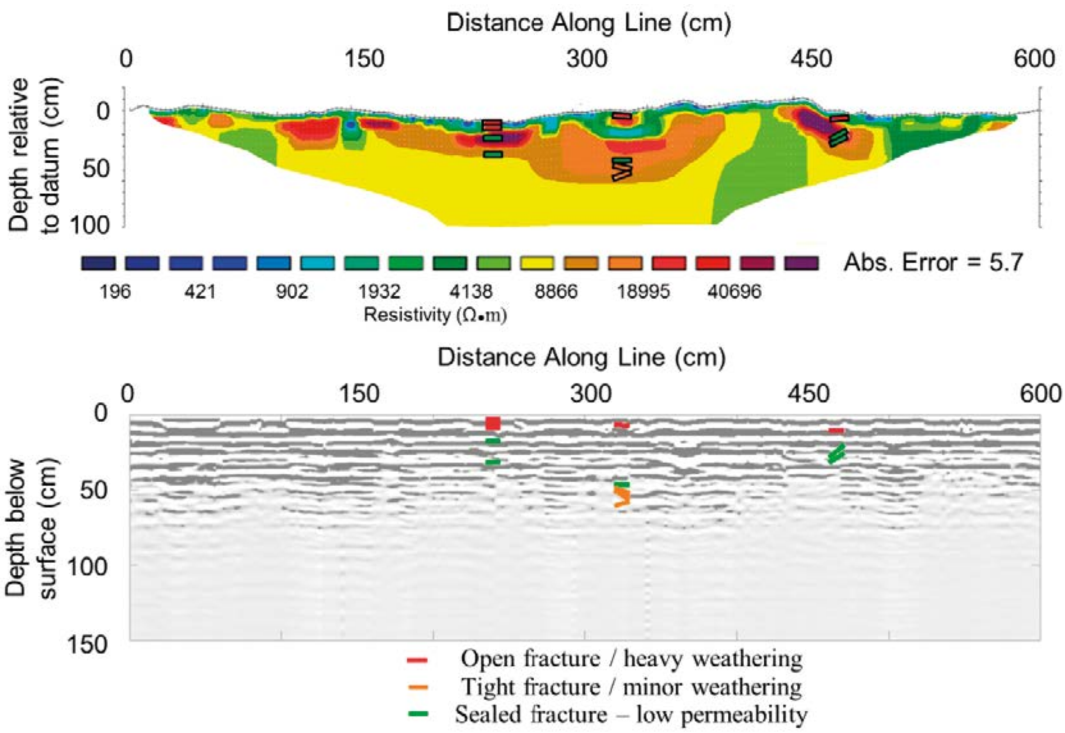



***Figure 7-12.*** *The inverted resistivity model and stacked GPR data (lower frequency) overlain with known fracture locations from boreholes at NASA 2376A.*

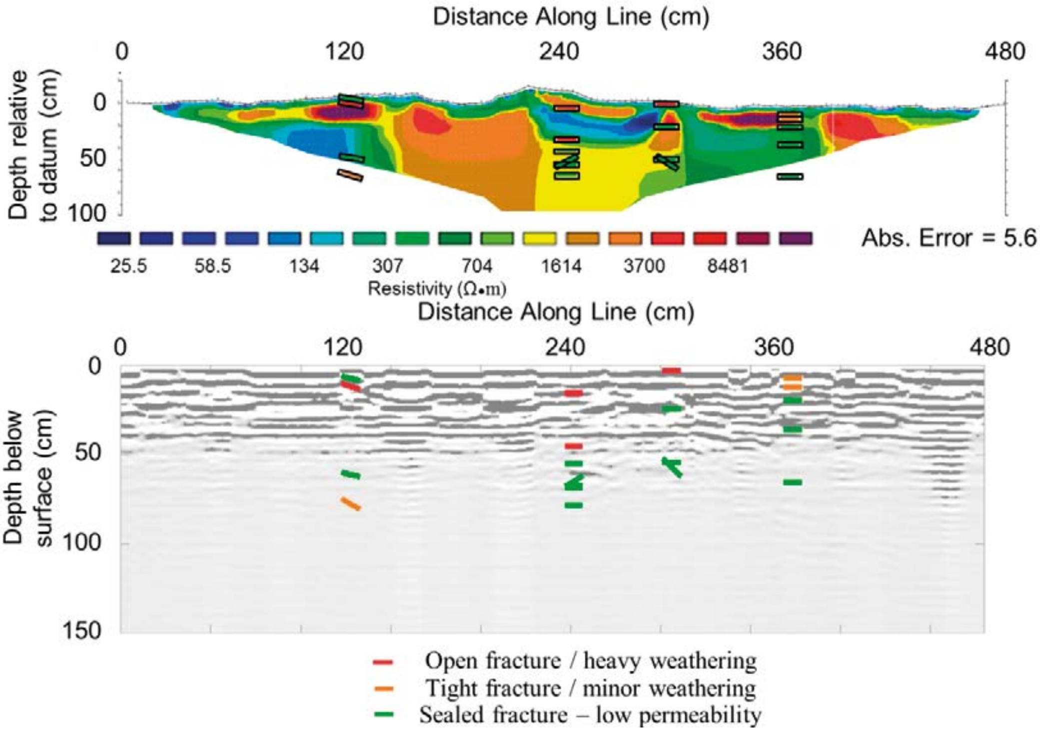



***Figure 7-13.*** *The inverted resistivity model and stacked GPR data (lower frequency) overlain with known fracture locations from boreholes at NASA 2715A.*

#### *Spin-off*

This research project is a preliminary proof of concept phase of a potentially larger project. Research in 2015 was focused on developing a better understanding of the field results obtained at Äspö through lab-based testing and calibration. In addition to this work, there are many other potential spin-off effects. Some of these are summarized below:

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

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

## 7.4 Geothermal

The aim of the geothermal project as described below is to improve methods for extracting heat from boreholes drilled at large depths (1–7 km) by fracturing the bedrock. By circulating groundwater the excess heat can be used for central heating or the steam can be used for electricity production. The ultimate goal is to be able to construct an industrial scale power plant that is environmental friendly and provides endless energy from the deep bedrock.

### 7.4.1 The geothermic fatigue hydraulic fracturing experiment at Äspö Hard Rock Laboratory

Project leader: **Arno Zang, GFZ Potsdam**

#### *Aim of the project*

We aim at optimizing geothermal heat exchange in crystalline rock mass at depth by multi-stage hydraulic fracturing with minimal impact on the environment, i.e. reduction of seismic events. For this different water-injection scenarios are tested and the hydraulic testing procedures are mapped with high-resolution acoustic emission, seismic and electro-magnetic monitoring system.

#### *Status of the project*

The operational phase of the project is completed. In May 2015 the testing and monitoring boreholes were drilled, and in June 2015 the hydraulic testing and monitoring phase of the project was completed.

At the moment, the first ISI publication of the project with preliminary results is being prepared. As an example, the relocated acoustic emission events with the in situ monitoring array operated by GmuG Bad Nauheim (Germany) are shown in map view and side view in Figure 1. Acoustic emission (AE) events recorded during the different fracture experiments clearly delineate the fractures and display differences between the different hydraulic fractures generated. AE hypocenters are color coded (green = HF1, blue = HF2, red = HF3, bright blue = HF4, orange = HF6). Three of these fractures were generated in Ävro granodiorite (HF1, HF2, HF3), one in fine-grained diorite gabbro (HF4), and one in fine-grained granite (HF6). The seismic events from one fatigue test with cyclic fluid injection are represented by red dots (HF3). The pulse hydraulic fracturing test in fine-gained diorite gabbro (HF5) did not generate any seismic signals relocated by the in situ monitoring array (Figure 7-14).

Overall, further investigations are necessary to understand the parameters influencing the AE activity and magnitudes. Potential parameters are not only the condition of the rock material and the influence of pre-existing fractures, but also the parameters of the hydraulic fracturing like pressure and flow rate applied. The preliminary results suggest that cyclic fatigue fracturing results in less seismic radiated energy.

Data of all hydraulic fractures will be presented in following publications after the advanced analysis of AE data. We also expect that the total number of localized AE events will significantly increase after more time consuming trigger and pick-algorithms have been applied. Many seismic events were spotted during the fracturing time periods when manually reviewing the triggers that were not localized using the automatic procedures. This together with relative localization will allow increasing the resolution of observation further.

#### *Spin-off*

Our geothermal pilot project at Äspö HRL may have triggered other geothermal activities in the area of Oskarshamn. A geothermal workshop was held at Äspö Hard Rock Laboratory on November 4–5th, 2015 with 36 participants from Sweden, Finland and Germany discussing future activities at Äspö HRL.

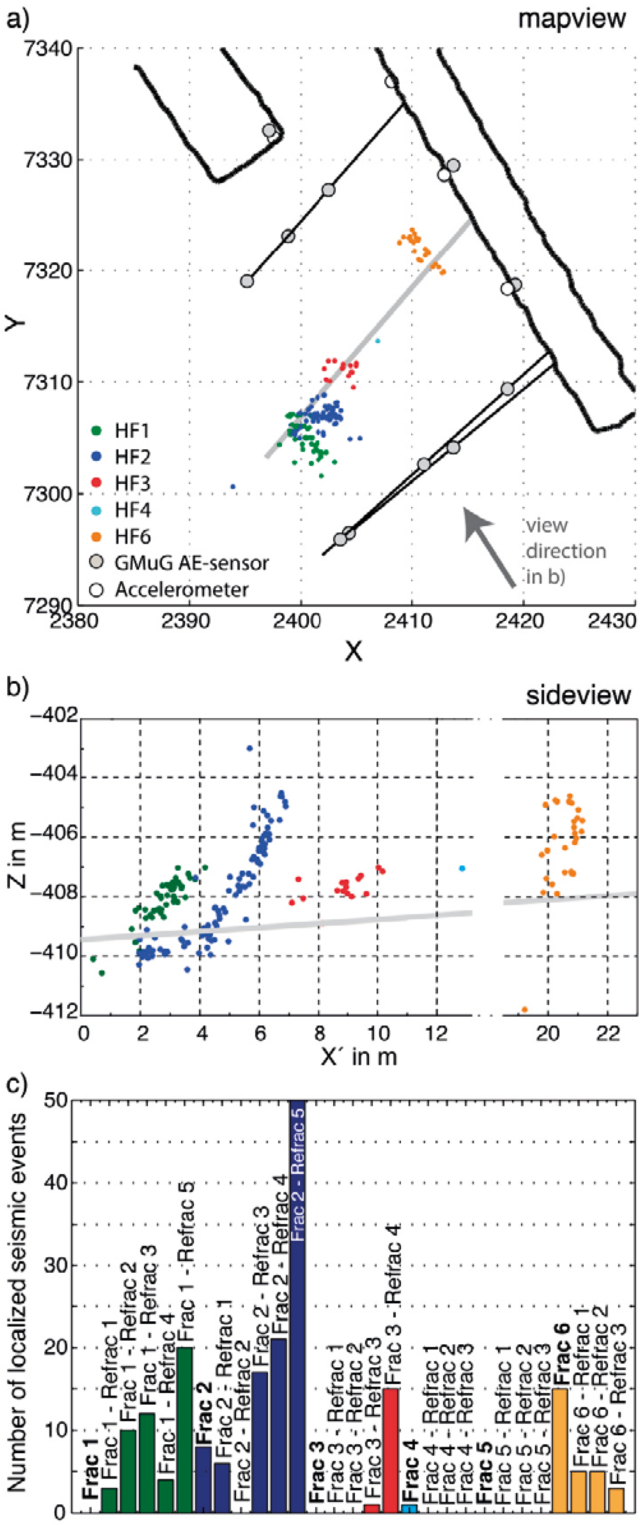



***Figure 7-14.*** *Seismic AE events presented in map view (a), side view (b), and (c) versus time in histrogram. For side view the coordinate system was rotated clockwise by 148° around the Z axis, as shown by arrow in (a). The seismic AE activity outlines the fractures of the different fracture experiments. Solid black lines outline the tunnel at the experimental site. Thin black lines outline the long monitoring boreholes. The solid grey line outlines fracturing borehole F1. Circles symbolize the sensors (grey = AE sensor, white = Accelerometer) of the in situ AE monitoring network.*

## 7.5 Geosphere Studies at Surface, Coast and Depth

The aim of the geospehere projects as described below are to improve the understanding, methods and tools when studying natural systems at surface, coast and at depth in the bedrock. The circulation of water and chemical elements influence the environment we are living in. The ultimate goal is to be able to understand the natural processes occurring and to be able to provide solutions for improvements.

### 7.5.1 Fluorine in surface and groundwaters

Project 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 (troughout regolith and the fractured bedrock) 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 7-15), (2) characterise and model fluoride abundance, transport and speciation in streams in the Laxemar-Äspö area, and (3) characterise fluoride abundance and sources in shallow (regolith) and deep (fractured bedrock) groundwaters of the Laxemar-Äspö area. A project focusing on fluoride exposure in Kalmar County has also been carried out.

#### *Status of the project*

In total three papers have so far been published in scientific journals during the project. In May 2015, a study focusing on aluminium speciation in fluoride-rich stream waters was published in Chemical Geology. We investigated the role of high levels of dissolved fluoride on the release and speciation of aluminium in boreal stream waters. For this, we utilised Sicada-data from three catchments in the Laxemar area in combination with a geochemical equilibrium model (Visual MINTEQ). Through analytical and modelling data, we showed supporting results of that fluoride may play a significant role in the bioavailability of aluminium in acidic, boreal waters. A manuscript focusing on fluoride hydrogeochemistry in the regolith and fresh fracture groundwater, including analyses of fluorine-bearing minerals, in the Laxemar area is currently being finalized for submission to a scientific journal.

#### *Spin-off*

The spin-off effects from this project will be increased knowledge on fluorine abundance and transport in surface and ground waters in the Laxemar and Äspö area, Kalmar County and other areas across the world with similar geology, which has practical implications in terms of water supplies (concerning both private wells and public water resources). Many groundwaters, both in the regolith and bedrock, in these areas contain fluoride concentrations well above the permissible limit for drinking water, an issue being thoroughly discussed and highlighted within the project. Also, the project has investigated how risk characterization of fluoride is affected by the basis of comparison, that total fluoride exposure may be overlooked when only focusing on one pathway (e.g. drinking water) and the importance of considering variability in all relevant pathways. Such knowledge can be of importance in a global perspective in areas where fluorosis is abundant and the need of identifying relevant sources and exposure levels is crucial (the study was presented at an international conference in Chiang Mai, Thailand, back in 2014). The findings may also lead to spin-off effects of economical value related to the addressed issues.

*Figure 7-15. 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).*

### 7.5.2 Fluorine in soils in the Laxemar area: Abundance, speciation and leaching potential

Project leader: **Mats Åström, Linnaeus University**

#### Aim of the project

The aim of the study is to characterise the abundance, speciation and leaching-potential of fluoride throughout the soil and regolith strata in the Laxemar area, Oskarshamn.

#### Status of the project

The field work (soil and regolith sampling) was successfully carried out within the Kärrsvik-stream catchment (Laxemar area) in February 2015, with the aid of drilling equipment as shown in Figure 7-16. After the sampling, the soil and regolith samples were dried and analysed for pH, total fluorine concentrations, easily-extractable fluorine concentrations and a number of ancillary variables. This data are currently beeing analysed by statistical methods and interpreted. Additionally, a draft manuscript where the results are presented has been prepared. The project is thus somewhat delayed relative to what is indicated in the time schedule in the application. We expect the project to be completed in June 2016.

The fluorine concentrations in the soil and regolith were unexpectedly low, that is, considerably lower than in both the TIB rocks and, in particular, the fluorine-rich Götemar granite. These results indicate that a large part of the fluorine in the soil and regolith has been dissolved and leached into the aquatic system, in line with the high dissolved fluoride concentrations previously found in both streams and groundwater in this region. The fluorine concentrations were similar in all identified soil and regolith types and overall increased slightly with depth (Figure 7-17). The latter feature indicates that the leaching of fluorine has been particularly strong in soil layers close to the surface.

***Figure 7-16.** Soil/regolith sampling in Laxemar.*

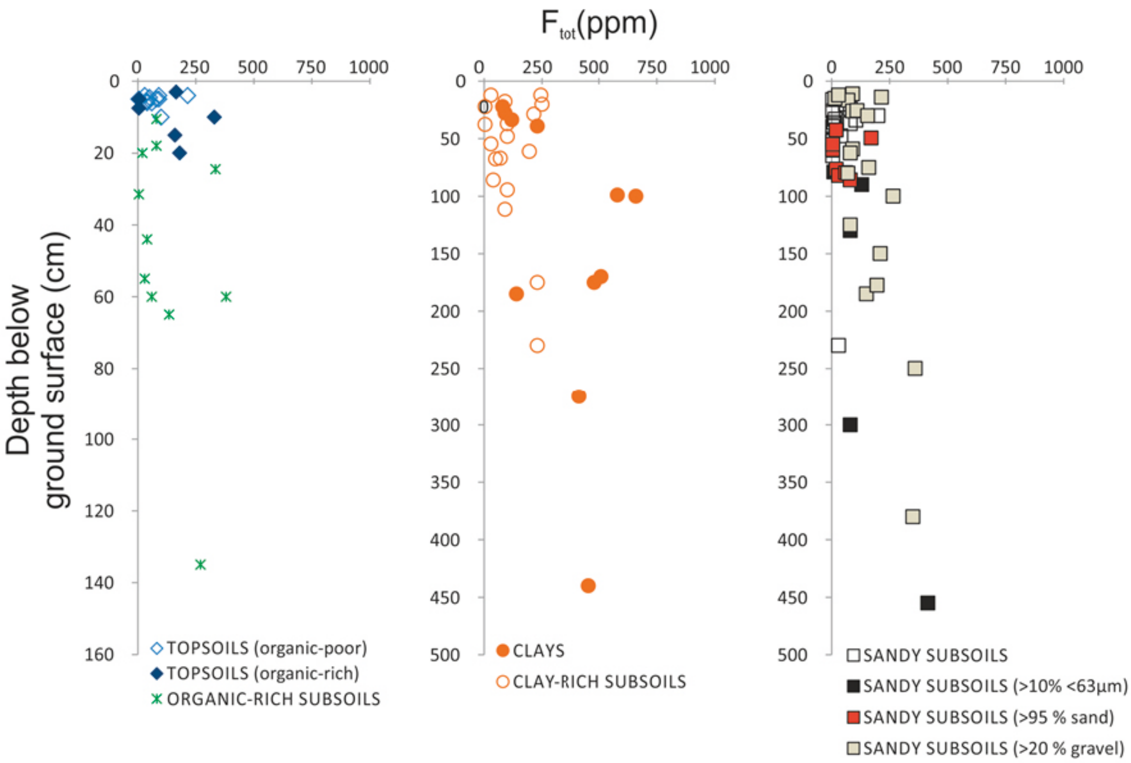



***Figure 7-17.** Total fluorine concentrations versus depth in various soil/regolith types.*

### *Spin-off*

Due to the character of the geology, Kalmar County faces a problem of potentially high fluoride concentrations in ground waters. Indeed, 24 % of private wells in the County exceed the World Health Organization's guideline value for drinking water of 1.5 mg/L. This guideline value is regularly exceeded also in the surface waters and shallow regolith groundwaters of the Kärrsvik catchment in the northern part of the Laxemar area. Fluoride, which is harmful to toxic at high intake rates, is therefore a potential threat to people, especially children, in the region.

By using the results presented here it is possible to determine the relative proportion of fluoride leaching from bedrock versus soil/regolith and define the mechanisms of fluoride leaching from the latter. This, in turn, will have several potential spin-off effects: (i) it will enhance the possibility to estimate where and when harmful or toxic fluoride levels may occur in groundwater, and (ii) it may contribute to develop the design of current and future wells used for extraction of potable water.

### *Literature*

No papers published as yet within the project.

## 7.5.3 Exposure to arsenic, lead and cadmium via drinking water consumption near contaminated glassworks sites

Project leader: **Anna Augustsson, Linnaeus University**

### *Aim of the project*

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

### *Status of the project*

All sampling and analytical work was completed in the summer of 2014. Water samples from 57 households were collected and the metal content (Sb, As, Ba, Cd, Pb) was analyzed with ICP-SFMS. Other main chemical parameters were also determined with standard methods: pH, alkalinity, conductivity, permanganate index, and concentrations of calcium, magnesium, sodium, potassium, and fluoride.

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

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

### *Spin-off*

In addition to relevant regional research being tied to Nova R&D and NGL, the project provides knowledge about how metal contaminated point sources may impact groundwater resources, and how the risks following consumption of water from private wells can be assessed in a way that increases the useability of the risk assessment as a descision tool. This is relevant also for risk assessments of other kinds of metal contaminated sites, around which drinking water is extracted. The latter of the two manuscripts is a spin-off idea that came up during analyses of our primary data.

### *Literature*

The samling and laboratory work is completed and the aim is to have two manuscripts written and submitted during 2016.

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

Project leader: **Georgia Destouni, Stockholm University**

### *Aim of the project*

KLIV has investigated critical questions for sustainable management of water resources, with a geographical focus on coastal regions. KLIV investigation sites have included the Swedish Water Management District of Southern Baltic Proper, which in turn includes the Äspö Hard Rock Laboratory (HRL) and the wider Oskarshamn coastal region related to the National Geosphere Laboratory (NGL). Methodological development and comparative catchment studies have also been carried out for other parts of the world. During 2015, the last year of the Nova R&D – financed project, the KLIV research group has continued its work primarily with synthesizing previous KLIV research into the main research questions:

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

Based on investigations aimed to answer these questions KLIV has provided new insights and knowledge on water system change and its management.

To arrive at answers, the KLIV research has integrated the inland water system and its adjacent coastal waters, following the water flow and waterborne transport of tracers, nutrients and pollutants, as well as the climate change effects on these, along the different water pathways from the land surface for main climate drivers, main sources of water, and nutrient and pollutant inputs, through the associated hydrological catchments, and into coastal waters. The main KLIV working hypotheses have been that:

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

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

### *Final project status*

The KLIV project started in 2012 and finished in 2015. In the final year, the work has been focused on synthesis of project results as presented in this final report. While the financed project cycle is now finished, the KLIV members plan to meet and work together on continuation of their KLIV research.

### *KLIV Synthesis Report*

KLIV's water-following approach, as mentioned in the *Aim of the project*, has been further advanced through the KLIV synthesis report: *Needs and means to advance science, policy and management understanding of the freshwater system – A synthesis report* (Destouni et al. 2015).

In this synthesis report, it is argued that traditional freshwater conceptualisations display gaps and inconsistencies. To overcome these, a new conceptualization is presented which treats freshwater as a continuous system and emphasises often neglected system aspects of: i) the unmonitored coastal divergent catchments; ii) the multiple zones of freshwater changes (surface, subsurface, coastal, observational); iii) the need to account for and link all main water pathways as key system- and zone-coupling agents, and iv) the multiple interactions of the freshwater system with the anthroposphere. The synthesis report highlights the implications of paying attention to these aspects with some selected examples of changes in large-scale water fluxes and nutrient loads. The developed freshwater system conceptualization can be used as a framework of understanding and help advance science, policy and management of freshwater.

**Work finalized and published**

The main KLIV research activities, results and publications from the project start in 2012 until 2015 have been summarized in three previous annual reports:

- KLIV Research Report 2014 – http://www.klivresearch.se/wp-content/uploads/2015/06/KLIV-Report-2014.pdf
- KLIV Research Report 2013 – http://www.klivresearch.se/wp-content/uploads/2015/06/KLIV-Report-2013.pdf
- KLIV Research Report 2012 – http://www.klivresearch.se/wp-content/uploads/2015/06/KLIV-Report-2012.pdf

and in the synthesis report:

- *Needs and means to advance science, policy and management understanding of the freshwater system – A synthesis report* (Destouni et al. 2015).

Relevant 2015 publications by the KLIV researchers are listed under List of papers and articles published 2015, Section 9.2.

### *Future Research*

KLIV members will continue to collaborate and seek new funding opportunities together on KLIV-related research.

## 7.5.5 Coastal modelling

Project 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 R&D project resources was used for the analyses of transport pathways from land to sea in a broader context of catchments as well as groundwater in the Forsmark region.

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

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

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

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

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

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

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

As an interesting case study, we shall consider the Oskarhamn harbour and simulate the transport of pollutants that are present in the sedment. The bathymetry scales for the analysis are shown in Figure 7-18. During 2016, we plan to complete the hydrodynamic and contaminant transport simulations at these three resolutions and demonstrate the potential spreading of contaminants from the harbour along the Swedish coast. This analysis will be particularly interesting since drudging measures are to be implemented in the Oskarshamns harbour.

**Outcomes**

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

### *Spin-off*

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

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

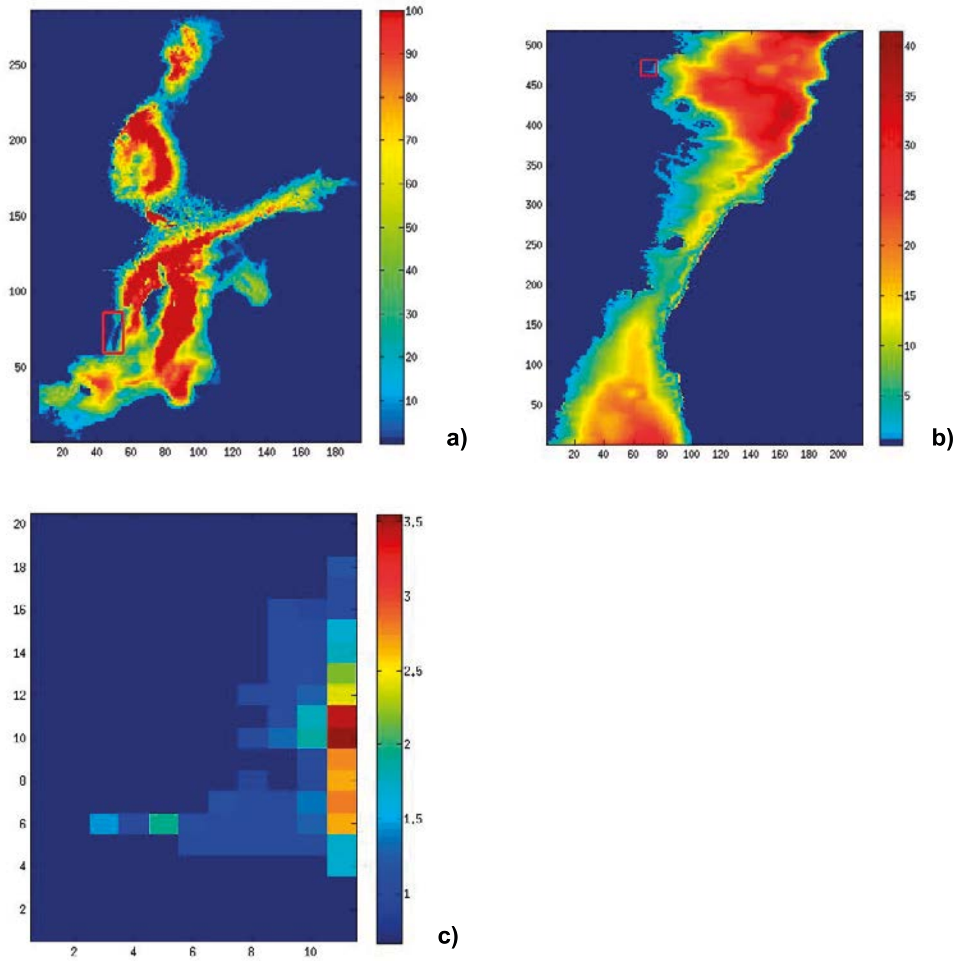



*Figure 7-18. Scate transition from the Baltic Sea to the Oskarshamn harbour: a) Bathymetry of the Baltic Sea with resolution of 5 km; b) Bathymetry of the mid-scale region with resolution 250 m; c) Oskarshamn harbour scale with resolution of 10 m.*

**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.

### 7.5.6 Expert group for the harbour remediation project in Oskarshamn

Author: **Marcus Laaksoharju, Nova R&D**

#### *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 has been formed consisting of scientific experts with KTH and Lnu connections.

#### *Status of the project*

Expert meetings have been held with the project leaders and personnel conducting the harbour remediation project. The expert group have reviewed the methodology, approach, new research projects, monitoring program and documentation used within the project.

#### *Spin-off*

The spin-off of the project is:

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

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

Project leader: **William Hogland Linnaeus University**
Project member: **Mats Åström, Linnaeus University**

#### *Aim of the project*

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

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

#### *Status of the project*

The XRF equipment has been bought and used both in research and education. The instrument has mainly been used in by Swedish Institute sponsored project "Closing the Life Cycle of Landfills – Landfill Mining in the Baltic Sea Region for future" and "Glass Mining as a Part of the Urban Mining – A Challenge in the Baltic Sea Region". It has also been used in thre PhD courses organized by professors William Hogland (LNU), Mait Kriipsalu (Estonian Univeristy of Life Science) and Kenneth Persson (LU). Companies as Ragn-Sells AB and Sydvatten has contributed to the studies with personnel, laboratory, chemical analyses and financial support to the PhD courses.

Results from use of the instrument have been presented at:

1) Fullscale Landfill Mining tests, at Saaremaa landfill, Estonia, 31 January–9 April 2013.
2) Landfill mining in Practice part I, at Högbytorp landfill in Sweden, 21–25 April 2014.
3) Landfill mining in Practice part II, at Högbytorp landfill in Sweden, 07–13 July 2014.
4) Recycling dagen, 24 April, 2013, Dunkers Kulturhus, Helsingborg.
5) Visning av Landfill Mining projekt Vika Deponin, Katrineholm, 2013-04-25.
6) Fou och aktuellt inom deponering, fredagen den 26 april 2013, Örebro.
7) International seminar, Landfill Mining – experiences, future challenges, and planning of full-scale projects, 19 September 2013, Saaremaa, Estonia.
8) ERASMUS visits and International seminar"Landfill mining in the context of global environmental mitigation"**,** Department of Environmental Technology, Kaunas University of Technology, Kaunas, Lithuania, 06–11.04.2014.
9) Linnaeus Eco-tech 2014, 9th International Conference on Natural Sciences and Technologies for Waste and Wastewater Treatment, Remediation, Emissions Related to Climate, Environmental and Economic Effects, 24–26 November 2014, Kalmar, Sweden.

10) PhD course “Circular Economy and Waste Management Summer School”, LUT, Lappeenranta 9–12.6.2014, LUT EnvironmentalTechnology, Finland.

11) PhD course “Mining in Sludge Landfill: characterization of sludge from drinking water treatment, and metal extraction”. Lunds University, Sweden, June 12–18, 2015.

12) PhD Course “Landfill Mining and waste characterisation”. Estonia University of Life Science, June 18–22, 2015.

13) The PhytoTech Park Project, The First Workshop at Linnaeus University and at Boda Glass Factory, Boda, Sweden, 7–9 October, 2015.

XRF results has been presented (e.g. Figure 7-19) in many scientific papers as in article Journal of Environmental Analytical Chemistry which was greatest success as good downloaded and asked time to time. There was comparison of screening by FP XRF and AAS methods (Figure 7-20). The TEM-EDX imaging technique was successfully applied to microtome-sectioned samples of uniform thickness. The advantage of X-ray imaging in a TEM is the high-spatial resolution imaging of multiple elements within an area of interest and its applicability to tissues which are unsuitable for the use of fluorescent probes. The elemental images of agar standards provided a feasible means to make simultaneously semi-quantitative estimations of the concentrations of multiple elements in different cell compartments.

Handheld XRF Analyser (Figure 7-21) with 4 W X-ray tube and optimised beam settings for environmental purposes. Measurements were done for homogenised samples of fine fraction during the field investigations directly after the excavation and separation of fractions according to methodological guidelines.

### *Spin-off*

The instrument has a very high potential in the research and education activities that the ESEG (Environmental Science and Engineering Research Group) are carring out. More research is planned in landfill mining, harbour mining and glass mining in the Baltic Sea Region. Just in Saaremaa there were 17 researchers from 7 countries learning how to use the instrument and now a new PhD course is planned this time in thae area of research in Glass Mining with participants from Ukraine, Estonia, Latvia, Lithuania and Sweden. The ESEG expect the instrument to be used a lot also in the future in particular when running in to research studies of landfilled sludge and recovery potential.

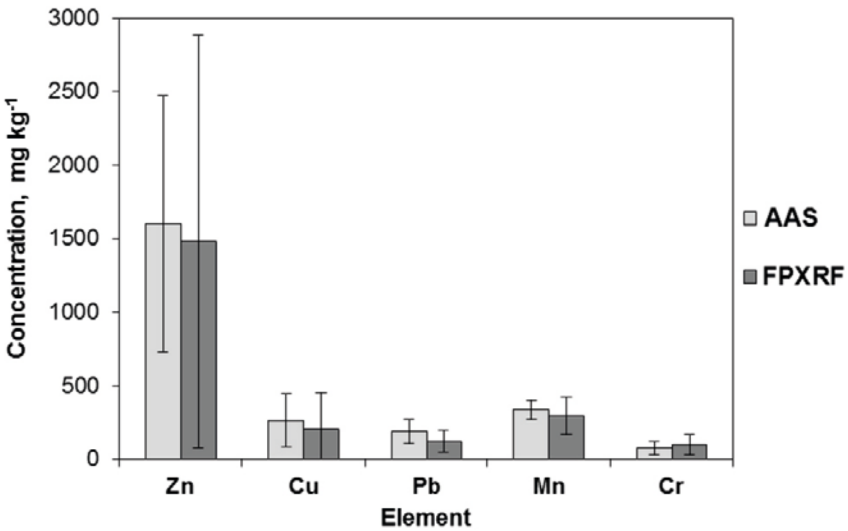



***Figure 7-19.*** *Example of results from use of XRF. Average concentration of trace metallic elements dominating in waste fine fraction from the Kudjape Landfill detected by AAS and FPXRF (n = 48).*

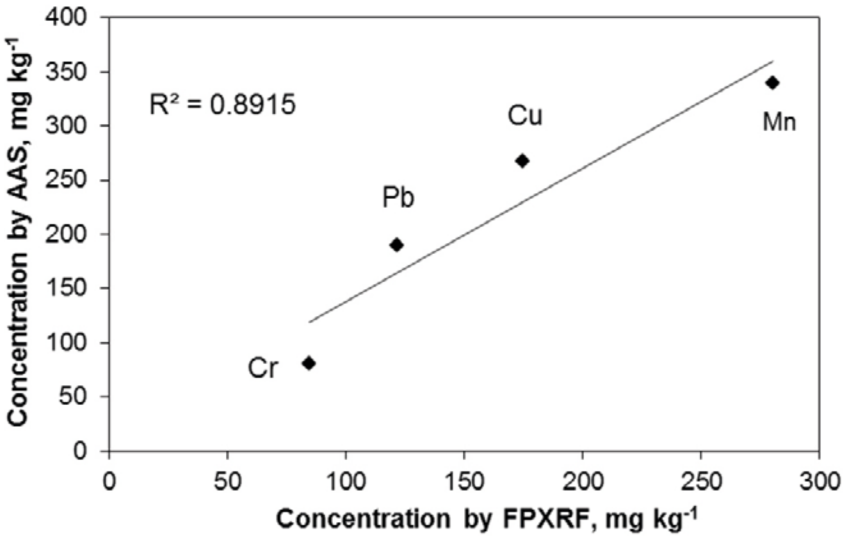



***Figure 7-20.*** *Average concentration of trace metallic elements dominating in waste fine fraction from the Kudjape Landfill detected by AAS and FPXRF (n = 48).*

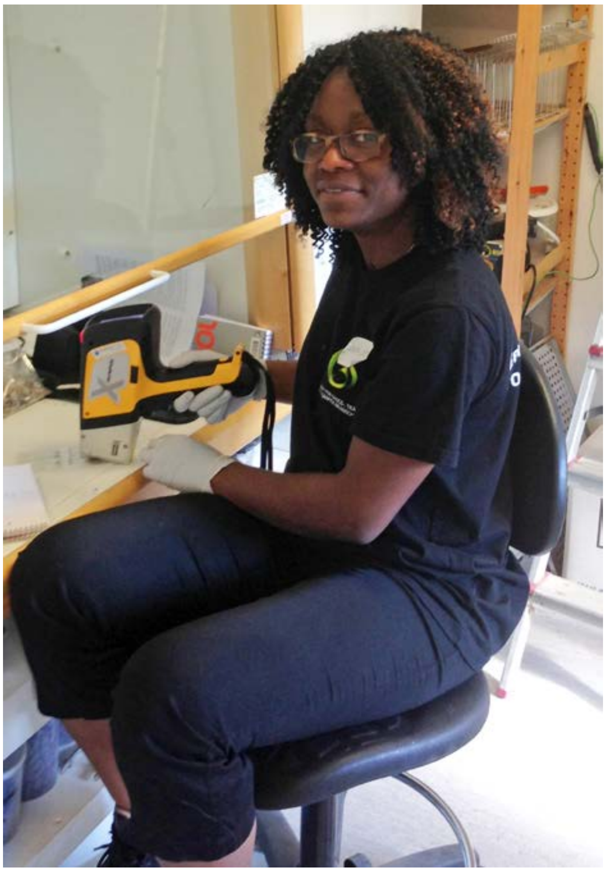


***Figure 7-21.*** *PhD candidate Charlotte Marchand using the XRF instrument during a PhD course. (Photo William Hogland).*

### *Literature*

Submitted papers*:*

1) Field portable X-ray fluorescence spectrometry as rapid measurement tool for landfill mining operations: Comparison of field data vs. laboratory analysis
2) Mobility of metals in sorted fine fraction of waste from excavated landfill
3) Ecotoxicological assessment of landfill fine fraction eluates
4) Toxicological characterization of petroleum hydrocarbons and metals contaminated soils,
5) Characterization of Mined Fine Fraction and Waste Composition at the Largest Swedish Landfill)
6) Exploring the potential of Timothy Grass to rehabilitee an old landfill site (manuscript)
7) Toxicity and characterization of waste glass from Pukeberg glasswork (manuscript).

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

Project 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 summarize and describe general patterns in past research with regard to perspectives, methodological approaches, and the type of systems and organisms that have been studied to date.

The major results are that: (1) across all disciplines and categories the number of published studies concerning global warming and climate change totals more than 73.000 ( up to 2011), (2) publication rate has increased from less than 10 papers per year prior to 1985 to nearly 12.000 papers per year in 2011; and (3) the number of studies that concern global warming and climate change specifically within the field of marine and freshwater environment and biology has increased at a relatively slow rate, and currently amounts to about 2.800 studies (see Figure 7-22).

We have studied and categorized all ca 750 published studies that focus on biology. The resulting data set has been entered into a spreadsheet and will be used for more in depth statistical analyses to identify knowledge gaps and fruitful lines of future investigations, intended for publication as a review. We also intend to conduct an inventory of past base-line studies and ongoing monitoring programs, investigations and data bases associated with emissions of heated cooling water from the power plant at Oskarshamn, investigate how to obtain access to existing data, and evaluate how available data may be used to address crucial questions.

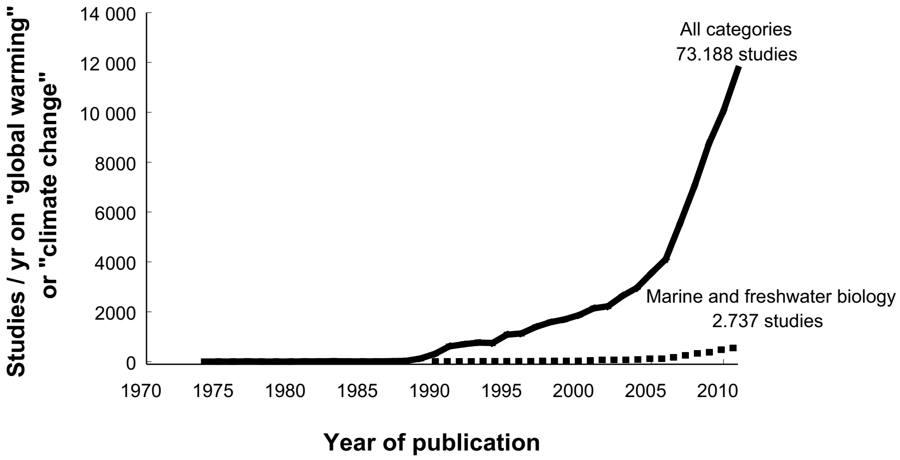



***Figure 7-22.*** *Trends in research output on global warming across all disciplines (filled line) and for marine and freshwater biology (dotted line). Figure shows number of publications per year and is based on data extracted February 2, 2012, from ISI Web of Knowledge.*

#### *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.

#### *Literature*

The work is completed and a manuscript has been submitted, reviewed and it is currently being revised for resubmission.

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

Project leader: **Bo Olofsson, Royal Institute of Technology, KTH**

#### *Aim of the project*

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

#### *Status of the project*

The project has three primary deliverables. The first is a study based on the development of a new methodology which uses geological indicators (such as distance to lineament, distance to water, soil type, bedrock type) in order to estimate the groundwater resource potential (GRP) of an area. This study uses analysis of variance (ANOVA) and principal component analysis (PCA) to generate regional GRP maps which correlate with specific capacity values estimated from the Geological

Survey of Sweden's well archive with more than 95 % confidence. Parameters are classed according to a positive or negative influence on specific capacity estimates using ANOVA. PCA is then used to weight the different parameters by identifying the principal components which are most influenced by specific capacity and then weighting the other parameters based on their loadings on these components. Finally, classes and weights are combined to produce a statistical indicator of the GRP of a particular area. The results of this deliverable were published in *Groundwater* in 2015 (available online during 2014).

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

Presentations were made at several conferences in 2013–2014, including *SGU's Groundwater Days* in Lund (Oct 16–17, 2013) and Gothenburg (Oct 13–14, 2015) , the *28th Nordic Hydrological Conference* in Stockholm (Aug 11–13 2014), and *Hydrology Days* at Stockholm University (Mar 18 2014). Additionally, a poster was presented at the *NGL Annual Science Meeting 2014* in Oskarshamn (Nov 2014).

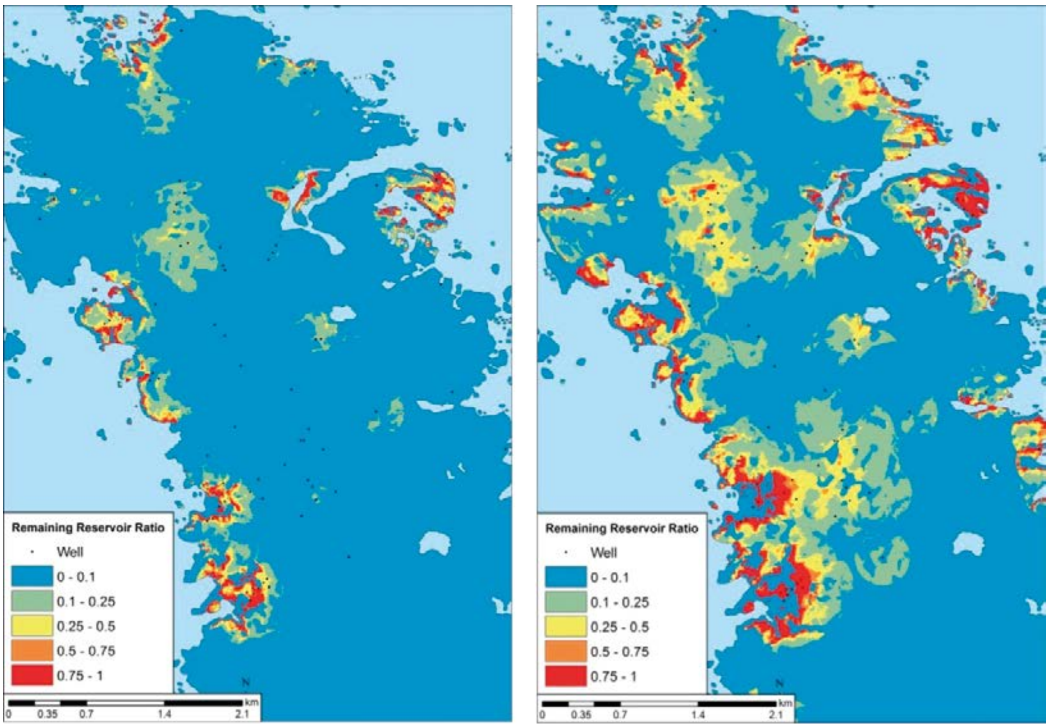



***Figure 7-23.*** *A comparison of month scenarios, left: 20 % and 40 % permanent residency; and right: 80 % and 100 % permanent residency.*

### *Spin-off*

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

## 7.5.10 Hydrogeochemical investigation and modelling

Project leader: **Frédéric Mathurin, Linnaeus University**

### *Aim of the project*

The different processes influencing the hydrochemistry in the fractures are: mixing (of several water types of different origin), transport, water-rock interactions and bacterial activity. 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.

### *Status of the project*

The completed first stage of this project 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 completed second stage focused on the understanding of the natural variability of dissolved concentrations of certain trace elements, i.e., Cs and REEs, which are, on broad term, good analogues of certain nuclides composing the spent nuclear fuel. The ongoing third stage, started in the end of 2014, focuses on the modelling of aqueous and colloidal speciation of dissolved REEs, in the fracture groundwater in the Laxemar-Äspö Area, in continuation to the gained experienced from stages 1 and 2. This third stage aims mostly to emphasis the partitioning of REEs between groundwater and secondary fracture minerals and to improve the understanding of the involved geochemical processes. A fouth stage, focusing on the hydrogeochemistry applied to drinking water supply and medical geology, was started within the framework of a survey regarding the natural variability of dissolved F concentration in fresh groundwater in the Laxemar area.

For the reporting period, the completion of stages 1 and 2 included in this project resulted in the completion of the doctoral degree and publication of a doctoral thesis (Mathurin 2015).

Withing the ongoing stage 3 of this project, the modelling work was delivered as contributions to various independent projects leads by other researchers (co-authorship):

1. The study of the role of carbonate complexes on REE uptake in low-temperature calcite in the fractured crystalline bedrock (Laxemar) was published (Maskenskaya et al. 2015).
2. The study of the Ce anomaly features in facture coatings and groundwater (Laxemar) has been submitted (Yu et al. under revision).
3. The study of the partition coefficients of minor and trace elements between modern groundwater and low temperature calcite precipitated on borehole equipment is still in progress (Drake et al. in preparation).
4. Understanding of the REE features measured in the fracture groundwater at Äspö, via diffusive gradient thin-film (DGT) sampling method under in situ high-Pressure conditions, is still in progress (Alakangas et al. in preparation).

The work performed within the ongoing stage 4 of this project is currently under writting (Berger et al. in preparation), in continuation to a recent publication (Berger et al. 2015).

### *Spin-off*

The findings of stages 3 and 4 of this project are relevant in term of technical/societal challenges:

- The behavior of aqueous and colloidal YREE species and the sequestration properties of fracture mineral reported in the ongoing studies are relevant for indirect assessment of actinide (radionuclide) retention in the bedrock fractures.
- Geochemical processes limiting/controlling the dissolved fluoride concentrations in local aquifers are of environmental importance in context of local extraction and supply of drinking water from private wells.

## 7.5.11 Detailed fracture mineral investigations

Project 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 by advective transport along fractures and different groundwaters subsequently flowing along fractures may precipitate a sequence of minerals on the fracture walls. Examination of these mineral coatings ideally yields a paleohydrogeological record of formation temperatures, fluid compositions, microbial activity, and potential origin and comparisons between fluid and mineral chemistry (trace elements and isotopes) can reveal processes on a very local scale in the fractures.

### *Status of the project*

Investigation has been focused to calcite and pyrite (Figure 7-24) 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 and gases, especially regarding the uptake of trace elements and isotopic fractionation that can reveal microbial activity. It therefore adds to the knowledge of trace element partition coefficients in calcite in natural granite systems and to the knowledge of past and present activity of microbes, such as sulphate-reducing bacteria (SRB) and about anaerobic oxidation of methane (Figure 7-24). These studies are collaborations between Linnaeus University other universities and laboratories, including University of Gothenburg, Scottish Universities Environmental Research Centre (SUERC), UK and Museum of Natural History, Stockholm, Sweden (in particular the NordSIM lab), Universtiy of Göttingen, Germany, and have been published in *Geochimica et Cosmochimica Acta* (one 2015 paper) presenting evidence and nature of sulphate reducing bacteria and *Nature Communications* (one paper published 2015) presenting previously unseen C-isotope variations in calcite, related to previously unknown methane-consuming processes deep in the crystalline bedrock fractures. One collaborative article with of the Nova project leaders (Olga Maskenskaya) was published as well.

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

- Greenland analogue project; redox-studies from fracture coating samples. First sampling and analytical campaign finished and presented at Goldschmidt Conference 2011, second in planning. Collaboration with University of Helsinki and Conterra AB.
- Investigation of metal uptake in calcite grown on borehole equipment in the Äspö tunnel, and comparison with groundwater data. Collaboration with University of Gothenburg.
- Stable isotope characteristics of pyrite and calcite of Paleozoic age from several deep sites in Sweden: Forsmark, Götemar, Laxemar, Äspö, Simpevarp. The preliminary results indicate previously unseen isotope-variations and temporally and spatially widespread microbial activity in this environment.
- Chemistry and reducing capacity of fracture coatings in water-conducting fractures and fracture zones.
- Iron isotopes in SRB-related pyrite.

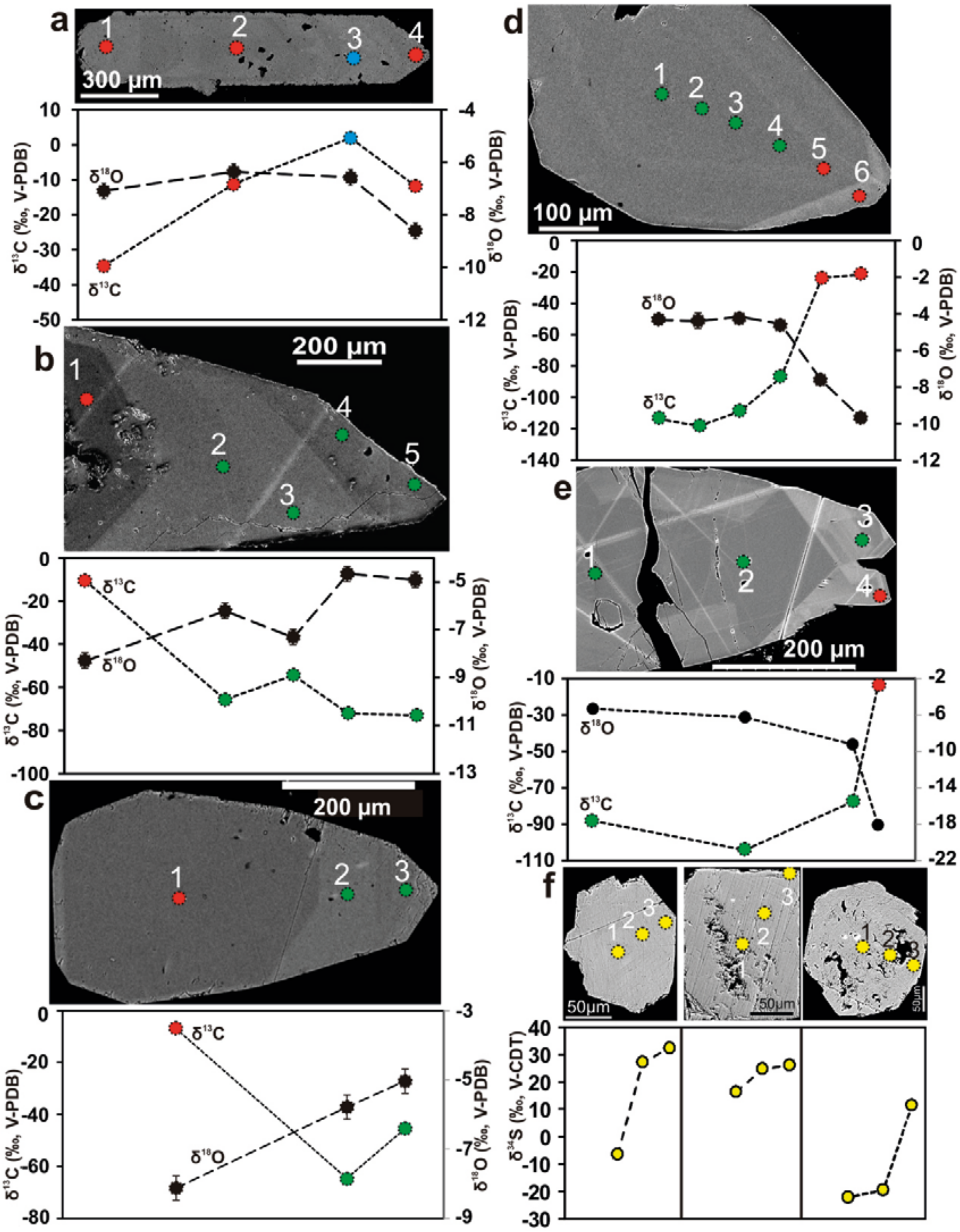


*Figure 7-24. SEM-images of calcite and pyrite crystals from open fractures, with extreme variation in δ13C, δ18O and δ34S shown for the 10 µm spots in transects through the crystals. Modified from Drake et al. (2015).*

### 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.

### 7.5.12 Apatite fission-track analysis of samples from SKB Oskarshamn drillcores

Project 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, b, Söderlund et al. 2005). GEUS and Geotrack have previously undertaken and published results from such investigations in different settings; e.g. in Greenland, the North Sea and Brazil (Japsen et al. 2005, 2007, 2012).

#### *Status of the project*

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

#### *Spin-off*

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

The Phanerozoic burial and exhumation history of Scandinavia is a field of intense scientific interest. The collapse of the Caledonian mountain chain in the late Paleozoic has been recognized since long, but the subsequent thermotectonic history in Mesozoic and Cenozoic times is a field of ongoing research (e.g. Rohrman et al. 1995, Cederbom 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).

### 7.5.13 Fe(II) biomineralisation and La enrichment during oxidation of fracture groundwater

Project leader: **Changxun Yu, Linnaeus University**

#### *Aim of the project*

The aim of the project is to examine the speciation and microscale distribution of Fe and Ni in Fe-rich microbial mats haverested from two flow-reactor experiments at sites 1327B and 2156B, using synchrotron-based techqniues. The results will provide new molecular insight into the mechanisms whereby Ni was accumulated by microbial mats to a greater extent than the inorganic and abiotic Fe oxyhydroxide references. The enrichment of La in a thin-layer of a natural microbial mat sampled from Äspö is no longer the focus of this project, because further examination has shown that it was an artefact due to the incorporation of clay particles.

### *Status of the project*

In 2015, Fe X-ray absorption spectrospy data of six microbial mats as well as relavant reference compounds were collected at beamline I811 at MAX-lab, Sweden. Iron $k^3$-weighted extended X-ray absorption fine structure (EXFAS) spectra of these microbial mats (Figure 7-25) show strong resemblance with that of 2-line ferrihydrite in terms of line-shape, amplitude, and frequency, suggesting a dominance of 2-line ferrihydrite like phase in these samples. However, the peak at $k = 7.0–7.5$ $Å^{-1}$ for the sample spectra is much weaker than 2-line ferrihydrite, reflecting that BIOS in the mats are less short-range ordered than 2-line ferrihydrite, as previously found for biogenic Fe oxyhydroxides.

Addtionally, to ensure that it is technically feasible to collect usable Ni XAS data from the microbial mats, one Ni K-edge X-ray absorption near edge absorption spectroscopy (XANES) spectrum was collected from the 3.5-year-old microbial mat at site 1327B on the Hard X-ray Micro-Analysis (HXMA) beamline at Canadian Light Source (CLS). Although the spectrum is noisy, we are convinced that high quality Ni XAS data can be obtained by averaging multiple scans. The XANES spectrum differs significantly from that of metallic Ni foil (Figure 7-26), suggesting Ni in the sample occurs as Ni(II). Real Ni XAS data of the microbial mats and reference materials will be collected at HXMA beamline early 2016, in collaboration with Dr Ning Chen at CLS.

### *Spin-off*

The results of the planned Ni XAS experiment in combination with Fe XAS and Scanning transmission X-ray microscopy data will further provide molecular insights into the fundamental biogeochemical processes underlying the preferential enrichment of Ni during the development of the microbial mats at the two sites. Understanding these biogeochemical processes will have implications with regard to (i) assessment of Ni partitioning and bioavailability in natural microbial mats; and (ii) bioremediation of Ni-contaminated sites. Also, the preferential enrichment of Ni in microbial mats points to a potential utility of Ni as a biomarker for ancient iron oxyhydroxide rich microbial mats on earth.

### *Literature*

No paper or poster presentation was presented in 2015.

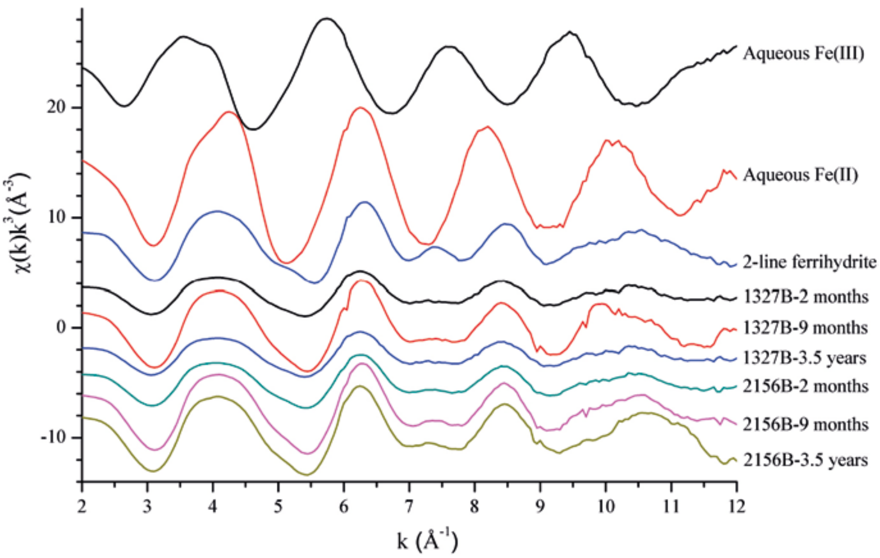



***Figure 7-25.*** *Normalized k3-weighted EXAFS spectra for iron in microbial mats. The spectra for aqueous Fe(III), aqueous Fe(II), and synthetic 2-line ferrihydrite are given for comparison.*

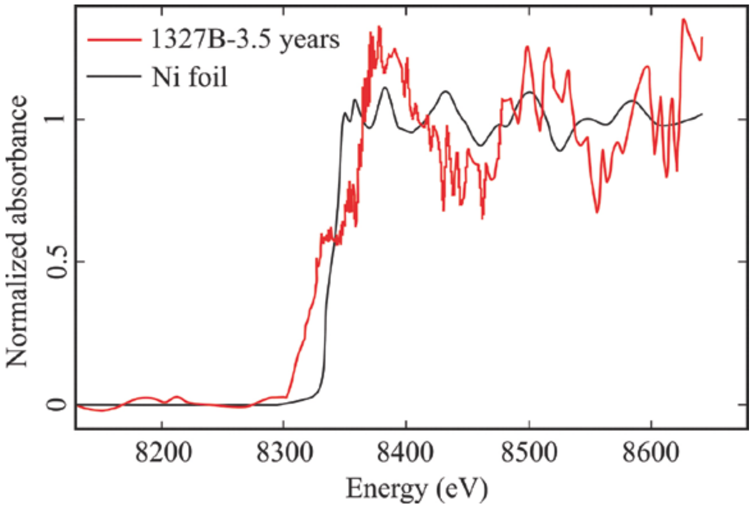



***Figure 7-26.*** *One scan of normalized Ni XANES spectra of the 3.5 years old microbial mat at site 1327B and metallic Ni.*

### 7.5.14 Modeling of in situ hydraulic mixing, water-rock interaction and microbiological effects when marine water intrudes into fractures surrounding the Äspö HRL

Project leader: **Frédéric Mathurin, Linnaeus University**

#### *Aim of the project*

The aim of this project is to quantify, through modelling, how *in situ* hydraulic mixing, chemical reactions and microbial processes modify the chemical composition of brackish (Baltic) sea water that has penetrated into the fractures since the excavation of the Äspö HRL tunnel.

#### *Status of the project*

The modelling approach consists of three steps for final validation of the quantification of ongoing short term reactive processes (Figure 7-27):

1. An assessment and comparison of the mixing proportion, through various inverse mass balance modeling methods, for mixing calibration.
2. A qualitative estimation of short term reactions from inverse modelling, after critical discussion of appropriate borehole sections for the modelling exercice.
3. An integration of the hydrogeochemical results with hydrogeological knowledge of the site, in a reactive transport model.

For the reported period, the two first steps have been completed. The results and interpretations have been reported in a manuscript included in a published doctoral thesis (Mathurin 2015), before submittion to a scientific journal during year 2016.

#### *Spin-off*

The findings of this study are relevant in term of technical/societal challenges:

- By providing indirect assessment of magnitude of cation-exchange processes/capacity along the penetration path of marine water toward the underground facility.
- With a direct interest for the update of the Äspö Site Description and Modelling.
- With a direct relevance for any forthcoming NGL project focusing on fractures carrying groundwater consisting entirely of partly of intruding modern Baltic Sea water.

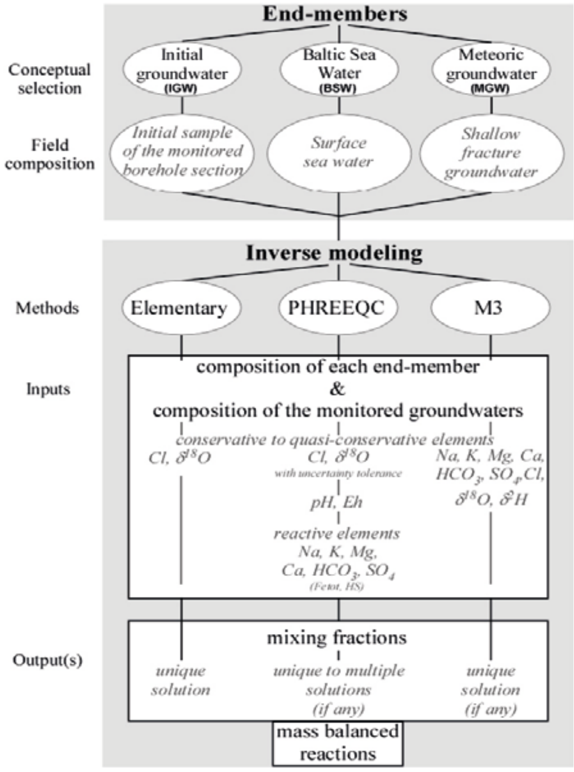



***Figure 7-27.** Flowchart showing the conceptualisation and variables included for reactive process quantification from inverse modelling (steps 1 and 2 of the project).*

### 7.5.15 Geobiology of microbial mats in the Äspö tunnel

Project 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 biomineralization processes, including EPS-controlled selective cation binding and complex formation, (3) inorganic and organic biosignatures for biogeochemical processes involving recent and ancient deep biosphere microorganisms.

#### *Status of the project*

Three sets of flow reactors, each consisting of four units, were installed in 2006 and connected to aquifers of different chemical composition and age at sites TASA1327B, NASA 2156B, TASF. These flow reactors enable a contamination-free study of the spatial and temporal development of microbial mats and associated mineral precipitates. The active research phase ended in 2013. In 2014 and 2015 no research activites were conducted at Äspö, the main focus was on finalizing the project and preparing manuscripts. Most of the manuscripts were published in the special issue "Geobiology of Organo- and Biofilms" Geomicrobiology Journal, volume 32, issue 3-4.

#### *Spin-off*

- Microbial systems in the Äspö HRL may serve as model systems for the biodiversity and structure of the deep continental biosphere.
- Microbes showing increased capacities for the accumulation TREE may potentially be used for the recovery of precious trace elements, and for water remediation purposes.
- Algal cells within a phototrophic microbial mat growing in the flow reactors at TASA 1327B, identified as diatom P. lanceolatum, contain high amounts of triacylglycerols (TAGs). Diatoms with a high TAG content are important for the research and development of microalagal biofuels (Hildebrand et al. 2012).
- Defining biosignatures of recent and ancient deep biosphere environments will be helpful for paleo reconstructions, which may also affect considerations about the long-term storage of nuclear waste.

### 7.5.16 Fossilized microorganisms at Äspö HRL

Project leader: **Magnus Ivarsson, The Swedish Museum of Natural History**

#### *Aim of the project*

The aim of the project is to search for and characterize fossilized microorganisms preserved in vein-filling minerals like carbonates and quartz in drilled samples from the Äspö Hard Rock Laboratory (HRL). Our aim is to understand the presence of microorganisms through time and depth in the crystalline rocks related to Äspö HRL. We also want to understand how the microorganisms migrate through the pore space, how they colonize and are being preserved, and how they interact with the host rock and secondary mineralizations.

#### *Status of the project*

During the last year the project has changed direction and a close collaboration with Henrik Drake, Linneus University, has been intitated. Samples from drill cores with known microbial isotopic signatures have been the aim of the investigations. Fossilized microorganisms and remains of microbial communities in association with minerals with isotopic signatures characteristic for microbial presence have been observed and are now under investigation. The fossilized microorganisms are characterized by Raman spectroscopy and ToF-SIMS, and their nature and origin is established. New results indicate the presence of fungi in the drill cores, and an intimate interaction between the fungi and secondary mineralizations are seen. This may have impact on the nuclear waste storage and the mineral and material that are supposed to be used as cover, and more in detail work is planned for 2016. The project is in an intense stage including analytical work and preparation of several manuscripts which will be submitted during 2016.

#### *Spin-off*

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

### 7.5.17 Structure and function of microbial communities in the deep biosphere

Project leader: **Mark Dopson, Linnaeus University**

#### *Aim of the project*

The purpose of the activity is to sample deep sub-surface fracture systems containing waters of different ages and origins 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 detailed below.

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 reconstructing (near complete) genomes. The data will be utilized to answer how the cells are able to grow in the oligotrophic environment including potential novel metabolisms; if the cells are lithotrophic or heterotrophic; if the cells use indigenous or exogenous (i.e. from meteoric water) carbon and energy sources; are the deeper microorganisms using other potential energy sources than the hypothesized abiotic $H_2$ generation; and how the microorganisms alter the geochemical environment? The project has been carried out with Karin Holmfeldt, Daniel Lundin, and Mats Åström (Linnaeus University) along with Stefan Bertilsson's research group (Uppsala University).

The deep subsurface is suggested to be highly stable with little change occurring over long periods. This hypothesis is being tested using three-time series of samples from boreholes with water turnover times from a month to thousands of years. This project is in collaboration with Christine Heim (University of Göttingen); Danny Ionescu (Leibniz Institute of Freshwater Ecology and Inland Fisheries); and Alexander Eiler and Stefan Bertilsson's research groups (Uppsala University).

Microorganisms exist either as free swinning 'planktonic' cells or in complex, multi-cell 'biofilm'communities attached to a surface. DNA extracted from biofilms will be evaluated for the different populations' capacity to form a biofilm; if the microbial community in the planktonic study described above differs from the biofilm community; and if there are significant differences in metabolic strategies between the planktonic and biofilm communities. Collaboraters in the project are Karsten Pedersen and co-workers at Microbial Analytics Sweden AB; Mats Åström (Linnaeus University); and Stefan Bertilsson (Uppsala University).

Bacteriophages are viruses that infect bacteria and have been recently discovered in the deep biosphere at the Äspö HRL. However, the role they play in this environment is completely unknown and community viral DNA analysis will identify the different viral populations, if they are temperate, and if they mediate DNA transfer between cells? Project partners include Karin Holmfeldt's group and Daniel Lundin (Linnaeus University); Anders Andersson's group at KTH Royal Institute of Technology; and Stefan Bertilsson (Uppsala University).

### *Status of the project*

Sampling from the Äspö HRL has been completed and the obtained nucleic acid has been sequenced. The present activity is to analyze the results of the four sub-projects ready for publication.

Community DNA has been sequenced from 'modern marine', 'old saline', and 'undefined mixed' groundwaters, the data analyzed, and sequences allotted to species by binning. The experiments also showed that approximately 50 % of the cells in the deep groundwaters at the Äspö HRL passed through a 0.22 µm filter, the size usually used to retain bacteria for analysis. These data have been analyzed and a paper published (Wu et al. 2016) detailing the microbial community structure (Figure 7-28).

DNA from a time series taken from boreholes containing 'recent' Baltic Sea and meteroric groundwaters (retention time ~ 4 weeks), 'intermediate' meteoric water (retention time 5 years), and 'ancient' glacial melt and meteoric waters (4000 to 5000 years old) has been analyzed. A manuscript detailing these results is submitted.

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

### *Spin-off*

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

### *Literature*

One article (Wu et al. 2016) has been published in an international journal:

The project has also been presented at the following meetings/conferences:

1. Wu, Holmfeldt, Hubalek, Åström, Bertilsson & Dopson (2015) Workshop for Microbial Sulfur Metabolism, Helsingør, Denmark.
2. Dopson (2015) The Deep Biosphere & Äspö Hard Rock Laboratory. Linnaeus University open lectures. Oral presentation.
3. Dopson, Holmfeldt, Ionescu, Heim, Andersson, Pedersen & Bertilsson (2014) Shining a Light into the Terrestrial Deep Biosphere: Next Generation Sequencing of the Äspö Hard Rock Laboratory Microbial Community. National Geosphere Laboratory Meeting, Oskarshamn, Sweden. Oral presentation.
4. Wu, Holmfeldt, Hubalek, Lundin, Åström, Bertilsson & Dopson (2015) The microbial interactome of the terrestrial deep biosphere reveals metabolic partitioning among populations. SAME Conference, Uppsala, Sweden. Poster presentation.
5. Wu, Holmfeldt, Bertilsson, Andersson & Dopson (2014) Viral metagenomes from the terrestrial deep biosphere. 9th International Symposium on Subsurface Microbiology, Pacific Grove, California USA. Poster presentation.

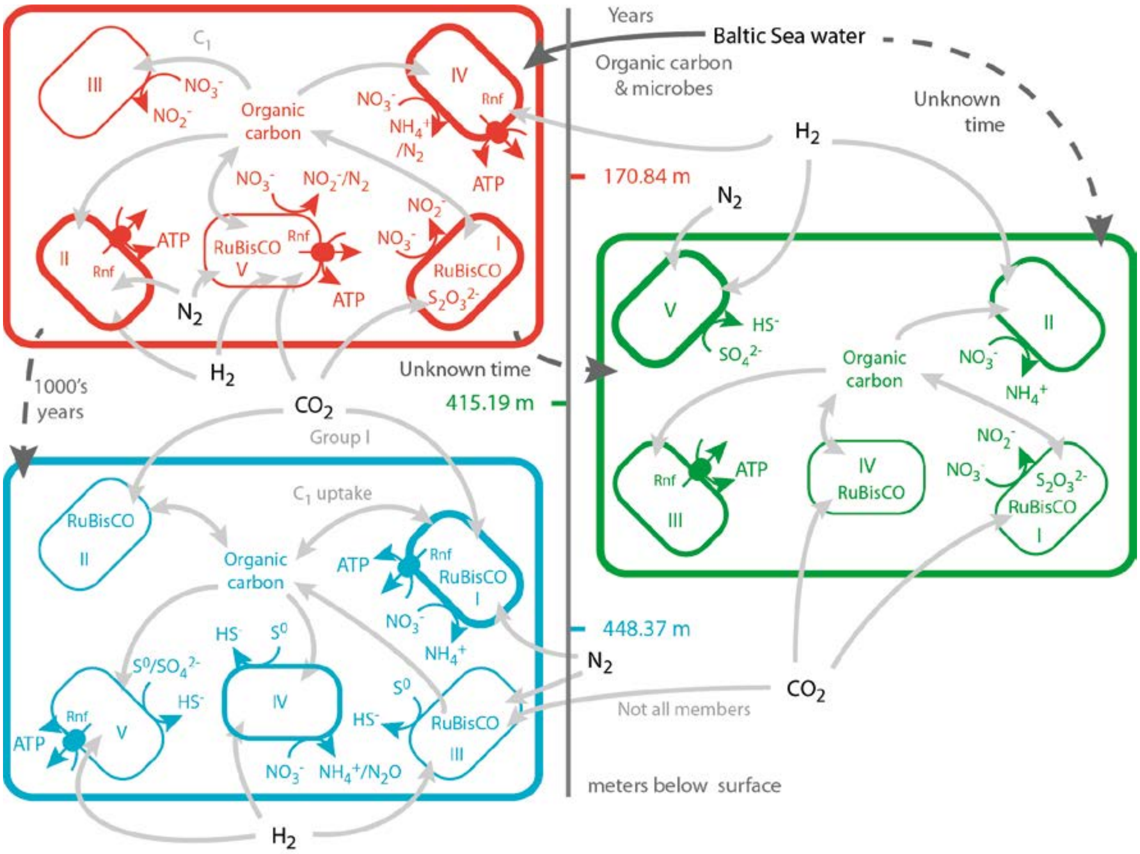



*Figure 7-28. Model of potential metabolic pathways in the modern marine (orange), undefined mixed (green), and old saline (blue) waters. The Roman numerals refer to the groups defined in reference 1 below. The figure shows recharge of the modern marine water from the Baltic Sea (providing organic carbon and microorganisms) and the gases hydrogen and carbon dioxide. The cell wall thickness represents < 10 % (thinnest line), 10 to 50 % (medium line), and > 50 % (thickest line) of the average percent mapped reads divided by the total percentage of mapped reads in all bins from the respective duplicate metagenomes. Figure taken from Wu et al. (2016).*

### 7.5.18 Activity of deep biosphere microorganisms in an extremely oligotrophic environment

Project leader: **Mark Dopson, Linnaeus University**

#### *Aim of the project*

The purpose of the activity will be to sample borehole waters with various origins to understand the activities of the microbial populations at the sub-surface interface between a terrestrial and marine environment. The study is being carried out in collaboration with Stefan Bertilsson's research group (Uppsala University) and Anders Andersson's group (KTH). The questions that will be addressed are detailed below.

Are the main groups of deep biosphere microorganisms active or dormant? Matching community RNA to metagenome sequences assigned to different species by 'binning' will provide exact data regarding the active versus dormant species within the population. This will provide novel data on the proportion and identification of species that are living and active (i.e. which species are actively growing and which just exist in the environment?).

Do deep biosphere microorganisms use special adaptations to maintain their viability under low energy flux conditions? Community RNA sequencing will identify the microorganisms' metabolic capacities and the genes that the microorganisms use under *in situ* conditions. The results will be utilized to more specifically address how cells are able to grow in the oligotrophic environment and whether lower available energy correlates with a smaller cell size? We will also address whether the microorganisms using other potential energy sources (e.g. carbon compound release from autotrophic species, sulfur disproportionation etc.)? The experiment will identify whether or not the expressed genes are related to maintenance or cell division.

How deep biosphere microorganisms respond to a changing environment? Community RNA sequencing will be carried out after an alteration in the cells environment in the absence and presence of substrate. The results will identify if the population (or a portion thereof) rapidly reacts to a change in the extracellular environment or if the microorganisms require an exogenous energy source to generate mRNA to respond to such a change.

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

### *Status of the project*

The *in situ* RNA sampling device (Figure 7-29) required to obtain valid RNA preparations from boreholes (i.e. under *in situ* pressure and redox potential) has been constructed, tested, and sampling underway. The RNA will be sequenced by next generation sequencing and the resulting sequences analysed using bioinformatics.

A second sampling system in flow cells has also been designed with the goal of sequencing RNA from attached cells in biofilms on rock surfaces. This is designed to mimic growth within the fissure systems in the deep subsurface. These experiments will be carried out in the next year.

### *Spin-off*

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

***Figure 7-29.*** *Sampling vessel for preservation of RNA from borehole water maintained under in situ conditions.*

## 7.6 Demonstration, education and public relations

The aim of the demonstration, education and public relation activities as described below are to inform about the unique nuclear technology know how at SKB in Oskarshamn and to market the open research infrastructure Nova R&D to the academia and decision makers.

### 7.6.1 Baltic Region Initiative for Long Lasting Innovative Nuclear Technologies (BRILLIANT)

Author: **Eva Hjälmered, Nova**

#### *Aim of the project*

The BRILLIANT project helps to achieve the objectives of the Energy Union Strategy in the EU (EC initiative announced in February 2015) in terms of:

- Diversification of energy sources,
- Ensuring security of energy supply,
- Reducing of EU countries dependency on energy imports,
- Reduction of greenhouse gas emissions in the EU,
- Fighting against climate change.

This is a 3 year Project financed by the European Commission's program EURATOM and has the following organization:

Lead Partner: Lithuanian Energy Institute (LEI)

Project leader/Swedish Partner: KTH, Waclaw Gudowski

Sub-contractor: Municipality of Oskarshamn/Nova R&D.

The objectives for the project are:

- Create cooperation platform for modern nuclear technologies and electrical power solutions in Baltic Sea countries.
- Establish and develop links with decision makers (governmental structures) and industrial partners in Baltic see countries and demonstrate advantages of regional cooperation in energy sector development.
- Identify the real barriers for nuclear power development in Baltic countries region and prepare the ground for overcoming them.
- Support the exchange of scientific knowledge and competences between Baltic region countries.
- Development of better synergies with on-going and future Euratom projects in particular those offering access to research infrastructures in conjunction with education and training.

#### *Status of the project*

The project started in July 2015. A scientific board has been elected and one of the board members is Rector Bengt Karlsson, Nova. A website has been created: www.balticbrilliantproject.eu

The project arranged a first study visit to Oskarshamn 9–11th of December, 2015 for a group of scientists. A second study visit is being planned in September 2016 for high-level decision makers.

#### *Spin-off*

Possible spin-off of the BRILLIANT project:

- Brilliant Fellowships for EMINE (or other nuclear programs) studies. Best students from each partner states will be offered a Master Fellowships for 2 years being also active associates with the Brilliant Project
- Master Thesis offered by the project
- Support for new national educational initiative in partner states. Supporting mobility of educators
- Support for "gender balancing" educational and promotional activities through educational visit to schools and promoting example of carries in nuclear field
- Special links with WiN (Women in Nuclear).

### 7.6.2 Summer training course: Elements of the Back-end of the Nuclear Fuel Cycle: Geological Storage of Nuclear Spent Fuel

Author: **Anna Rockström, Nova R&D**

#### *Aim of the project*

The aim of the training course Elements of the Back-end of the Nuclear Fuel Cycle (university education code: SH262V, 7.5 ECTS) is:

1. Education of master students in different aspects of the back-end of the nuclear fuel cycle and geological storage of spent nuclear fuel
2. Extensive use of the Äspö Hard Rock Laboratory, canister laboratory and other facilities in Oskarshamn for educational purposes
3. Establishing cooperation between KTH and the Oskarshamn community
4. Build-up of international cooperation and international promotion of Oskarshamn facilities and their research and educational potential.

During two weeks in June 2015, 43 international students from 15 countries (Figure 7-30 and Figure 7-31) participated in an intensive course in management of spent nuclear fuel. The course was taught at Nova in Oskarshamn, Sweden. This course is organized by the Royal Institute of Technology (KTH), the Center for University Studies Research and Development (Nova – Oskarshamn) and by the Swedish Nuclear Fuel and Waste Management Company (SKB) and was supported by the Linnaeus University, the University of Illinois at Urbana-Champaign, and the European Master in Innovative Nuclear Energy program – EMINE.

The course consisted of a combination of classroom lectures and field excursions/work. The unique feature of the course is that the students visit Clab (an interim geological repository for spent fuel), the Laxemar Site (study area for bedrock and surface geology), the Äspö Hard Rock Laboratory, and the Canister Laboratory.

This course is an integral part of the KTH Master in Nuclear Energy Engineering and European Master in Innovative Nuclear Energy (EMINE).

#### *Status of the project*

The summer training course was evaluated by the participating students, who responded with positive feedback (Figure 7-32). This summer training course is scheduled to become permanent.

#### *International cooperation*

International cooperation has a strong focus in this project. The summer training course gathers not only international students but also international lecturers. In 2015 lecturers from University of Illinois Urbana Champagne in USA, from Korean Institute of Advanced Science and Technology (KAIST) in Republic of Korea aside of the Swedish colleagues from SKB, KTH, Linnaeus University lectured at the course.

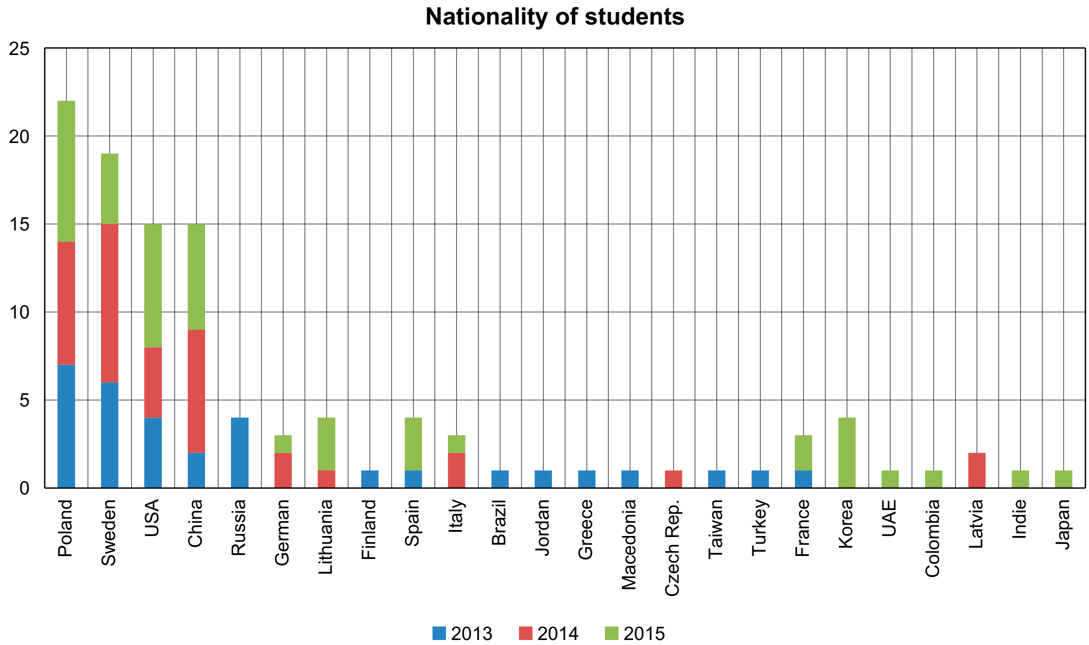



***Figure 7-30.*** *Nationality of the students of the summer course in the years 2013–2015.*


***Figure 7-31.*** *Participants of the summer course 2015.*

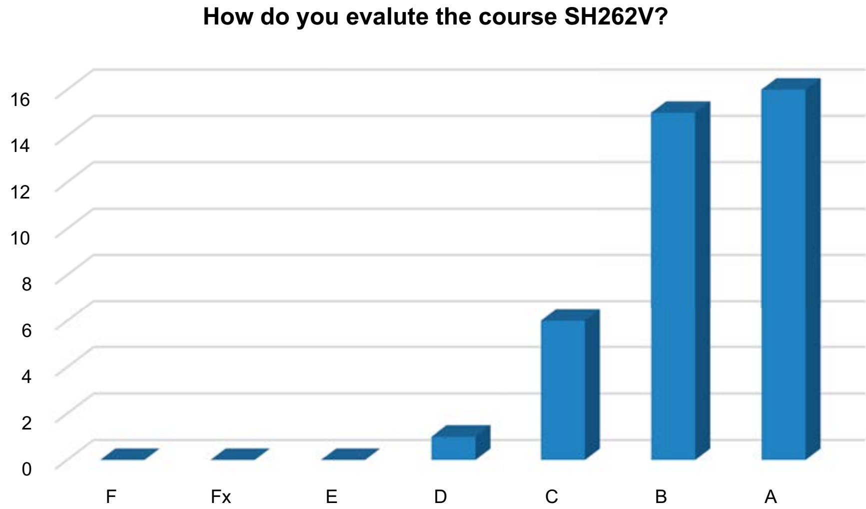



***Figure 7-32.*** *Students' evaluation of the course SH262V. The y-axes show the number of answers, A = Excellent, D = Average and F = Poor.*

#### *Spin-off*

The spin-offs from the summer training course are:

- Establish new and unique Master's education program in Oskarshamn
- Market the unique Oskarshamn know-how and the open research infrastructure
- Establish new domestic and international academic contacts.

### 7.6.3 Public relations

An important activity for a municipality organisation such as Nova R&D is information to the public or public relations. This activity can be press releases or arranging scientific workshops and meetings. Examples of public relations are articles in the local press about the BRILLIANT project, visit of a Polish delegation in September 2015 and a visit of a high level Chinese scientists and politician delegation in December 2015.

## 7.7 Spin-off effects in summary

Examples of spin-off effects from the Nova R&D 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 enhance heat extraction from large detpths for geothermal use in large scale industrial plants. Study rock weaknesses and corrosion problems underground. Development of new characterisation techniques to be used for tunnel construction projects.
- **Commercialisation:** Identification and commercialisation of research results in research projects.
- **Environmental technique:** 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.

## 7.8 Progress in summary

The actual situation at Nova R&D by the end of year 2015 was:

- 34 ongoing scientific projects representing a value of 55 million SEK
- 157 researchers
- 14 domestic and international universities
- 2 public organizations
- 2 research institutes
- 2 companies
- 46 peer review publications, 4 theses and 3 reports.

The progress of Nova R&D in terms of development of projects during the last six years are shown in Figure 7-33.

## 7.9 Steering Committee and personnel

**Nova R&D steering committee**

Mats Ohlsson, Manager 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, Coordinator
Caroline Oscarsson, Administrator.

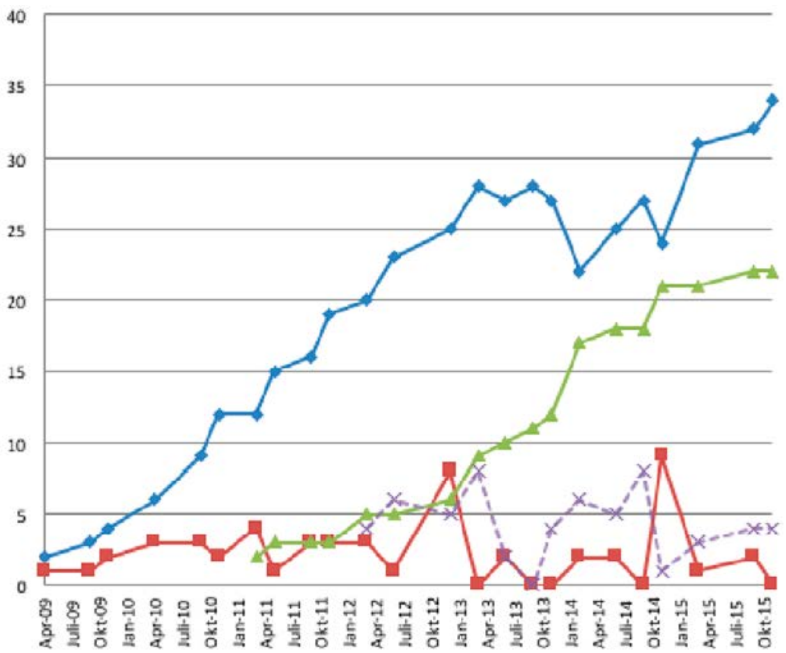



***Figure 7-33.*** *Development of projects at Nova R&D during the last six years. X-axes show date and y-axes the number of projects. Blue curve = on-going projects, green curve = finished projects, red curve = to be approved, magenta = projects for evaluation.*

# 8 International co-operation

## 8.1 General

During 2015 eleven organisations from six countries in addition to SKB participated in the cooperation at Äspö HRL. Five of them; BMWi, RWM, NUMO, CRIEPI and JAEA formed together with SKB the Äspö International Joint Committee (IJC), which is responsible for the coordination of the experimental work arising from the international participation.

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

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

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

In February SKB International organised a two days topical workshop regarding "Borehole sealing". The purpose of the workshop was to present the development of borehole sealing in different countries and specially the work done by SKB and Posiva.

April 21st–23rd, 2015 SKB together with Posiva organised the Äspö HRL Symposium. The symposium covered research and development at SKB and Posiva with special focus on the activities at the Äspö HRL and the Canister Laboratory in Oskarshamn. In total over 60 persons from 17 organisations participated.

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.

## 8.2 BMWi

In 1995 SKB and the then Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMFT) signed the co-operation agreement being the framework and the basis for the participation of German research institutions in the R&D activities in the Äspö HRL. In 2003, the agreement was prolonged for the first time. In 2008, it was extended a further five years, and in 2012 for another year. In 2013, it was agreed to continue the cooperation for another three years. On behalf of and/or funded by the Federal Ministry for Economic Affairs and Energy (BMWi) the following research entities 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) gGmbH, Braunschweig.

The general purpose and the benefit of the co-operation are to broaden the state of knowledge on crystalline rock as a potential host rock for high-level waste repositories. In particular the focus is on extending the knowledge on the behaviour of the engineered barrier system and issues related to hydrology and transport.

Topics of special interest are:

- studying and investigating buffer material(s),
- studying the processes occurring in a repository system to increase process understanding,
- modelling of coupled processes,
- improvement, refinement and test of codes.

### 8.2.1 Task Force on Groundwater Flow and Transport of Solutes

GRS is the German research organisation participating in this Task Force.

GRS has created a groundwater flow model describing the pre-installation phase of the Prototype Repository (PR) and contributed herewith to Task 8e in the Task Force on Groundwater flow and Transport of Solutes (TF GWFTS). This model follows the conceptual model for flow at the BRIE (Task 8d) in that

- background fractures are considered to form a homogeneous continuum that adds to the "undisturbed matrix",
- large fractures are treated as discrete features in the model,
- a thin zone is arranged around tunnels and boreholes where matrix and fracture permeabilities are reduced to account for the skin-effect.

Noteworthy is the fact that only one of the nine discrete fractures in the model had not been detected during the extensive hydrotesting program at the PR but was assumed to explain some outflow data in the PR-tunnel. This fracture is nevertheless consistent with the hydraulic investigations as it would be outside the large array of probing boreholes.

Hydraulic data concerning matrix and background fractures were taken from the much smaller calibrated model for the BRIE. Calibration of the PR-model took into account all outflow data along the PR-tunnel as well as into the six deposition holes. Only moderate changes in the permeabilities were sufficient to reproduce the measured data. Therefore, the application of the model concept for the BRIE to the PR can be considered as successful.

A closer look into the resulting velocity field reveals two phenomena that are specific for fracture flow. The first one concerns the sharp velocity contrasts across the fractures as shown in Figure 8-1. In the horizontal cross-section through the PR, depicting the absolute values of the velocity, the position of the fractures can clearly be identified by this phenomenon. These contrast form where water reaching the fracture from the matrix is diverted along the fracture because of the comparatively high fracture permeability. The second phenomenon can be observed at the rim of the fractures. Very high velocities can be found here because the catchment volume at the rim is much larger than at the face of the fracture.

Of potential further interest might be an effect triggered by the low permeability skin in the model. At the top end of a deposition hole where the skin of the tunnel and the skin of the borehole overlap, water outflowing into the borehole is diverted. Instead of reaching the edge between borehole and tunnel, most of the water enters the borehole below the height of the tunnel skin, Figure 8-1. According to the model results, a comparatively dry zone would form at the top of the borehole followed by a comparatively wet zone. It would be highly interesting if this effect could be confirmed in the field. Note that the permeability in the overlapping skins of tunnel and borehole is the same as in each single skin.

A discussion at the autumn workshop of the TF GWFTS about possible explanations for the skin-effect motivated GRS to look for further evidence and observations. This effect refers apparently not only to flow but also to diffusive solute transport. A framework for a systematic compilation and interpretation was prepared as a basis for a joint report involving the partners of the Task Force or for a special workshop at the upcoming joint meeting of the Task Forces in spring 2016.

### 8.2.2 Prototype Repository

A poster on mineralogical-geochemical analysis of BGR's work on the prototype repository was presented at an international meeting (Dohrmann and Kaufhold 2015).

### 8.2.3 Alternative Buffer Materials

A poster on modeling work on "ABM1" was presented at an international meeting (Wallis et al. 2015).

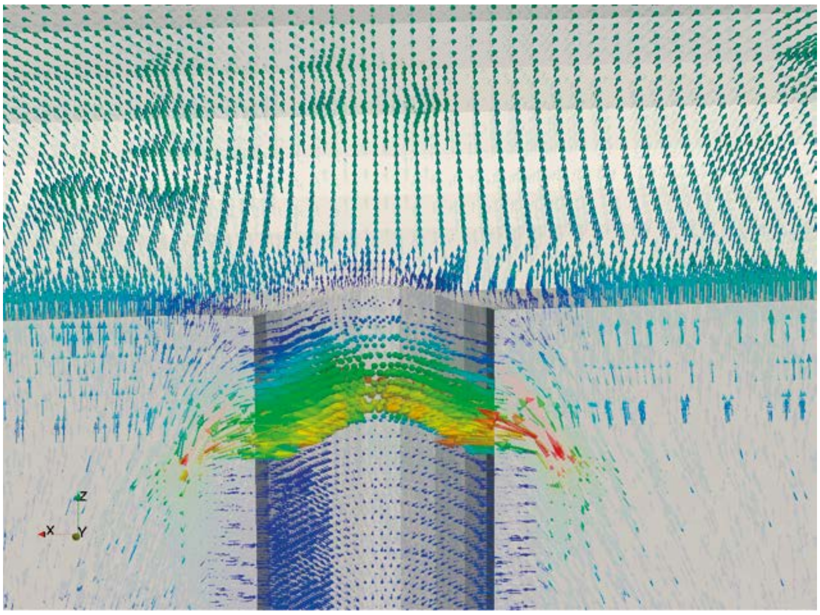



***Figure 8-1.*** *Vector field of the velocity in a vertical cross-section through the PR; blue: low velocity, red: high velocity.*

In 2015, BGR analysed samples of all blocks of "ABM2" with samples taken from the contact between the bentonite and the heater (up to 1 mm) and another four samples deeper into the blocks (horizontal profiles). Two blocks approximately in the center were totally destroyed; these blocks were not analysed. The "contact" samples were analysed using more methods as the "horizontal profiles" samples because more complexity was expected at the "contact".

An analytical program of all samples was carried out: CEC and exchangeable cation (EC) values were determined; a chemical analysis (applying XRF, Leco-TIC, TOC and S) was performed and a mineral analysis (applying XRD) as well.

An additional analytical program was conducted of the "contact" samples: mineral analysis using infrared spectroscopy, thermal analysis, electron microscopy (IR, DTA-MS, and SEM) and XRD of clay fractions.

BGR presented results on the ABM meeting in Helsinki, Finland, April 29–30, 2015.

After this meeting the interpretation of results was continued and works on a publication started. It is foreseen to publish the results in a peer review publication in 2016.

### 8.2.4 Large Scale Injection Test

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

### 8.2.5 Task Force on Engineered Barrier Systems

BGR and GRS are participation in this Task Force.

In 2015, 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, serving as a benchmark example for coupled thermo-hydro-mechanical simulations of the near field. The code comparison is divided into different stages with increasing complexity:

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

Currently, seven teams are participating in this subtask using seven different numerical codes. BGR, who is also the task leader, is using the finite-element code OpenGeoSys for their simulations. Comparisons of the results were presented and discussed at the Task Force meetings in Barcelona and Lausanne. For some of the above mentioned stages an excellent agreement between the results of different codes was already achieved. Deviations in the results of the multi-phase flow and the mechanical stages are currently being investigated.

In the framework of the benchmark "Task 8" of the Task Force on EBS (TF EBS), GRS analysed post-test data from the buffer-rock interaction experiment (BRIE) at Äspö concerning bentonite re-saturation.

Earlier results had indicated that flow from a water producing fracture would exceed the maximum uptake rate of the bentonite, while flow from the matrix would be significantly below that rate. Therefore it was looked for data that could clearly be related either to just one fracture or only to the matrix. These requirements appeared to be met by the "dry" and the "wet section" of test borehole 17. Measuring the relative humidity in the bentonite during the test provided data on the evolution of the water content. Based on these data, simplified models were created for both cases. In both cases a good agreement between measurements and model results were found. The resulting flow rate from the matrix was consistent with the data from the groundwater flow model. A third model demonstrated, though, that the slow water uptake in the "dry section" could also be explained by water migration from a "wet section", inhibiting further conclusions about the actual water uptake rate from the matrix.

To determine the flow rate from the matrix, the end-of-test water content distributions were alternatively looked at. A section above the "dry section" appeared not to be influenced by water coming from below. However, looking closely at the outer rim of the buffer a characterristic increase towards this rim by about 3 % water content could be detected as depicted in Figure 8-2. This is probably an artefact from the initial artificial flooding of the outer slot between buffer and rock. This is quite remarkable since it is still present after the 450 days test duration. The same phenomenon had already been observed in the water uptake test (performed in the laboratory of Clay Technology) that had been mimicking the situation at the BRIE.

Since from the established resaturation models comparatively fast moisture redistribution might be expected, this phenomenon could not be reproduced by numerical models. The presumption is an influence by the presently not yet considered hysteresis of the retention curve / adsorption isotherm. The attempt to back calculate the outflow rate from the matrix using BRIE-data has thus failed, which implies a certain necessity to examine the phenomenon of hysteresis more closely as well.

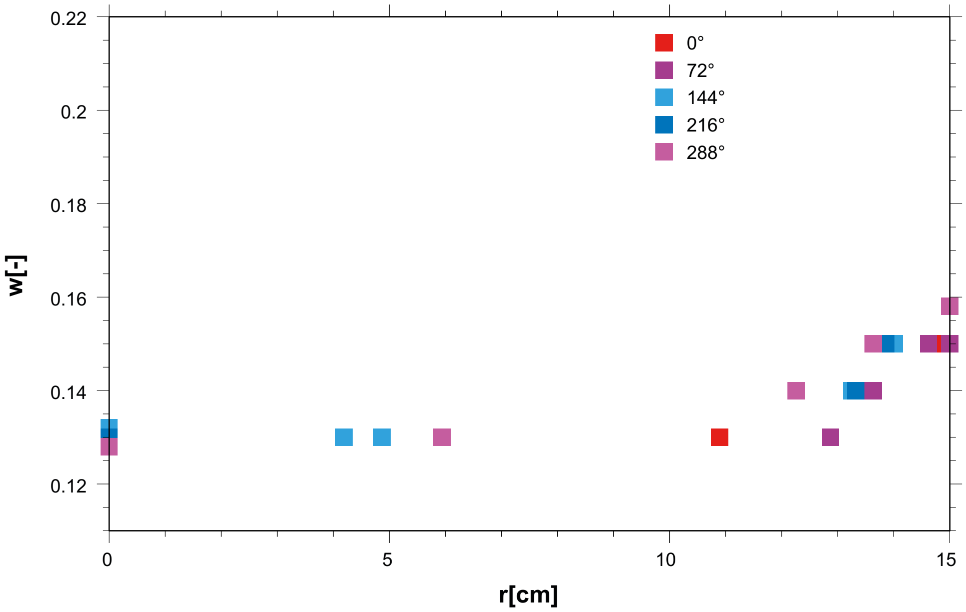



***Figure 8-2.*** *Water content in 5 radial directions in a dry section of the buffer after 450 days.*

## 8.3 NUMO

In 2015, SKB International AB, Nuclear Waste Management Organization of Japan (NUMO), Japan Atomic Energy Agency (JAEA) and Central Research Institute of Electric Power Industry (CRIEPI) signed the renewed agreement on cooperative activities in relation to Äspö Hard Rock Laboratory. Based on the agreement, NUMO participated in Topical workshop and International Joint Committee (IJC) this year.

It is important to develop the technology for deep borehole sealing in order to prevent the risk that boreholes become a fast pathway for radio nuclides transportation from the repository to the biosphere. Borehole investigation programme should be established taking into account the sealing methodology. NUMO plans to carry out R&D to develop borehole sealing technology in sedimentary rock formations. In line with this, NUMO joined the workshop of borehole sealing, which was organized by SKB and Posiva in February 2015, to exchange technical information on current status of the technology development. NUMO is also interested in the project of borehole sealing conducted in Äspö HRL programme. The outcomes of the workshop and/or the project as well as NUMO's own R&D will be reflected to preparation of reliable borehole sealing technologies for both crystalline/sedimentary rock formations before initiating the siting investigation. Accumulation of technical knowledge and know-how on the borehole sealing technologies is also expected.

In the IJC meeting held in January 2016, the information of site characterisation programme on coastal areas was obtained, including the sub-seabed formation in SFR project and the underground formation of the project for final repository for spent nuclear fuel at Forsmark, as well as discussion of Äspö HRL programme, since NUMO is investigating examples of site characterisation and construction on the repository in coastal areas.

NUMO and JAEA held a meeting at NUMO's office in November 2015 to share technical information obtained from the activities of the Task Force on Modelling of Groundwater flow and transport.

## 8.4 CRIEPI

CRIEPI has been developing the thermal-hydrological-mechanical (THM) coupling FEM code "LOSTUF" for evaluating the phenomena that will occur around the engineered barrier system. In 2015, CRIEPI conducted 3D TH coupled numerical simulation of the Prototype Repository considering the hydrological effect of fractures in host rock in Task Force on Engineered Barrier System.

THM benchmark simulation of Prototype Repository (PR) is carried out in Task Force on Engineered Barrier System. There are three suggested tasks in benchmark of Prototype Repository. First is 3D H-modeling of the PR before installation, second is 3D T/H/TH-modeling of the PR after installation, and the third is THM-modeling concerning on depositon hole 6 which is the outermost one.

The smeared fracture model was installed into LOSTUF in order to consider water inflow from fractures. Figure 8-3 shows the analytical domain and boundary conditions for PR before installation. CRIEPI modelled 40 fractures in the analytical domain based on delivered CAD data (see Figure 8-4). The permeability of each fracture was calibrated in the simulation of PR before installation so that calculated water inflow into the each 6 m section of TBM tunnel and into each deposition hole was in good agreement with measured inflow. Figure 8-5 shows a half of the analytical domain and boundary conditions for PR after installation. The permeability of surrounding rock mass and fractures, and distribution of initial pore water pressure were determined from the results of the simulation of PR before installation (see Figure 8-6).

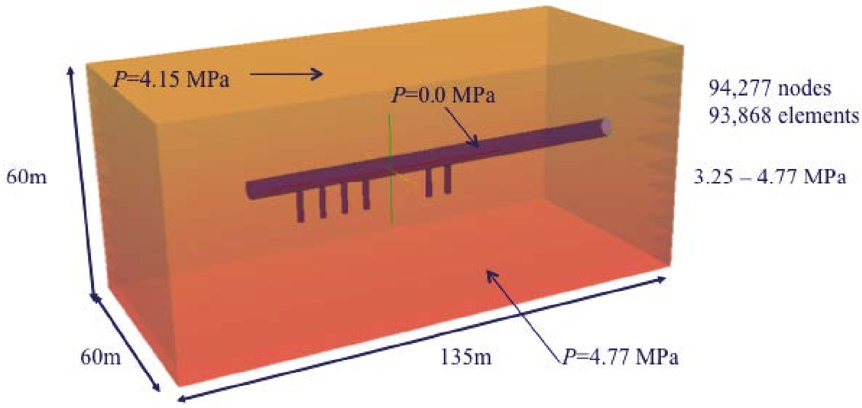



***Figure 8-3.*** *Analytical domain and boundary conditions for the H-simulation of PR before installation.*

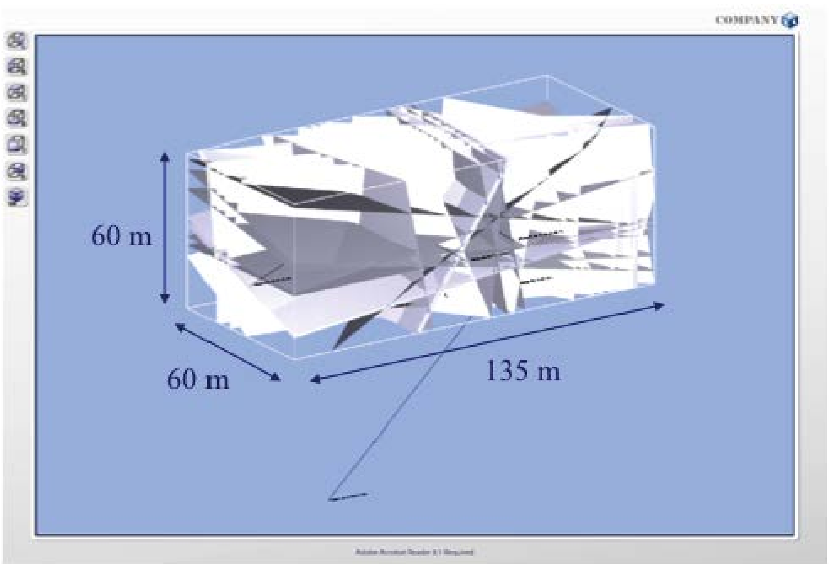



***Figure 8-4.*** *Fractures around Prototype Repository.*

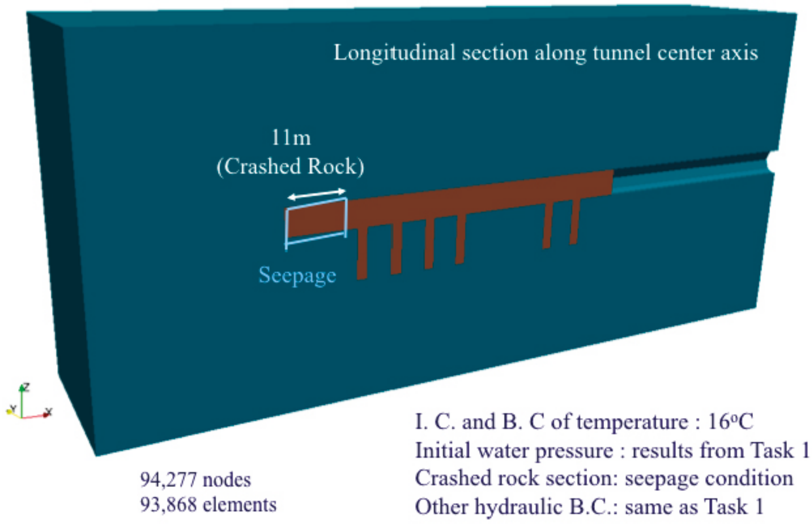



***Figure 8-5.*** *A half of analytical domain and boundary conditions for the TH simulation of PR after installation.*

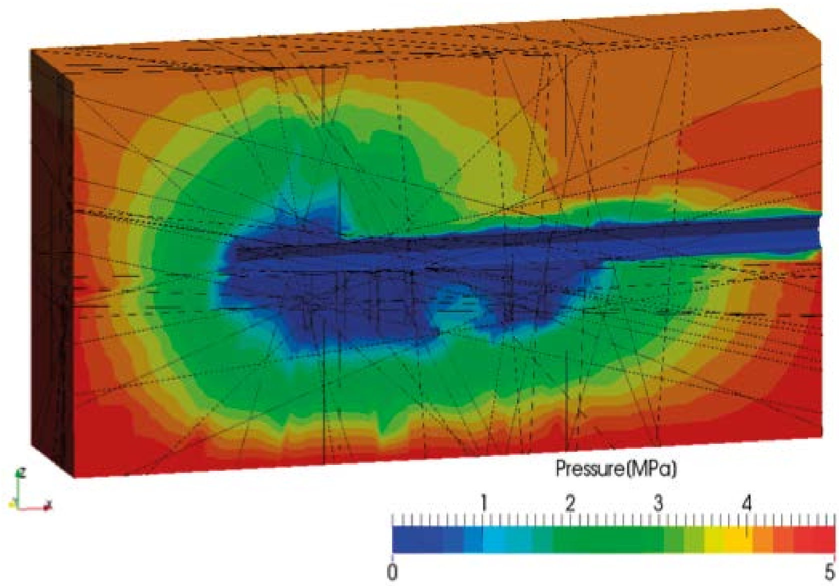



***Figure 8-6.*** *Initial pore water pressure distribution for the TH simulation of PR after installation.*

Figure 8-7 shows the calculated temperature evolution in R5 block, which is on the mid-height of the canister, in the depositon hole 3. X axis was placed along the tunnel and −X is headed against the tunnel face, then +X was the opposite direction. Numbers in the legend means a distance from the center axis of a deposition hole in the unit of mm. Calculated temperatures were in good agreement with the measured temperatures. Figure 8-8 shows the calculated suction evolution in R5 block in the deposition hole 3. Water infiltration from +Y direction was faster than that from +X direction. The distribution of fractures made this difference. Calculated water infiltration was much faster than measured.

CRIEPI will in 2016 continue to conduct TH-simulation of PR after installation.

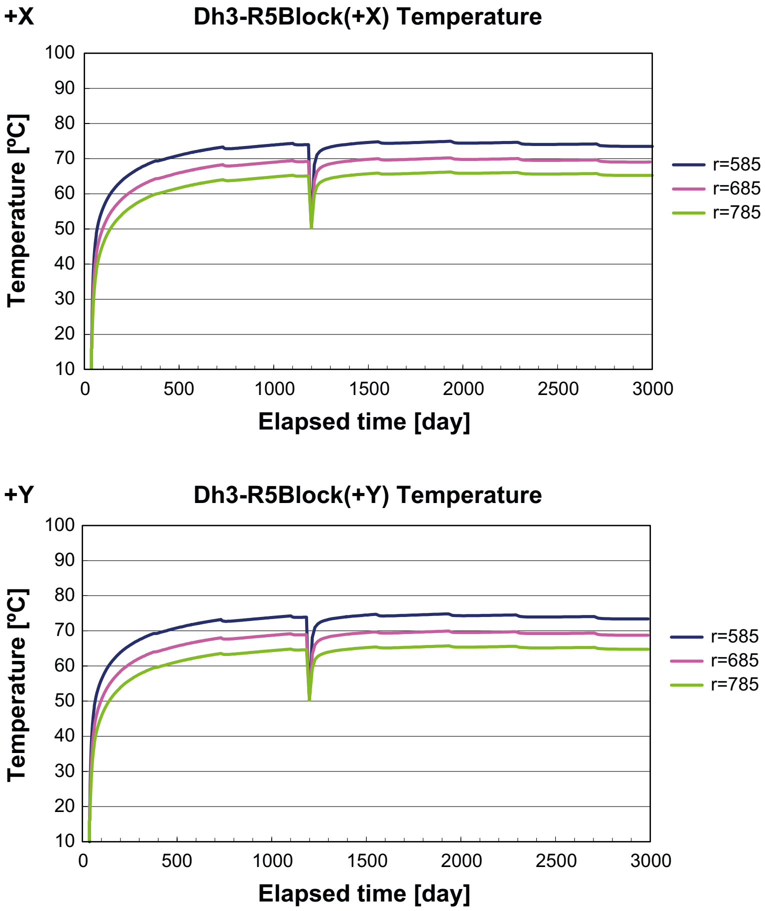



***Figure 8-7.*** *Calculated temperature evolution in R5 block in the deposition hole 3.*

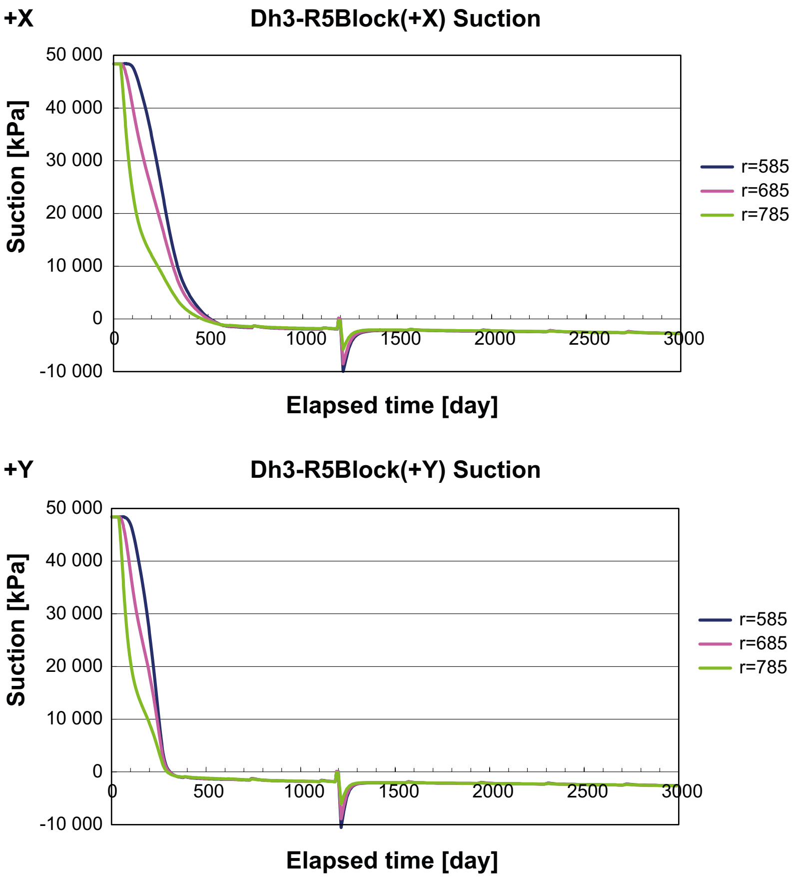



***Figure 8-8.*** *Calculated suction evolution in R5 block in the deposition hole 3.*

## 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 2015 include the followings:

- Improve understanding of site characterisation technologies.
- 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 expected to provide and support sound scientific and technical basis for both implementer and regulator in Japanese geological repository programme of high-level radioactive waste, which includes repository siting and safety assessment.

### 8.5.1 Task Force on Modeling the Bentonite Rock Interaction Experiment

The overall aim of Task 8 is to improve understanding of the bedrock-bentonite interface with regard to groundwater flow by modeling the BRIE (Bentonite Rock Interaction Experiment) and PR (Prototype Repository) in situ experiments at Äspö HRL. JAEA has focused on the importance of individual discrete fractures on this process, and therefore utilized a discrete fracture network approach based on FracMan/MAFIC codes (Dershowitz et al. 2012, Miller et al. 2001). And, Thames code (Chijimatsu et al. 2000) was used to model non-linear hydration behaviour in bentonite (buffer and backfill materials) by coupling with FracMan/MAFIC at each time step.

During 2015, JAEA updated the hydroDFN (hydrogeological discrete fracture network) model in order to better model resaturation behavior in bentonite. The hydroDFN provided by Task8 specification was modified by calibrating a correlation between transmissivity and fracture size to hydraulic test measurements in the boreholes around PR tunnel (Figure 8-9). The calibration was carried out by simulating hydraulic tests at different oriented boreholes oriented parallel to those in which packer tests conducted. These "virtual" hydraulic tests were conducted under the simplified condition of constant head boundary condition at the outer boundary (0 m) and at each water injecting borehole (1 m). The calculated borehole flow rate Q ($m^3/s$) at each injecting borehole was evaluated by the Thiem's equation to provide fracture transmissivity T ($m^2/s$).

$$T = \frac{Q}{\Delta h}\frac{\ln(R_{outer}/r_{hole})}{2\pi}$$

where $R_{outer}$ is the radius of the outer boundary (m), $r_{hole}$ is the borehole radius (0.038 m) and $\Delta h$ is the hydraulic head difference. Assuming an outer boundary radius $R_{outer} = 30$ m, $\ln(R/r)/2\pi$ is close to 1. Then, T is approximately equivalent to the specific capacity, $Q/\Delta h$, (Sawada et al. 2000). A set of 100 realizations of the stochastic DFN model was used to obtain a simulated transmissivity distribution, and the calibration was made by adjusting the correlation parameters to improve the match between simulated and measured hydraulic tests (Figure 8-10). The calibrated correlation between fracture size, r, and transmissivity is described in the following equation:

$T = \mathrm{lognorm}(\mu, \sigma^2) \times r^{4,7}$

where lognormal($\mu$, $\sigma^2$) is lognormal distribution with average $\mu = 1 \times 10^{-13}$, and standard deviation $\sigma^2 = 3 \times 10^{-13}$. The random variables of the lognormal distribution are also taken in account, in addition to a linear correlation to fracture radius. This calibrated hydroDFN model was then applied to simulate groundwater flow behavior for Task 8E (PR) and Task 8F (BRIE). An example of the calibrated hydroDFN model for simulating BRIE is shown in Figure 8-11. The example uses a relatively wider transmissivity distribution.

Figure 8-12 shows a visual investigation of the bentonite column surface dismantled from hole KO0018G. This indicates that the wetting area identified by relatively dark color might be distributed along the traces of the fractures intersecting to the hole. Within the project, these fractures have been called "Bentograph features", as they are a first indication that bentonite resaturation is directly driven by smaller discrete fractures. This suggests that the fractures geologically observed along the boreholes might have a potential to behave as connecting void space to provide groundwater to the bentonite. The location and orientation of the sub horizontal features are generally similar to the observed fractures along KO0018G borehole compiled in the SKB's database.

Given this "bentograph" data, JAEA made an additional modification to the hydroDFN for Task 8F to better condition to smaller observed fractures. Stochastically generated DFN models were conditioned to fractures in the SKB fracture database for five probe boreholes around BRIE site as shown in Figure 8-13.

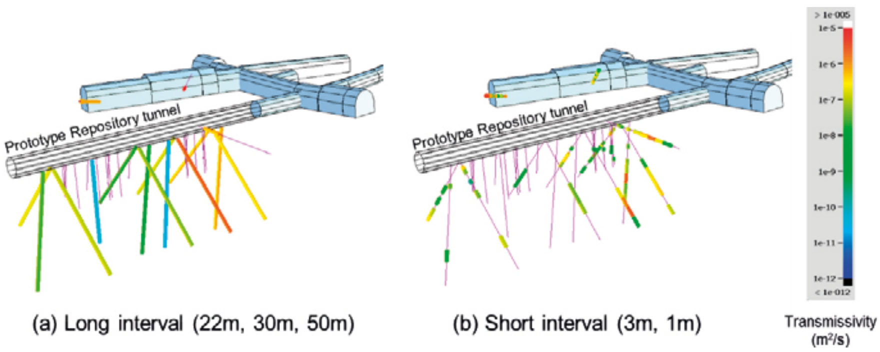



***Figure 8-9.*** *Transmissivity distribution measured at the boreholes around PR tunnel.*

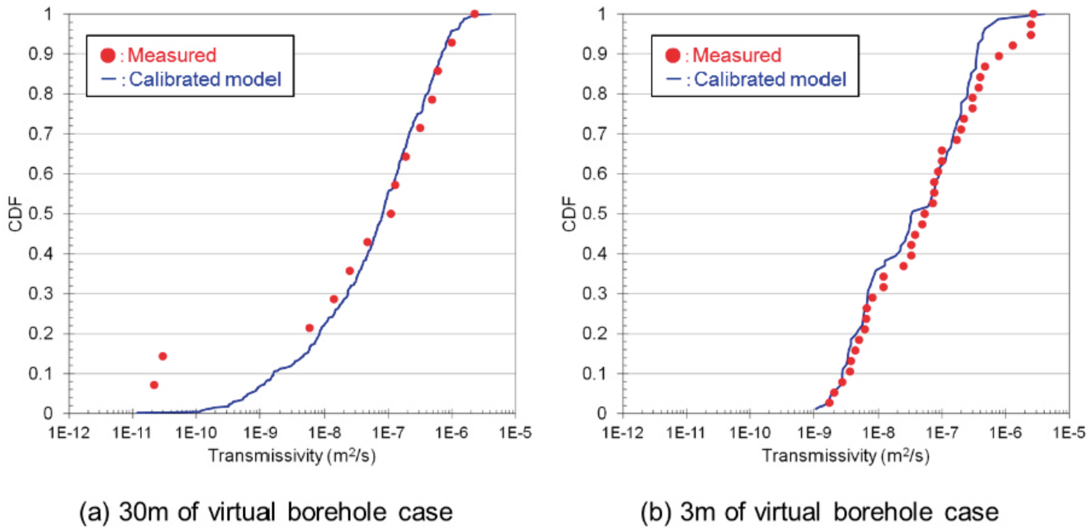



***Figure 8-10.*** *Cumulative transmissivity distribution of the calibrated model comparing with measured data.*

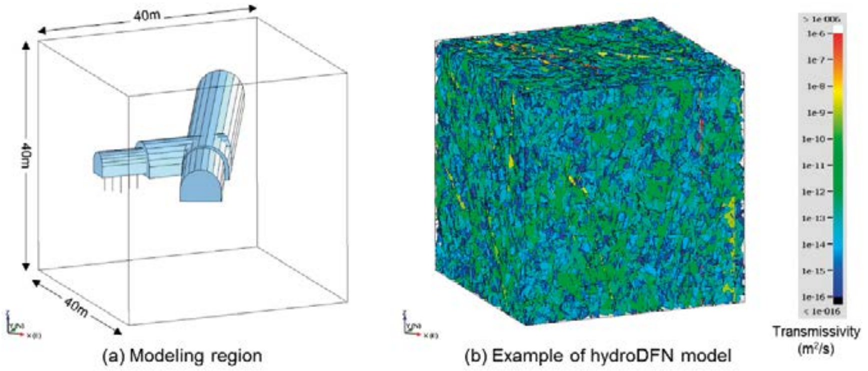



***Figure 8-11.*** *An example of the calibrated hydroDFN model for simulating BRIE.*

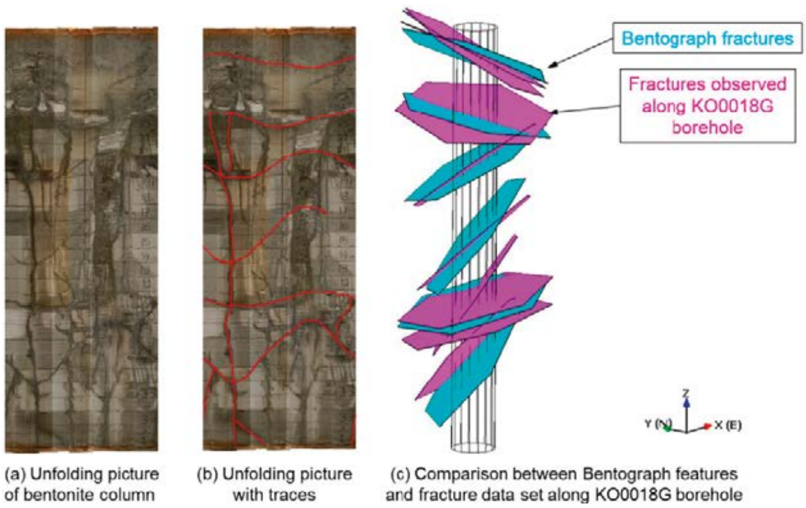



***Figure 8-12.*** *Visual comparison with Bentograph features and fractures observed at the borehole.*

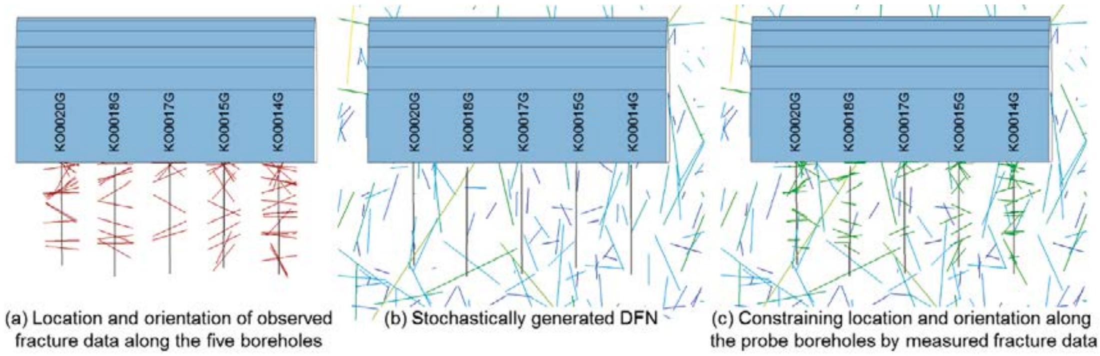



***Figure 8-13.*** *Conceptual picture for constraining fracture location and orientation intersecting to the probe boreholes; vertical cross sectional view along the boreholes.*

The parameter values (Table 8-1) used with Thames code for calculating BRIE bentonite hydration were verified by laboratory test data of the water uptake using same bentonite block, with the same MX-80 bentonite and the same radial dimensions, density and water content as in the field experiment, BRIE. The axis symmetrical model was made for representing circular bentonite block. The spatial resolution along the cylindrical axis of the bentonite was 1 mm. The same thickness as the bentonite block (10 cm) was assumed. A homogeneous single constant porosity (44 %) was assumed throughout the model. An initial saturation of 42 %, corresponding to an initial suction value of 89.9 MPa based on the retention curves, was applied for the bentonite block except for the outer 5 mm of the model. The initial water filling of the outer slot (1 mm of clearance between bentonite block and test cylinder) was taken into account by applying water saturated conditions from the start in the outer 5 mm of the model as specified. The liquid pressure at the outer boundary was kept constant at an atmospheric level (0.1 MPa). The other faces of the model, inner, top and bottom was specified as no flow boundaries. Thames simulations were carried out under an isothermal condition at 20°C. The results are compared with the experimental data, as shown in Figure 8-14. In general, the model results are in good agreement with the measured data.

### 8.5.2 Modelling of REPRO and LTDE-SD

JAEA joined Task 9 of the Äspö Task Force on modelling of REPRO and LTDE-SD, started in 2015. The modelling works on Task 9A focusing on the preliminary modelling of WPDE in REPRO was performed.

**Table 8-1. Parameter values used for Thames calculation of water uptake tests.**

| Parameter | unit | value |
|---|---|---|
| Porosity | – | 0.44 |
| Intrinsic permeability | m² | $6.4 \times 10^{-21}$ |
| Relative permeability, $k_r$ | – | $k_r = S_l^3$<br>$S_l$: water saturation |
| Water retention curve | | van Genuchten's equation<br>$$S_l(P_l) = \left\{1 + \left(\frac{P_g - P_l}{P_0}\right)^{\frac{1}{1-\lambda}}\right\}^{-\lambda}$$<br>$P_l$: water pressure<br>$P_g$: Gas pressure: 0.1 MPa<br>$P_0$: empirical constant: 10 MPa<br>λ: empirical constant: 0.28 |
| Water density | kg/m³ | 1000 |
| Water viscosity | Pa s | 0.001 |

The JAEA's approach for semi-predictive modelling of WPDE-1&2 in REPRO project is based on the combination of the scaling approach from laboratory to in situ condition developed for Grimsel LTD project (Tachi et al. 2015, Soler et al. 2015) and key features of rock properties at REPRO site. We identified key features at REPRO site; (1) dominant veined gneiss (VGN) with strong foliation, (2) banded pegmatitic granite (PGR) distribution, and (3) heterogeneous flow in fracture. These features were stepwisely modeled, although banded PGR effect was ignored in this preliminary modeling. The model assumes advection and dispersion within an artificial fracture and diffusion and sorption within two-layered matrix, i.e., borehole disturbed zone (BDZ) and undisturbed matrix, adjacent to the fracture. The spatial discretization was made by cylindrical coordinate system, in GoldSim code. The $D_e$ parameters for all tracers were scaled from lab-data to in situ conditions, assuming Archie's law. The effects of strong foliation on $D_e$ values were estimated from comparison of $D_e$ between parallel and perpendicular direction to foliation. Batch-derived $K_d$ values for crushed rocks from REPRO site were assumed to be directly applied to BDZ, and were scaled for undisturbed matrix by considering particle size dependence of $K_d$. As for the effect of heterogeneous flow in the fracture, we applied the simplified dual pathway model. From our predictive modelling, we could find key uncertainties and challenges, e.g., heterogeneous flow, $D_e$ data for cations and their relation to foliation, in situ porosity, and irreversible sorption for Ba case. These uncertainties will be further analyzed and may be reduced by some additional experiments.

### 8.5.3 Alternative Buffer Materials

Bentonite samples (Kunigel V1, Kunimine Industries) retrieved from parcel 1 (ABM1) and 2 (ABM2) were analysed by electron probe microanalyser (EPMA). The distribution of elements in the bentonite samples adjacent to the iron heater were obtained and compared between the ABM1 and ABM2 samples.

Figure 8-15 shows the EPMA mapping images of Si, Fe, Ca and S for ABM1 (a) and ABM2 (b). The size of images is 1 mm square. The upper side on each image is the contact surface with iron heater. As shown in Figure 8-15, Ca was concentrated on the surface in contact with iron heater. High concentration of S was found on the area where Ca was concentrated. These results suggests that gypsum/anhydrite was precipitated at the heater-bentonite interface. The precipitation of gypsum/anhydrite has been reported in laboratory and in situ experiments and explained mainly by the decrease in water content near the heater by the evaporation of bentonite pore water (e.g. Samper et al. 2008). The amount of precipitation was larger in ABM1 sample than in ABM2 sample, as the concentration of Ca and S on the surface in contact with iron heater was high in ABM1 sample as shown in Figure 8-15. The compacted bentonite was saturated before heating in ABM2 while the heating by iron heater started at the beginning of the ABM1 experiment. The water content near iron heater was considered to be higher in ABM2 condition than in ABM1. Gypsum/anhydrite might dissolve into the pore water and diffuse outward from the surface in ABM2 sample.

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

(a) EPMA mapping images of Si, Fe, Ca and S (ABM1).

(b) EPMA mapping images of Si, Fe, Ca and S (ABM2).

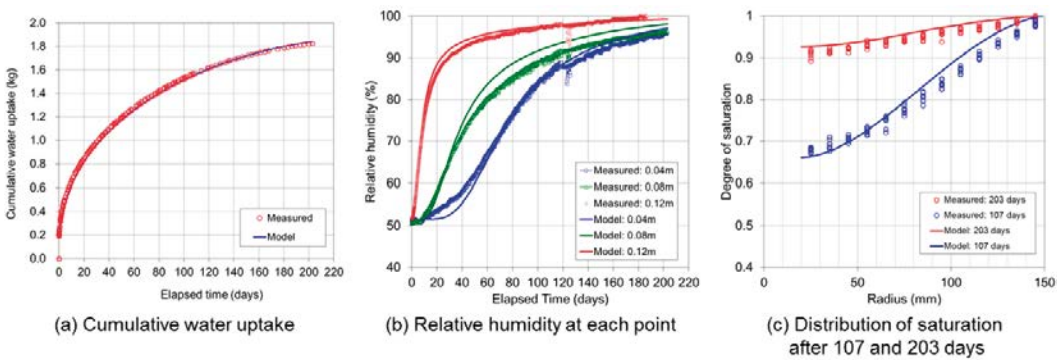
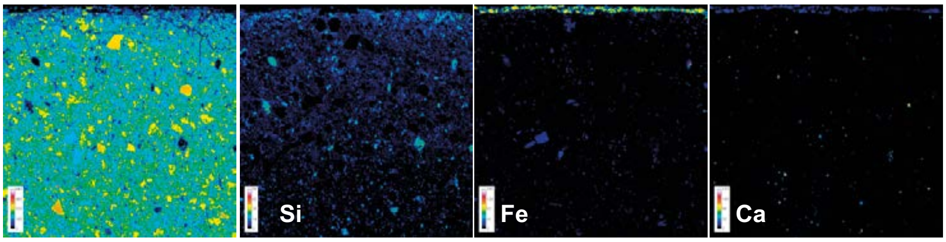
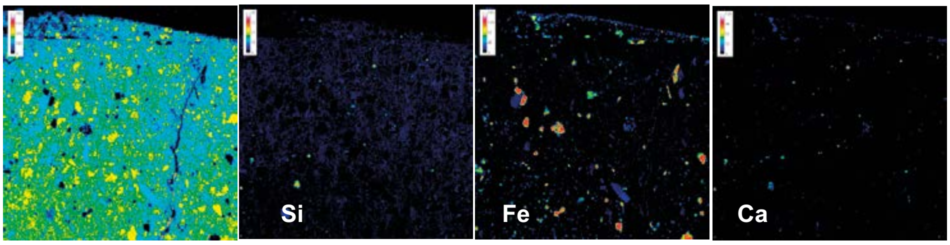



***Figure 8-14.*** *Comparison between Thames calculations and experimental data.*




(a) EPMA mapping images of Si, Fe, Ca and S (ABM1)




(b)EPMA mapping images of Si, Fe, Ca and S (ABM2)

***Figure 8-15.*** *EPMA mapping images of bentonite sample adjacent to the iron heater. The upper side on each image is the surface in contact with iron heater.*

## 8.6 Posiva

Posiva's co-operation with SKB continues with the co-operation agreement for years 2014–2018 signed in the autumn of 2014 and the co-operation has been organised in five areas divided to the:

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

The focus of the co-operation is to plan and implement the research and development activities related to the KBS-3 disposal concept together with SKB as joint projects. Part of the activities is performed within Äspö HRL facility and/or within ONKALO underground rock characterisation facility (URCF). 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 HRL is divided between activities within Engineered Barriers and more generic work that can lead to demonstrations in Äspö HRL or in ONKALO URCF. Posiva also contributes to several of the research projects within Geosciences or Natural Barriers.

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

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

The role of Posiva and the projects are described more detailed in the main chapters.

## 8.7 Nagra

### 8.7.1 Task Force on Engineered Barriers Systems

Nagra continued its active participation in both the THM- and the C-Group. The C-Group is headed by U. Mäder (University of Bern). The modelling team of P. Alt-Epping is involved in reactive transport modelling of chemical processes in the bentonite backfill at Olkiluoto. A modeling group (Prof. Laloui and coworkers, EPF Lausanne) is involved in two benchmarks of the THM-Group, namely in the "Sensitivity Analyses" and in the "Homogenisation" task.

### 8.7.2 Alternative Buffer Materials

Collaboration with SKB on the investigation of Fe-Bentonite interactions has started and subsamples from ABM-2 test could be taken at the Äspö HRL. The chemical and mineralogical investigations are on-going as part of a post-doctoral project at the University of Bern in Switzerland under the supervision of Paul Wersin.

## 8.8 SÚRAO (Rawra)

The contractors of SÚRAO, Technical University Liberec (TUL) participated in THM tasks and Nuclear research Institute (ÚJV Řež) took part in Chemistry Session. The activities concentrated on modelling problems with the aim to use the experience in Czech geological repository programme.

### 8.8.1 Task Force on Engineered Barrier System (EBS)

The contractors of SÚRAO, Technical University Liberec (TUL) participated in THM tasks and ÚJV Řež took part in Chemistry Session.

#### *Work by the TUL team (Milan Hokr and Ilona Hančilová)*

The TUL team continued the work from the previous years on the two tasks Prototype Repository and Task 8 (BRIE) and additionally started to participate in the Sensitivity analysis task.

For the Prototype Repository, the existing water transport model based on nonlinear diffusion solved in the ANSYS simulation software was updated in several issues:

- The real buffer geometry is used for the model solution (instead of former simplified).
- A larger-scale model comprising both the buffer and the inhomogeneous rock has been tested.
- Retention curve parameters have been corrected to the real initial conditions of the buffer.

Also, new comparisons of the model with the sensor data of the buffer humidity evolution have been done. The results are illustrated in Figure 8-16. The rate of hydration fits well under condition that the place of water inflow in the model coincides with a place of water inflow in reality – this depends on selection which of the rock wall water discharge measurements are used for the model boundary.

For the Task 8, the same model principle has been used, with appropriate bentonite data and water inflow conditions (see Figure 8-17). The water inflow is prescribed by means of a boundary condition at the buffer/rock and buffer/fracture interfaces. The model results are newly compared with the provided measured data of humidity distribution from the dismantling and with the humidity evolution in sensors. There are areas with good fit between the model and the measurement, while other areas with disagreement. The explanation is that the real water inflow is somewhere else then the prescribed borehole/fracture intersection (either due to a complicated rock inhomogeneity or to a model geometry error in the fracture position).

In Sensitivity Analysis task, the TUL team started participation while the other teams are in a final phase of evaluation. The used simulation code ISERIT, i.e. coupled heat and water transport with vapor and sorbed water, has been used; it solves only part of the defined phenomena in the task. The results are in reasonable agreement with other teams in most cases, but some of the results are not evaluated. Very different level of sensitivity was detected on different parameters.

The results of the Prototype Repository and Task 8 are included in Ph.D. thesis of Ilona Hančilová (Škarydová), finished in 2015 (Hančilová 2015).

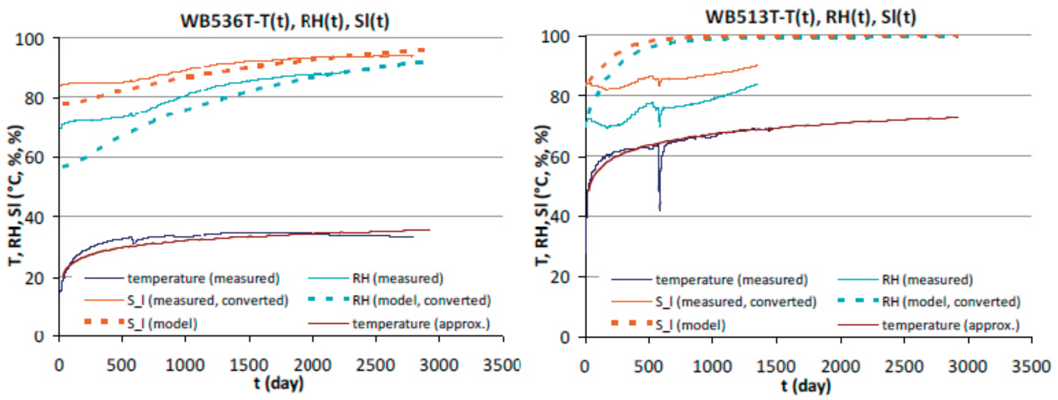



*Figure 8-16. Examples of relative humidity comparison between the model and the sensor measurement for BH6 of the Prototype Repository – left is a position with good fit and right is a position with worse fit.*

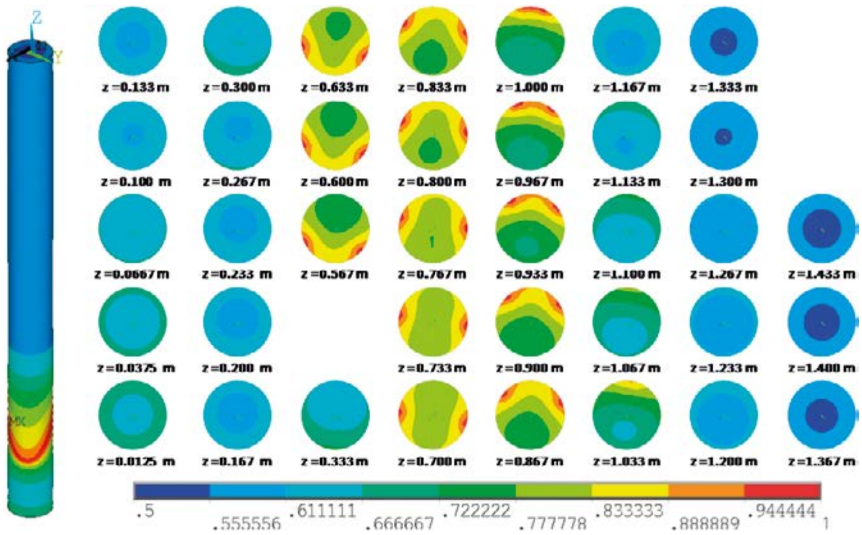



*Figure 8-17. Saturation distribution in sections of the KO0017G01 borehole calculated by one of the model variants with adapted rock permeability.*

### *Work by the ÚJV team (Radek Červinka and Eva Hofmanová):*

ÚJV Řež participated in the chemical section of the international project EBS TF. The benchmarks results are important for better understanding of chemical behaviour of bentonite as an EBS component. The evaluation of benchmark no. 1, which is a classic example of through diffusion method, which can be evaluated with robust codes as GoldSim software, was a substantial part of the work. For more complicated tasks / benchmarks where it is necessary to describe further chemical reactions inside the bentonite (such as cation exchange within the smectite clays interlayer, the electrostatic effects on permanently negatively charged surfaces of smectite clays), it is required to use modelling codes including these phenomena (e.g. geochemical code PHREEQC). The analysis of benchmark no. 3 was performed, where diffusion transport and cation exchange are involved, including the possible solution.

### Benchmark 1 modelling

Benchmark 1 is a series of through-diffusion experiments performed on saturated and compacted Na- or Ca- montmorillonite. Cations in the interlayer are the same as in source solutions – electrolytes (NaCl or CaCl2) – > no cation exchange assumed. Three through-diffusion experiments in saturated Na-montmorillonite with 0.1 M, 0.4 M and 1 M NaCl.

There were set up three through-diffusion experiments in saturated Ca-montmorillonite with 0.025 M, 0.1 M and 0.4 M CaCl2. Boundary conditions were specified as: constant concentrations of input and output reservoirs. As an evaluation method, there were defined "Time lag" method, analytical solution, numerical modelling and improved numerical modelling.

Different way of evaluation using effective porosity concepts lead to slightly different estimation of transport parameters. Implications for performance assessment were as follows: PA uses robust models, but processes are simplified (e.g. Kd – linear sorption), for radionuclide transport calculations in low permeability materials (bentonites and clay based materials) only effective diffusion coefficients and accessible porosities are used and small differences in effective diffusion coefficients are not so important.

Measured absolute concentrations of NaCl in the output reservoir and comparison to simulation of a simple diffusion. Diffusion coefficients are generated by a "time lag" method, see Figure 8-18.

### Benchmark 3 modelling

Diffusion of cationts and ionic exchange on a montmorillonite sample was a basis for the task. Electrolyte solutions were cicled on both sides a the montmorillonite block, the task has been divided to two identical subtasks assuming, that ionic exchange and diffusion shall be identical in both halves of the sample. The simulation was performed with one half of the sample, then the concentration was doubled. First set of results is shown on the picture. In the course of the experiment, diffusion of Ca ionts to montmorillonite is observed as well as the exchange of Na ionts on exchange positions. Concentration of Ca ionts in the input reservoir is lowered and the concentration of Na ionts in the output reservoir increases, see Figure 8-19.

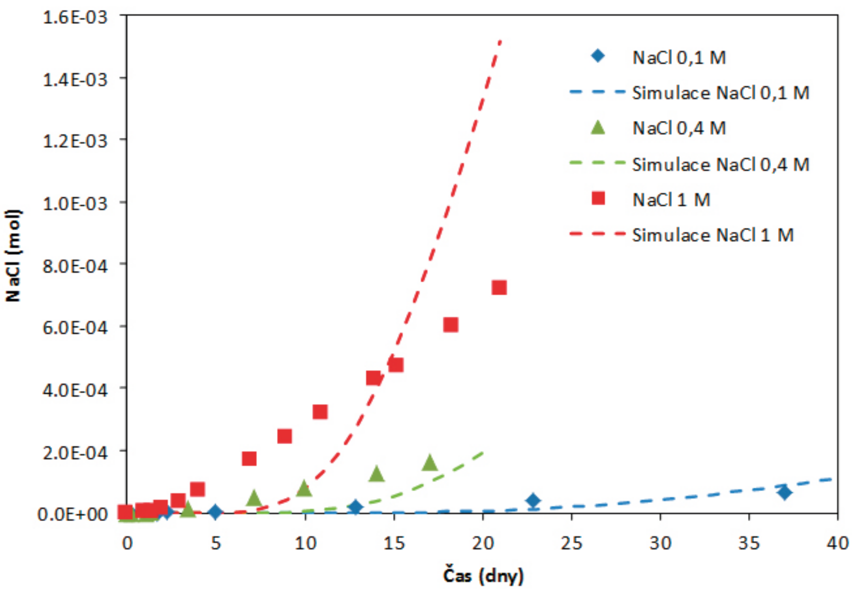



***Figure 8-18.*** *Absolute concentrations of NaCl in the output reservoir and comparison to simulation of a simple diffusion.*

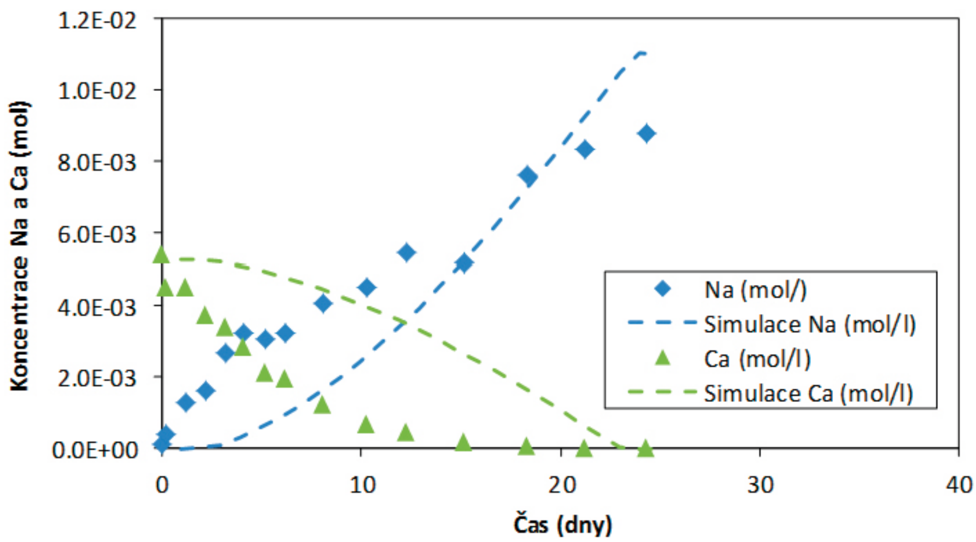



***Figure 8-19.*** *Comparison of experimental values and simulation of Na concentrations (output reservoir) and Ca concentrations (input reservoir) for Na-montmorillonite and CaCl2 electrolyte, 25 % CEC.*

## 8.9 RWM

Radioactive Waste Management Limited (RWM) of the United Kingdom has had long standing involvement in experiments conducted at Äspö HRL (RWM is a wholly-owned subsidiary of the Nuclear Decommissioning Authority (NDA), created in April 2014. Involvement in activities at Äspö commenced through RWM's predecessor, NDA's Radioactive Waste Management Directorate (RWMD)). In March 2012, NDA signed an agreement with SKB International AB to further increase access to scientific and technical information and results from experiments performed by SKB at Äspö HRL. This is designed to support an increase in involvement of RWM personnel in field work and facilitate a step-change of the R&D programme from (predominately) laboratory-scale activities to activities that include large-scale demonstration experiments. Through 2014 and 2015, RWM has been actively supporting and contributed to the experiments and initiatives considered of greatest relevance to the current stage of the UK disposal programme, including the EBS Task Force, the LASGIT experiment, and the DOPAS experiment.

### *Task Force on Engineered Barrier Systems (EBS)*

The SKB Engineered Barrier System Task Force offers a unique opportunity to develop methodologies, software and modelling approaches to develop understanding of bentonite saturation and coupled thermal, hydraulic, mechanical, and chemical (THMC) processes. RWM, through its contractor AMEC Foster Wheeler, is actively involved in this project.

The final modelling (Task 8F) of the Buffer Rock Interaction Experiment (BRIE), which includes additional information gathered upon completion and dismantling of the experiment, is underway. The final report on the previous Task 8D modelling of the BRIE has been completed and will be published early in 2016. The Prototype Repository experiment is also being modelled. Three phases corresponding to: the open tunnels (H calculation), the time between installation of Section 1 and Section 2 (coupled TH calculation) and the time after the installation of Section 2 (also coupled TH calculation) are being modelled using ConnectFlow. The six canisters, the two tunnel sections and the concrete plugs are all represented.

Work on code validation has continued with Stages 2c and 3 of this task based on a model of a copper canister in a single deposition hole. Stage 2c adds two phase flow and Stage 3 introduces mechanical coupling to the TH models developed in the task. A comparison of modelling results from TOUGH2 with those from ConnectFlow for Stage 1 of this task shows good agreement between the temperature and saturation profiles from the two codes.

RWM are also funding collaboration between Amec Foster Wheeler and Clay Technology to develop a 'single porosity' solute transport model based on the conceptual model proposed by Clay Technology. The prototype of the model will be development-tested against one or two of the EBS Task Force benchmark tests in Spring 2016.

### *Large scale gas injection test (Lasgit)*

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

1. The minimum pressure gas will become mobile and enter the clay,
2. 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
3. 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.

This year experimental activity has focussed on completing the first phase of gas experiments examining the processes and mechanisms governing gas entry and subsequent migration through the initially saturated bentonite buffer. These experiments have specifically focussed on coupling between the formation of the dilatant pathways and their impact on stress and porewater pressure within the clay. The stability of these pathways during propagation events has also been explored as has the distribution of flow within the sample, providing insight into the dissemination of the gas. A draft peer-reviewed paper describing these observations has been prepared and will be submitted to the journal Applied Clay Science.

### *Full-scale Demonstration of Plugs and Seals (DOPAS)*

As part of the Full-Scale Demonstration of Plugs and Seals (DOPAS) project, a set of full-scale experiments, laboratory tests, and performance assessment studies of plugs and seals for geological repositories are being carried out. One of the experiments being undertaken as part of the project is the full-scale test of SKB's Dome Plug (DOMPLU) design.

RWM is the lead organisation for work package 4 (WP4). The work package concentrates on the activities subsequent to WP3 field experiments (design and construction of seal and plug), in particular on the appraisal of the plugs and seals functions and performance on the basis of the experiment monitoring data and dismantling outcomes.

Among these activities, RWM has participated in an evaluation of the compliance of the DOPAS experiment with the design basis. One of the main outcomes from the DOMPLU experiment was the demonstration that it is possible to build the dome plug system. This includes practical aspects of logistics and arranging of parallel construction activities in a tunnel system. Analysis of the performance of the DOMPLU experiment is on-going and will be reported in 2016 in the Integrated Report (D4.4).

RWM has also peer-reviewed two key DOPAS deliverables for SKB; the Work Package 2 Final Report Design Basis for DOPAS Plugs and Seals (D2.4) and the DOMPLU Summary Report (D4.3). SKB is now providing input data on the performance of DOMPLU for the Integrated Report (D4.4) for WP4.

### *Pilot Backfill Leaching and Migration Experiment*

In conjunction with SKB, RWM is evaluating the possibility of setting up a long-term demonstration experiment of the 'chemical containment' properties of hyperalkaline cement systems typically envisaged in the design of disposal facilities for intermediate level waste (ILW).

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