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Äspö Hard Rock Laboratory
Annual Report 2016

SVENSK KÄRNBRÄNSLEHANTERING AB

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Abstract

The Äspö Hard Rock Laboratory (HRL) is an important part of SKB's work with the design and construction of a deep geological repository for the final disposal of spent nuclear fuel. Äspö HRL is located in the Simpevarp area in the municipality of Oskarshamn. One of the fundamental reasons behind SKB's decision to construct an underground laboratory was to create opportunities for research, development and demonstration in a realistic and undisturbed rock environment down to repository depth. The underground part of the laboratory consists of a main access tunnel from the Simpevarp peninsula to the southern part of Äspö where the tunnel continues in a spiral down to a depth of 460 m. Äspö HRL has been in operation since 1995 and considerable international interest has been shown in its research, as well as in the development and demonstration tasks. A summary of the work performed at Äspö HRL during 2016 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 objective for producing *Äspö Site Descriptive Model* is to describe the geological, hydrogeological and groundwater chemical conditions of Äspö HRL including updated geometrical and numerical models for each geoscientific discipline. Data from the underground excavations as well as from the ground surface will be compiled systematically for these three disciplines.

The hydro monitoring programme constitutes a cornerstone for the hydrogeological research and a support to the experiments undertaken in the Äspö HRL. The monitoring system relies on a about 1 500 measuring points of various hydrogeological variables.

The hydrochemistry 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. During the year 2016, 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.

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 2016, the focus within Task 7 has been on

finalisation of reporting,.The Task 8 work mainly contained interpretation of *BRIE* and reporting. Task 9 started up by modelling of WPDE 1 and 2 of the REPRO experiment. The modelling results have been compared to experimental results, and reporting of this exercise is ongoing.

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 2016 the Tunnel Production project completed a full scale test in TAS04 to study the possibility to level the tunnel floor by means of wire sawing.

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 2011–2017. It covers all areas of the KBS-3 method but the focus is on the KBS-3H specific issues. During 2016, a large scale test with heated Supercontainer has been performed, to find out how big a problem the drying of the buffer during storage and installation is.

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 2016 (day 3 985 – day 4 351) the test programme of Lasgit continued a phase of prolonged “hibernation” with moniotoring 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. During 2016 the packages of MiniCan 4 and 5 were examined regarding corrosion and microbiology.

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 2016, 12 of the steel containers containing organic material were opened and the water in them analysed for the presence of degradation products from the material specimens.

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 2016; one in Prague on May 9–12 and one in Oxford on November 15–17.

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 2017. 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 2016 a test was installed in the Äspö tunnel, testing the second of two installation methods currently being investigated. This followed on a test of the first method being performed in 2015.

In order to verify that the suggested design solutions for a planned extension of SFR can be utilized and to show that the long term safety of the repository is likely to be ensured over the entire post-closure period an R&D programme has been initiated. The final task of this programme is the test casting of a fully instrumented representative section of a caisson in the Äspö Hard rock Laboratory using a newly developed concrete. A representative section of the caissons planned for 2BMA was cast in TAS05 in the Äspö HRL.

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 activities have been ongoing through 2016, including development of test methods and a universal chassie.

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. Activities during 2016 include CE-marking of the pellet press and its surrounding equipment, tests of a Universal machine chassie and a mockup test on sealing of boreholes.

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. During 2016, much focus has been on reporting of the *Material Science project*.

The operation of the facility during 2016 has been functioning very well, with a very high degree of availability. An external Rock inspection was carried out at the end of 2016. This showed that there is a need for reinforcement measures in addition to ongoing rock maintenance based on previous choice of material in the tunnel. A projects based on this will be launched in 2017.

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 2016, 3 757 people visited the Äspö HRL and with the visitors at Clab and the Canister Laboratory included resulted in a total of 5 444 people. The total number of visitors to SKB's facilities in both Oskarshamn and Forsmark/Östhammar was 7 929 people. The unit also arranged a number of events and lectures during 2016.

Open research and technical development platform, Nova FoU

Äspö Environmental Research Foundation was founded in 1996 on the initiative of local and regional interested parties. In 2008, the remaining and new research activities were transferred within the frame of a new co-operation, Nova Forskning och Utveckling (Nova FoU). Nova FoU is a joint research and development platform at Nova Centre for University Studies and R&D supported by SKB and the municipality of Oskarshamn. Nova FoU is the organisation which implements the policy to broaden the use within the society concerning research results, knowledge and data gathered within the SKB research programme and facilitates external access for research and development projects to SKB facilities in Oskarshamn. Nova FoU provides access to the Äspö Hard Rock Laboratory and Bentonite Laboratory at Äspö and the Canister Laboratory in Oskarshamn.

SKB International

SKB International offers technology, methodology and expert resources to international clients. SKB International has access to all expertise, experience and technologies that SKB has acquired and developed in its programme, and provides services to organisations and companies in spent nuclear fuel and nuclear waste management and disposal and hence provides the opportunity to save time and cost and minimise risk. For the Äspö International partners SKB International arranged different events during 2016. Three *topical workshops* were organised, two of them regarding development of borehole sealing of investigation boreholes drilled from the surface. In the third workshop SKB presented SKB's development of Site Descriptive Modelling, SDM.

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.

Syftet med att producera Äspö Site Descriptive Model är att beskriva Äspö HRL:s geologiska, hydrogeologiska och grundvattenkemiska förhållanden, inklusive uppdaterade genometriska och numeriska modeller för de olika geovetenskapliga diciplinerna.

Programmet för hydromonitering utgör en grundsten i Äspö HRL:s hydrogeologiska undersökningar, och stödjer olika experiment som genomförs. Moniteringssystemet baseras på cirka 1 500 mätpunkter för olika hydrogeologiska variabler.

Programmet för hydrokemisk monitering utför provtagningar i intervall från månadsvis till två gånger per år, beroende på typ av vattenmiljö. Ytvatten samlas in från permanenta mätstationer, samt temporära provpunkter i strömmar, sjöar och hav.

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 2016 har fokus inom Task 7 legat vid slutförande av 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).

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 2016 genomfördes ett fullskaleförsök i TAS04 för att studera möjligheten att utjämna golv genom vajersågning.

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. Under 2016 genomfördes ett storskaligt försök med en uppvärmd Supercontainer, för att studera uttorkning av bufferten under lagring och installation.

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 2016 fortsatte 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 2015, och analyser av dessa fortsatte under 2016.

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 2016 öppnades 12 stålbehållade innehållandes organiskt material, och vattnet i dem analyserades för närvaro av produkter relaterade till materialens nedbrytning.

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 2016; ett i Prag under maj, och ett i Oxford under november.

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 2016 har ett försök installerats i Äspötunneln för att testa den andra av de två installationsmetoder som utvärderas. Den första metoden testades under 2015.

Under 2016 genomfördes ett test med gjutning av betongkassun i TAS05. Testet syftade till att utvärdera teknik och designlösningar inför utbyggnaden av SFR.

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 aktiviteter har pågått under 2016, däribland framtagande av testmetodik, samt utvecklingen av ett universalchassi.

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. Aktiviteter i Bentonitlaboratoriet under 2016 inkluderar CE-märkning av utrustning för pelletspressning, och ett test av borrhålsförslutning.

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. Under 2016 har fokus legat på rapportering av *Materialstudieprojektet*.

Driften av anläggningen under 2015 har fungerat mycket bra med en mycket hög tillgänglighet. En extern bergbesiktning genomfördes under slutet av 2016. Denna visade ett behov av förstärkande åtgärder såväl som löpande bergunderhåll baserat på tidigare val av material i tunneln. Ett projekt baserat på detta kommer att initieras under 2017.

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 2016 besöktes Äspölaboratoriet av 3 757 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.

SKB International

SKB International erbjuder teknologi, metodologi och expertresurser till internationella klienter. SKB International har tillgång till all den expertis, erfarenhet och teknik som SKB har införskaffat och utvecklat i sitt forskningprogram, och tillhandahåller service till företag och organisationer inom slutförvar av använt kärnbränsle. De kan därmed bidra både till besparingar i tid och pengar, samt en möjlighet att minimera risker. SKB International arrangerade olika evenemang under 2016, däribland tre stycken *topical workshops*.

Contents

1	**General**	13
1.1	Background	13
1.2	Goals	14
1.3	Äspö Hard Rock Laboratory – 30 years of research, 1986–2016	15
1.4	Organization	16
1.5	International participation in Äspö HRL	16
1.6	Allocation of experiment sites	17
1.7	Reporting	17
1.8	Management system	17
1.9	Structure of this report	18
2	**Geoscience**	19
2.1	General	19
2.2	Geology	19
2.3	Hydrogeology	20
	2.3.1 Hydro monitoring programme	21
2.4	Geochemistry	22
	2.4.1 Hydrochemistry monitoring program	23
3	**Natural barriers**	25
3.1	General	25
3.2	The integrated sulphide project	25
3.3	Task Force on modelling of groundwater flow and transport of solutes	28
3.4	Tunnel production	29
4	**Engineered barriers**	35
4.1	General	35
4.2	Prototype Repository	35
4.3	KBS-3 Method with Horizontal Emplacement	39
4.4	Large Scale Gas Injection Test	50
4.5	In Situ Corrosion testing of miniature canisters	52
4.6	Concrete and Clay	54
4.7	Low pH-programme	56
4.8	Task force on engineered barrier systems	57
4.9	System design of plug of deposition tunnel	62
4.10	System design of buffer	68
4.11	Large scale casting test of 2BMA cassions	70
5	**Mechanical- and system engineering**	75
5.1	Development of test methods	75
5.2	Universal chassie	76
6	**Äspö facility**	81
6.1	General	81
6.2	Bentonite Laboratory	82
6.3	Material Science Laboratory	82
6.4	Facility Operation	83
6.5	Communication Oskarshamn	83
7	**Open Research and Technical Development Platform: Nova FoU**	85
7.1	General	85
7.2	Mission, focus and status	85
7.3	Geotechnology	87
	7.3.1 Transparent underground structure – management (TRUST 1)	87
	7.3.2 Geoelectrical and seismic tomography along access tunnel to Äspö Laboratory (TRUST 2.1 and 4.2)	87

7.3.3 CSRMT measurements on water surface over the Äspö tunnel (TRUST 2.2) 89
7.3.4 Development of standards for functional requirements at underground facilities with respect to the chemical environment (TRUST 2.4) 90
7.3.5 Structural analysis of shotcrete samples from Äspö HRL 92
7.4 Geothermal 93
7.4.1 The geothermic fatigue hydraulic fracturing experiment at Äspö Hard Rock Laboratory 93
7.5 Environmental 95
7.5.1 Fluorine in surface and groundwaters 96
7.5.2 Fluorine in soils in the Laxemar area: Abundance, speciation and leaching potential 96
7.5.3 Exposure to arsenic, lead and cadmium via drinking water consumption near contaminated glassworks sites 98
7.5.4 Coastal modelling 99
7.5.5 Rock, harbour/bay/lagoon sediment and soil metal analyses instrument for fast areal distribution estimations 101
7.5.6 Documenting long-term biological and chemicals consequences of increased water temperatures in the Baltic Sea associated with global warming before they have happened 103
7.5.7 Detailed fracture mineral investigations 104
7.5.8 Biomineralisation and La enrichment during oxidation of fracture groundwater 106
7.5.9 Fossilized microorganisms at Äspö HRL 109
7.5.10 Structure and function of microbial communities in the deep biosphere 109
7.5.11 Activity of deep biosphere microorganisms in an extremely oligotrophic environment 111
7.6 Materials 112
7.6.1 Investigation of rock waters corrosivity by corrosion testing of steel samples in the Äspö tunnel 112
7.6.2 Centre for Friction Stir Welding 113
7.7 Education 114
7.7.1 Baltic Region Initiative for Long Lasting Innovative Nuclear Technologies (BRILLIANT) 114
7.7.2 Summer training course: Elements of the Back-end of the Nuclear Fuel Cycle: Geological Storage of Nuclear Spent Fuel 116
7.8 The spin off effects from Nova FoU work 119
7.9 The Nova FoU progress 120
7.10 The Nova FoU Steering Committee and personnel 120

8 SKB International 121
8.1 Background history 121
8.2 Support and services related to Äspö 121
8.2.1 The following facilities are available at Äspö HRL: 121
8.2.2 SKB International can customise following services: 124
8.3 Activities and support during 2016 126
8.4 Contact information 126

References 127

1 General

The Äspö Hard Rock Laboratory (HRL) is a unique research facility that extends down to a depth of 460 metres in the Swedish bedrock. Since 1986, this site has been central for the development of methods for final disposal of spent nuclear fuel. At Äspö HRL, SKB has built up a large part of the knowledge that is now being used in preparation for the construction of the Spent Fuel Repository in Forsmark, as well as knowledge that will be used in the construction and future operation of the repository.

The Äspö HRL is more than an underground facility. On the surface lies Äspö Research Village with laboratories for chemical analyses, material investigations and a special bentonite laboratory. Activities are often carried out in cooperation with researchers and stakeholders from other countries.

This annual report is an anniversary edition that, besides the technical reporting of 2016, highlights 30 years of research and development conducted at the laboratory. We would also like to say that this year's report is the starting point of a new era in the laboratory's future. In 2016, SKB acknowledged an ambition to open the facility for a broader range of activities in the future.

1.1 Background

Äspö HRL is located in the south east coast of Sweden, on the island Äspö, 25 kilometers north of Oskarshamn.

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 at representative 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. This work also includes the development and testing of methods for use in the characterisation of a suitable repository site.

The underground part of the laboratory consists of a main access tunnel from the Simpevarp peninsula to the southern part of the Äspö island where the tunnel continues in a spiral down to a depth of 460 m, see Figure 1-1. The total length of the tunnel is 3 600 m where the main part of the tunnel has been excavated by conventional drill and blast technique and the last 400 m have been excavated by a tunnel boring machine (TBM) with a diameter of 5 m. The underground tunnel is connected to the ground surface through a hoist shaft and two ventilation shafts.

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

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

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

The Operational phase began in 1995. A preliminary outline of the programme for this phase was given in SKB's Research, Development and Demonstration (RD&D) Programme 1992. Since then the programme has been revised every third year and the detailed basis for the period 2017–2022 is described in SKB's RD&D-Programme 2016 (SKB 2016).

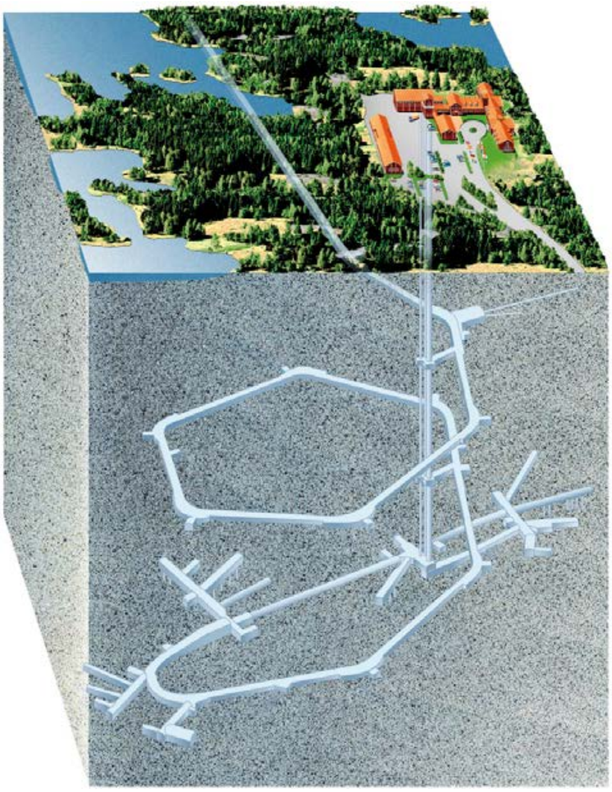

Figure 1-1. *Overview of the Äspö HRL facilities, including the new areas produced in the tunnel expansion, and the Simpevarp peninsula.*

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 tests, 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, and the expansion of new galleries, 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 Äspö Hard Rock Laboratory – 30 years of research, 1986–2016

It was in the SKB R&D programme 1986 that SKB first presented the idea of a new underground research facility. Investigations of potential sites started and in 1988 the decision was made to locate the new facility to the island of Äspö. Since then the activity at the Äspö island and in the underground laboratory that was built later, has been a key component in the progress with the Swedish waste disposal programme.

The Äspö HRL has played a central role in the development, testing and verification of technology and methods for site investigations and for execution of investigations during ongoing construction. The methods were used during the site investigations in Laxemar and Forsmark and produced conclusive foundation to the site selection for the Spent Fuel Repository.The experiences from Äspö HRL will also be of benefit for the coming detailed characterisation in the Spent Fuel Repository and the extension of the existing final repository for short-lived waste, SFR, in Forsmark.

The construction of the Äspö HRL, which took place between 1990 and 1995 gave important technological experience and invaluable knowledge about the design and construction of underground facilities. For example both blasting and full-face drilling were used to excavate the tunnels which made it possible to study how the rock around a tunnel is affected by the different excavation methods and what impact there could be on the flow patterns of groundwater.

After the start of operation in 1995, experiments began gradually to investigate how the barriers and the other components of the Spent Fuel Repository (canister, buffer, backfill and closure) could be designed and managed in order to provide optimal functionality. A great number of experiments have been conducted to probe the features of the rock and not least what significance such features could have for the long-term safety of a geological repository for spent nuclear fuel. This can, for instance, concern how the rock retards the movement of radioactive substances or how microbes affect conditions at repository depth. The results and knowledge from these efforts have served as a basis for defining the rock's safety-related function in relation to the engineered barriers.

Äspö HRL has also been important for development and demonstration of methods for operating the Spent Fuel Repository. Tests have been carried out on almost all of the KBS-3 method's subsystems in a realistic setting, a number of them in full scale. The results from several of these experiments comprised important material to support SKB's application for the KBS-3 system that was submitted to the Swedish authorities in 2011.

Since the activities at Äspö started, SKB has invited neighbours, local resident, politicians, decision-makers as well as the general public to visit the facility and learn more about SKB:s RD&D work and the plans of building a spent fuel repository. In this manner Äspö HRL has played an important role in building public acceptance for the issue of final disposal of radioactive waste. From the beginning up until today more than 170 000 people have visited the laboratory al together.

Much of the research in Äspö HRL is undertaken in collaboration with other experts, universities and organizations. There is extensive collaboration when it comes to sharing technological expertise and experiences with SKB's peer organizations in other countries. Some of the research at the Äspö Laboratory takes place within the EU's Framework programme for Research and Technological Development. In special forums, Äspö Task Force, specialists and modelling groups from several countries are collaborating on selected issues of importance for final disposal of nuclear waste.

In all these aspects Äspö HRL has contributed to world-wide knowledge about final disposal of radioactive waste in crystalline rock and today the facility serves as a model to other countries which are planning for design and construction of deep geological repositories for nuclear waste.

1.4 Organization

The research, technical development and safety assessment work is organised into the Technology department, in order to facilitate co-ordination between the different activities. The Technology department comprises six units; the Technology Staff Support, Project Office, Repository Technology, Encapsulation/Canister Laboratory, Technical design, Research and Safety Assessment, and Requirements management and safety.

The unit *Repository Technology* is the residence of Äspö HRL and 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.
- 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 *Repository Technology (TD)* unit is organised in the following groups;

- *Technology Development (TDT)*, providing competence for the technology development required for production and installation of concrete- and bentonite barriers; plugs, backfill, buffer and closure including the equipment, machines and vehicles needed in the repository facility. Project managing competence is also included in the group.
- *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. Also responsible for the co-ordination of projects undertaken at the Äspö HRL, providing services (design, installations, measurements, monitoring systems etc) to the experiments.
- *Business support (TDV)*, responsible for planning, reporting, QA, budgeting, workers safety and environmental co-ordination and administration. Project administration and the staffing of the Äspö reception and the SKB switchboard are also included in the function.
- *Chemistry Laboratory and Geoscience (TDL)*, responsible for water samling and chemical water analysis and bentonite material analysis, as well as development and management of investigation and evaluation methods, measurement systems with tools and field equipments.

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.

1.5 International participation in Äspö HRL

During 2016 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.

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.

1.6 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.

1.7 Reporting

The plans for research and development of technique 2017–2022 is described in SKB's RD&D-Programme 2016 (SKB 2016). 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 2016.

Detailed project information is continuously published in SKB's report series (TR-, R- and P-reports). SKB also endorses publications of results in international scientific journals. Data collected from experiments and measurements at Äspö HRL are mainly stored in SKB's site characterisation database, SICADA.

1.8 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.

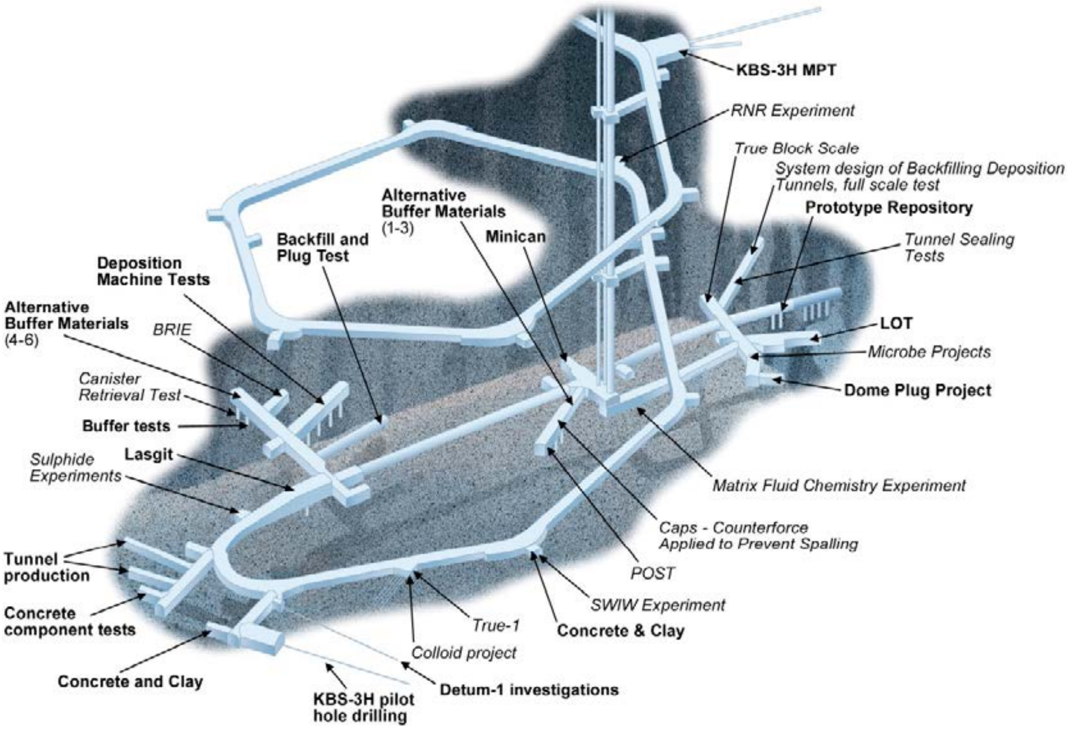

Figure 1-2. Allocation of experiment sites from −220 m to −460 m level. Ongoing experiments in bold text.

1.9 Structure of this report

The achievements obtained at Äspö HRL during 2016 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.
- SKB International.

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 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 spacial distribution of different rock types, including description of their properties.

Objectives

The main objectives of the geological activities are to:

- Provide geological support to projects and experiments at Äspö HRL.
- Provide geological expertise to SKB at large.
- Develop and maintain Äspö site descriptive model.
- Develop and maintain the geological conceptual understanding of the site.

The objective for producing Äspö site descriptive model is to describe the geological, hydrogeological and groundwater chemical conditions of Äspö HRL including updated geometrical and numerical models for each geoscientific discipline. Data from the underground excavations as well as from the ground surface will be compiled systematically for these three disciplines. The description and the resolution of the models have to have a detailed scale and density of data so that the increasing interest for experimental sites at Äspö HRL can be met.

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.

The work performed concerning Äspö site descriptive model includes

- comprehensive quality check of available geological, hydrogeological and hydro-geochemical data,
- testing of the developed methodology for iterative and integrated modelling,
- compilation analyses of datasets as bases for the modelling work.

2.3 Hydrogeology

Background

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

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

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

Objectives

The major aims of the hydrogeological activities are to:

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

Experimental concept

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

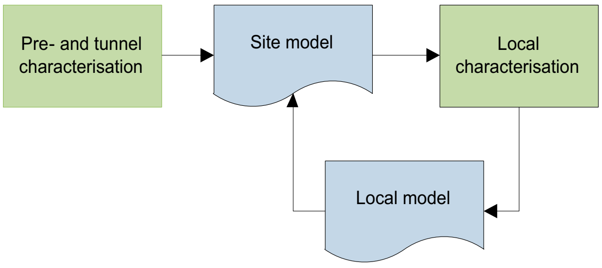

Figure 2-1. *Evolution of local- and site descriptive model.*

Results

Hydrogeological resources were largely provided to the following projects:

i) An update of the Äspö site descriptive modell was initated with data mining and compilation.

ii) A cooperation project with the german research institute GRS (Gesellschaft für Anlagen- und Reaktorsicherheit) to perform a regional flow modelling based on existing regional hydrogeological model of Äspö with the d3f-simulation code. The results aim att providing boundary conditions for a detailed facility scale model.

iii) 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)

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

The borehole skin project

The borehole skin project undertaken at 400 m depth in the Äspötunnel investigates energy losses caused by non-Darcy flow to boreholes and tunnels at large depths. Field activites were completed during 2016. Data evaluation and analysis is on-going but preliminary results indicate considerable effect on energy losses due to non-Darcy flow but also some effects due to rock stresses which impact on the flow/drawdown relation and hence on results from hydraulic tests.

2.3.1 Hydro monitoring programme

Background

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

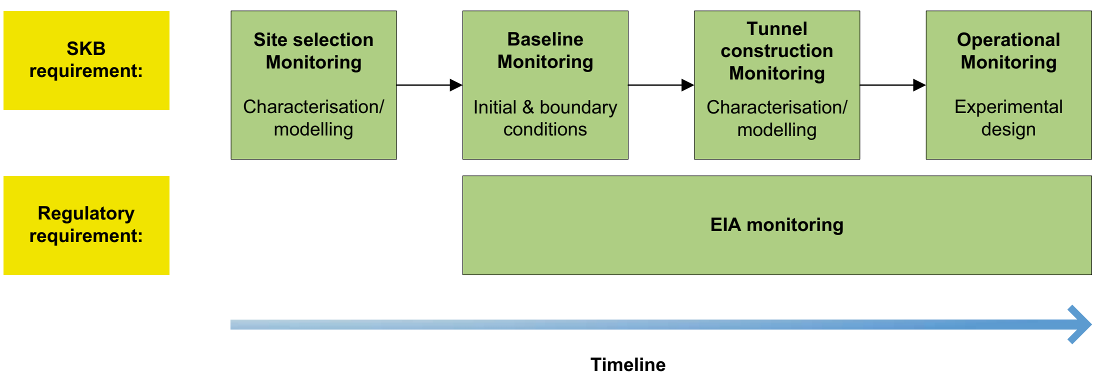

Figure 2-2. *The staged approach of monitoring at Äspö.*

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 1 500).

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

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 continued. This is sustained on a structured and recurrent basis comprising technical, organisational and Q/A & Q/C issues.

2.4 Geochemistry

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.

2.4.1 Hydrochemistry monitoring program

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 2016, 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 ground waters, 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.

__Figure 2-3.__ Ongoing sampling of shallow boreholes (soil tubes) (left figure), and the equipment such as field instrument and bottles for the extensive analyse program (right figure).

In 2016, data that has been produced between 2010 and 2015 started to be evaluated and summarized with the aim to develop and enhance further understanding of the area, to provide basis for qualified advice for future experiments and research projects. Additionally, this study provides an opportunity to customize and improve efficiency of the hydrochemistry monitoring program and is an extra step in quality assurance. Figure 2-4 and Figure 2-5 are examples of upcoming results of that study that present various groundwater types at the site.

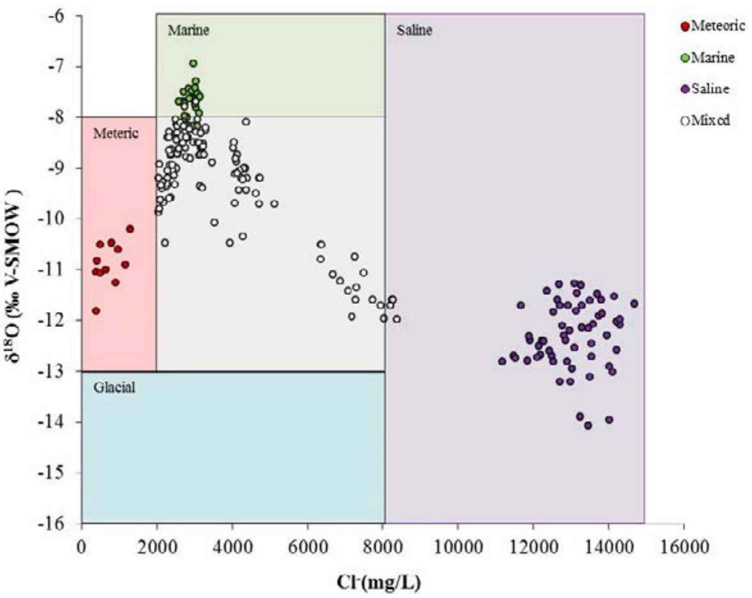

Figure 2-4. *Scatter plot of Cl⁻ concentration versus $\delta^{18}O$ values for groundwater collected at the Äspö HRL between 2010 and 2015. A classification model to identify different water types in the tunnel, except mixed water the boreholes contains marine, meteoric and old saline water type.*

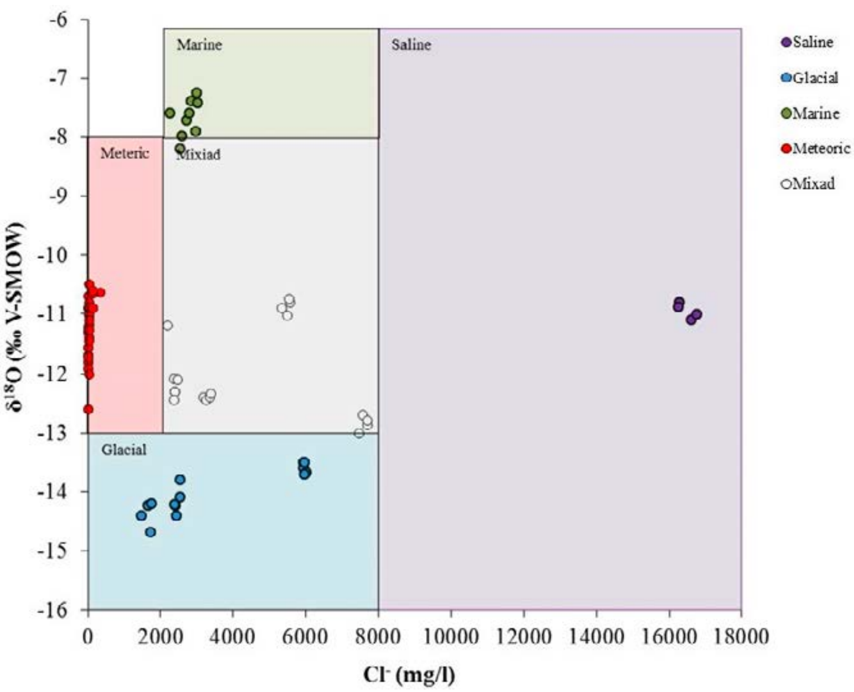

Figure 2-5. *Scatter plot of Cl⁻ concentration versus $\delta^{18}O$ values for groundwater collected from percussion and core-drilled boreholes from the surface (subvertical surface boreholes) between 2010 and 2013. A classification model to identify different water types, except mixed water the subvertical boreholes contain marine, meteoric old saline and glacial water type.*

3 Natural barriers

3.1 General

Since the start of the tunnel construction in 1990, SKB has carried out experiments in order to investigate properties of and processes in the rockmass of Äspö. The purpose of these activities is to give a good knowledge of the long term function of the geological repository and to obtain data relevant for the assessment of the long term safety.

Chemical properties, groundwater flow and radionuclide migration have been the main issues in previous research programmes. Presently the only on-going research activities are within the Integrated sulphide project (3.2). New task are being handled within the Task Force for Groundwater Flow and Transport of Solutes (3.3).

Experiences are made with new methods for rock excavation (3.4).

3.2 The integrated sulphide project

Development and testing of gas samplers in tunnel environments

Two gas sampling methods have been tested in selected boreholes and borehole sections at the Äspö Hard Rock Laboratory (Äspö HRL).

- Sampling of groundwater for determination of dissolved gases (H_2, He, Ar, O_2, N_2, CO_2, CO, CH_4 and other hydrocarbon gases).
- Sampling of released gas in order to determine stable isotope ratios in gases (deuterium in H_2 and CH_4, $\delta^{18}O$ in CO_2 as well as $\delta^{13}C$ in CO_2 and CH_4).

The use of boreholes drilled from a tunnel system facilitated the sampling since no pumping was needed due to the pressure gradient out from the boreholes.

Collection of sample series during continuous discharge of water revealed that the amount of dissolved gas in the groundwater initially present in the borehole sections (the first samples in the series) may be larger than the amount in the groundwater directly from the bedrock formation (the latter samples in the series). Furthermore, the size of the pressure drop (back pressure) was found to be important, especially for the amount of dissolved hydrogen. Generally, the results stress the importance of a proper and well tested sampling procedure when investigating dissolved gas concentrations in groundwater.

Another factor that affects primarily the amount of dissolved hydrogen but may also affect gases like carbon dioxide and/or methane, is corrosion of equipment parts in the borehole. Significant differences in the hydrogen concentrations were observed between boreholes with metal parts solely made of stainless steel and those with aluminium parts.

The results from determinations of isotope ratios using samples of released gas from a gas trap generally diverged somewhat from those few samples obtained in earlier investigations using extracted gas from groundwater samples. Additionally, some differences in the isotope signatures were observed in borehole sections affected by corrosion of aluminium. The clearest effect is the higher $\delta^{13}C$ values. The reasons are difficult to deduce and more sampling and analyses have to be done in order to understand the implications of different equipment and establish a reliable procedure for sampling. For more information please see Nilsson et al. (2017).

Conclusions

It is a general impression that the handling of the sampling equipment and the method for dissolved gas is somewhat too complicated for routine sampling. However, with some minor measures and improvements on the design of the equipment and the procedure this could probably be solved. It is of utmost importance though, to develop and test equipment for gas extraction at the site. It is not an optimal procedure to send the sampling equipment to another laboratory for extraction.

The few determinations of isotope ratios in gases that have been carried out prior to this study were all of them from a previous sulphide project in the Äspö HRL (Drake et al. 2014). The new data show differences between borehole sections with aluminium and stainless steel equipment which is what could be expected, although the causing processes are not fully known. Furthermore, there is generally a systematic difference between the new dataset from this study and the earlier dataset, however, the data are too few to deduce an explanation. More isotope determinations in gases have therefore to be performed in order to improve the understanding and the reliability. An aggravating circumstance is the often quite long time needed to collect a sufficient gas volume for the determinations. For the moment there is no solution proposed to this problem. Although the present procedure seems unfavourably time consuming it is still recommended to collect more sample series and vary the purged volume, to use more than one laboratory for the analyses and to compare different sampling equipment.

Regular yearly sampling for dissolved gas as well as isotope ratios in gases is suggested in order to overcome the lack of data and estimate the optimal sampling conditions. A few carefully selected boreholes without equipment parts made of aluminium and collection of sample series including at least two samples, one initial sample and one sample after discharge of at least two plug flow volumes is recommended. For more information please see Nilsson et al. (2017).

Table 3-1. Summary of borehole sections and collected samples.

Borehole: section	Section (m along borehole)	Permanent equipment material	Pressure drop (dissolved gas sampl.)	No of samples × duplicates for dissolved gas	Comment	No of samples for isotope determ.
KA2511A:4	111–138	Al				1
KA2563A:1	242–246	Al	150 KPa	4 × 2	The sampling was repeated at two different pressure	–
KA2563A:1	242–246	Al	750 KPa	4 × 2	drops (totally 16 vessels)	–
KA2563A:4	187–190	Al	–	–		1
KA2051A01:5	120–135	Stainless steel	300 KPa	1 × 2		1
KA2051A01:9	51–67	Stainless steel	150 KPa	4 × 2		Not enough gas
KA3510A:2	110–124	Al	200 KPa	1 × 2		1
KA3385A:1	32–34	Stainless steel	–	–	Sampling in 2010–2011, Al in equip.	1
K08028F01:1	84–94	Stainless steel	–	–		1

Experiments with bentonite and sulphide – results from experiments

Experiments were performed with Ibeco backfill (Milos, Greece) and MX-80 (Wyoming, USA) bentonite and sulphide solutions. The main target was to determine the solubility of the sulphides in the bentonites and their equilibrium concentrations. The concentration was determined to be lower than the reporting limit of the method, however, oxidation and/or H_2S loss, may have caused a lowering of the sulphide concentration in the samples, thus introducing an uncertainty. When sulphide was added as Na_2S solution, it was shown that the bentonite reduced the amount of sulphide in the solution. The mechanism of this can be absorption or some kind of transformation or reaction with the sulphide, but these details are unknown. The observation that bentonite reduces the amount of sulphide in solution when Na_2S is added supports that no sulphide could be detected when Na_2S was not added. Two different methods were used for sulphide detection, the methylene blue method and the copper sulphate method (precipitating sulphide as CuS). The final experiments were done in a glove box with < 1 ppm O_2. It was found that it was critical that all bentonite (montmorillonite) was removed from the solution before the reagents were added for the sulphide determination. This removal was performed by adding $CaCl_2$ to a final concentration of 0.1 M and by filtering the solution by a 0.45 μm filter.

Based on the data, a very rough estimation was done indicating that 1–10 kg of sulphide seemed to be removed per 1 000 kg of bentonite. This can be compared with that 0.5 wt% or 50 kg of sulphide in minerals is currently allowed per 1 000 kg of bentonite buffer.

Conclusions

The sulphide loss mechanism (absorption/transformation/reaction) is not known but is fast and 1–2 hours seems to be enough for the reaction to take place. A very rough estimation was done from the data, indicating that the bentonite seemed to reduce an added amount of sulphide in the range of 1–10 kg per 1 000 kg of bentonite.

Further experiments would be needed in order to understand this behaviour further and to better quantify the sulphide loss by the bentonite. This was however outside the scope and time frame of this project. One experiment was done with kaolin clay and no similar behaviour on sulphide was seen with kaolin. Please see Svensson et al. (2017) for details.

Uranine – influence on bacterial cultures with the fluorescent bacterium Pseudomonas fluorescens

A study has been performed at Äspö Chemistry Laboratory during 2016, and evaluation of results is ongoing.

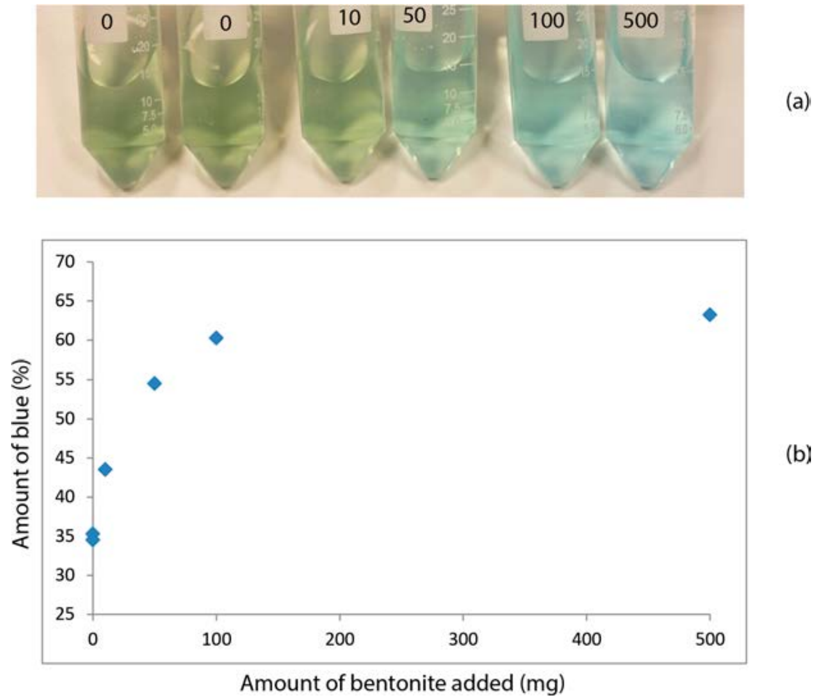

Figure 3-1. *CS-II. Constant sulphide addition (29 mg/L in 33 ml) different mass of bentonite (0–500 mg) added to each tube. In the picture (a) the filtered supernatant is shown after Cu^{2+} addition (1 ml 1 M/tube). From left: 0, 0, 10, 50, 100 and 500 mg. Blue colour indicate Cu^{2+}. A colour measurement by software (b) estimated the amount of blue in the samples which is proportional to Cu^{2+} and inversely proportional to S^{2-}.*

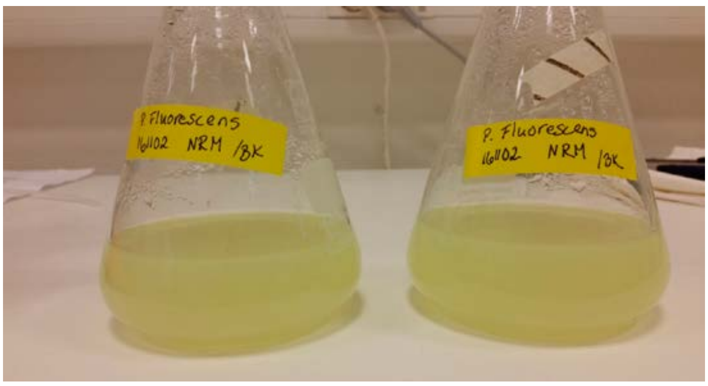

Figure 3-2. *Cultures of Pseudomonas fluorescens in groundwater medium.*

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. More information may be found at www.skb.se/taskforce.

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 (final reporting ongoing).
- Task 9: Modelling of the field experiments REPRO and LTDE-SD (ongoing).

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 is addressing hydraulic tests performed at the Olkiluoto Island in Finland, and the possibility of reducing uncertainty in performance assessments. 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. In addition, Task 7 is addressing the usage of Posiva Flow Log (PFL) data and issues related to open boreholes.

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. The task has provided a good possibility to compare the modelling results to the experiment. Task 8 has continued in terms of interpretation 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. In 2016 the task started to focus more on modelling of LTDE-SD.

Results

During 2016, the focus within Task 7 has been on finalisation of reporting (Frampton et al. 2015, Sawada et al. 2015, Svensson 2015). The Task 8 work mainly contained interpretation of BRIE and reporting (e.g. Dessirier 2016, Dessirier et al. 2017). The Task 8 modellers have been updating their modelling reports based on review comments. Task 9 started up by modelling of WPDE 1 and 2 of the REPRO experiment. The modelling results have been compared to experimental results, and reporting of this exercise is ongoing. In addition modelling of LTDE-SD has started up to try to explain the unexpected experimental results.

The 34th international Task Force meeting was held in Prague, in May. A joint session with EBS TF was held for Task 8. The presentations were mainly addressing modelling results on sub-task 8F (updating models based on new experimatal data, e.g. pictures of wetting patterns on the surfaces of retrieved bentonite blocks). In addition, an evaluation session for Task 8 was held. In Task 9 that is addressing both SKB's LTDE-SD and Posiva's experiment REPRO, updated results of sub-task 9A were presented, i.e. modelling of WPDE 1 and 2, and preliminary results of sub-task 9B, i.e. modelling of LTDE-SD.

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

Minutes of TF meeting 34 and Task 9 workshop have been distributed to the Task Force together with presentation material. The description and the status of the specific modelling sub-tasks within Task 8 and 9 are given in Table 3-2.

Table 3-2. 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	Final results (reporting ongoing)
8E	Final results (presented at Task Force meeting 34)
8F	Revisit to models with more field data (presented at Task Force meeting 34)
9	**Interaction between engineered and natural barriers**
9A	Modelling of REPRO WPDE 1 and 2, updated results (presented at Task Force meeting 34)
9B	Modelling of LTDE-SD (preliminary results presented at Task Force meeting 34)

3.4 Tunnel production

Background

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

During 2016 a full-scale test of a method to level the floor in the deposition tunnels were conducted in TAS04. In addition evaluation of MWD-data and core drillings in the tunnel walls was conducted with the purpose to study excavation damage.

Levelling of tunnel floor with wire sawing in TAS04

A smooth floor is required in the deposition tunnels in the planned repository for spent nuclear fuel and during 2016 the Tunnel Production project completed a full scale test in TAS04 to study the possibility to level the tunnel floor by means of wire sawing. The project was documented and evaluated in a bachelor thesis by Enér (2016).

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 was pulled through the slots towards the tunnel entrance. Figure 3-3 to Figure 3-5 depicts the ongoing work.

The result after sawing is shown in REF _Ref476808959 Figure 3-6 and REF _Ref476808966 Figure 3-7. The sawed floor has a slight tilt with a maximum deviation of 7 cm from the theoretical tunnel floor at the right side (in relation to the tunnel heading).

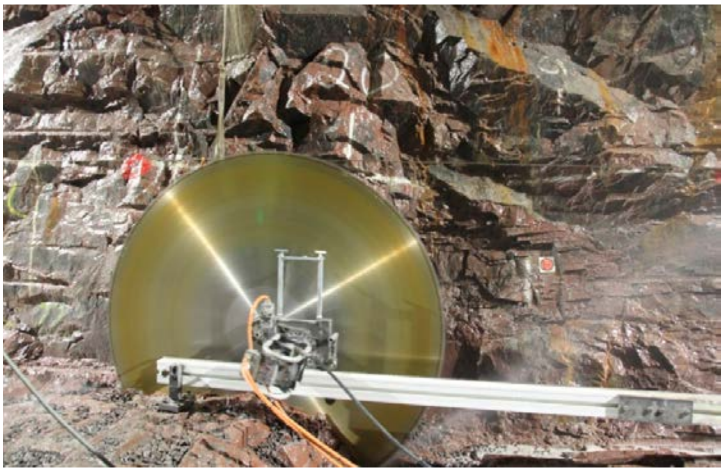

Figure 3-3. *Sawing of the slots on sides. Two parallel cuts are made on each side and the rock between them are removed (Photo by Rickard Enér).*

Figure 3-4. *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 3-5. *Ongoing wire sawing in TAS04 (Photo by Rickard Enér).*

***Figure 3-6.** Results from wire sawing in TAS04 (Photo by Rickard Enér).*

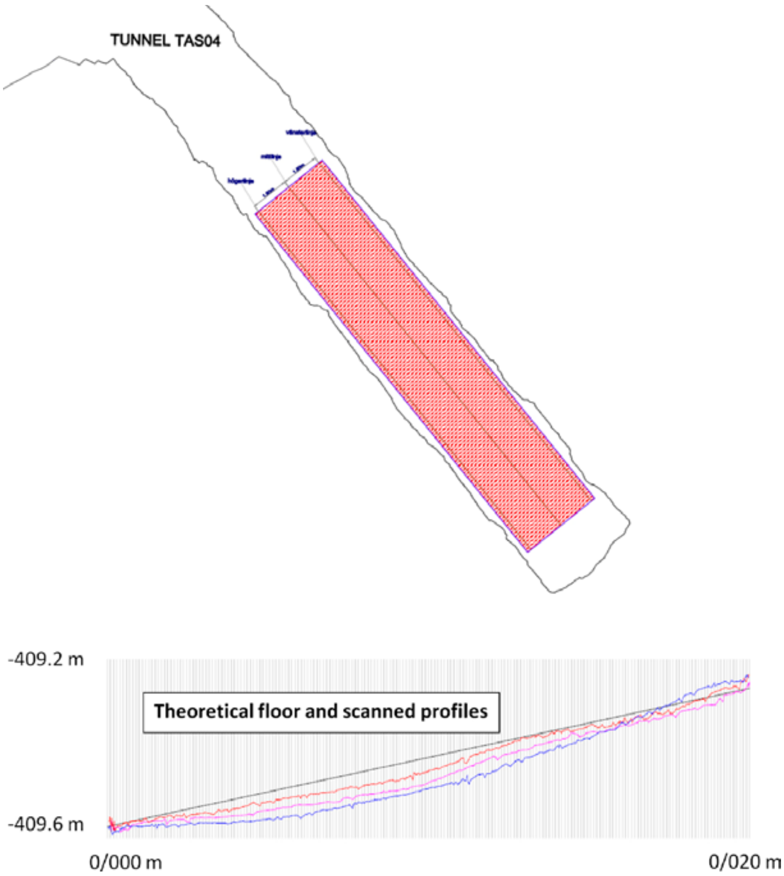

***Figure 3-7.** Wire sawed area in TAS04 and results from lasersanning of three sections along the tunnel floor. The lines represent the theoretical floor after wire sawing with red, purple and blue lines representing left, middle and right (in relation to the tunnel heading). The scanned profiles are parallel at 1.8 m distance from the middle line. Modified from Enér (2016).*

Diamond core drilling and evaluation of MWD data in TAS04

Measurement While Drilling (MWD) is a technology where drilling parameters are logged by the drill rig. In TAS04 data was collected from a Sandvik tunnelling Jumbo during the expansion of Äspö HRL in 2012 (Ericsson et al. 2015), see Figure 3-8. The parameters collected contained the sample location (hole ID and depth), operational pressures (feed, percussion, flushing etc.), rotary speed, water flow and penetration rate. Additional to the drilling parameters production data was collected on drilling and charging precision, with a specific focus on the contour holes (Ittner et al. 2014).

Recent developments in the tunnelling industry instigated by the Swedish Rock Engineering Research Foundation, BeFo and Swedish Blasting Research Centre, Swebrec financed project: "Analysis of blasting damage range depending on geology by using MWD data – a technique that prognoses the extend in the remaining rock mass". The project goal is to relate MWD data to blasting damage. A first attempted was made by Van Eldert et al. (2016) and further data collection was performed in TAS04.

During the construction of TAS04 and in the period after the construction many methods for estimation of the EDZ were applied (Ericsson et al. 2015). In addition to this data 20 diamond core holes (Ø50 mm, length 70–100 cm) were drilled in the walls, see Figure 3-9, and Ground Penetration Radar (GPR) measurements of the walls were taken, see Figure 3-11. The diamond core holes were selected based on the MWD data, geological and geo-mechanical mapping and charge density (string or bottom charge). These drill cores were mapped, Figure 3-10, and diametrical P-wave velocity measurements were taken, see Figure 3-12. In the case of blasting damage the P-wave velocity is reduced due to the development of micro fractures during blasting (Olsson et al. 2009). A similar affect is show by dispersion in the GPR data.

The MWD data is collected in a very careful matter and the rock quality in Äspö is very high, resulting in a limited variation of the drilling parameters collected, with the exception of manual interference, see Figure 3-8. The core samples taken and mapped show a correlation between the RQD and the rock typed drilled. The P-wave velocities show a slight decrease in the first 20 cm of the diamond core meaning that the EDZ of the micro fractures is within the first 20 cm of the walls. This is consistent with the results shown by the GPR data. The P-wave velocity done increase to the same extent seen in other investigation, indicating that the blasting damage in TAS04 was less severe, probably caused by the extreme careful blasting and control from the client on production parameters.

The next step is to relate the MWD data to the measured and observed blasting damage, while taken the tunnel production field notes into account. This comparison will show the degree of correlation between the drilling parameters with the measurement of the EDZ applied by the discussed methods.

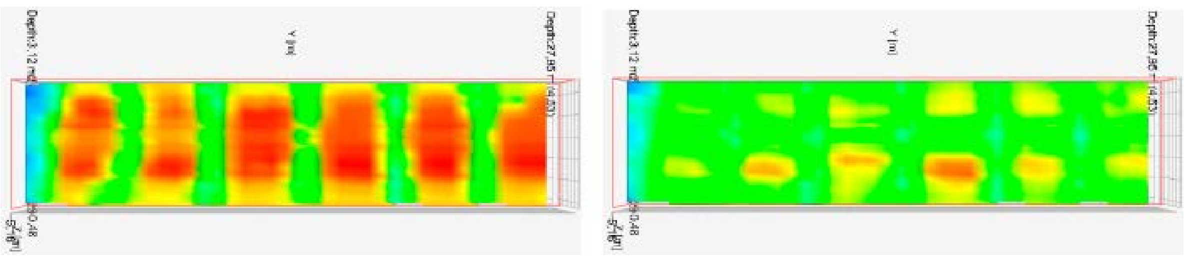

Figure 3-8. *MWD data from TAS04 (Percussion Pressure and Penetration Rate).*

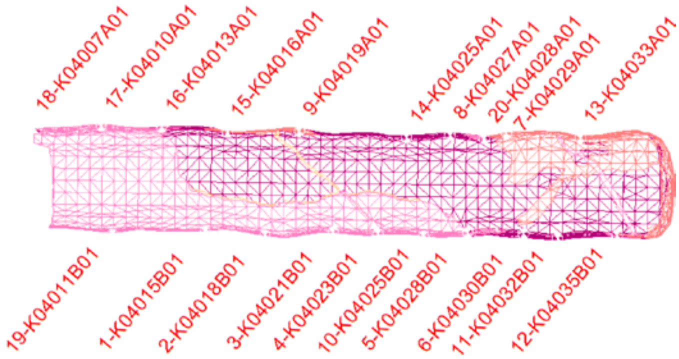

Figure 3-9. *Diamond Core Hole locations along TAS04.*

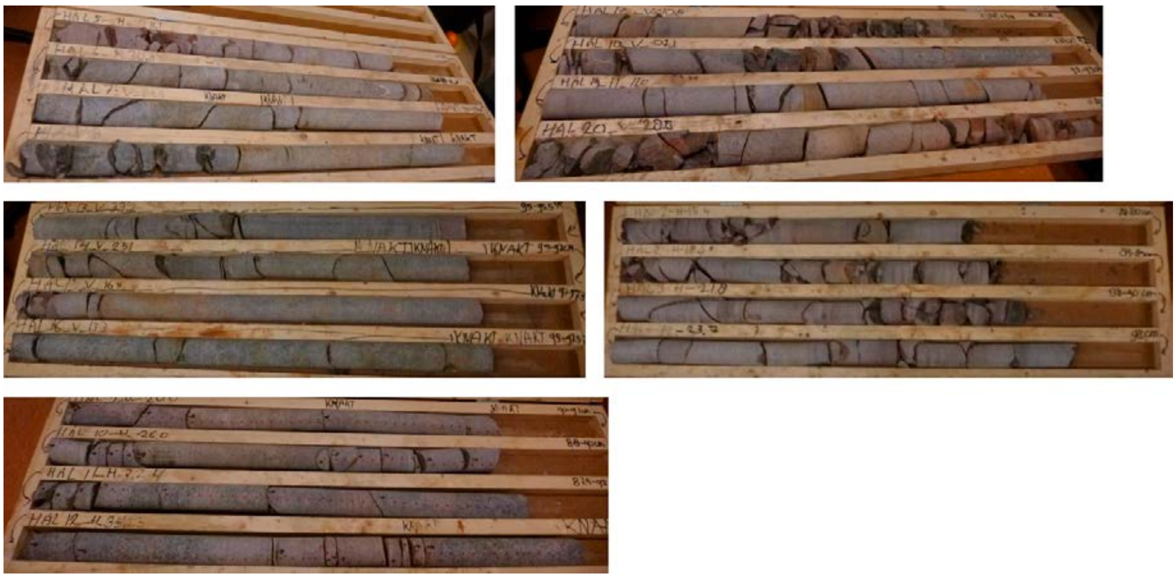

Figure 3-10. *Core samples of EDZ investigation taken in TAS04.*

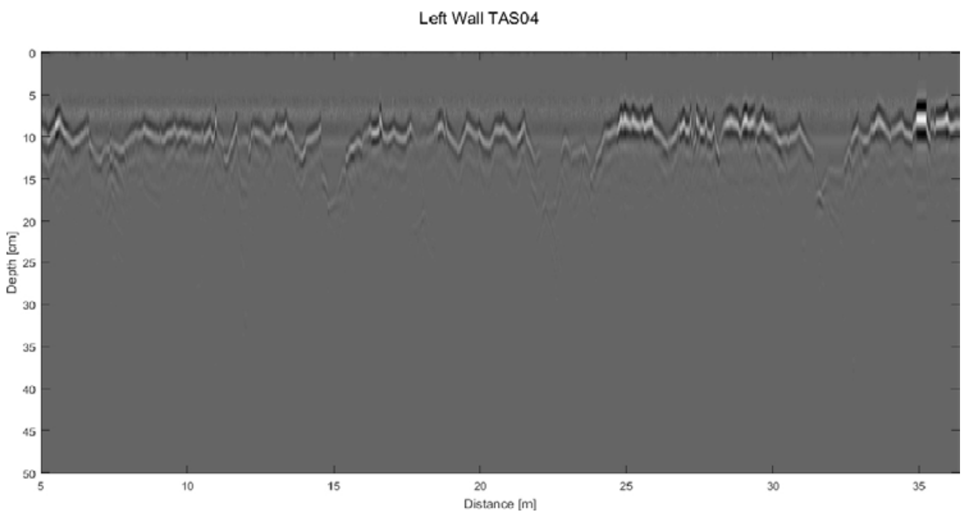

Figure 3-11. *GPR profile of left wall in TAS04, 1.0 meter above drift floor.*

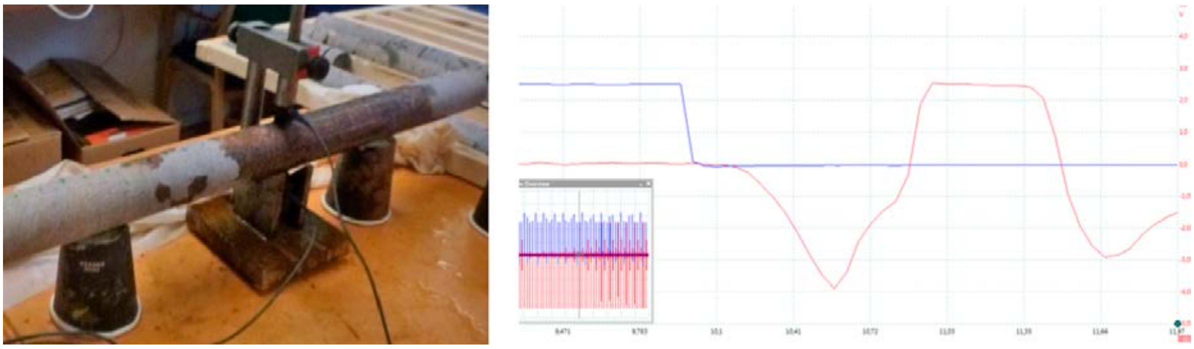

Figure 3-12. *Diametric P-wave velocity measurements on TAS04 cores.*

4 Engineered barriers

4.1 General

To develop the engineered barriers of the repositories for spent fuel and radioactive waste and to demonstrate their function, work is performed at Äspö HRL. The work comprises translation of current scientific knowledge and state-of-the-art technology into engineering practices 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 2016 the following experiments and projects concerning the engineered barriers were ongoing, either in active or in monitoring stage:

- Prototype repository.
- Alternative buffer materials.
- KBS-3 method with horizontal emplacement.
- Large scale gas injection test.
- In Situ Corrosion testing of miniature canisters.
- Concrete and clay.
- Low-pH programme.
- Task force on engineered barrier systems.
- System design of plug of deposition tunnels.
- System design of buffer.
- Large scale casting test of 2BMA cassions.

Those project that performed activities during 2016 are described in the following sections.

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 2014.

Objectives

The main objectives for the Prototype Repository are to:

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

Experimental concept

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

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

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

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

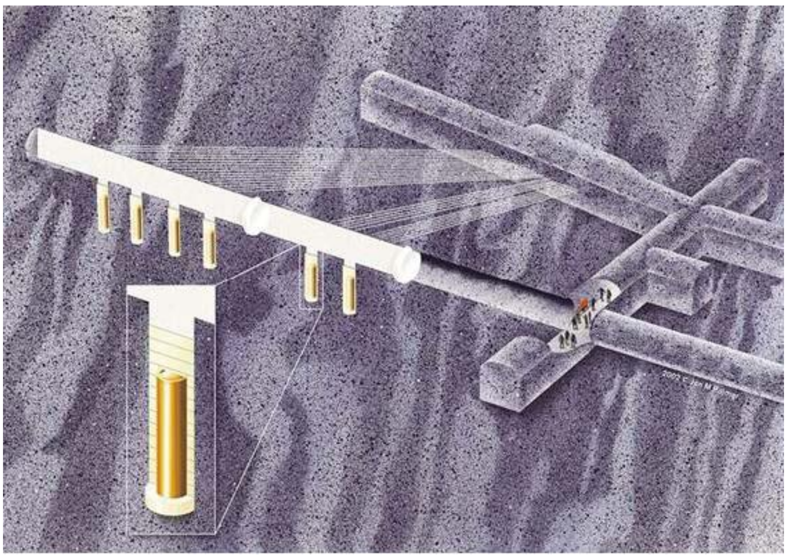

Figure 4-1. *Schematic view of the layout of the Prototype Repository (not to scale).*

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 1 160 W. Additional problems with the heaters in canister 1 and 3 were observed during 2013–2015 and the power was reduced to about 1 100 W for canister 1 and to about 400 W for canister 3.

Measurements in rock, backfill and buffer

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

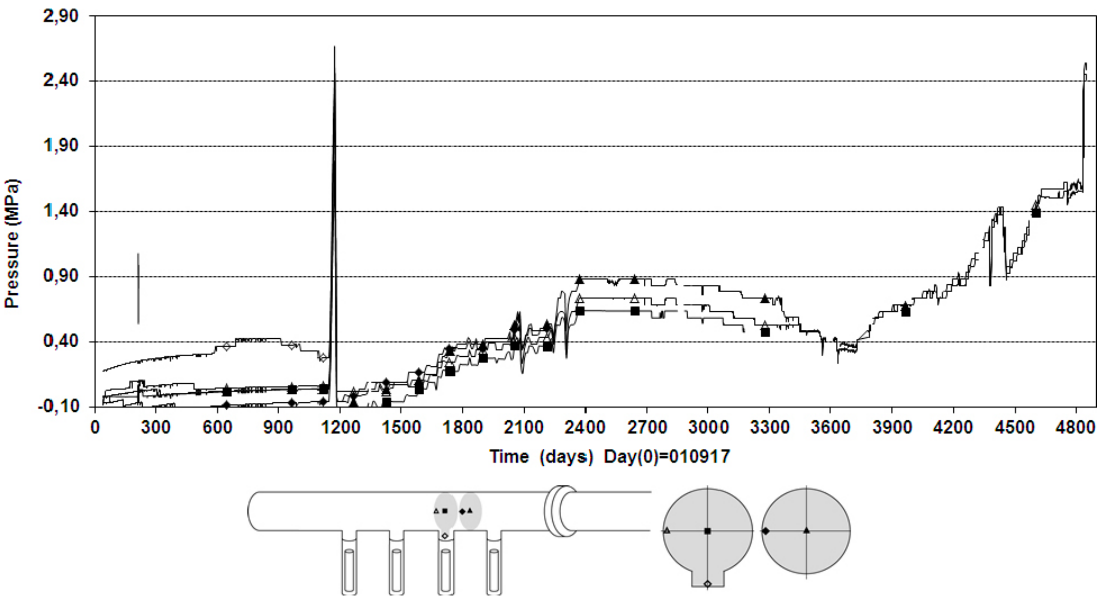

Figure 4-2. *Examples of measured total pressure in the backfill around deposition hole 3 (17th September 2001 to 1st January 2015) (Goudarzi 2016).*

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.

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, 2011).

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

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

Many of the sensors for measuring total pressure, relative humidity and pore pressure in deposition hole 1 indicated that the buffer around the canister was close to saturation after about 4–5 yerars while the buffer above and under the canister was not saturated at that time. Most of the sensors in this deposition hole have stopped giving relaibale data which makes it difficult to follow the continuing saturation of the buffer.

Corresponding measurements in the buffer in deposition hole 3 are indicating that the saturation of the buffer is slower compared to deposition hole 1. Also in this hole most of the installed sensors hole have stopped given reliable data.

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 an 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 variant 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.

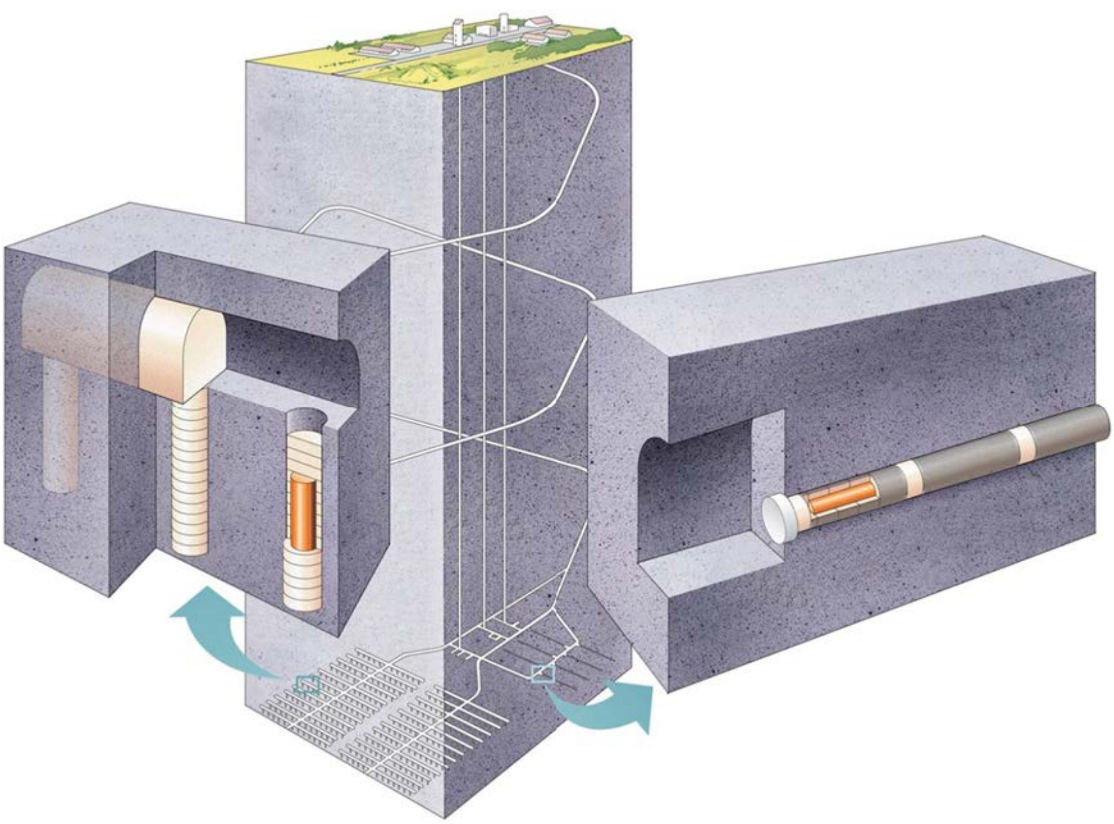

Figure 4-3. Schematic drawing of the KBS-3V reference design (left) and KBS-3H (right).

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.

Experimental concept

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 possibility 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. 1 850 mm, and they have a slight upward inclination (c. 2º), which is why water is removed from the drifts by gravity

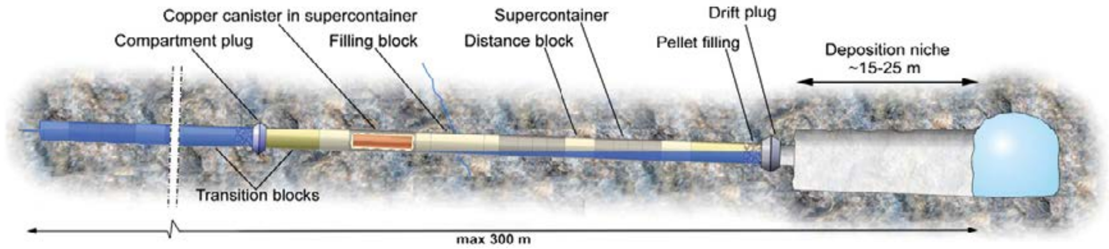

Figure 4-4. *KBS-3H reference design DAWE with its main components; the plugs with their transition zones, the Supercontainers, and the distance and filling blocks. The illustration shows an ongoing artificial water filling procedure of the second compartment.*

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 gap between the Supercontainer and the drift wall is 44.5–48 mm.

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.

Results

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 Multi Purpose Test (MPT)

The MPT is basically a down-scaled (spatial and temporal) non-heated installation of the reference design, DAWE, and includes the main KBS-3H components, see Figure 4-5. 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). For further details see Kronberg (2016).

Monitoring of Multi Purpose Test (MPT)

The MPT test has been instrumented with 227 sensors and 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 2017 based on the dismantling criteria, which remain to be finalized by SKB and Posiva.

Approximately half of the sensors are functioning normally and a second data report covering the test evolution to the end of 2015 is about to be published. The bentonite is starting to saturate, but still predominantly in the outer parts of the components.

Heated Supercontainer test

None of the earlier KBS-3H tests (scale tests or full scale tests) have been carried out with heated canisters. However, there is extensive experience on heated conditions from KBS-3V, both from tests and modelling. Recent work has been carried out within the BUSTER (Johannesson et al. 2014), and BÅT projects. The KBS-3V results confirm that the heat emitted from the canister causes a redistribution of water in the buffer blocks surrounding the canister, which can make the buffer crack after a certain time period due to local dryness.

The KBS-3H design differs from KBS-3V in several ways but it has been concluded that the issue regarding redistribution of water in the buffer can be a potential problem also for the KBS-3H design. Cracking of the KBS-3H buffer can risk the integrity of the supercontainer and possibly lead to buffer loss. Buffer fall-out can also disturb the transport, deposition and DAWE air evacuation process.

For KBS-3H the cracking problem may firstly occur during a supercontainer storage period prior to deposition, which with SKB's current design is assumed to be 10 days at most. Secondly, it may occur during the time period after deposition but prior to water filling of the compartment, which with the current design also equals 10 days at most for the first supercontainer deposited in a drift. The maximum risk period is thus 10 + 10 = 20 days for SKB. In this context it should be noted that Posiva's current KBS-3H reference design is that the assembly is directly followed by deposition which only leaves the 10 days after deposition as the risk period.

To find out how big a problem the drying of the buffer during storage and installation is a full scale test has been carried out simulating 10 days in storage at room temperature and 10 days in the drift with cooler surroundings. The basic test outlining is presented in Figure 4-6, a supercontainer placed inside the transport tube.

The Heated Supercontainer test also assesses a potential new buffer design with harmonised water content in blocks and rings, 14 ± 1 %, compared with the current reference design of 11 ± 1 % rings and 17 ± 1 % blocks.

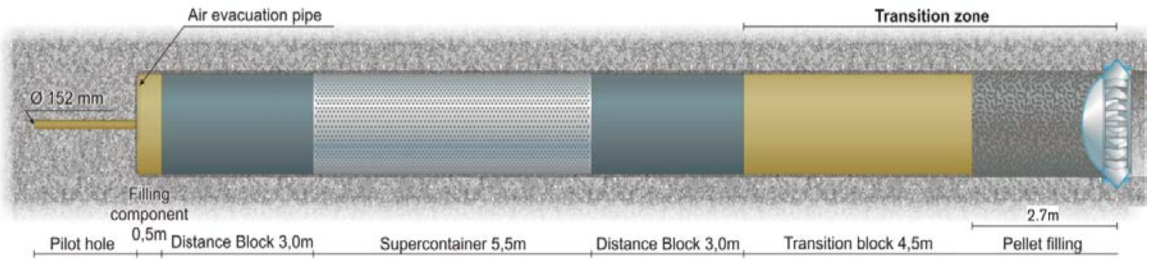

Figure 4-5. Schematic illustration of the MPT layout.

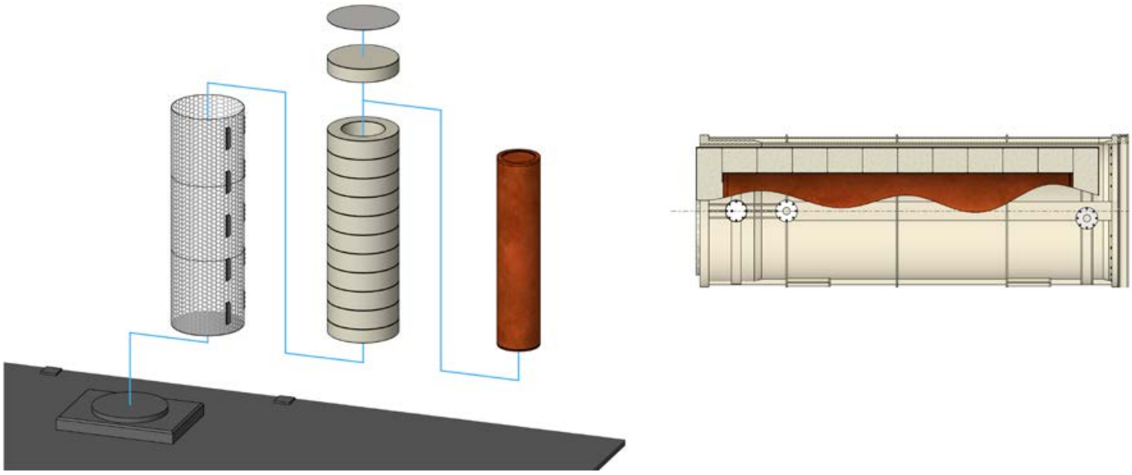

Figure 4-6. *Basic outline of the Heated supercontiner test, left figure illustrating the supercontainer assembly and the right figure illustrating the supercontainer placed inside a sealed transport tube in horizontal position.*

Pre-modelling

The test was preceded by pre-modelling in order to predict its outcome and to support an instrumentation plan. A thermal power of 1 700 W was used for the canister. The pre-modelling predicted that very little cracking would happen if the initial canister temperature was below 40 °C. With an initial canister temperature of 80 °C the crack depth was predicted to be approximately 1 cm on the inner side of the buffer rings after 10 days in the transport tube. Given that a KBS-3H repository assembly hall is not designed, an accurate canister starting temperature cannot be defined at this time but the project eventually decided at around 60 °C for the actual test based on the expectation that the canisters will be placed in a transport cask in a repository scenario and that the cask will provide some isolation. If instead placed in open air it would be in the order of 40–45 °C, dependent on ventilation.

The model cannot predict if there are any flow path for air between the inner gap and the outer gap. It has been seen in other tests that there can be leakage between the blocks. Any leakage between the gaps, i.e. air paths between blocks, would increase the drying and therefore also the cracking. Possible thermal stresses from the asymmetric heat distribution were not accounted for in the model used to predict crack depth.

The model also predicted that there would not be much change in the water content distribution in the blocks during the simulated time in the drift with a cooler 'rock' surface surrounding the supercontainer, i.e. the water content profiles inside the blocks should not change that much during those 10 days according to the modelling.

Instrumentation

Based on modelling and earlier experience a total of 78 temperature sensors and 8 RH sensors were included the test. Table 4-1 lists their locations in the test. The sensors were relatively evenly distributed, and Figure 4-7 show the position of rings and blocks, and gives the sensor positions in ring R5 as example of sensor positioning.

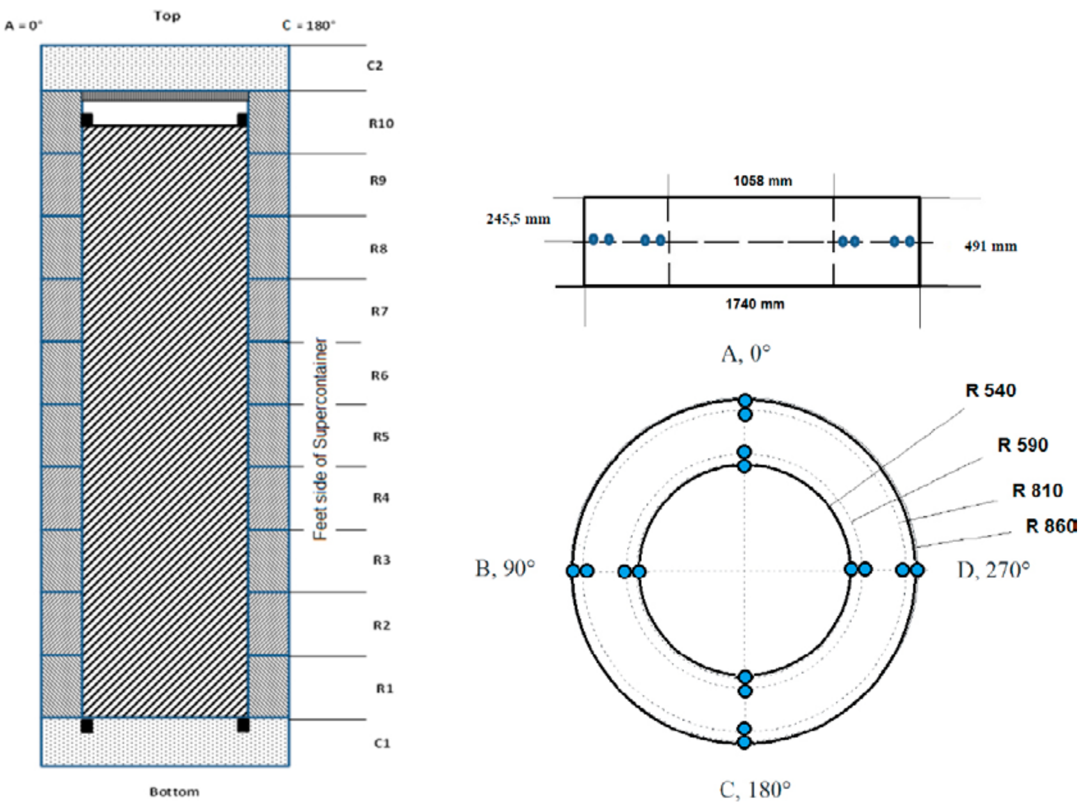

Figure 4-7. *Left: Side view of the supercontainer with labelling of the blocks; C1, C2 and R1–R10. Right: Temperature sensors in ring R5.*

Table 4-1. Heated supercontainer test instrumentation.

	Number of sensors	
	Temperature	**RH**
Bottom block, C1	6	
R2	16	
R5	16	
R9	16	
Top block, C2	6	
Canister	6	
Transport tube	12	
Assembly hall		2
Air void between shell and transport tube		6
Sum:	**78**	**8**

Assembly and test period

MX80 bentonite was used and the blocks were compacted in Ystad similarly as the MPT blocks. The bottom block was machined to a height of 350 mm and the top block to 278 mm, both having a dry density of 1 753 kg/m^3. The 10 rings had a dry density of 1 885 kg/m^3 and were machined to 491 mm. All blocks had a water content of 14 %.

Given the experiences from the MPT, the assembly was straight forward and with the harmonised water content in both blocks and rings, the air humidity in the assembly hall could be regulated to an appropriate level for all blocks, 63.5 %.

Figure 4-8 illustrates final preparations for the canister lift. The canisters sensors and heaters had to be disconnected during the day when the canister was installed in the Supercontainer and turned horizontally, September 26th 2016. Once the heaters and canister sensors were connected again, in the evening of September 26th the canister temperature had come down from approximately 60 °C to an average of 45 °C with the hottest part, the top of the canister, still at 52 °C at that time. It was also noted that the canister temperature continued to drop a few degrees after the heaters and sensors were connected. This is as expected as the blocks with room temperature cools the canister.

Figure 4-9 illustrates block R5 as an example of the temperature development in the blocks during the test period. It can be seen that the block temperatures equilibrates during the test period. The temperature data follows a logical pattern with the sensors in the buffer closest to the canister showing the highest temperature. The effect of the horizontal Supercontainer is also evident as the lower sensors show the highest temperature due to the canister leaning on to the buffer on the lower side.

When comparing with the pre-modelling and taking mid canister with a starting temperature of 40 °C and comparing to ring R5 in the test, the modelled temperatures of the buffer rings is approximately 5–7 °C lower than the test data. The most likely reason for this is that the heat transfer from the transport tube to the surroundings has been overestimated in the modelling.

Cooling was initiated after 10 days, on the 6th of October, however, the cooling equipment malfunctioned and only a very small temperature drop was achieved in the transport tube. A small response can be seen in Figure 4-9. There is also a small increase in the temperature a few days before cooling, on the 4th of October which origin is currently unknown. The malfunctioning cooling equipment was unfortunate; however, the model predicted limited effects from cooling so the overall test results are still deemed to be good.

Figure 4-8. *Pre-heated canister being prepared for installation inside the Supercontainer.*

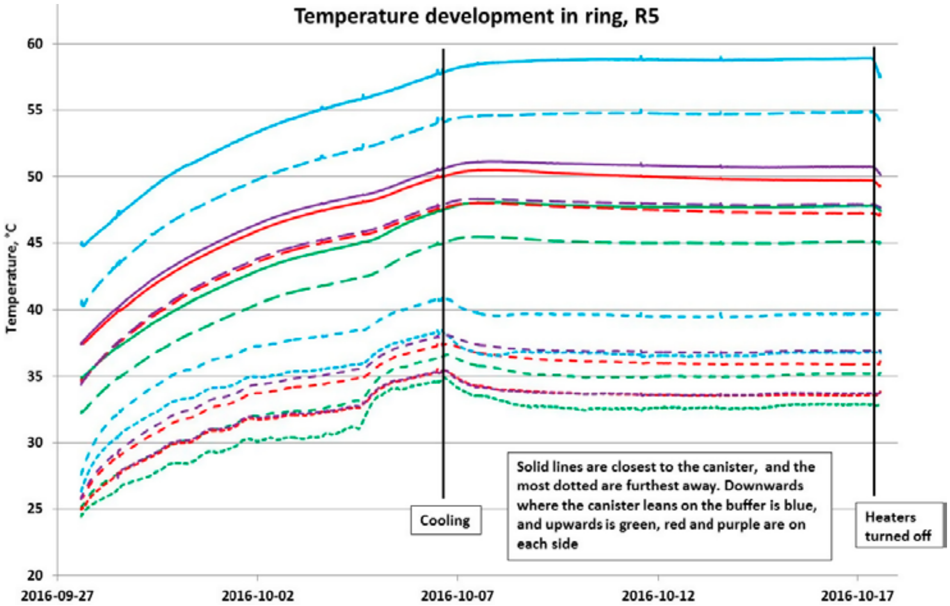

Figure 4-9. Temperature development in ring, R5.

The RH in the air void between the supercontainer and the transport tube climbed quickly above 80 % and evened out around 90 % after approximately 3 days, this compares to 63.5 % which would be expected without the heaters turned on. The RH test data is difficult to compare to the model as the RH in the model varies with the position in the void (being highest close to the transport tube and lowest close to the blocks), the sensors exact position is not that detailed, however they indicate that the transport tube has a fairly even and high RH.

Water accumulating at the bottom of the transport tube was measured, Figure 4-10. 1 161 ml of water was collected during the full test.

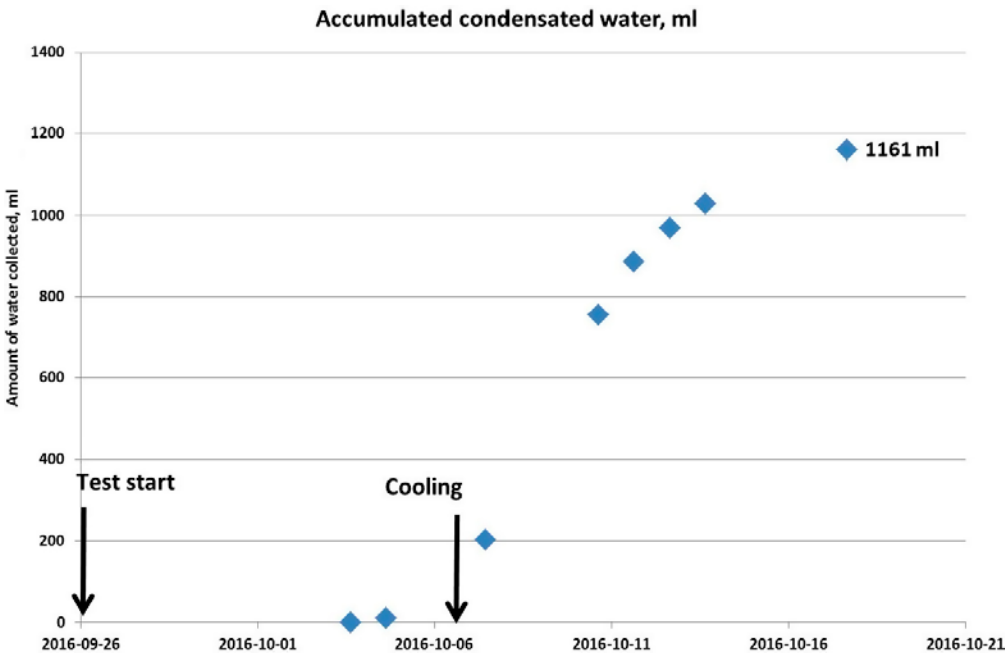

Figure 4-10. Accumulated amount of condensate water collected during the test period.

The cooling of the transport tube is clearly noted in the amount of water collected. Given that each block contains several hundreds of litre water the total amount of condensate water is small in comparison. The model predicts somewhat less, however, this is likely related to the thermal boundary conditions between the transport tube and the surroundings being somewhat incorrect as seen from the temperature data.

During the test period, a peep-hole camera was used to look underneath the supercontainer, Figure 4-11 illustrates one position on block R8. As can be seen in the photos, minor cracking has started after two days with 1 700 W (left photo), and after 3 days it has increased further (right photo). The photos below are examples from ring R8, but there were cracking on other blocks after 3 days as well. However, even with the cracking the amount of material coming loose from the Supercontainer was limited. Once the test was terminated all that loose material was collected and weighed to 4.1 kg wet and 2.2 kg dry. Most of this material had come lose at the end blocks in the form of flaking, see Figure 4-12, possibly due to tension building up against the endplates of the Supercontainer. Overall 2.2 kg of dry buffer mass is a small amount of 'eroded' material which will not compromise the buffer function. There were no larger pieces either so the risk of bentonite clogging the gap underneath the Supercontainer and possibly compromising the DAWE drainage is most likely small. It should be noted that the material collected was very wet, and have collected condensate water, 1.4 kg, thus the total condensated water is likely closer to 2.6 kg rather than the 1.16 kg collected.

Dismantling and analysis

The dismantling was initiated right away after the heaters had been turned off and the Supercontainer rose vertically. It was noted that there was a quite extensive cracking pattern on the outer surface of the rings and as mentioned earlier, flaking at the Supercontiner end blocks, Figure 4-12. The cracking was mainly on the surface, however, there were a few cracks going all the way through the rings and some ending a couple of centimetres inside the blocks.

Core holes were drilled in the top and bottom blocks for sampling, and sheets of bentonite were sawed out from the rings, Figure 4-13. The samples were cut down further and water content and dry density measurements taken.

Figure 4-14 gives an example of the water content profile in ring R5, downwards and Figure 4-15 illustrates the dry density in the same direction. It can be seen that the surface against the canister has dried to some extent. The outer buffer surface towards the air void, between the supercontainer and the transport tube has also dried but actually more than the inner surface. The model predicted an opposite situation and it is currently not fully explained why the outer surface seems to have dried faster, however, it could possibly be due to the air circulation outside of the blocks.

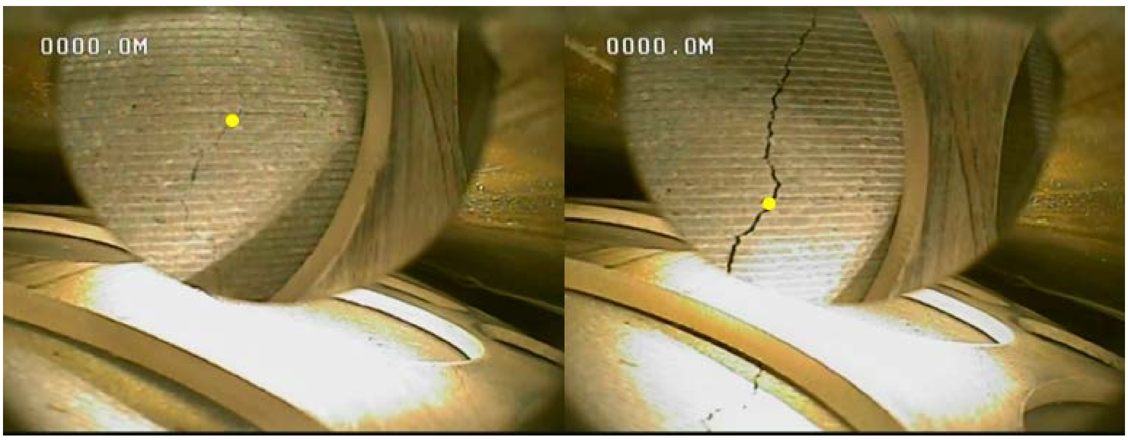

Figure 4-11. *Left, a photo from Wednesday the 28th September (2 days of heating with 1 700 W), and to the right a photo from Thursday the 29th September (3 days of heating with 1 700 W). The yellow dot is a reference point for comparison.*

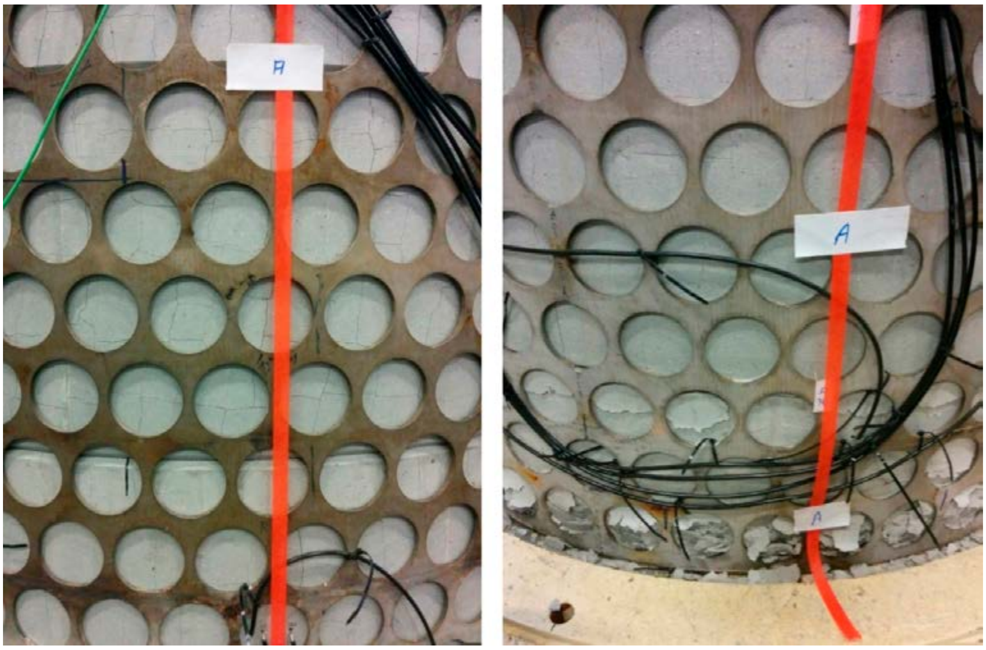

Figure 4-12. *Left, cracking pattern on outer surface on the rings, right, flaking on the bottom block, C1.*

Figure 4-13. *Taking samples from the buffer rings.*

With respect to density, the changes follow the changes in water content quite well.

All measurements in the supercontainer show similar patterns although there is less drying on the outside of the blocks towards the sides and upwards of the buffer (when horizontal). The overall changes in water content are small, which is in line with the model. However the cracking was more extensive in the test than the model had predicted. Cracking is known to be difficult to predict, but the heated supercontainer test has provided additional data for further modelling development.

Results

The heated supercontainer test has provided valuable experiences on how the heat from the canister influences the supercontainer buffer during assembly and deposition. It is clear that the buffer will start to dry, however, the changes are limited over the short time periods that are of interest for the KBS-3H design.

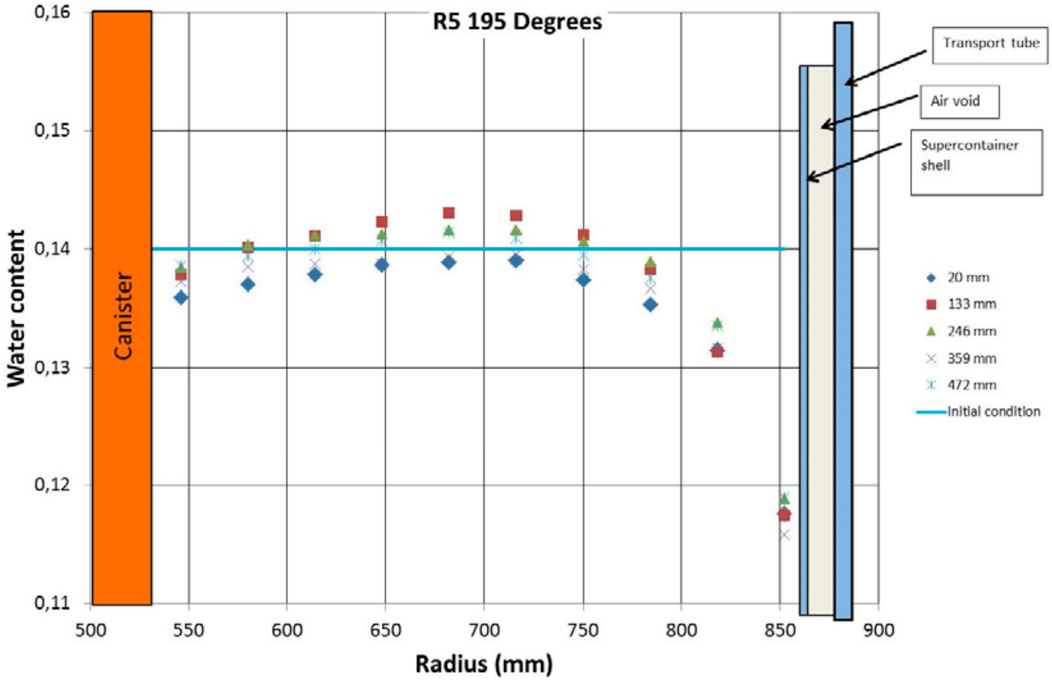

Figure 4-14. *Water content data from ring R5, downwards, on the side where the canister leans on the buffer surface.*

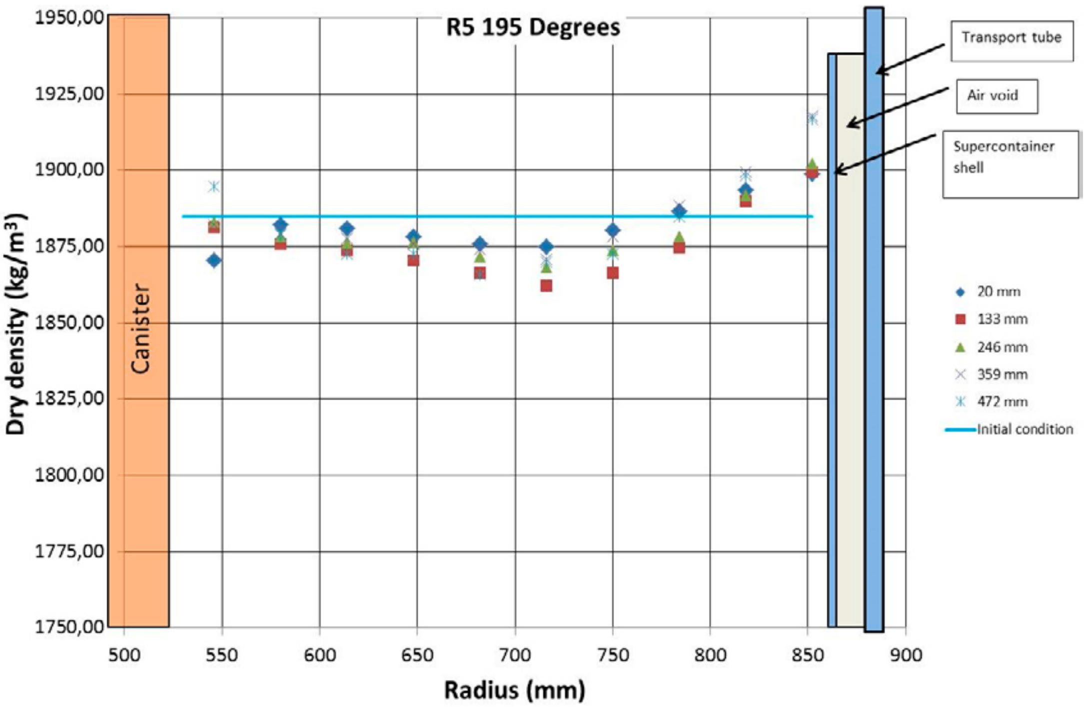

Figure 4-15. *Dry density data from ring R5, downwards, on the side where the canister leans on the buffer surface.*

It is also clear that the buffer surface will start to crack inside the supercontainer before the DAWE water filling can be carried out, however, the supercontainer shell seems to maintain the integrity of the component very well and the buffer mass loss should not compromise the required buffer densities and the buffer that may fall on to the deposition drift floor will most likely be so limited that it will not clog the drainage underneath the components. If KBS-3H development is continued tests could be carried out where bentonite flakes are dropped in a deposition drift at different water flow rates to assess and ensure that there is no risk of dams building up.

The test has also provided lots of valuable data in support of future model development.

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 1 110). A further year of artificial hydration occurred (Stage 3, day 1 110 to 1 385), followed by a more complex programme of gas injection testing in filter FL903 (Stage 4, day 1 430–2 064). In late 2010 attention moved from the lower array filter (FL903) to the upper array (FU910). Stage 5 started on day 2 073 and was completed on day 2 725. Focus then returned to the lower array (FL903) in late 2012 and involved a gas injection test throughout 2013. In 2014, the focus of the experiment was to determine the hydraulic properties of the bentonite buffer at all measurable locations by means of two-stage hydraulic head tests. 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 (Figure 4-16). A deposition hole, 8.5 m deep and 1.8 m in diameter, was drilled into the gallery floor. A full-scale KBS-3 canister (without heater) has been emplaced in the hole. Thirteen circular filters of varying dimensions are located on the surface of the canister to provide point sources for the injection of gas to mimic canister defects. Pre-compacted bentonite blocks with high initial water saturation have been installed in the deposition hole. The hole has been capped by a conical concrete plug retained by a reinforced steel lid capable of withstanding over 5 000 tonnes of force.

In the field laboratory instruments continually monitor variations in the 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.

Results

During 2016 (day 3 985 – day 4 351) the test programme of Lasgit continued a phase of prolonged "hibernation" with moniotoring of the natural and artificial hydration of the bentonite buffer. For the majority of the year, the buffer was monitored for natural hydration only. Artificial hydration, aimed at aiding the hydration of the buffer, was restarted in October. However, in December the decision was taken to cease artificial hydration and to continue to monitor the natural maturation of the buffer.

Figure 4-17 shows the complete history of the Lasgit experiment and shows that stress is continuing to increase in the deposition hole, although since artificial hydration has been ceased it could be argued that stress has equilibrated and only shows signs of annual cyclicity. Pore pressure within the bentonite buffer continues to increase, although the rate of increase has slowed since the cessation of artificial hydration. It may take several more years to equilibrate with the pore water within the host rock. The reduction in pore pressure of the host rock as a result of draw-down from the tunnel excavation has continued.

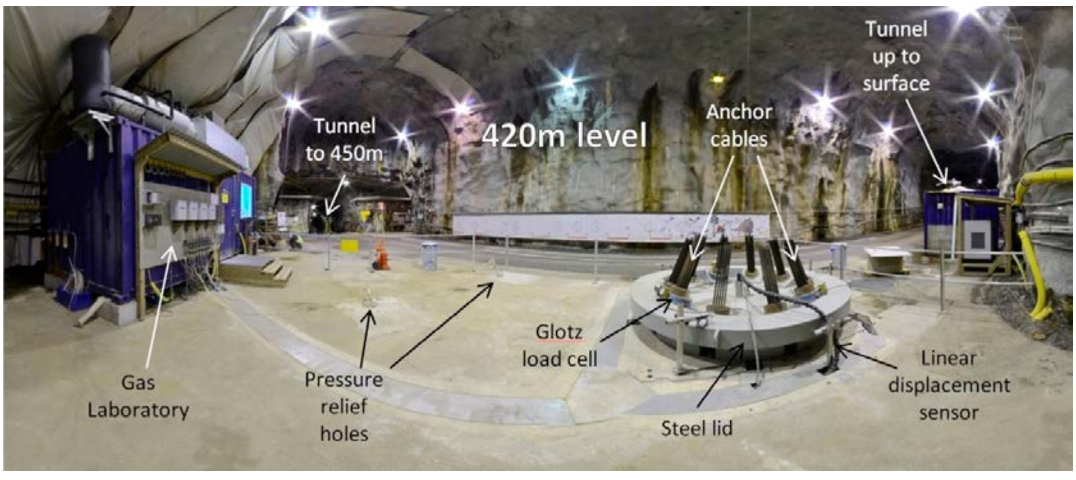

Figure 4-16. *The Large scale gas injection test at the −420 m level in Äspö HRL.*

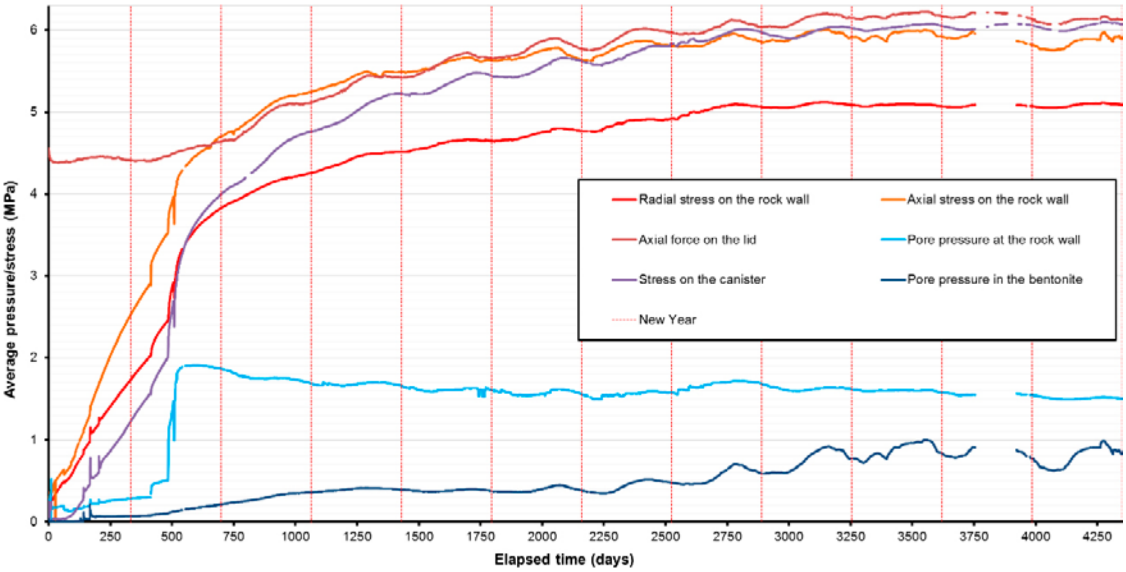

Figure 4-17. *Average pore water pressure and stress readings up to the end of 2016. As can be seen pore water pressure readings at the deposition hole wall has been decaying since day 500 due to the draw-down of the Äspö HRL due to pumping of the galleries. Stress, axial force and radial stress at the rock wall all continue to increase as the buffer matures, although these have nearly reached plateau.*

A visit to the Äspö HRL in September by project staff serviced the Lasgit experiment and commissioned a replacement pneumatic control valve board. This system replaced the life-expired board that had been in continuous operation for over 10 years. All syringe pumps and the Lasgit PC were also serviced in readiness for the next phase of testing.

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 in a failure scenario. After failure of the outer copper shell, the course of the corrosion in the gap between the copper shell and the cast iron insert will determine the subsequent release of radionuclides. A possible scenario is that the formation of solid iron corrosion products could exert an internal load on the copper shell, which could lead to deformation. This process has been studied earlier both in laboratory experiments (Bond et al. 1997) and by modelling (Smart et al. 2006).

In the MiniCan *In Situ* test, 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 and allow corrosion of the iron insert, millimetre defects were introduced into the outer copper shell. 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 to provide information about; 1) how the environment inside a copper-cast iron canister would evolve if failure of the outer copper shell was to occur, and 2) how microbiological activity affects canister corrosion. The results of the experiment will be used to support process description in the safety assesment.

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 layout

In late 2006, five experimental packages containing 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 4-18), 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 experimental package 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.

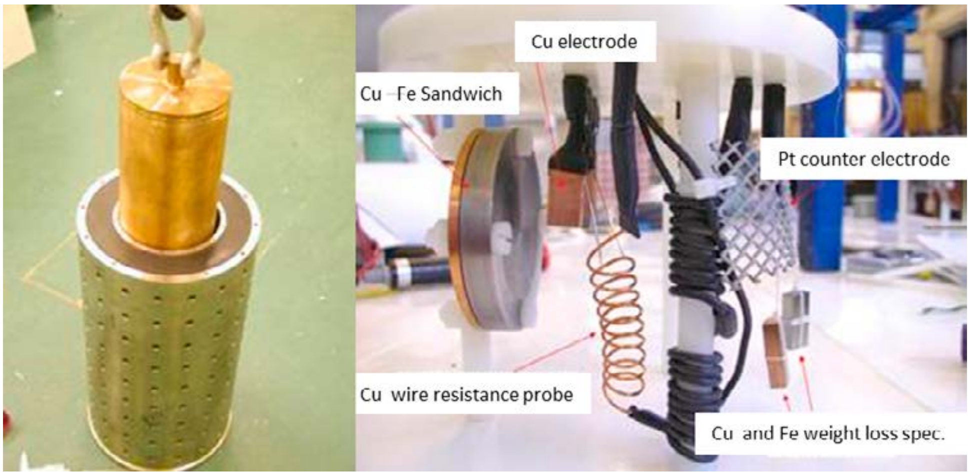

Figure 4-18. *Model canister being lowered into support cage containing bentonite pellets in annulus (left). Test electrodes inside support cage around model canister experiments (right).*

The boreholes are located in a region with many fractures, leading to a plentiful supply of groundwater to the canisters. The experiments are continuously monitored to measure the following parameters:

- Corrosion potential of the model canister, cast iron and copper.
- Electrochemical potential of gold, platinum and a mixed metal oxide Eh probe.
- Corrosion rate of cast iron and copper, using linear polarisation resistance (LPR), AC impedance (ACI), electrochemical noise (ECN), and the electric resistance in a copper wire.
- Strain on the surface of two of the model canisters.
- Hydrostatic pressure in the boreholes.

Water samples are taken 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).

Results

Three packages from the MiniCan series have been retrieved and examined. The first package to be retrieved was MiniCan 3 in 2011, and in late 2015 both MiniCan 4 and 5 were retrieved.

During 2016 the packages of MiniCan 4 and 5 were examined regarding corrosion and microbiology. Comparisons were made with the results from the previous examination of MiniCan 3, since the three retrieved packages differ regarding the presence and density of the bentonite clay. Preliminary results were presented at the conference *Long-term prediction of corrosion in nuclear waste systems*, in May 2016 in Toronto. The final results are to be published in a scientific journal as well as technical reports during spring 2017.

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.

4.6 Concrete and Clay

Background

In the present SFR and future repositories for low- and intermediate level waste; SFL and SFR 3, 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 understanding of processes that may occur in SKB's repositories for low- and intermediate level waste, the final repository for short-lived radioactive waste, SFR, and the future final repository for long-lived radioactive waste, SFL.

Objectives

The objective of this project is to increase the understanding of the processes occurong 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 (Ø270 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.

The project was initially expected to run for up to 30 years but some of the experiments prepared in 2010 have now been retrieved and analysed. 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 2010 also 20 steel containers containing cement buffered Äspö water and material specimens representative of low- and intermediate level waste were prepared. About half of these containers were stored at 50 °C in a temperature controlled water bath and the remaining simply under a protective roof in the Äspö tunnel at a temperature of about 13 °C.

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 expeiments are now deposited in 5 different deposition holes in TAS06.

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

Analyses of decomposition of organic materials in cement buffered Äspö water

During 2016, 12 of the steel containers, Figure 4-19, containing organic material were opened and the water in them analysed for the presence of degradation products from the material specimens (Dvinskikh et al. 2016). Both samples stored at 50 °C and at 13 °C were analysed. All samples were studied by solution state NMR but for some containers, a piece of the solid material was also studied by means of solid state NMR.

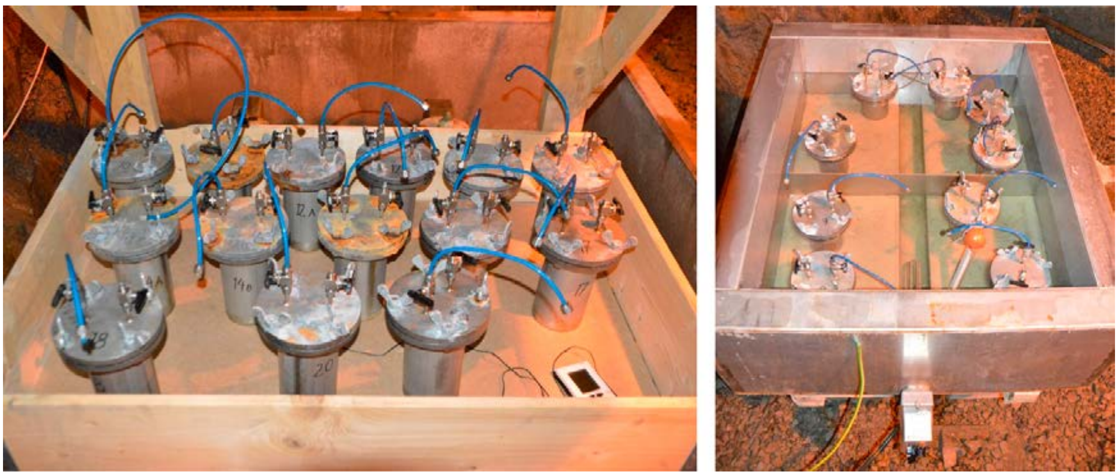

Figure 4-19. *Steel containers with material specimens representative for low- and intermediate level waste stored in the Äspö tunnel.*

The NMR spectra of samples from cylinders containing cellulose (cloth from an overall), carboxylate ion exchange resin and filter aid (UP2) showed signals indicating only a minor degradation of the materials. In these samples no structural assignments of the molecules present were possible due to low concentration of the compounds formed.

The diffusion data, however clearly suggest the formation of a number of different small molecules. Their concentrations are approximately the same and in the micro molar range. Because of their very low concentration it was assumed that their complex formation in the pH range of the test solutions (11–12) with radioactive actinide or lanthanide isotopes is negligible and cannot contribute to migration of these isotopes in nature.

In containers containing rubber gloves several organic compounds were identified regardless of whether the containers were stored at 13 °C or 50 °C. The NMR spectra were practically identical and showed signals from the same compounds. That indicates that difference in the storage temperature has no effect in this case. It was also concluded that the identified carboxylic acid derivates or alcohols are in accordance with well-known plasticisers (or softeners) and not from degradation of the rubber itself.

4.7 Low pH-programme

Background

The low-pH programme is subject to the progressive development of low-pH materials for different application areas in the Spent Fuel Repository. Current design premises and requirements on the Spent Fuel Repository assume use of low-pH materials for ensuring that leaching products do not adversely affect the bentonite in buffer and backfill. Low-pH materials have been developed for grouting, rock support and plugs for deposition tunnels. However, construction, operation and closure of the Spent Fuel Repository covers long periods of time, which means that the availability of products in the current mix designs will change over time. For this reason it is of importance that the low-pH materials are designed in such a way that the material properties will not be dependent on a specific product and that constituent components can be replaced with products with similar properties.

Objectives

The purpose of the low-pH programme is to develop robust low-pH materials within two areas in the Spent Fuel Repository; low-pH concrete for the plug system for deposition tunnels and low-pH materials for grouting and rock support. The focus of the development work is to ensure that the current mix designs are made robust towards changes in the availability of the constituent components. Furthermore, the programme focuses on developing industrially adapted methods for fabrication and inspection of cementitious low-pH materials.

Experimental concept

In order to achieve robust low-pH materials for the Spent Fuel Repository, studies are being conducted where the goal is to state clear requirements on the fundamental properties of constituent components. As a result the low-pH materials will not be dependent on a specific product. Current mix designs are therefore made more robust towards changes in the availability of constituent components such as cement or additives. This also means that the need for extensive testing and verification is reduced when availability of products for constituent components change.

Experiences from previous work within the programme and also follow-up work on performed field tests are important to take into account when developing robust low-pH materials and to meet set requirements.

Within the programme a low-pH concrete, B200, has been developed for the unreinforced concrete dome within the plug system (Vogt et al. 2009). A full-scale test of the plug system was performed in 2013 in Äspö HRL using the B200 concrete (the Domplu experiment), which showed that it was possible to construct the plug system in an appropriate manner and that the B200 concrete met performance requirements (Grahm et al. 2015). As part of the full-scale test a monolith of the B200 concrete was also casted so that long term properties of the concrete could be investigated and evaluated. The programme will follow the changes in material properties by taking core samples from the monolith during three years or more if needed. Material sampling and measurements will also be carried out when the plug is to be excavated in 2017. All results from field tests will be evaluated and serve as a basis for further development work.

Low-pH cement material for grouting (Bodén and Sievänen 2005) and rock support (Bodén and Pettersson 2011) has been developed. In 2009 rock bolts were installed with low-pH grout in Äspö HRL. 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. In addition, corrosion on embedded steel in both low-pH concrete and conventional concrete is also being studied in Äspö HRL. In total, 24 samples are placed in an open container in a niche in Äspö HRL. The results of corrosion tests after one year of exposure are reported in a SKB report (Bodén and Pettersson 2011).

Results

In 2013, three of the installed rock bolts in Äspö HRL, two horizontally and one vertically emplaced, were over-cored and investigated. Due to demanding and time consuming work only one vertical bolt was over-cored. The corrosion behaviour of the bolts after five years of exposure in the field was investigated and showed no signs of corrosion (Aghili 2014). In addition, six concrete samples containing three steel bars each, were also investigated during 2013 following the corrosion experiment. A comparison between the steel bars embedded in low-pH concrete and conventional concrete, both in presence of chlorides and without chlorides was done. Results are presented in 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 in 2018 and the date for the last investigation will be settled with respect to the results from the investigation in 2018.

Concrete samples taken from the monolith that was casted as part of the full-scale test in Äspö HRL has been evaluated with regard to compressive strength after 28, 90, 120 and 180 days. Also the modulus of elasticity has been determined in some cases. All results are presented in Mathern and Magnusson (2015). The programme will continue to take out core samples from the monolith and evaluate them together with ongoing long term investigations, i.e. creep investigations. Investigations will be published in the future.

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 following tasks has been ongoing or finalized during 2016:

- Sensitivity analysis.
- Homogenisation.
- Task 8 (common with TF Groundwater Flow).
- Prototype Repository.

The following tasks have been initiated during the year:

- Water transport in pellets-filled slots.
- Febex in-situ test.
- Gas transport in bentonite.

Participating organisations are besides SKB at present BMWi (Germany), CRIEPI (Japan), NAGRA (Switzerland), Posiva (Finland), RAWRA (Czech Republic), RWM (England) and DOE/UFD (USA). All together approximately 10 modelling teams are participating.

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 2016; one in Prague on May 9–12 and one in Oxford on November 15–17.

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. 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.
   c. Elastic material behaviour + linear swelling of bentonite (isothermal).

Five modelling teams have presented results on this task during 2016: SKB-1/ClayTech using COMSOL Multiphysics; RWM/Amec using TOUGH2-FLAC3D; CRIEPI using LOSTUF; The CodeBright Consortium at UPC (Polytechnic University of Catalonia); and BMWi/BGR using the code OGS. The task is now considered to be finished except for reporting.

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 September 2012 and dismantled during the winter of 2013/2014. This task is divided into several subtasks (T8a–T8f). The project is described in more detail in Chapter 3.

Four modelling teams submitted final reports on Task 8 during 2016. Review comments on these from the task reviewer were distributed in November 2016. A workshop on uncertainty and comparative analyses was held during the taskforce meeting in May 2016. Three modelling teams have presented results on this task during 2016: SKB-1/ClayTech using Code_Bright; RAWRA/TUL using the code Ansys; and RWM/Amec using ConnectFlow and TOUGH2.

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.

Three teams have presented results on this task during 2016: SKB-1/ClayTech using a new developed material model (implemented in MathCad); SKB-2/ClayTech using a porous elastic and the Plastic Cap or Drucker-Prager model (implemented in Abaqus), and Imperial collage using a BBM (Barcelona Basic Model) type model (implemented in ICFEP, Imperial College Finite Element Program). The task is now considered to be finished except for reporting.

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 presented results on this task during 2016: SKB-1/ClayTech using Code_Bright; CRIEPI using LOSTUF; RAWRA/TUL using Ansys; RWM/Amec using ConnectFlow.

Water transport in pellets-filled slots

The aim of the task is to develop models for water transport in pellet fillings and to calibrate and check their ability to model water transport at different boundary and inflow conditions and at different temperature situations. The task consists of four subtask:

- A. 1D-tests with water freely available (water uptake tests).
- B. Constant water inflow rate from point inflow.
- C. 1D-tests with water redistribution in a temperature gradient.
- D. 1D-tests with water freely available in a temperature gradient.

The status of the laboratory program for this task is the the tests for subtask A is mostly fulfilled according to the plans, and that only a limited number of tests have been made for subtask C. There is currenty no budget for more tests.

The tests are performed by Clay Technology, Sweden. A task description and a compilation of experimental results were distributed in September 2016. Two modeling teams began to work on this task during 2016: SKB-1/ClayTech using Code_Bright; and SKB using Comsol Multiphysics.

Febex in-situ test

The aim of the task is to model the THM behavior of the buffer in the Febex in situ test at the Grimsel TS, Switzerland, and addresses the evolution and distributions of temperature, relative humidity and stresses; special attention will be given to the prediction/reproduction of the state of the barrier after dismantling. Full material characterization information on FEBEX bentonite and Grimsel granite will be provided. The work to be performed in the Task has been divided into 2 stages:

- Stage 1: Operational period of the FEBEX experiment up to and including the dismantling of the first heater (5.0 years).
- Stage 2: Operational period of the FEBEX experiment after the dismantling of the first heater up to and including the final dismantling of the test (13.2 years).

A task description was distributed at the end of the year. Sensor measurments and dismantling data was made available at the same time. No modelling team started to work with this task during 2016.

Gas transport in bentonite

The aim of this task is to survey existing modelling tools for simulation of gas percolation in bentonites, to compare different modelling approaches; and to complement existing modelling capabilities. The task consists of two subtask:

1. Calibration of hydro-mechanical models for the behaviour of unsaturated bentonite.
2. Verification & Validation of coupled hydro-mechanical response of bentonite during water saturation and gas injection under oedometer conditions.

Tests are performed by UPC, Spain. A task description was distributed in August 2016, and a data package was made available in September 2016.

Three modeling teams began to work on this task during 2016: EPFL using the code Lagamine; UPC using Code_bright; and Intera using the code TOUGH2.

Geochemistry

At the spring meeting in Prague, Martin Birgersson acted as surrogate chairman (Urs Mäder was unfortunately unable to attend). He started the chemistry session by giving an overview of the benchmarks, as well as discussing different concepts adopted for modelling them. Martin Birgersson then continued by presenting new model results of benchmarks 1, 2 and 5, including ion pairs within an interlayer only approach. He demonstrated that taking ion pairs into consideration may be necessary even if their amount is negligible in any external solution. Eva Hofmanová continued the session by presenting new experimental results on through-diffusion of chloride, selenate, and iodide in B75 bentonite. She demonstrated that the diffusive behaviour is basically identical, independent of whether the target solution is kept at similar ionic strength as the source solution, or if it is kept ion free. In addition, Eva Hofmanová presented results on iodide through-diffusion in Cs-converted bentonite. She demonstrated that the effective diffusion coefficient is considerably larger in Cs-bentonite in comparison to (sodium/calcium dominated) untreated bentonite at the same ionic strength. Both of the presented results are in agreement with predictions of an interlayer-only view of bentonite. Andreas Jenni presented work on transport modelling across claystone interfaces. Specifically, he addressed the issues of “plugging” the interface due to chemical precipitation, and the numerical challenges of treating interfaces using a dual-porosity approach. Martin Birgersson then presented a talk on behalf of Andrew Hoch regarding ongoing work on implementing the “homogeneous mixture model” in a numerical transport code. The model combines ion equilibrium theory with multi-component transport. Magnus Hedström discussed ion equilibrium theory and the role of anions in montmorillonite. He showed that result of molecular dynamics (MD) simulations agree qualitatively with that of “Donnan theory”, and that including activity corrections in the latter is meaningful. He continued by demonstrating that the so-called effective diffusion coefficient may be infinite or negative under certain conditions. In principle this would allow for an uphill diffusion effect for anions. Ola Karnland presented an overview of the LOT-test, which has been under consideration for modelling in the Task Force. Finally, Paul Wersin presented work on deriving bentonite reference porewaters, using different types of porosity concepts, as part of the safety assessment of Posiva. He showed that the composition of the “free water” becomes very simila, independent of whether the concept of anion-free interlayers or that of a “Donnan space” is invoked.

At the fall meeting in Oxford, Urs Mäder started the chemistry session by giving an overview of the "issues" of concern, and the current benchmarks on which modelling work is or has been performed. Andreas Jenni presented a literature review on porosity, hydraulic conductivity and swelling pressure in bentonite, and how these quantities are influenced by chemistry. Then Radek Cervinka presented new modelling work performed on benchmark 3 (Ca/Na ion exchange on compacted montmorillonite) using phreeqc. Eva Hofmanová presented new experimental work, which extends the data set of benchmark 5. The results concerned through-diffusion of nitrate in B75 bentonite, and it was shown that the effective porosity for nitrate was approximately twice as large as that for iodide and chloride. This effect is difficult to explain using a multi-porosity approach, since these ions have the same charge. Using the interlayer-only approach, the effect is principally explained by differences in activity coefficients for these ions in the interlayer pores. Eva Hofmanová also presented results of iodide and nitrate diffusion in potassium exchanged bentonite. While the iodide effective porosity was about twice as large in K-bentonite as compared to the untreated B75 bentonite, the difference in effective porosity for nitrate was not very large. Finally, Eva Hofmanová presented results also for nitrate diffusion in Cs-exchanged bentonite. At density of approximately 1 500 kg/m^3 and an ionic strength of 0.1 M, the effective porosity for nitrate in this system was shown to basically equal the total porosity, i.e. there appears to be no "exclusion" of nitrate in this system. Again, this is difficult to explain using a multi-porosity approach. Andrew Hoch continued the session by giving an update on the ongoing work of implementing a numerical tool for transport of ions in interlayers in compacted bentonite. He discussed how the hypothesis that solute transport occurs through interlayers leads to a natural explanation of the permeability and swelling pressure. This description is thus a candidate for a description of coupled HMC-processes. Magnus Hedström continued by presenting MD simulations which studied interfaces between charged (montmorillonite) and uncharged surfaces, which special focus on pressure. The study of such interfaces is highly relevant i, since they are expected to appear e.g. at interfaces to accessory minerals in the buffer, as well as to the metal canister. In the simulations, two initially tri-hydrate interlayers – one between montmorillonite-montmorillonite, and another between montmorillonite-pyrophyllite – were exposed to a force and the dehydration of the interlayers were observed. As part of an ongoing discussion regarding a new benchmark tests on so-called hyper-filtration (reversed osmosis), Mattias Åkesson gave an overview of water-uptake lab tests made within the BRIE project (results will be available in report R-14-11). Focus were on the distribution and of salt in these tests, and analysis of dissolved salt appear to support the notion of Donnan equilibrium at bentonite/filter interface and accumulation (i.e. hyperfiltration) in the filter. The test is accurately controlled, and a quite a lot of data is available, and is therefore a candidate for a benchmark on the hyperfiltration effect. Finally, Martin Birgersson gave a presentation on the suitability to use the LOT-experiment as a benchmark. He concluded that the LOT A2 parcel was not in equilibrium with the groundwater during the course of the test, and that the only clear-cut effect in this test is the redistribution of sulfate in the hot parts. He speculated that in order to model this effect, it may be needed to take into account the unsaturated state (i.e. a gas/vapor phase).

4.9 System design of plug of deposition tunnel

Background

In a few years, SKB plans to start construction of the Spent Fuel Repository in Forsmark. Approximately 200 horizontal deposition tunnels, singly with up to 40 vertical deposition holes for canisters, will be needed in the Swedish KBS-3 programme and each tunnel will be sealed by an end plug. Between 2010 and 2015, SKB and Posiva (Finland) conducted system design development of the dome plug and a full-scale experiment (DOMPLU) was installed in the Äspö HRL during 2013.

The deposition tunnel end plug consists of an arched concrete dome, a bentonite seal, a filter zone and material delimiters between each layer, see Figure 4-20. 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. The design basis for the plug has been presented by Malm (2012). The dome plug is designed to withstand 2 MPa of swelling pressure and in addition 5 MPa water pressure. At the total design load of 7 MPa the plug must resist both displacement and leakages to prevent damages on the bentonite buffer and backfill. A design requirement is therefore to allow at most 200 m^3 of water leakage past the plug until the backfill in the tunnel has been saturated.

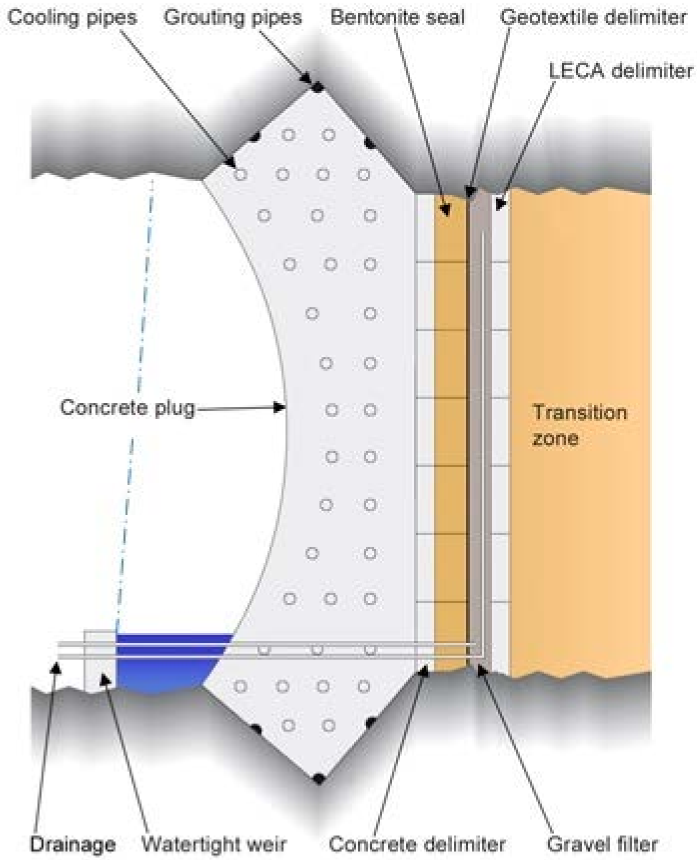

Figure 4-20. *Layout of the full-scale experimental set-up DOMPLU.*

The DOMPLU test been monitored since 2013 and has so far successfully demonstrated the system design, construction and performances of the dome plug. Results presented by Grahm et al. (2015) shows that the plug has good potential to be utilized in a crystalline-rock repository but will still need further verification and optimizations before the detailed design can be announced.

Below, a description is given of the experimental set-up and the monitoring of leakage past the plug until 2016-12-31. Furthermore, a plan is presented for the final phase of the system design during 2017–2018, including study of gas tightness, high-pressure testing of the mechanical strength, dismantling, sampling and evaluation of the plug.

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 main goal of the full-scale test DOMPLU is to determine leakage through the plug (and the contact surfaces between the rock and the concrete) at a water pressure representative to the hydrostatic groundwater pressure in the repository. Accordingly, water has been injected inside the plugged volume at a pressure of 4 MPa.

In the final project phase, i.e. at the end of the measurements just before dismantling of DOMPLU, the plan is to perform a load test close to the design load of at least 7 MPa of total pressure.

Experimental concept

The experimental site for DOMPLU is located at Äspö HRL −450 m level, which is a representative depth for the deposition area in a KBS-3 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 remainder of sensors monitor 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. 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 experimental set-up is shown by Figure 4-20.

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 (2014). In Figure 4-21 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 4-21 were filled by mortar before casting of the dome.

The installation of the inner plug components began in late 2012 and was completed in the beginning of 2013 see Figure 4-22 and Figure 4-23. 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).

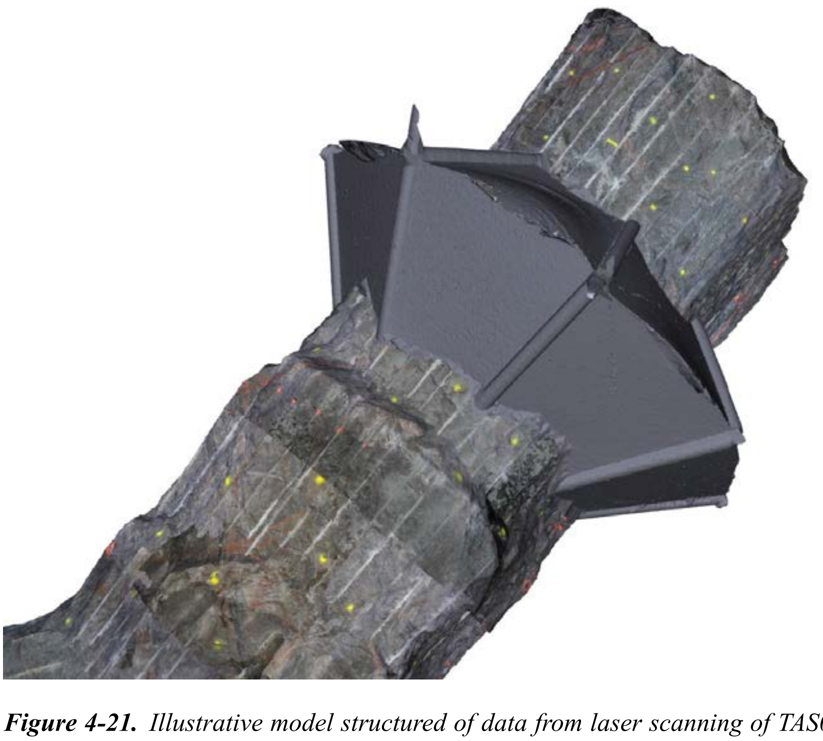

Figure 4-21. *Illustrative model structured of data from laser scanning of TAS01 as well as of the excavated slot abutment (seen from above).*

Figure 4-22. *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 4-23. *Installation of concrete beams, bentonite seal, gravel filter and sensors.*

On March 13, 2013 the casting of the concrete dome took place, see Figure 4-24. The use of the B200 concrete (Vogt et al. 2009) was evaluated by Magnusson and Mathern (2015) to have been successful for the 94 m^3 structure. Dismantling of the formwork began three weeks after casting. The exposed dome structure is seen in Figure 4-25. In June 2013, about 100 days subsequent to casting, to await the early concrete shrinkage, contact grouting was performed over three sections of the dome to close any gaps in the concrete – rock interface. A cooling system was used to to contract 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 dismantling and the detailed design phase.

Figure 4-24. *Concrete is pumped in behind the formwork for casting of the concrete dome structure.*

Figure 4-25. *The hardened concrete dome structure after removal of formwork. The steel beams in front of the dome are used for displacement sensors.*

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 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 4-26.

As seen in Figure 4-26, initially about 1 600 ml/min injection water was needed to keep the 4.0 MPa water pressure in the filter. After three years of plug operation, just about 120 ml/min is 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. (The jumps in the purple line are due to different calibration of one pump).

The mesasured leakage rate collected in the weir (green line in Figure 4-26) has been steadily reduced. On September 30, 2014 (month 12), the recorded leakage rate was about 2.6 litres per hour (43 ml/min). Subsequently Grahm et al. (2015) reported that the leakage rate is believed to decrease further since the swelling pressure of bentonite seal will continue increasing for a couple of years. On December 31, 2016 (month 36), the leakage rate had decreased further to 1.8 litres per hour (30 ml/min).

The monitored swelling pressure (total pressure minus pore pressure) in the bentonite seal has increased slowly with time as expected. In December 2016, the swelling pressure ranged between 200 and 1 300 kPa. A fully watertight function of the seal is expected only from about 500 kPa of swelling pressure.

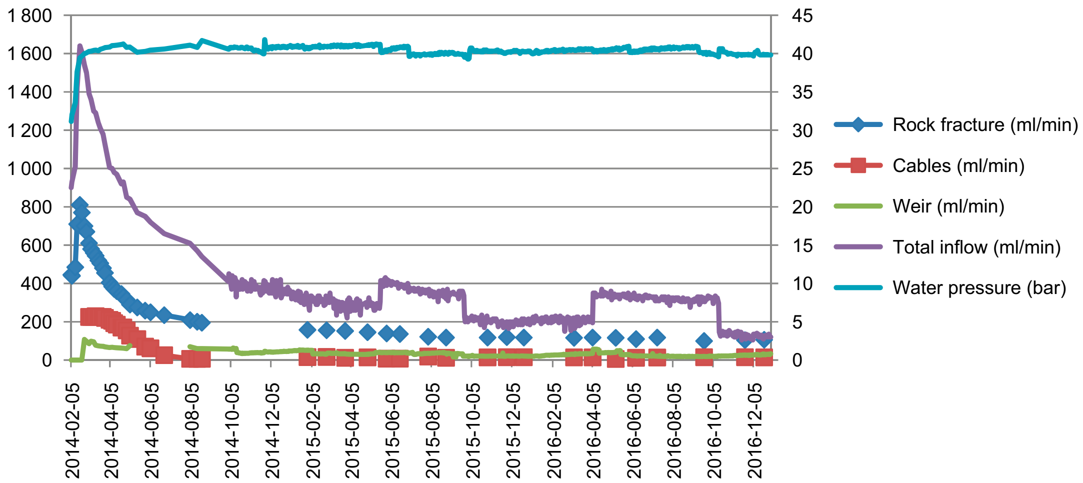

Figure 4-26. *Measurements of leakage together with total water injection flow needed to keep the water pressure stable near at 4 MPa (about 40 bar).*

Monitoring of the concrete dome has 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.

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 late 2017.

Future plans

Beginning in late 2017, the DOMPLU experiment will be interrupted, dismantled and evaluated. This project phase will increase the level of knowledge for plugging of deposition tunnels so that design basis can be set for a detail design of a new dome plug, used in a future system integration test at SKB.

Project objectives are specifically to:

- Investigate if the plug is gas tight.
- Perform a strength test (by increased pressurization to at least 7 MPa) of the concrete dome and investigate leakage paths.
- Breach the concrete dome and conduct various sampling of materials and material interfaces.
- Analyse and evaluate results from the dismantling activities.
- Evaluate and report the monitoring phase 2014–2017.
- Update the design specifications (bottom level in the requirements database).

More generally, the project outcomes can be used by the international waste management community to enhance the design, construction and quality management practices for future tunnel plugs used in various types of repository configurations and geological conditions.

4.10 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 reported in the previous report. The second installation test was dismantled in the autumn of 2016 and is desctived in this report.

Objectives

The objective of the tests are to test and develop the suggested buffer installation method.

Experimental concept

The buffer protection was developed based on knowledge from laboratory scale tests, the first full scale tests and modelling. In Figure 4-27 the buffer protection desing is shown.

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 outer gap was filled with bentonite pellets. The test was conducted with a full scale canister with a power of 1 700 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 from the installation are shown.

Results

The test was installed as intended but already during the test it could be concluded that it did not develop as predicted. A camera was lowered into the outer slot between the rock and the buffer blocks and the video showed pronounced cracks in two top bentonite rings.

The unexpected fracturing of the blocks could be explained when open fractures between the inner and outer slot was introduced in the numerical model. The simulation showed that for some fracture widths hot air would flow from the hotter inner slot to the outer slot. The temperature of the air decreases enough to cause condensation of water at the outer parts of the bentonite blocks, see Figure 4-28. The condensed water then caused swelling and cracking of the bentonite rings. The magnitude of cracking where parts of the blocks fell into the outer slot is not considered to be acceptable since it obstructs the pellets installation and thereby yields a lower installed buffer density.

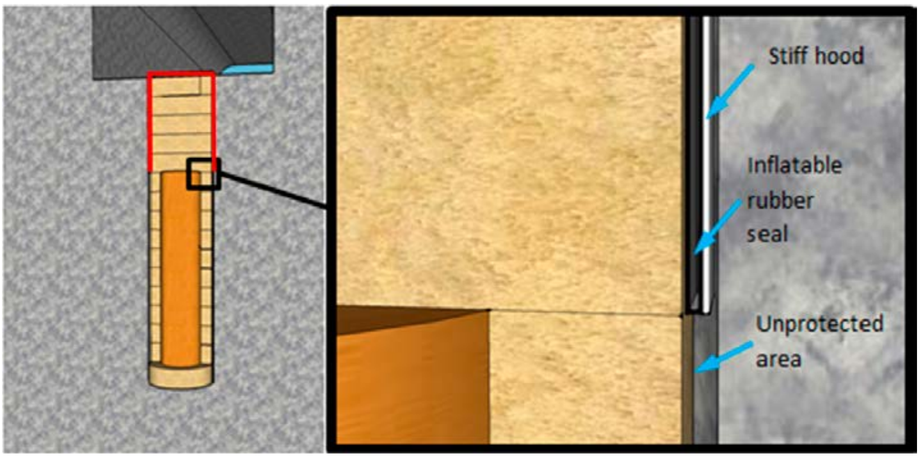

Figure 4-27. *The design of the developed buffer protection.*

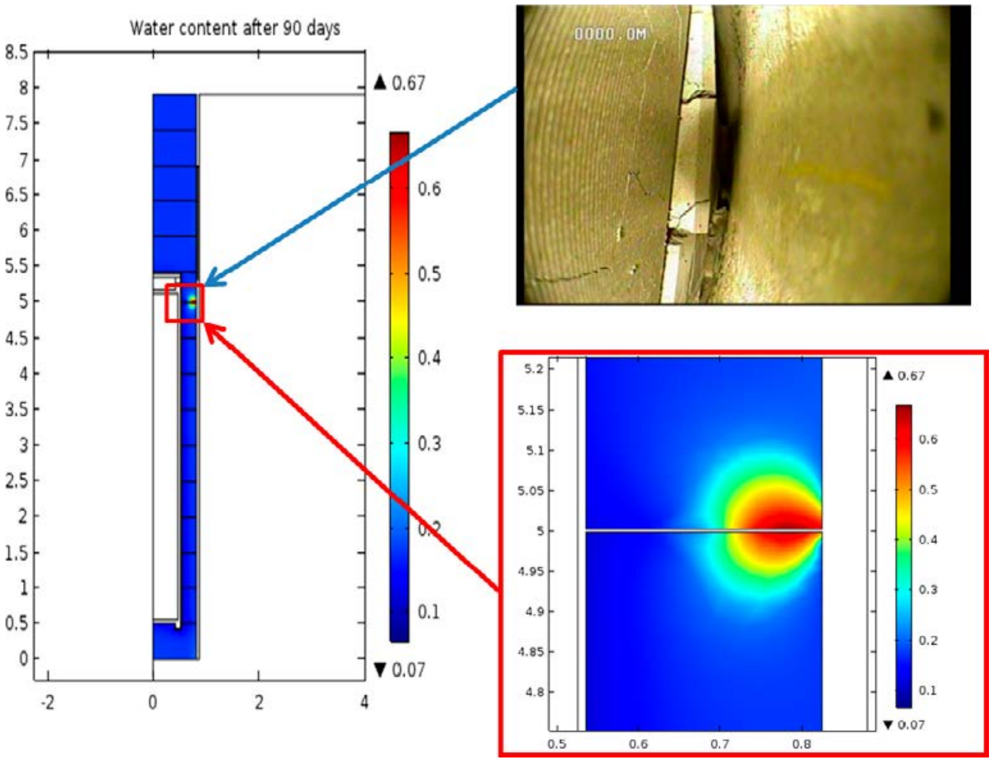

Figure 4-28. *The location of the fractures and the modelled global water content distribution (left), a photo of the fractures (top right) and the modelled water content distribution in the volume of fractures (down right). The photo is taken from above with a wide angle lens looking down into the hole.*

The results from the test 2 in combination with the increased understanding of the early THM processes made it evident that the developed buffer protection does not result in a robust installation process.

Based on the predicted water inflow to the deposition holes and the results from test 1 this installation method (no buffer protection and block and pellets installed at the same time) will give a robust installation for about 6 000 deposition holes in the planned repository in Forsmark. If the installation sequence is modified so that the deposition holes with water inflow > 1E–4 m/s are installed in conjunction with the backfilling of the tunnel the majority of the remaining deposition holes can also be used for deposition.

4.11 Large scale casting test of 2BMA cassions

Background

The repository for short-lived low- and Intermediate level waste, SFR, was taken into operation in 1988. Today, the facility comprises 4 rock vaults and one silo in which short-lived Low- and Intermediate Level Waste, LILW, is disposed. An extension of the existing facility is now planned for disposal also of LILW from the dismantling of the nuclear power plants.

The SFR extension will comprise altogether 6 rock vaults: 4 rock vaults for low-level waste, one rock vault for reactor pressure vessels and one rock vault for intermediate level waste. In the rock vault for intermediate level waste, 2BMA, the waste will be placed in concrete caissons with the preliminary dimensions 16.2 × 16.2 × 8.2 meters with a thickness of the walls and bottom slab of 500 mm, Figure 4-29 (SKB 2014).

In order to verify that the suggested design solutions can be utilized and to show that the long term safety of the repository is likely to be ensured over the entire post-closure period an R&D programme has been initiated. The final task of this programme is the test casting of a fully instrumented representative section of a caisson in the Äspö Hard rock Laboratory using a newly developed concrete.

 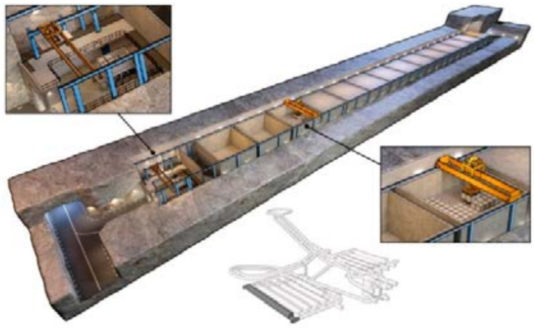

__Figure 4-29.__ The left illustration presents an overview of SFR after the extension has been finalised and the right image a more detailed illustration of 2BMA.

Objectives

The objective of this project is to verify the properties of the newly developed concrete in a large scale text casting and to investigate the design solutions suggested. The following main fields of interest have been identified:

- Confirm that the concete can be produced in a concrete production plant
- Verify that the properties of the concrete do not differ from those obtained in laboratory scale developement
- Verify that the properties of the concrete are not changed during transport and to verify that the concrete can be pumped using a standard concrete pump.
- Investigate the function of a friction reducing layer between a precast concrete base slab and the representative section of the caisson on the strain levels, dimensional changes and fracture formation in the structure.
- Investigate the possible use of joint seals, the properties of the joints and their influence on shrinkage and fracture formation of the concrete structure.

Experimental concept

A representative section of the caissons planned for 2BMA was cast in TAS05 in the Äspö HRL. In order to ensure unrestrained shrinkage of the concrete structure a friction reducing plastic foil was placed on the concrete base slab which was cast in the tunnel early 2016, Figure 4-30.

__Figure 4-30.__ The tunnel (TAS 05) which was used for the test casting. In this image the tunnel has been prepared for test casting with a concrete base slab and means to secure the tunnel walls against rock fall-outs. The dimensions of the concrete base slab are 15 × 4 meters and the available tunnel height is about 4.5 meters.

The basis for the design of the representative section was a previous study of strain distribution in a full scale caisson caused by shrinkage of the concrete (Vogt 2014). In Vogt (2016) the design and dimensions of the representative section was further evaluated.

After calculations of the available space for the component considering space required for formwork and staff working around the formwork it was recommended that the component should be represented by a base slab with the dimensions 13.5 × 3 meters on which two L-shaped walls with a height of 3 meters should be erected, thus creating two corner sections of the full scale caisson. One of the walls was cast simultaneously with the base slab and the other will be cast in March 2017. As a preparation för the casting of the second wall, casting joints was placed in the base slab during the casting of the first section, Figure 4-31.

Results

Formwork construciotn and installation of sensors

The casting was performed on November 16 and was preceded by formwork construction in TAS05, installation of different types of sensors, Table 4-2, and final production scale tests and verification of concrete properties and a concrete production unit in Kalmar. The formwork is shown in Figure 4-32.

Table 4-2. Installed Sensors.

To be recorded	Number	Duration	Sensor type (example)
Ambient temperature	2	Long term	PT 100 or similar
Heat of hydration	20	Short term	Type T thermocouple
Temperature at strain transducers	12	Long term	Included in the strain transducer
Internal strain	12	Long term	Manufactured strain gauge transducers
Internal strain	12	Long term	TML KM 100 or similar with temperature registration
External deformation	8	Long term	HBM WA-T 10 mm or similar
Formwork pressure	3	Short term	Wika S10 or similar
Humidity	7	Long term	Vaisala HMP40S or similar

Casting

The casting comprised a total of 46 m^3 of concrete which was delivered in 6 concrete trucks from the concrete production plant in Kalmar. Initially the casting proceeded according to plans but soon a number of problems caused by delays and unexpected fast setting of the concrete was experienced.

In order to solve these problems and to improve the pumpability the composition of the concrete was slightly adjusted on site by the addition of additional water and/or additional superplasticiser. By these measures the casting could be completed as planned.

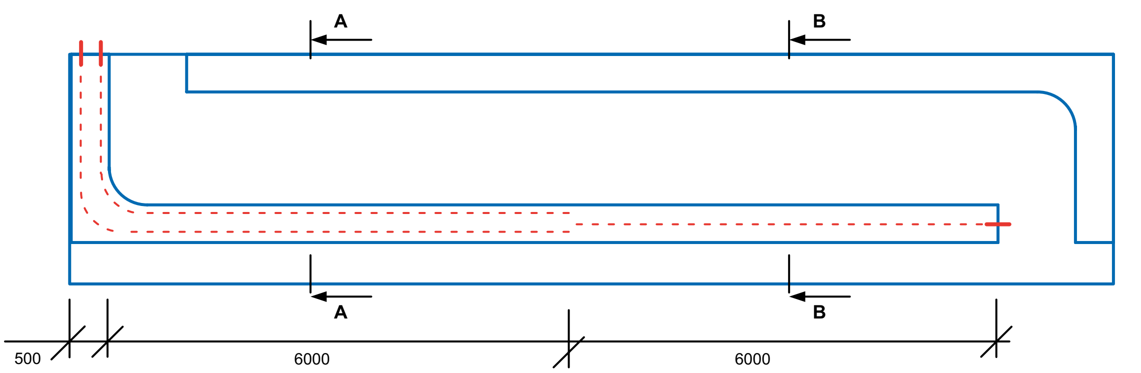

***Figure 4-31.** An illustration of the representative section showing the base slab and the two L-shaped walls as well as the position of the joint seals.*

***Figure 4-32.** The formwork is ready.*

Dimantling of formwork and follow-up

About 2 weeks after the casting the formwork was dismantled and visual inspection of the concrete structure could be undertaken, Figure 4-33.

Visual inspection showed that the concrete was dense and no fractures were identified. The visual inspection also showed that the adhesion of the concrete to the joint seals was good, Figure 4-34. Finally, no fractures have yet been detected. This can be an indication of that the friction reducing layer is working as expected and that unrestrained shrinkage can occur. Future follow-up will verify whether this is a long-term effect or only temporary during the initial period of the hydration of the concrete.

***Figure 4-33.** The concrete structure after dismantling of the formwork. The cabinet in the right part of the image contains equipment for data collection from the sensors in the concrete structure.*

Figure 4-34. The interface between the copper joint seal and the concrete.

5 Mechanical- and system engineering

5.1 Development of test methods

During the past five years, test methods have been developed and gradually integrated in machine development at Äspö. This has been done because of the need to effectively be able to decide what to test, how to test and how to measure the results. Clear demands must be set on what is expected of the product, so that testing can ensure that all those functions are evaluated.

In 2016, all machine-related projects were carried out with these test methods. It has been noticed that this has not only improved the quality of products, but also meant that fewer resources are needed, because testing can effectively focus on the right things.

The following describes the procedure for how the test method works.

Test methods are used in order to increase the quality of delivery and minimize the number of defects found in production environments. A vital part of this model is that a well thought-out, structured and quality assured testing of deliveries performed confirm and ensure functionality as far as possible. To deploy an object or system that is not properly tested can cause major problems causing delays and increased costs. Testing is carried out to provide information about the quality and functionality of the product to be delivered before it is commissioned.

The main purpose is to detect mistakes in the design of the delivery, so that they can be addressed. Testing does not verify that a product works under all conditions, but it can verify if the product does not work under certain conditions.

A prerequisite for the implementation of the tests is that there is a document, agreed upon by both the party setting the requirements and the party performing the tests, that describes the contents of the delivery agreement. This type of documentation can be a specification of requirements, a product specification or a quote. Since these are the documents that describe the delivery functionality, tests should always be carried out against this document.

Testing is a critical review that aims to confirm quality standards, reliability or documented properties of an object or system before it is used. Even documentation that comes with the system or items must undergo critical testing.

The approach of a test can differ between different projects, but the general rules of procedure are:

1. Collect and compile demands made on the object or system to be tested.
2. Analyze the overall requirements.
3. Formulate strategy for the testing and describe it in a test plan.
4. Approved test plan.
5. Formulate the test case.
6. Acceptable test cases.
7. Execute test cases.
8. Compile test protocols.
9. Compile test report.

Before the test begins, a test plan is drawn up and agreed on by both parties. The test plan is a document that describes the strategy that will be used to verify the functionality of the delivery that is described in the delivery document, and other documents.

A test plan can have different content depending on the extent of the object to be tested, but the following must always be included:

- What is to be tested.
- What methods should be used.
- Who is responsible for different areas.
- Objectives and limitations of the tests.
- What kinds of tests to be carried out to verify functionality.
- In which test environment the tests will be conducted and the configuration of this.
- What kind of tools are needed for the tests.
- Procedures for handling deviations, application delivery routine during the test sessions, reporting procedures and which documentation that should be available and how it should be handled.
- Criteria for the test object must be approved.
- Resources and schedule.
- Organization of roles and responsibilities.

Before the test begins, the acceptance criteria have been developed and agreed upon between the parties. These criteria must be documented in the test plan. The criteria are approved by both parties when the test plan is approved.

An evaluation to ensure that the test period agreed criteria for approval are met will be done after each test period. The basis for approval is a test report.

A test case is a description of what should be tested and step by step instructions how to perform the testing, including input and answers with the expected results. The basic idea is that each test case includes only one requirement of the specification. The actual result of the test case will then be compared to the expected result. If parts of a test case for any reason must be rewritten during the test period, the test case must then be performed in its entirety.

When a function is not performing as expected, an incident report must be written. A deviation report should also be written for defects which appear but is not linked to a test case. An incident report should clearly and simply describe how the operation was performed, and how the results deviated from the expected result.

Bug fixes, regression tests and monitoring solutions are based on the deviation report. It is therefore important that the differential is clearly described. If possible, photographs, test data and other important information should be attached to the report.

After completing the test run, a test protocol must be performed. The test protocol should include the outcome of each test case. If abnormalities have been reported in the test cases, the deviation report the error generated will be cited. A test protocol may in its simplest form be a test case where the outcome of the test case is written.

After testing has been completed, all test cases have been reviewed and test protocols have been issued, a test report is compiled. The test report describes the tests and their results and provides the basis for the approval of the system. The test report will show the summary of the test result and a recommendation for further works.

5.2 Universal chassie

Background

In the repository a large amount of material consisting of compacted bentonite clay will be transported through the tunnels. The tasks of building the buffer and backfill will need approximately 200 tonnes of material a day.

A concept model of a transport system has been developed to help identify the different processes the equipment performing the task of transporting the material will be involved in.

Analysis of the model gives a hint of what magnitude of work will go into the different projects. In Machine and System development these are divided into three categories:

- Standard Equipment.
- Modified Standard Equipment.
- Custom made Equipment.

Many of the tasks performed by the equipment can be done by standard equipment but some modifications have to be made to the buffer and backfilling process equipment.

Objectives

The main objective in transporting material is always to do this in a safe and cost effective way.

Cost effectiviness doesn't only involve the cost for energy taking a payload from point A to point B. For example it also includes maintenance, storage of critical parts, training of personnel and so forth throughout the systems entire lifecycle.

To minimize the overall costs it would be of interest if the chassie used to transport the material could be used in other parts in the process too. It would not only cut costs in maintenance and parts storage since the same parts are used for all the equipment, but also give the means to develop a cost effective system to control the buffer and backfilling processes through a common interface.

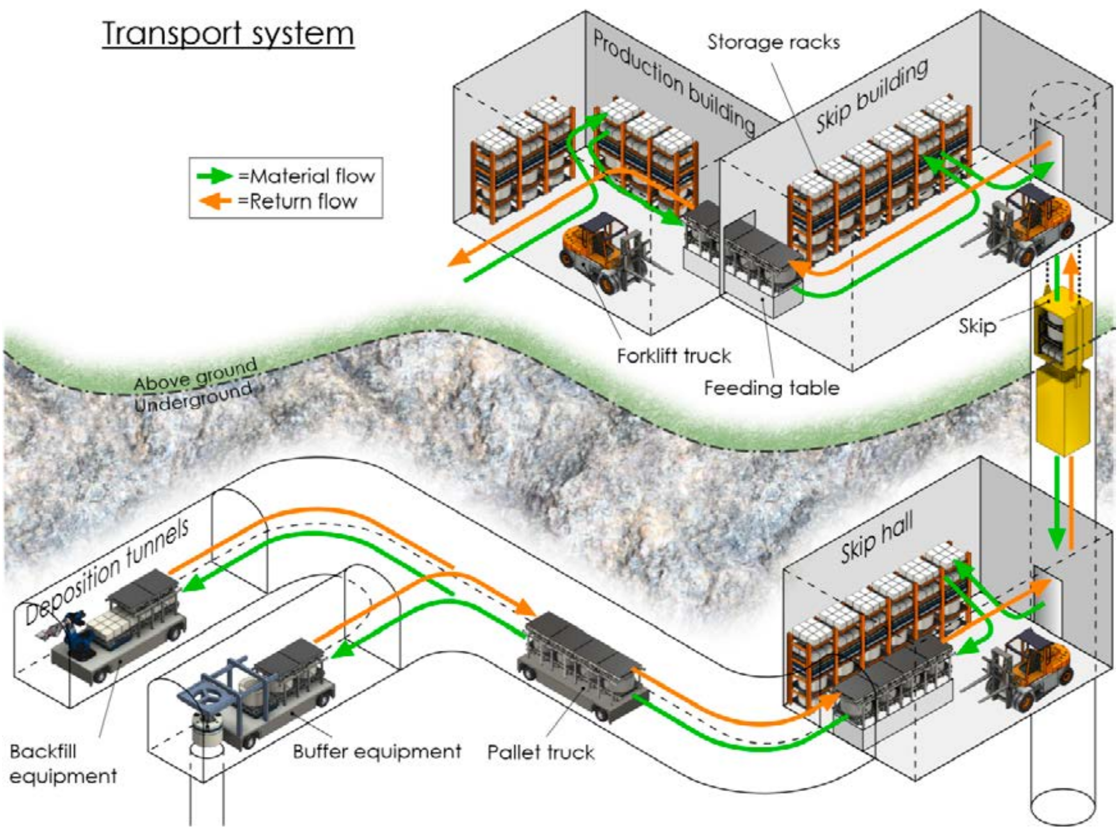

Figure 5-1. *Conceptual design of the transport system.*

The functions the universal chassie would have to perform in the system would include:

- Act as a platform to transport both buffer and backfill material.
- Act as a platform to aid the buffer installation process.
- Act as a platform to aid the backfill installation process.

Experimental concept

The approach to solve the differences in functionality where the universal chassie is going to be used is to make the configuration of it modular.

From analyses and empirical experiments of the processes the universal chassie will be involved in a modular concept of the parts needed to perform different functions were developed.

The chassie is here called a universal vehicle and consists of a fully automated heavy transporter.

Similar transporters can be bought from several different manufacturers. They are mostly used to transport heavy loads up to several hundred tonnes in shipyards, steel factories and in other heavy industrial applications.

Due to the modular design the maximum load the universal chassie will have to carry is almost the same regardless of which configuration is used. The maximum load it has to be designed for is approximately 20 tonnes. This design feature is implemented to make the calculations of the maintenance easier. If the stress on the chassie is known and equal throughout its usage, key indexes for maintanence will be easier to identify.

Since it will work in the underground facility the carbondioxid footprint from the equipment has to be as low as possible.

The distance to travel will differ due to the progress in deposition of the spent nuclear fuel. In the beginning of the process the average distance is around one kilometer and in the end of the deposition process the distance will grow to about 5 kilometers.

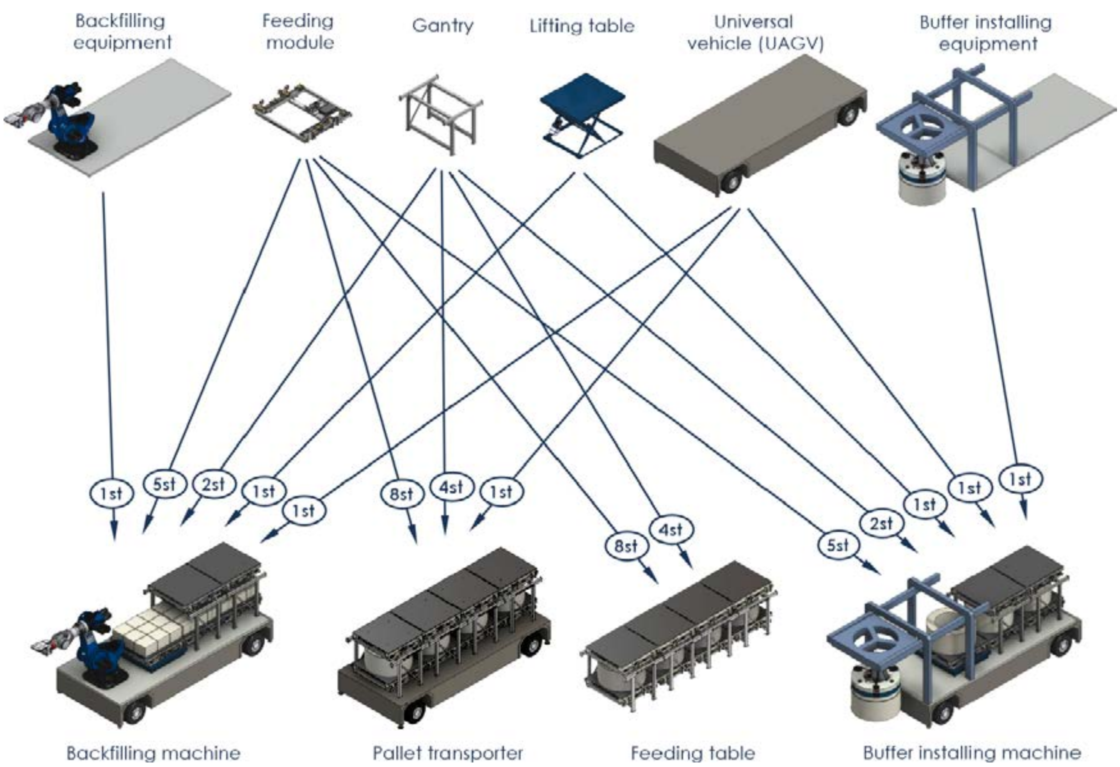

Figure 5-2. *Conceptual design of the modular chassie.*

When the transports are perfomed over short distances electrical propulsion is preferred, but for operation over longer distances or longer timespans like when buffer or backfill is performed some kind of alterntive energy source is required.

For practical reasons an electrical cable support is dismissed because of the long distances and the risk of damage to the cable due to the ongoing sourrounding activities which is hard to control.

The solution is a hybrid powered chassie. When running short tasks it will utilize battery power and when more demanding tasks are done a combustion engine will assist to generate the electricity needed. Hybrid technology is used widely in the automotive industry but has been moderately utilized in heavy transporters.

Results

In project KBP2007 the concept of a universal chassie is developed.

The project is conducted as a part of a joint effort together with a heavy transporter manufacturer. The choice of manufacturer depended on the design parameters of the universal chassie. The chosen in this case is the manufacturer Cometto Industries; they already had a transporter called EMT (Electrical Modular Transporter) which fits the design profile. It has a payload of approximately 20 tonnes.

The issue with only having a battery powered platform was addressed and the conclusion was made that it is possible with minor modifications to fit a combustion engine into the EMT to make it more versatile for use in a final repository.

As a natural step a detailed design study of the other modifications needed to be done to fulfill the requirement specification derived from the transport system an analyses was conducted.

It has resulted in a design of the universal chassie that will fit into the modular concept.

No prototype of the modified design has yet been built.

But to test the functionality and the ability to be interfaced to a system running the universal chassie fully automated a standard EMT platform has been provided by Cometto.

The system to control the universal chassi was developed as a prototype system in project KBP2003 and was used to test the deposition machine in fully automated driverless mode.

The objective here was to investigate if the EMT with minor modifications could be adapted to the same control system as the deposition machine.

This system consists of:

- A supervisory system to control the route and driving of the equipment.
- Laser sensors which are used to scan the operating environment.
- Navigation system which enables the equipment to validate its route.
- An automated machine control system which in this case emulates the commands done by an operator using a remote control.

The EMT was modified with these features and the tests of them were successful.

Figure 5-3. *Conceptual design of the universal chassie, here it is configured as a material transporter.*

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 1.4 in this report.

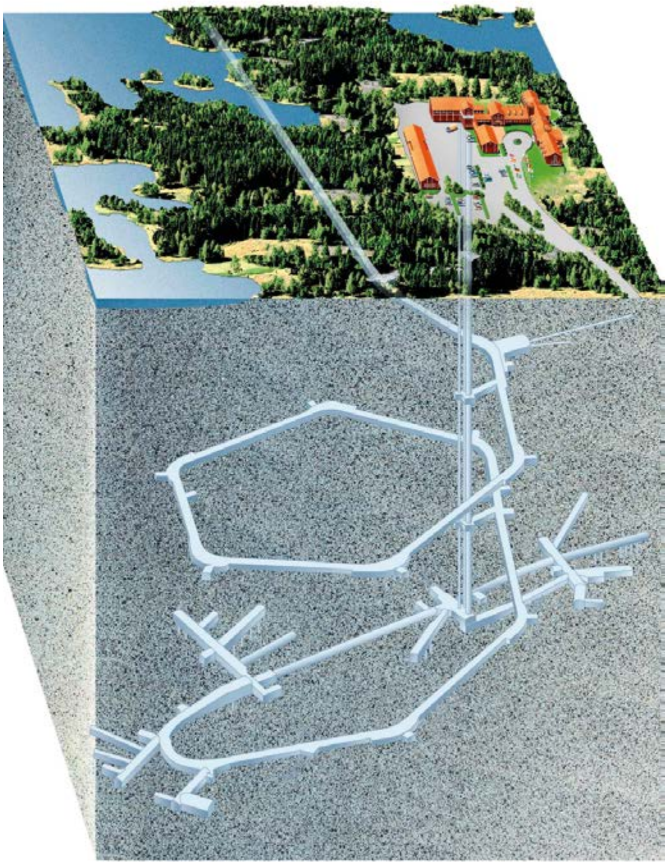

Figure 6-1. *The Äspö tunnel system below the island of Äspö.*

6.2 Bentonite Laboratory

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

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

Other equipment in the laboratory includes an Eirich bentonite mixer with a load capacity of 1 000 kg to allow mixing of bentonite with desired water ratio, and a KAHL press for fabrication of extruded pellets combined with a Baron CXL 4500 transporter and a CZ Multiscreen. 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.

After intensive work in 2015, much work has been focused on reporting, and the activity in the Bentonite laboratory has been lower during 2016. Activities during 2016 include CE-marking of the pellet press and its surrounding equipment, tests of a Universal machine chassie (see Section 5.2) and a mockup test on sealing of boreholes.

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.

Results

The laboratory work during 2016 was focused on (i) swelling pressure and hydraulic conductivity of different bentonites, (ii) validation of the CEC method, and (iii) uncertainties and accuracy of the X-ray diffraction (XRD) and X-ray fluorescence (XRF) methods. Different qualities of bentonite has been simulated by blending a MX-80 bentonite with different proportions of sand (1, 5 and 10 wt%). This also mimic the situation if the bentonite is contaminated during shipping or handling. The idea is to investigate how well the blends can be characterised (quantification of montmorillonite and accessory minerals) and how big the impact from the sand is on the properties of the bentonite. An addition of 1 % was on the level of what could be detected with XRD and XRF, and a 5 % addition was easily detected. The material science project have now been finalised and a lot of focus has been on reporting during 2016. The final report will soon be available.

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, alarmand communications are available in the underground laboratory at all times.

Results

The facility has had a stable operation during 2016, with almost 100 % accessibility.

An external Rock inspection was carried out at the end of 2016. This showed that there is a need for reinforcement measures in addition to ongoing rock maintenance based on previous choice of material in the tunnel. A projects based on this will be launched in 2017.

A practical fire training has been designed for personnel working underground. The training is mandatory and cover topics such as use of respirators in the rescue chamber, handling of escape hoods and passage through different fire compartments during fire ventilation.

For several years, the synthetic fuel Ecopar has been used for vehicles driving in the tunnel.

Extensive ventilation work has been performed at the −450 m level in the Äspö tunnel, as old ventilation ducts have been replaced with new ones.

Throughout the whole year, there has been a focus on operational efficiencies such as energy efficiency, optimization of storage, and vehicles, and review of alarm management.

This has resulted in a large number of measures that will eventually create a cost-effective facility.

6.5 Communication Oskarshamn

General

The main goal for the Communication unit in Oskarshamn is to create public acceptance for SKB. This is done by presenting information and showing SKB's facilities and the RD&D work e.g. at Äspö HRL often i cooperation with other departments at SKB.Furthermore the unit is responsible for visitor services at Clab and the Canister Laboratory as well. In addition to the main goal, the Communication unit takes care of, and organises visits for international guests every year. The international visits are mostly of technical nature, but increasing interest is shown regarding societal consensus questions. The Communication unit has a booking team which books and administrates all visitors at SKB. The booking team also work for Oskarshamn NPP's service according to agreement.

In addition to above, the unit also is responsible for school information in Oskarshamn, press release matters locally and internal as well as external communication on site at the different facilities.

During 2016, one person retired and at the end of the year Communication Oskarshamn consisted of eight persons.

Special events and activities

During 2016, 3 757 people visited the Äspö HRL and with the visitors at Clab and the Canister Laboratory included resulted in a total of 5 444 people. The total number of visitors to SKB's facilities in both Oskarshamn and Forsmark/Östhammar was 7 929 people. The visitors represented the general public, students, professionals, politicians, journalists and international visitors. The total number of international visitors to the Äspö HRL was 384.

The special summer arrangement “Berg500” was arranged during six weeks and 956 persons visited the underground laboratory. Tours for the general public also took place some Saturdays during the year.

During 2016 the school information officer visited to schools and high schools within the Municipality of Oskarshamn to inform about SKB’s work. 19 female students from the scientific and technical programs at the high school in Oskarshamn participated in an activity called “Tjejresan”, an initiative aiming to show the career opportunities within the technical field. Fieldtrips and meetings with employees are ways to increase the female students ‘interest for a subject area otherwise highly dominated by men. 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 May 14, a public jubilee day to celebrate that Äspö HLR had been in operation for 30 years was arranged. Staff of Äspö HRL informed the visitors about SKB’s work and special underground visits were offered. Around 300 people visited Äspö HLR this day.

A recurrent event that the unit takes part in is the national event “Geologins Dag” (The Geological Day).This year, arranged on September 10, and related to the Äspö HRL jubilee. Geological walks both above- and underground was arranged. The tours also reflected on the 30 year long work that has been done at the HRL.

On 22nd of November “Äspö Miljöforskningsstiftelse” handed out awards to two people that have contributed to increase the public knowledge and awareness about: “locally produced and short transported vegetables” and “the behaviour of fluorine in waters at different levels in the ground in the boreal environment”.

As a part of external information efforts, the unit arranges lectures on different themes related to SKB’s work. During 2016, four lectures were arranged, one on the issues of future decommissioning of nuclear power plants, one on Äspö HRL history and future, one on the actualities as regards to the upcoming encapsulation plant for spent nuclear fuel, and the last one on development of machinery.

On 26th of November, nearly 100 competitors participated in “the Äspö Running Competition”.

Every year members from the unit participate in “Almedalsveckan” in Visby.

7 Open Research and Technical Development Platform: Nova FoU

7.1 General

One of the fundamental reasons behind SKB's decision 1986 to construct an underground laboratory was to create opportunities for research, development and demonstration in a realistic and undisturbed rock environment down to a depth suitable for a final repository for spent nuclear fuel. The decision to construct the underground laboratory (Äspö HRL) has been invaluable in SKB's efforts to plan and implement the repository.

Äspö HRL has been in operation since 1995. The years before the commissioning of the laboratory local and regional parties wanted SKB to extend the use of Äspö HRL. This resulted in an agreement to form the Äspö Environmental Research Foundation in 1996. After some years it turned out that it was more difficult than anticipated to fund environmental research at Äspö HRLwith state aid (Mistra et cetera). This situation ended up in an idea to set up a research school in the field of environmental geochemistry. The idea was realized by establishing the Äspö Research School. Professor Mats Åström was recruited from Åbo Akademi to lead the development of the school and to be supervisor for the phd-students. The Äspö Research School is governed by Linnaeus University and is partly funded by SKB.

In 2008, the ongoing research activities at the Äspö Research School were connected of a new co-operation, Nova Forskning och Utveckling (Nova FoU). Nova FoU is a joint research and development platform at Nova Centre for University Studies, Research and Development, supported by SKB and the municipality of Oskarshamn. Nova FoU is the organisation which implements the policy to broaden the use within the society concerning research results, knowledge and data gathered within the SKB research programme and facilitates external access for research and development projects to SKB facilities in Oskarshamn (Figure 7-1). Nova FoU provides access to the Äspö Hard Rock Laboratory and Bentonite Laboratory at Äspö and the Canister Laboratory in Oskarshamn.

Chapter 7 describes the major progress during the year 2016 for the Open Research and Technical Development Platform Nova FoU. The description is made in terms of the mission, status of the projects and spin-off effects.

7.2 Mission, focus and status

Nova Center for University Studies, Research and Development (www.oskarshamn.se/nova) 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 FoU mission is:

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

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

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

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

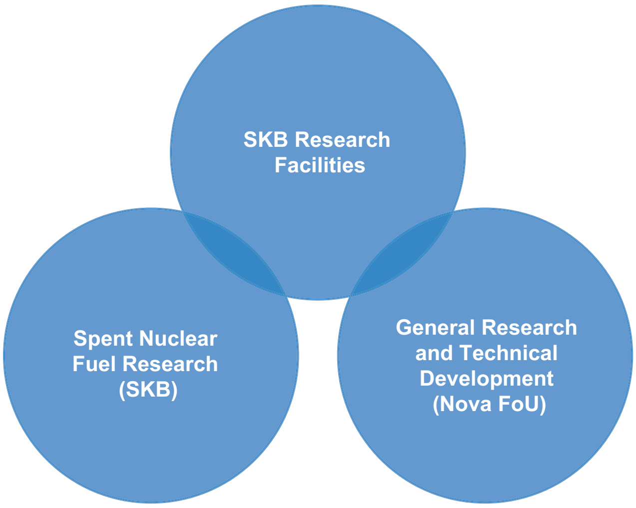

Figure 7-1. *Nova FoU provides access to the SKB facilities and data for universities and companies for general research and technical development. The nuclear waste management research is handled by SKB.*

The Nova FoU platform is used for the following research and development areas (see, Figure 7-2):

- *Geotechnology* projects used in infrastructure projects such as for underground construction of tunnels.
- *Geothermal* research projects for developing energy production from deep (1–7 km) boreholes.
- *Environmental* projects with a broad geosphere (land, bedrock and sea) focus.
- *Materials* studies concerning corrosion effects in underground constructions and to develop applications for friction steer welding.
- *Education* projects aims at informing about the unique technology and know-how in nuclear technology to academia and decision makers.

During the year 2016 about 130 researchers where using the Nova FoU research platform for various geotechnical, geothermal, environmental and material research projects. The total value of the research projects is about 50 million SEK. The annual research volume is 31 on-going research projects and 52 scientific publications.

During year 2016 several new research projects with a more technical focus were established and the Nordic Friction Steer Welding center was established at the Canister Laboratory in Oskarshamn. This is in accordance with the Nova FoU steering group decision to have a more technical orientation in order to increase the possibilities for spin-offs in form of business development. The annual international training course in Geological Storage was performed including more than 40 students from 15 different countries.

Further details concerning the research and educational projects are described in the chapters below.

Figure 7-2. *The focus areas within Nova FoU.*

7.3 Geotechnology

The aim of the geotechnology projects as described below are to improve methods, tools and understanding for underground construction work.

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 (Transparent Underground Structures, http://trust-geoinfra.se/) project 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 economic uncertainties and risks. TRUST Management, is responsible for coordination and dissemination of the different subprojects in the themes and providing guidelines for innovation and implementation of the research result.

Status of the project

The Äspö HRL was selected as one of the joint site investigation sites of the TRUST project. Surface-, sea- and tunnel investigations and analyses were conducted by four of the subprojects in 2015–2016 (TRUST 2.1, 2.2, 2.4, and 4.2). TRUST project 4.1 collected data from the SICADA database, but no GeoBIM model was built. Finally, TRUST 3.3 failed in identifying conductive fractures in the tunnel, resulting in that no tests could be conducted. The results are being published in scientific journals. In March 2016, several of the TRUST projects were presented in a "*BeFo medley*" at the annual workshop "*Svenska bergmekanikdagen*" in Stockholm. A number of the TRUST projects were also participated at the NGL annual conference in Kalmar (October 2016). The final report of TRUST 1 project is being prepared, and the project is scheduled to end 2017-04-01.

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 collaboration framework (http://trust-geoinfra.se/). 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 structures 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 with land based geophones in order to extend the seismics survey over a larger volume, and used our survey boat for offshore RMT electromagnetics.

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

The resistivity and seismics refraction data were first evaluated separately using the Res2dinv and Rayfract (Figure 7-4), and later with coupled inversion using the BERT/GIMLi inversion software package. A geological interpretation is that the low resistive zone in the right part of the resistivity section in Figure 7-4 corresponds to the NE-1 zone, although it is expected to have a steeper dip than indicated here. The apparent dip is probably 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 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 attention the evaluation of data is complicated, and joint inversion appears as a valuable tool for refined data interpretation.

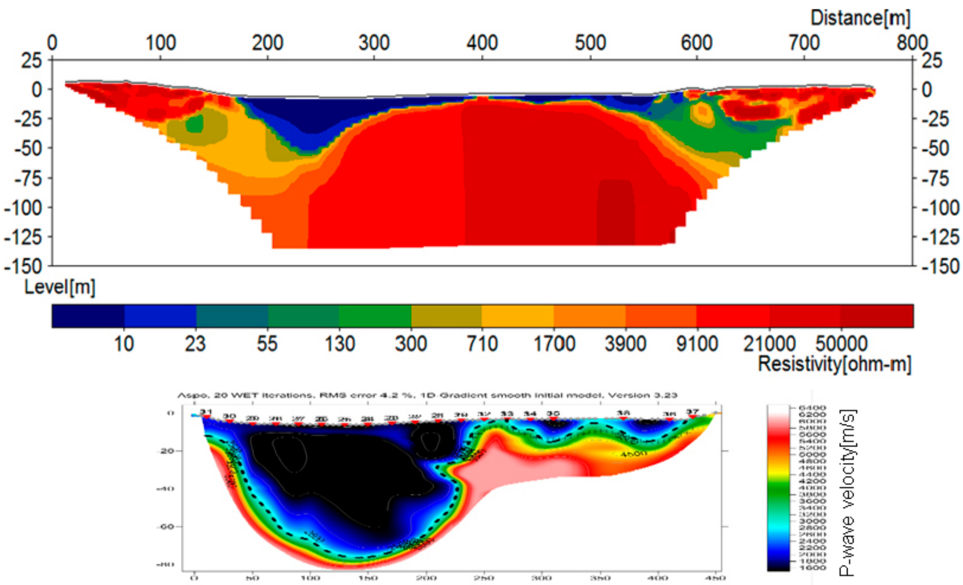

Figure 7-4. Preliminary tomography model results from separate inversion of resistivity (Res2dinvx64) and seismic refraction tomography (Rayfract) data. Observe difference in vertical scale.

The results of the combined evaluation of the data with so called coupled inversion and cluster analysis of the data were evaluated against the available documentation in the SICADA database. Results have been presented at the Nordic Geotechnical Meeting in Reykjavik (Ronczka et al. 2016), at the NGL conference 2016 in Kalmar, and in a scientific manuscript submitted for peer review. Joint inversion of the ERT and RMT data has been done with TRUST 2.2, and results presented in an international conference (Wang et al. 2016) and a manuscript submitted for peer review.

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 (Lindvall and Warberg Larsson 2016). Parts of the results have also been presented at a couple of international scientific conferences (Dahlin and Wisén 2016, Dahlin et al. 2016).

7.3.3 CSRMT measurements on water surface over the Äspö tunnel (TRUST 2.2)

Project leader: **Mehrdad Bastani, Geological Survey of Sweden**

Aim of the project

In April 2015 a group of researchers from Uppsala University, Lund University and SGU conducted a set of geophysical measurements using various methods with the aim to study the sensitivity of each method to detect and model the existing fractures within the crystalline bedrock. The group work within the TRUST project that was partly financed by FORMAS. One of the methods used was radio magnetotelluric (RMT) that utilizes the signal from the distant radio transmitters. The collected RMT data are used to map and model the electrical resistivity of the ground below the measurement stations. The RMT data were collected in the Äspö HRL tunnel, on the land and also on the water surface over the tunnel in the Borholmsfjärden. The last measurement technique was developed at SGU and is called boat-towed RMT. The data were collected along 10 profiles in four hours. The results of the boat-towed RMT measurements were very promising and reveal many details about the electrical resistivity structures below the water. However, the data lacked information below the depth of 10 meters where many interesting structures may reside (e.g. fractured bedrock). We had the possibility of increasing the penetration depth of the method by using a home-made transmitter that provides approximately four times deeper signal penetration. This method is called controlled source magnetotelluric (CSMT) and can be used in combination with the RMT in which we call it CSRMT. We managed to carry out this experiment successfully for the first time on the water surface over the Äspö HRL tunnel. Another aim of the measurements was to combine the collected CSRMT data with the data collected by the other methods (e.g. reflection seismic) to achieve more accurate resistivity models and reduce the uncertainties.

Status of the project

We carried out the CSRMT measurements along a profile. The CSRMT profile is shown in Figure 7-5a by green stars. The selected transmitter frequencies are 1.25, 2, 4, 6.25, 8, 10, 12.5 kHz. The source is remotely controlled from the receiver site using a radio modem (Bastani et al. 2001). After each measurement the boat is moved slowly along the rope. This setup guaranteed our boat-towed RMT system stable on the water even in windy conditions. The source was laid out on another island which is 310 m away from the nearest station (Figure 7-5a, c). The longest distance between the source and the stations is 430 m. 40 stations were observed both for CSRMT and RMT data on the water.

RMT 2D inversion code was used to carry out 2D inversion, since the distance between transmitter and receiver is at least 6 times larger than the skin depth and the controlled source electromagnetic signals can be treated as planar waves approximately under this situation. The 2D inversion results resolved the fracture zone at northern side of the profile only with very large error floor on CSRMT apparent resistivity data, this is benefited from 1D inversion which guides us to consider distortions

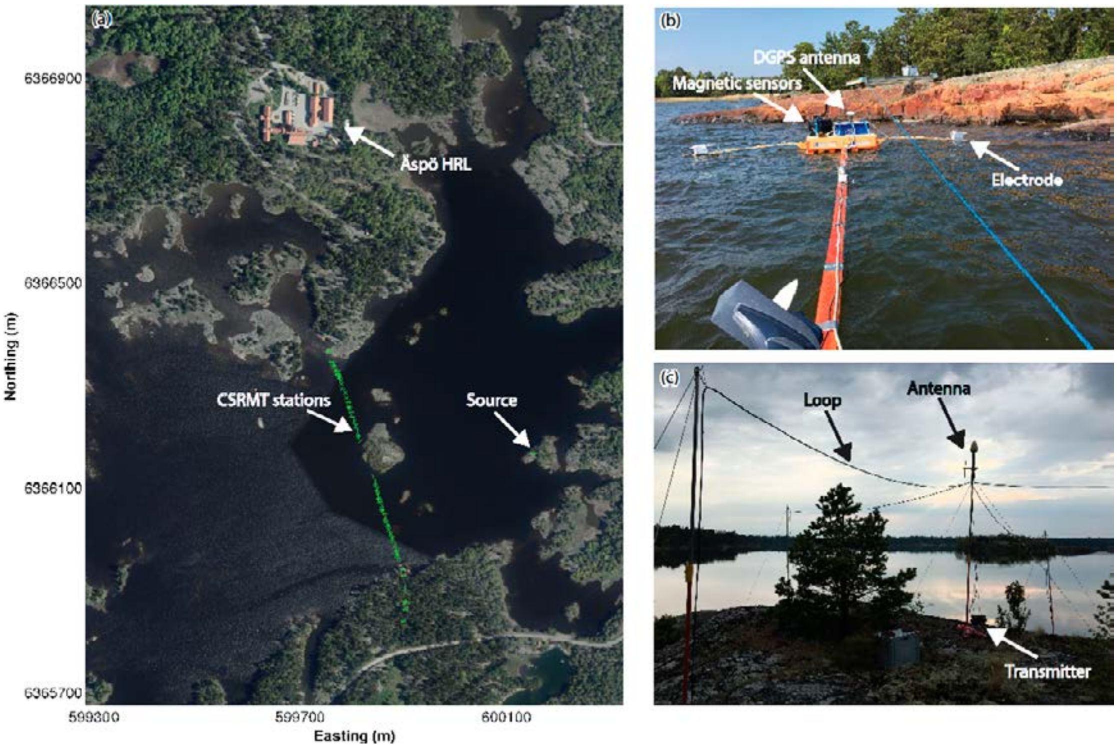

Figure 7-5. *(a) Arial map of research area. Green stars are the CSRMT and RMT stations and source positions marked by white arrows. Presence of a small island in the middle of profile and thus data acquisition has a gap. (b) The measurement system in the water. The sensors were mounted on a floating platform together with a DGPS antenna. The recoding units were inside the boat. The blue rope was used to keep the entire measurements system stable in the water. (c) The double horizontal magnetic dipole transmitter was used as source to generate EM signals.*

in 2D inversion. This study successfully proves using CSRMT gains better resolution at deeper depth than using RMT alone, especially on water, even though CSRMT measurement takes longer time than RMT measurements.

The project was finished by the end of 2016.

Spin-off

Based on the results achieved from this work we are planning to apply money from EU to further develop new data acquisition systems to carry out CSRMT measurements in faster and more effective way for mineral exploration on the ground and over water bodies.

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.

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 2016, Chalmers finalized a scientific paper on hydrochemical impact of construction of the western section of the Hallandsås rail tunnel in Sweden. Furthermore the Chalmers research group has made an evaluation of groundwater chemistry data from private and public water supplies by means of the SGU well data base. The evaluation focused on constituents implying steel corrosivity and degradation of cementitious building materials. A complementary field study on groundwater recharge and hydrochemistry has commenced at the Gårdsjö test site northeast of Gothenburg.

CBI has continued laboratory experiments in which cementitious materials with various recipes have been subjected to water with different concentrations of sulphate. KIMAB has also continued to perform laboratory tests of steel corrosion with water of different compositions. The chloride and sulphate concentrations have been varied in synthetic waters and tests were also performed in original groundwater from rocks. These experiments have been conducted with both stationary and flowing water on reinforcing bolts and the results illustrate the corrosion protective importance of calcium and bicarbonate in groundwater. In-situ investigations have commenced at the Äspö HRL. 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 Structural analysis of shotcrete samples from Äspö HRL

Project leader: **Mariusz Kalinowski, Swedish Cement and Concrete Research Institute**

Aim of the project

The aim of the project is to see how shotcrete is affected by water flowing through internal cracks. Samples of shotcrete with CEM I sulfate resistant cement (Anläggningscement Degerhamn) were taken from two sites in the Äspö HRL tunnel. The shotcrete was exposed to two different types of natural water, brackish water and saline water. Both waters contain sulfate and have pH > 7. The differences in water chemistry are i.a. concentration of Ca^{2+} and alkalinity.

Status of the project

The shotcrete samples were studied in thin sections with polarizing microscope (Figure 7-6) and scanning electron microscope (SEM) equipped with EDS for chemical analysis. The results showed a deleterious effect of water flow on the shotcrete's binder in form of calcium leaching, an increase in capillary porosity of the cement paste and break-down of the cement paste's structure (micro-cracking). The leaching of calcium is accompanied by an influx of magnesium which substitutes for calcium in the calcium silicate hydrate, the main constituent of the cement paste. This causes a degradation of the binder in the shotcrete. The study showed a good correlation between the depth of chemical attack on the cement paste and the depth of influx of magnesium in the shotcrete. No such correlation was found for increased concentrations of sulfate. Thus, the results indicate that sulfate attack is not the primal deleterious mechanism for shotcrete with Anläggningscement in the Äspö tunnel-like environment.

The study will be presented as CBI report to Trust/Geoinfra.

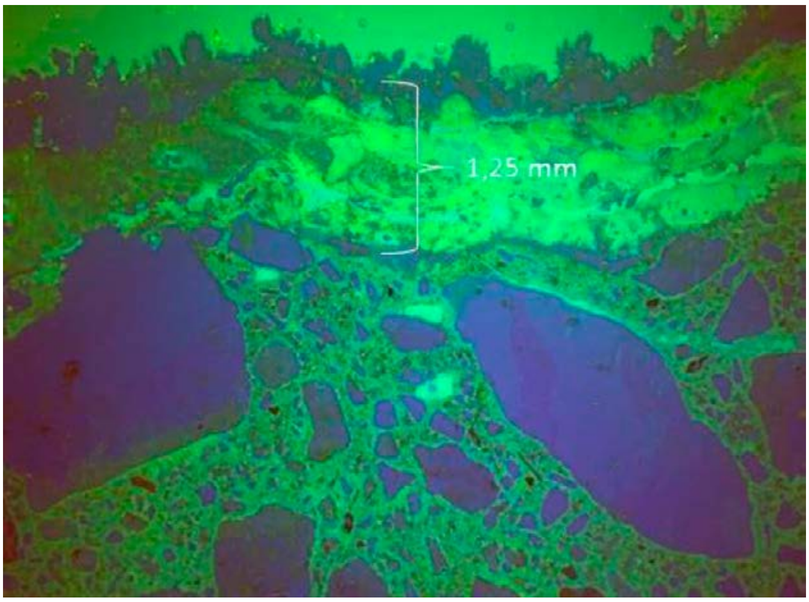

Figure 7-6. *Thin section in UV light showing degraded binder in connection to a crack (in the upper part of the picture).*

Spin off

The observations made in this study may give input for future guide lines for underground constructions and tunnel constructions.

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**
Project member: **Ove Stephansson, 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 induced seismic events. For this, three different water-injection schemes (continuous, progressive, dynamic pulse pressurization) are applied in a horizontal borehole 28 m in length (diameter 102 mm) at 410 m depth in Äspö HRL. An extensive acoustic emission, borehole geophone, and broad-band seismometer array is used to map pico-seismicity events with source dimensions in sub-decimeter range. Also, electromagnetic sensors were applied parallel and perpendicular to the expected fracture planes.

Status of the project

The operational phase of the project was completed in June 2015. In September 2015, a data workshop was held at GFZ to discuss and distribute data obtained by different monitoring arrays. As agreed in the workshop, the principal investigator took the lead in writing an overview paper of the fatigue hydraulic fracturing experiment at Äspö HRL including first-break results (Zang et al. 2016). This article serves as first publication of the experimental work and should be cited by subsequent publications related to more specific results and their interpretation. In 2016, three sections at GFZ analyzed the acoustic emission and seismic data from hydraulic fracture growth (2.1, 2.6 and 4.2).

Section 2.1 focused on the continuous acoustic emission full waveform analysis of data and increased the number of detected and located events compared to the triggered recordings by a factor of 10 to 20 (López-Comino et al. 2016, 2017). The event detector used is based on the stacking of characteristic functions. It follows a delay-and-stack approach, where the likelihood of the hypocenter location in a pre-selected seismogenic volume is mapped by assessing the coherence of the P onset times at different stations. Smooth characteristic function calculated from normalized amplitude envelopes allows reducing the spatial and temporal sampling. This improves the computational performance of the algorithm and allows its application to high-sampling data as a detector. Most detection is concentrated during the fluid injection, at the time of the fracturing and each refracturing stages (Figure 7-7). A low detector threshold is chosen, in order not to lose weaker events. This approach also increases the number of false detections. Therefore, the dataset has been revised manually, and detected events classified in terms of true AE events related to the fracturing process, electronic noise related to 50 Hz overtones, long period and other signals. Electronic noise is found temporally associated with the fluid injection stages. Its occurrence hinders the search of fracturing events, requiring a posteriori classification. Anthropogenic noise, long period and other signals are also detected throughout the whole experiment. For such cases, the values of amplitude of the characteristic function are usually low, so that these events could be easily removed by increasing the detection threshold.

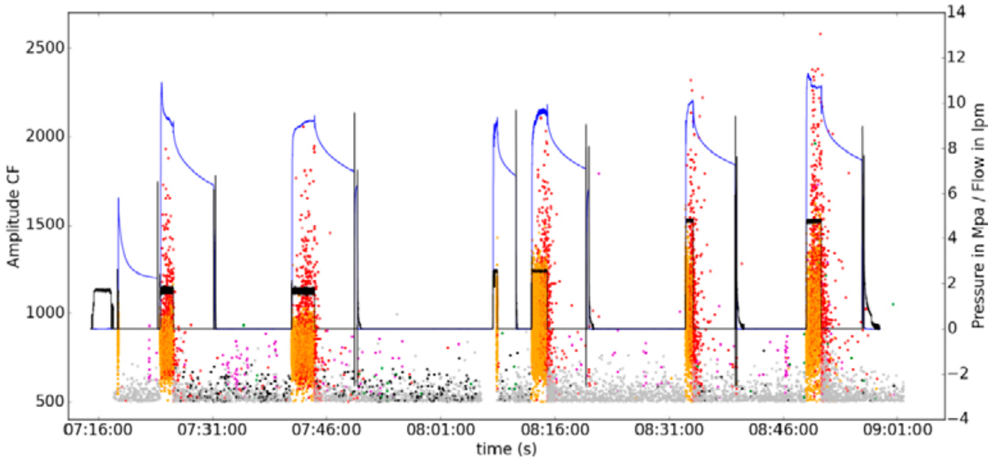

Figure 7-7. *Acoustic emission detections (red dots) using continuous recordings and other kinds of detected signals from a visual inspection that do not correspond with seismic events: false detections (gray dots), electronic noise (orange dots), anthropogenic noise (green dots), long period noise (black dots) and other signals (magenta dots). Amplitude of the characteristic function (left ordinate), injection pressure (blue line) and flow rate (black line) for hydraulic fractures (right ordinate) in the experiment HF2 are shown.*

In Section 2.6, the in situ triggered and located acoustic emission events were related to hydraulic testing data and data from fracture inspection via impression packer results (Zang et al. 2016). In the framework of the limited number of *in situ* tests performed, five conclusions are drawn based on the combined evaluation of hydraulic data with acoustic emission (AE) and seismic monitoring results. (1) In tendency a lower fracture breakdown pressure is found when single-flow rate, conventional fluid injection was replaced by multiple-flow rate, progressive or dynamic pulse water injection. Also, the total number of seismic events and their magnitude is found to be influenced by the injection style. In Ävrö granodiorite, AE events started at a later stage and the total number of events was smaller when the continuous injection scheme was replaced by multiple flow rate injections with progressively increasing target pressure and several phases of depressurization. (2) For all fractures, our first results suggest that the maximum magnitude of AE signals increases with time in the fracturing experiment, that is, the maximum magnitude of each refracture cycle increases with the number of cycles. (3) The *in situ* AE monitoring network successfully recorded seismic events in the frequency range above 1 kHz for most, but not all hydraulic fractures. AEs clearly outline not only the fractures location, its orientation, and expansion, but also the fractures temporal evolution. Clear differences between different hydraulic fractures are visible which need further investigation. With these new insights into the common HF operations and hydraulic stress measurement together with *in situ* AE monitoring is seen valuable. (4) Small rock deformation (40 μrad) induced by HF in a horizontal borehole was monitored with a broad-band seismometer operating in a tunnel in the near field. This finding allows obtaining additional information about the stability of the rock mass, and the response of the rock mass to loading. This can be used as a secondary source of information for tracking and modelling the fracture growth process at different stages. (5) To understand the physics of hydraulic fracture nucleation, propagation and arrest, *in situ* experiments at mine-scale can help only if the monitoring system is adapted to the frequency range expected, approximately from 10 mHz to 100 kHz. Apart from the seismic energy radiated by the fracture, also aseismic slip and heat dissipation are worth to be detected while the pumped in hydraulic energy is documented by advanced fluid injection protocols.

In Section 4.2, the focus was on refining the original triggered seismic catalog and providing detailed information on spatial and temporal evolution of acoustic emission (AE) activity and seismic source characteristics with respect to stimulation operations (Plenkers et al. 2016). The original catalog was re-picked, and relocated using first the absolute Equivalent Differential Time method followed by hypoDD-based relative relocation. The moment magnitudes of AEs were estimated by cross-calibration of AE sensors with available accelerometer recordings. The observed magnitude ranged from −5.6 to −4.6 (sources of approximately cm-scale). The source mechanisms and stress tensors have been investigated using hybridMT, MSATSI and MOTSI algorithms, as well as polarity based-technique.

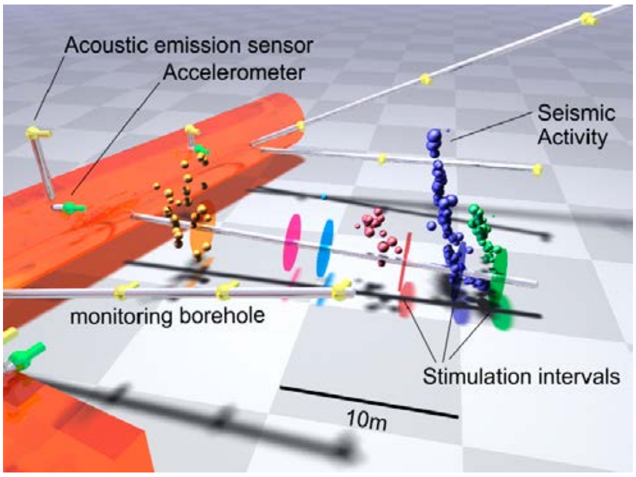

***Figure 7-8.** Seismic AE events from in situ triggered recording, re-localized.*

The derived mechanism and source properties display clear correlations with injection operations that are being now investigated in details. These observations include spatial-and-temporal characteristics (migration away from injection interval and retreat in response to injection pressure changes, stress tensor changes), Kaiser effect, as well as changing of faulting kinematics with injection rate and distance from injection interval (Kwiatek et al. 2017).

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 progressive water-injection treatment results in less seismic radiated energy as compared to convention, continuous water injection.

Data of all hydraulic fractures will be presented in following publications after the advanced analysis of AE data. The total number of localized AE events increased after more time consuming trigger and pick-algorithms were been applied to the continuous and in situ triggered recordings. This together with relative localization techniques 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 November 4–5th, 2015 with 36 participants from Sweden, Finland and Germany discussing future activities at Äspö HRL. The project was presented at "The Underground Space Challenge" workshop October 10–11th, 2016 in Kalmar, Sweden.

7.5 Environmental

The aim of the environmental 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, Linneaeus 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 (throughout 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, (2) characterize and model fluoride abundance, transport and speciation in streams in the Laxemar-Äspö area, and (3) characterize fluoride abundance and sources in shallow (regolith) and deep (fractured bedrock) groundwaters of the Laxemar-Äspö area. A project focusing on fluoride exposure in households with private wells, using Kalmar County as study area, has also been carried out.

Status of the project

The project has now been completed and the doctoral thesis entitled "Fluoride in surface water and groundwater in southeast Sweden – sources, controls and risk aspects" was presented and successfully defended on the 10th of June 2016 at the Linneaus University in Kalmar, Sweden. Out of five published papers in the thesis, four is a result of this project (Augustsson and Berger 2014, Berger et al. 2012, 2015, 2016a). On the 22nd of November 2016, the project leader was also awarded the Äspö Environmental Science Foundation Award for the work carried out as a part of this project.

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, and awarded, at an international conference in Chiang Mai, Thailand in 2014). The findings may also lead to spin-off effects of economic value related to the addressed issues.

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 characterize the abundance, speciation and leaching-potential of fluoride throughout the soil and regolith strata in the Laxemar area, Oskarshamn.

Status of the project

The project is successfully completed. The results have been presented in a PhD-thesis and in an article in a scientific journal (Berger 2016, Berger et al. 2016b). Examples of what the sampling and results looked like are presented in Figure 7-9 and Figure 7-10.

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 types of soil and regolith materials and were uncorrelated with depth (Figure 7-10).

Figure 7-9. *Soil/regolith sampling in Laxemar*

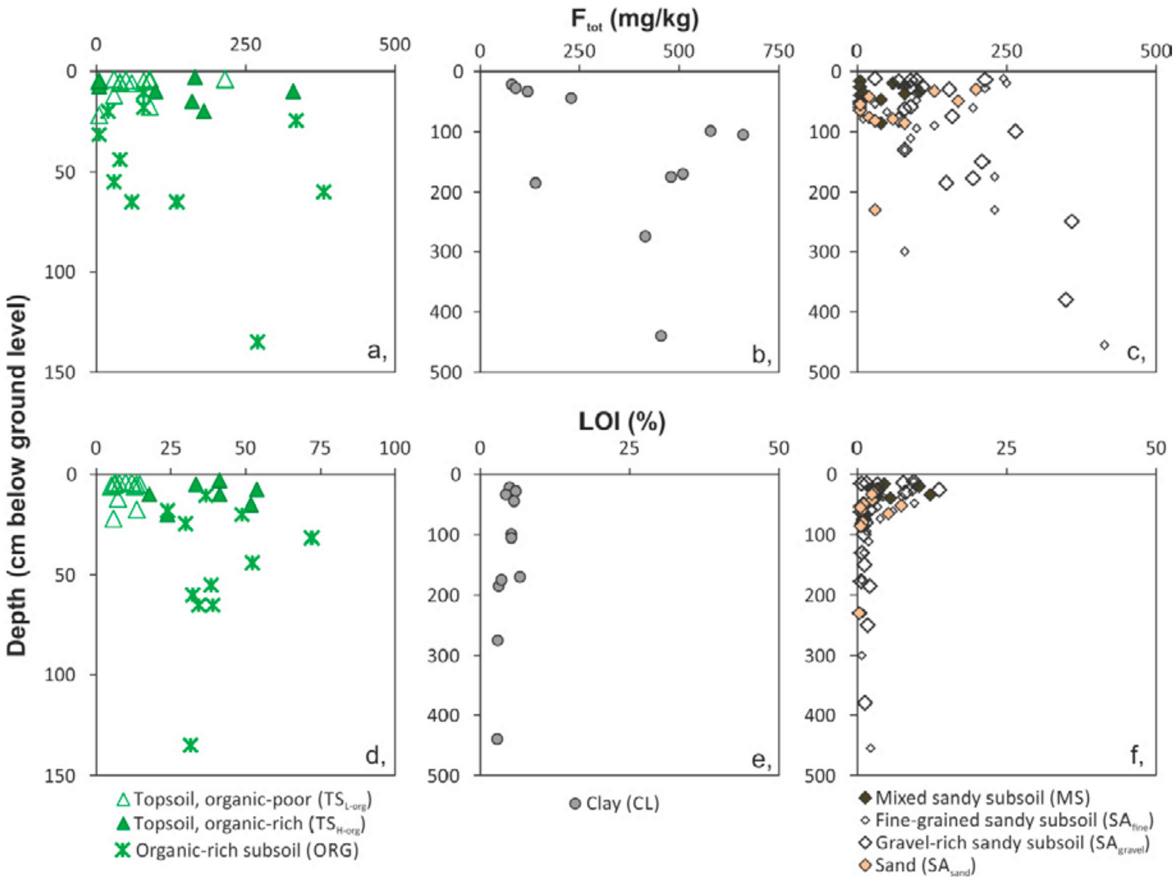

Figure 7-10. *Concentrations of fluorine and loss on ignition (LOI, approximately equal to organic matter) with depth in various types of soil/regolith materials within the Kärrsvik Stream catchment.*

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 or 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.

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 metal(loid)s in surface soils and groundwater at the glassworks properties, hence motivating studies of exposure and risks for those of the residents that use private wells. This Nova FoU project is conducted parallel to studies of exposure via other exposure pathways; for example via intake of home grown vegetables or wild mushrooms and berries, and they are linked to an extensive epidemiological study coordinated by 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 finished.

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 usability of the risk assessment as a decision tool. This is relevant also for risk assessments of other kinds of metal contaminated sites, around which drinking water is extracted.

7.5.4 Coastal modelling

Project leader: **Vladimir Cvetkovic, KTH Royal Institute of Technology**

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

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

The BALSYS project will build on synthesizing 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.

Apart from the Baltic Sea scale analysis, the focus of the BALSYS – Nova studies will be on down-scaling and analyzing 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 Oskarshamn harbour.

As an interesting case study, we shall consider the Oskarshamn harbour and simulate the transport of pollutants that are present in the sediment. The bathymetry scales for the analysis are shown in Figure 7-11. During 2017 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 Oskarshamn harbour.

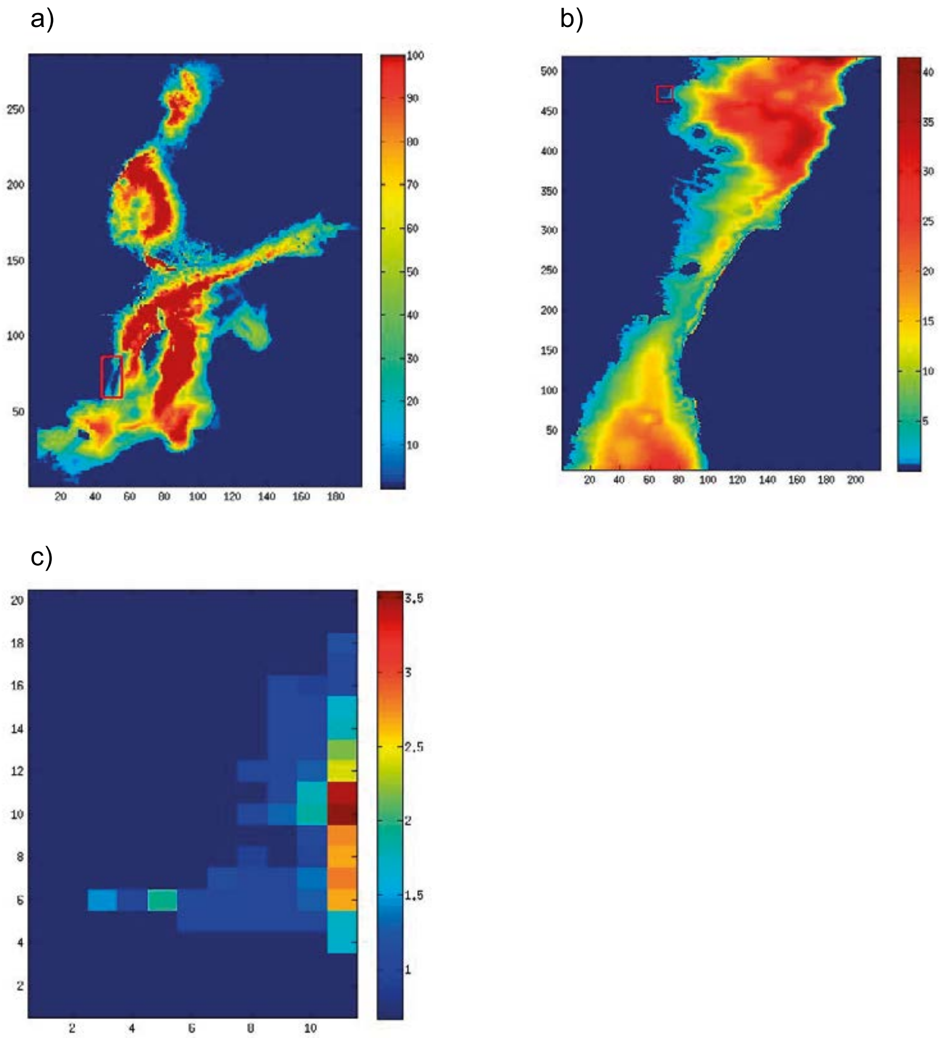

__Figure 7-11.__ Scate transition from the Baltic Sea to the Oskarshamn harbour: a) Bathymetry of the Baltic Sea with resolution of 5km; b) Bathymetry of the mid-scale region with resolution 250 m; c) Oskarshamn harbour scale with resolution of 10 m.

Outcomes

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

Spin-off

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

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

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

7.5.5 Rock, harbour/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 three PhD courses organized by professors William Hogland (LNU), Mait Kriipsalu (Estonian University 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) Full scale 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 Environmental Technology, 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 characterization”. 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 7-12) in many scientific papers, such as Journal of Environmental Analytical. There was comparison of screening by FP XRF and AAS methods (Figure 7-13). 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 7-14) 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.

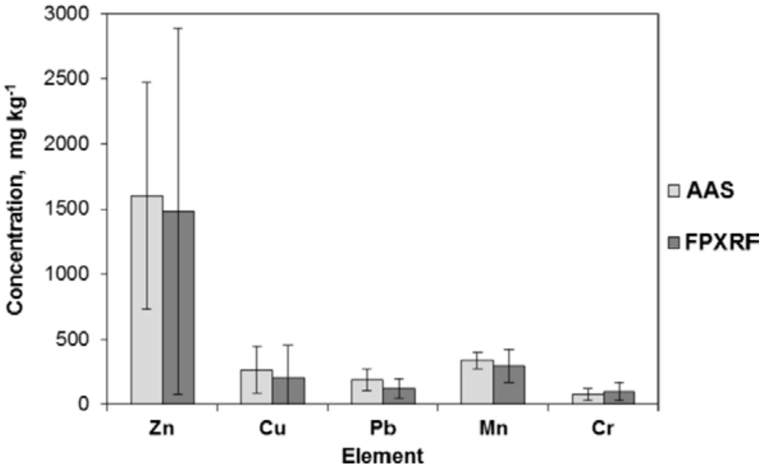

***Figure 7-12.** Example of results from use of XRF. Average concentration of trace metallic elements dominating in waste fine fraction from the Kudjape Landfill detected by AAS and FPXRF (n = 48).*

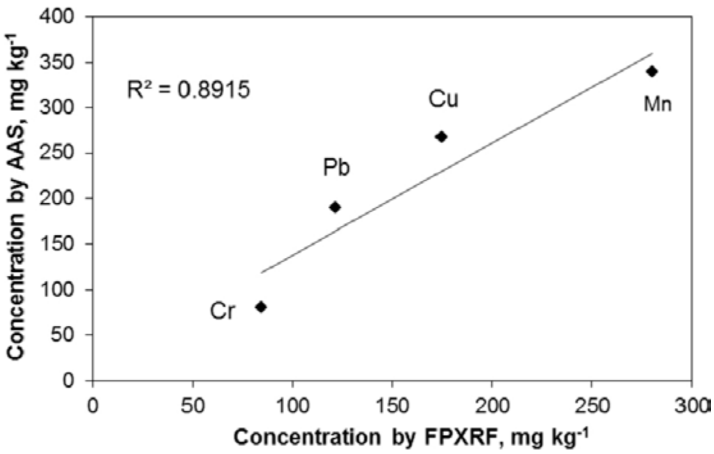

***Figure 7-13.** Average concentration of trace metallic elements dominating in waste fine fraction from the Kudjape Landfill detected by AAS and FPXRF (n = 48).*

Figure 7-14. PhD candidate Charlotte Marchand using the XRF instrument during a PhD course. (Photo William Hogland).

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 carrying 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 the 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.

7.5.6 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

The project is finalized and an article reporting on the project was published in 2016 (Forsman et al. 2016). The Abstract of the published article follows below:

It is broadly accepted that continued global warming will pose a major threat on biodiversity in the 21st century. But how reliable are current projections regarding consequences of future climate change for biodiversity? To address this issue, we review the methodological approaches in published studies of how life in marine and freshwater environments responds to temperature shifts. We analyze and compare observational field surveys and experiments performed either in the laboratory or under natural conditions in the wild, the type of response variables considered, the number of species investigated, study duration, and the nature and magnitude of experimental temperature manipulations. The observed patterns indicate that, due to limitations of study design, ecological and evolutionary responses of individuals, populations, species, and ecosystems to temperature change were in many cases difficult to establish, and causal mechanism(s) often remained ambiguous. We also discovered that the thermal challenge in experimental studies was 10 000 times more severe than reconstructed estimates of past and projections of future warming of the oceans, and that temperature manipulations also tended to increase in magnitude in more recent studies. These findings raise some concerns regarding the extent to which existing research can increase our understanding of how higher temperatures associated with climate change will affect life in aquatic environments. In view of our review findings we discuss the tradeoff between realism and methodological tractability. We also propose a series of suggestions and directions towards developing a scientific agenda for improving the validity and inference space of future research efforts.

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.

The project has given rise to a new idea for a future project. An application for funding for this new project "*Evolution in the face of climate change – the roles of temporal and spatial scale*" was submitted to Nova FoU during 2016.

7.5.7 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 7-15) 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 7-15) and methanogenesis in the fracture network. During 2016, significant breakthrough regarding radiometric dating of the minerals, and hence of the processes, have been done (results currently under review in scientific journals). These studies are collaborations between Linnaeus University other universities and laboratories, including University of Gothenburg, Scottish Universities Environmental Research Centre (SUERC), UK, NERC/British Geological Survey, UK, Stockholm University, Karlsruhe institute of Technology, Museum of Natural History, Stockholm, Sweden (in particular the NordSIM lab), and Universtiy of Göttingen, Germany, and have been published in *Geochimica et Cosmochimica Acta* presenting evidence and nature of sulphate reducing bacteria and *Nature Communications* presenting previously unseen C-isotope variations in calcite, related to previously unknown methane-consuming processes deep in the crystalline bedrock fractures. Collaborative articles with of the Nova project leaders (Changxun Yu and Tobias Berger) were published as well.

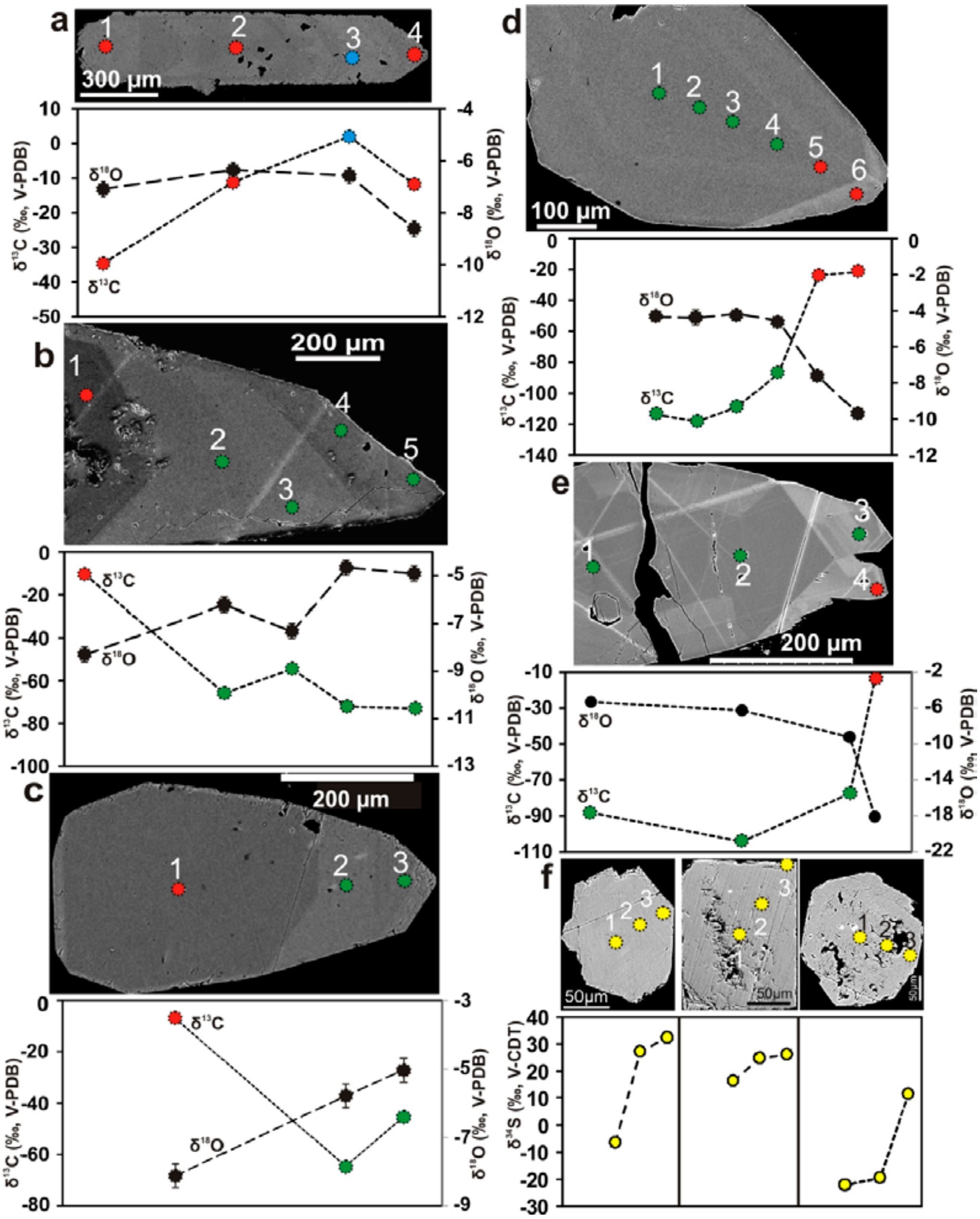

Figure 7-15. *SEM-images of calcite and pyrite crystals from open fractures, with extreme variation in $\delta^{13}C$, $\delta^{18}O$ and $\delta^{34}S$ shown for the 10 µm spots in transects through the crystals.*

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 Terralogica AB. (article accepted with minor revisions in 2016, Applied Geochemistry)
- Investigation of metal uptake in calcite grown on borehole equipment in the Äspö tunnel, and comparison with groundwater data. Collaboration with University of Gothenburg. (article to be submitted in early 2016)
- 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. (one article under review and one ready for submission)
- Chemistry and reducing capacity of fracture coatings in water-conducting fractures and fracture zones. (in draft)
- Iron isotopes in SRB-related pyrite. (in draft)

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 and radiometric dating protocols 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.

Oral conference presentations have been in Yokohama (Goldschmidt), Portugal (Water-rock interaction), Kalmar (NGL), and invited talks have been performed at the University of Göttingen, Germany.

7.5.8 Biomineralisation and La enrichment during oxidation of fracture groundwater

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

Aim of the project

The project focuses on six two months, nine months and 3.5 years old Fe-oxyhydroxide rich microbial mats harvested from two flow-reactor experiments at sites 1327B and 2156B at the Äspö Hard Rock Laboratory (Äspö HRL). The aim is to obtain molarcular understanding of (i) the speciation and micro-scale distribution of Fe, Mn, and Ni in the microbial mats; and (ii) the partitioning and accumulation mechanism of Ni during the growth of the microbial mats. The enrichment of La in a thin-layer of a natural microbial mat sampled from the Äspö HRL 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

During the first stage of this project (2014–2016), Fe, Mn, and Ni X-ray absorption spectroscopy (XAS) and Scanning transmission X-ray microscopy (STXM) data have been obtained from most of the microbial mats. The main findings are:

1) Iron XAS spectra of the six microbial mats show spectroscopic features that have been commonly observed for bacteriogenic iron oxyhydroxides (BIOS).

2) The STXM data show that Ni in the 2- and 9-month old microbial mats at site 1327B is preferably associated with Fe oxyhydroxide particles, not with extracellular polymeric substances (Figure 7-16a–h). The Ni/Fe ratios quantified based on the average optical densities are 0.0012–0.0015 (Figure 7-16i). The values are only one order of magnitude lower than the ratios (0.04–0.064) determined for biogenic ferrihydrite exposed to or co-precipitated with 170 uM Ni, 1 700 times higher than the Ni concentration in the aquifer feeding the microbial mats. This indicates that BIOS in microbial mats grown from natural waters with low Ni concentrations over a long time period could scavenge orders of magnitude more Ni than experimentally demonstrated.

3) The Mn X-ray absorption near edge structure (XANES) spectra of the 9-month old microbial mats from the two sites resemble closely to that of aqueous Mn^{2+} in terms of energy position of absorption peak and lineshape, suggesting that Mn in these two samples occurs as loosely sorbed divalent Mn species (Figure 7-17). The Mn L_3 edge Near Edge X-ray Absorption Fine Structure (NEXAFS) spectra extracted from the STXM stacks of two sub-regions of the 2-month old microbial mats at stie 1327B display very weak peaks corresponding to Mn(II), suggesting that only trace amounts of Mn(II) are present at this stage of precipitation (Figure 7-18). In contrast, the peak position of Mn XANES spectra of three points (with different levels of Ni concentration) in the 3.5-year old microbial mats at site 1327B shifts to higher energy and matches with that of pyrolusite, suggesting a dominance of +IV oxidation state in the sample. The spectra features and lineshape of these sample spectra, in particular the one collected at the spot with low Ni concentration, are similar to those of two synthetic birnessite, suggesting the formation of birnessite-like phases in this sample.

4) For the 3.5-year old microbial mats at site 1327B with highest Ni concentration, Ni K-edge XAS data were collected from the three points with different levels of Ni concentrations. The Ni XANES spectra of these points are very similar, suggesting a similar coordination environment of Ni at these points (Figure 7-19). Structural fitting of EXAFS spectrum of the Ni hotspot revealed that Ni octahedral (NiO6) is coordinated with FeO6 and MnO6. The Fe concentrations at the Ni- and Mn-rich region are relatively low (based on XRF mapping), implying MnO6 likely occupied octahedron sites of 2-line ferrihydrite. The occupancy of smaller MnO6 at FeO6 sites will decrease locally the average size of the ferrihydrite framework. Adding slightly larger NiO6 at FeO6 and/or MnO6 co-existed region will somewhat balance the structure changing induced by Mn-Fe replacement, making the overall ferrihydrite framework at Fe-Mn-Ni coexisted region somewhat balanced to the surrounding relative “pure” ferrihydrite region.

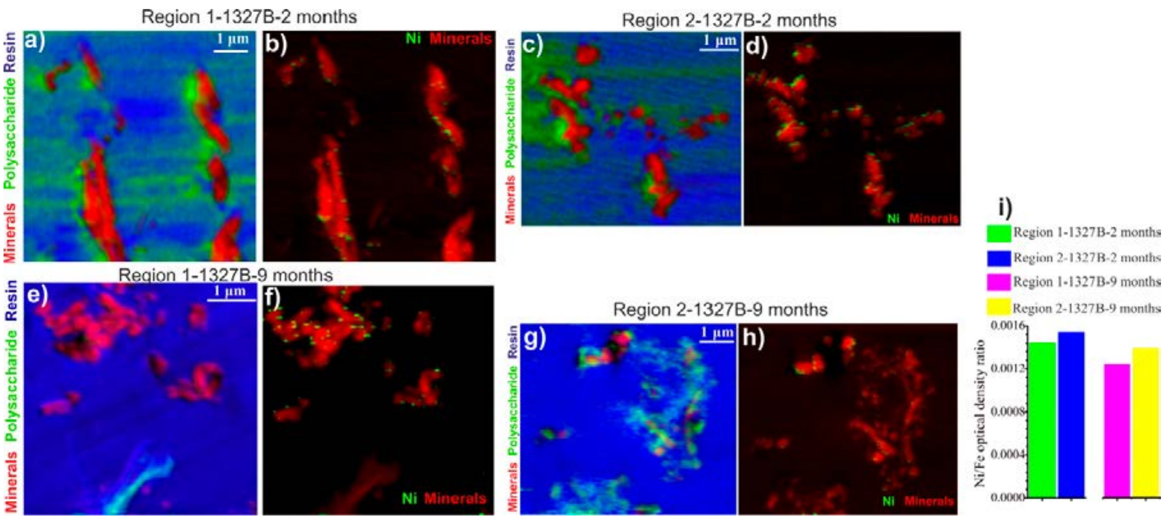

Figure 7-16. *1 STXM data of two selected regions of the 2- and 9-month old microbial mats at site 1327B. The quantitative maps a), c), e) and g) were obtained by linear decomposition at the C 1s absorption edge using reference spectra including albumin (protein), xanthan (polysaccharides), lipid, LR_white_C14H10O4 (resin), and H2O as non C 1s background (minerals). Nickel signals in maps b), d), f), h) were extracted by taking the difference between average optical density (OD) of 10 individual images taken below and above the Ni 2p edge. The Ni/Fe OD ratios in i) were calculated based on the OD in b), d), f) and h) and average OD of Fe extracted from Fe2p maps of the two regions.*

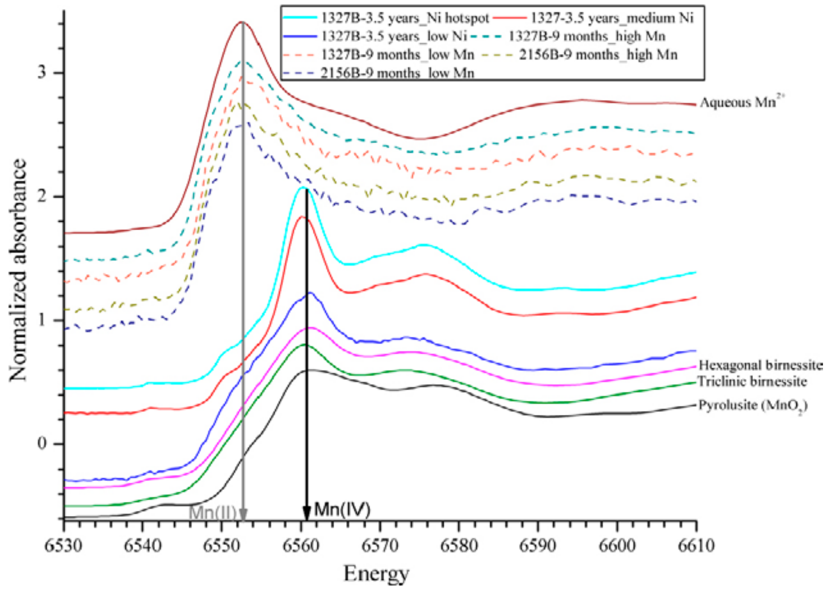

Figure 7-17. *Mn K-edge XANES spectra of three points with different levels of Ni concentration in the 3.5-year old microbial mats at site 1327B and two points with high and low Mn concentrations in the 9-month old microbial mats at the two sites, in comparison with the spectra of aqueous Mn(II), pyrolusite (MnO2), triclinic birnessite and hexagonal birnessite. The position of the white lines (absorption maxima) for Mn(II) (grey line) and Mn(IV) (black line) are also indicated.*

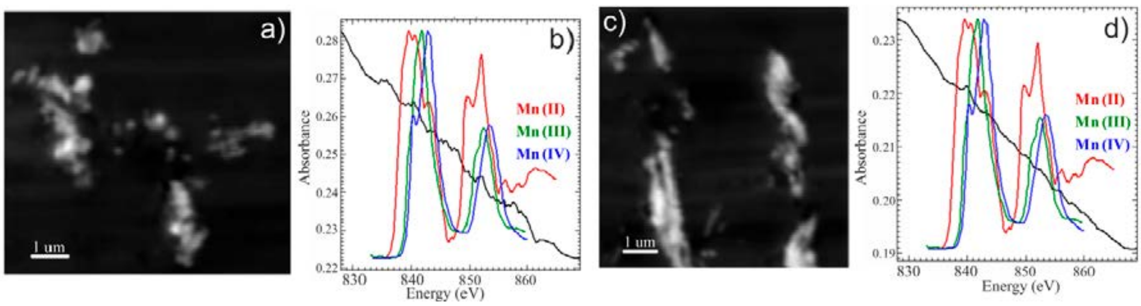

Figure 7-18. *Total Mn map (a, c) of the region 1 and region 2 of the 2-month old microbial mats at site 1327B shown in Figure 5-8 and Mn L3 edge NEXAFS spectra (b, d) obtained from points with strong Mn signal.*

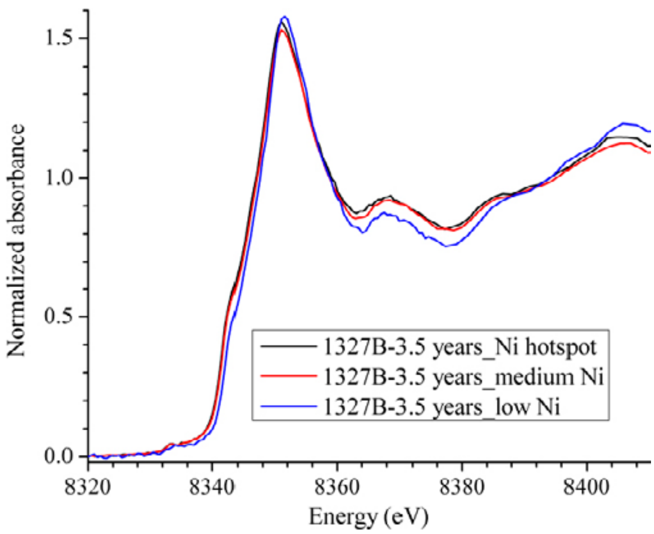

Figure 7-19. *Ni K-edge XANES data of the 3.5-year old microbial mats at site 1327B. The spectra were collected from three points with different levels of Ni concentration.*

No papers published as yet within the project. The analytical work was completed in the spring of 2016, and a manuscript was prepared and submitted by the end of 2016.

Spin-off

The results of STXM combined with XAS data will (i) provide molecular insights into the fundamental biogeochemical processes underlying the preferential enrichment of Ni as well as the partitioning of Ni during the development of the BIOS-rich microbial mats in natural environments; and (ii) contribute to advances in trace-metal geochemistry, in particular the understanding of trace-metal behavior in the solid-aqueous interphase in natural settings.

7.5.9 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 two years the project has changed direction and a close collaboration with Henrik Drake, Linnaeus University, has been initiated. 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 microscopic fungi in the drill cores, and an intimate interaction between the fungi and secondary mineralizations formed by sulfate reducing bacteria are observed. This may have impact on the nuclear waste storage and the mineral and material that are supposed to be used as geochemical barriers. The project is in an intense stage including analytical work and preparation of several manuscripts which will be submitted during 2017.

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.

7.5.10 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 was 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 was tested using three time series of samples from boreholes with water turnover times from a month to thousands of years. This project was 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 was 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); Anders Andersson (KTH Royal Institute of Technology); 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

The statuses of the four sub-projects are described below.

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 published (Wu et al. 2016). A second study using the data has been initiated to specifically investigate how the deep biosphere communities are adapted to the oligotrophic conditions. The previously generated metagenomes in this sub-project are being further analyzed and a manuscript will be prepared.

DNA from a time series taken from boreholes containing 'recent' Baltic Sea and meteroric groundwaters (retention time ~4 weeks), 'intermediate' meteoric water (retention time 5 years), and 'ancient' glacial melt and meteoric waters (4 000 to 5 000 years old) has been analyzed. The data from this study has been published (Hubalek et al. 2016).

In the third sub-project, flow cells were attached to boreholes containing either 'modern marine' or 'old saline' waters of different origin and degree of isolation from the light-driven surface of the earth. Using 16S rRNA gene sequencing, we showed that planktonic and attached populations were dissimilar while gene frequencies in the metagenomes suggested that the biofilms were enriched in populations with a chemolithoautotrophic and diazotrophic metabolism coupling hydrogen oxidation under oligotrophic conditions. A manuscript detailing this study has been submitted.

Viral community DNA has been prepared from the 'modern marine', 'old saline', and 'undefined mixed' groundwaters and data analysis is being 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.

7.5.11 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 RNA sampling has been completed, nucleic acids sequenced, and the data is presently being analyzed 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 are ongoing and will be completed in the next year.

A third system to investigate the activity of deep biosphere microbial communities used high throughput 16S rRNA gene sequencing of total and viable cells (i.e. with an intact cellular membrane) from three groundwaters with different ages and chemistries. The apparent stability of the microbial communities increased with temporal and physical separation from the surface. In addition, the difference in composition of the total versus viable subset of the community was greatest in the water closest to the surface where the proportion of viable candidate phyla and unclassified *Euryarchaeota* increased from 36.2 to 83.4 %. These differences highlight that many populations in the deep biosphere are predominantly non-viable and that many of the viable lineages constitute uncultured and candidate phyla. A manuscript of these data has been submitted.

Spin-off

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

7.6 Materials

Studies of materials aim at investigating corrosion effects in underground constructions and to develop applications for friction steer welding.

7.6.1 Investigation of rock waters corrosivity by corrosion testing of steel samples in the Äspö tunnel

Project leader: **Bror Sederholm, Swerea KIMAB**

Aim of the project

The aim of the project is to determine the corrosion rate on steel exposed to rock water with different chemical composition and microbiological activity. The most dominating factors affecting corrosion in rock water will be investigated.

The corrosion rate will be assessed on steel samples exposed in boreholes with high or low chloride concentration in the rock water. Samples will also be exposed in flow-cells connected to the boreholes with high or low microbiological activity.

By assessing the corrosion rates and the properties of the rock water the most important factors affecting corrosion of steel will be determined.

Status of the project

Ongoing.

Figure 7-20. *Test equipment to expose steel for different groundwater compositions in bedrock.*

Spin-off

The corrosion data can be used as input to develop a standard for the corrosivity of rock water.

7.6.2 Centre for Friction Stir Welding

Project leader: **Lars Cederqvist, Swedish Nuclear Fuel and Waste Management Co**

Aim of the project

The Centre for Friction Stir Welding (FSW) aims to be a strategic Nordic resource for FSW research and education, both for academy and industry. SKB has developed unique FSW competence, and unique competence to locate FSW defects with non-destructive testing (NDT) techniques. This expertise (for example, cascade control of welding tool temperature, control of weld depth, surface treatment of tools for longer life and use of argon shielding gas to eliminate oxides) could be used for other materials and applications to further spread the use of FSW in industry.

Status of the project

Since the project was approved in April 2016, the three following projects have been initiated:

- Welded aluminium lap joints for SAAB Aerostructures in Linköping, by using the University West's FSW robot (see Figure 7-21). The objective is to demonstrate FSW for the specific application and to use the results in the FSW-part of an EU application (Clean Sky 2).
- Welded 12 mm thick copper plates with varying properties due to varying heat treatments (annealing) for Siemens Energy at ESAB. Assisted welding parameters so defect-free welds are repeatedly achieved (see Figure 7-22). Before the modified parameters and less spindle deflection, all welds produced had defects.
- Welded 2.2 mm super duplex stainless steel for Swedish Steel Yachts AB at the Aalto University to test the potential use in steel constructed boats. Initial tests (Figure 7-23) showed that the welding start needs better control (for example, using the cascade power and temperature control developed by SKB).

In addition to these projects, presentations have been made at the Elmia Welding Fair and at the 11th International Symposium on FSW, and an EU-application for Euratom Manufacturing High Integrity Nuclear Reactors was submitted in October.

Spin-off

From the copper plate welds it was noted that the deflection of the spindle most probably causing the advancing side defect, which is an important experience that can be used when designing SKB's welding equipment for production.

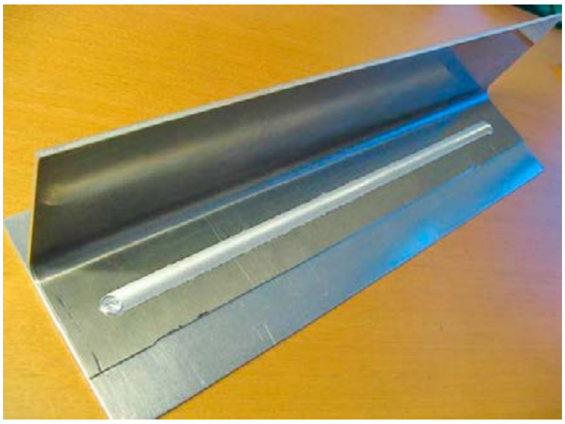

Figure 7-21. *Stringer on sheet (aluminum).*

Figure 7-22. *Copper plates.*

Figure 7-23. *Super duplex stainless steel.*

7.7 Education

Education aims at informing about SKB's unique technology and know-how in nuclear technology to academia and decision makers.

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

Project leader: **Waclaw Gudowski, KTH Royal Institute of Technology**
Project member: **Eva Hjälmered, Nova Center for University Studies Research and Development**

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.

Brilliant is a 3 year Project financed by the European Commission's program EURATOM with the following objectives:

- 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 Sea 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.

Project leader:
Lead Partner: **Lithuanian Energy Institute (LEI)**
WP56 Project leader/Swedish Partner: **KTH, Waclaw Gudowski**
Sub-contractor: **Municipality of Oskarshamn/Nova FoU**

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 took place in September 2016.

Spin-off

Possible spin-off of the BRILLIANT project:

- Future harmonisation of the spent nuclear fuel cycle policies in the Baltic Countries.
- Participation in the Summer Course on the Elements of the Nuclear Fuel Cycle in Oskarshamn.
- Support for new national educational initiative in partner states and supporting mobility of educators.

Second Brilliant study visit to Oskarshamn

Objects of the visit:

The facilities of OKG, unit 3, Clab (Central Interim Storage), Äspö Hard Rock Laboratory, Canister Laboratory.

Participants:

This was the second study visit to Oskarshamn and the facilities of the nuclear cycle that can be found here. The group consisted of participants from Lithuania and Poland. The special guests of this visit were the Polish Ambassador, Mr. Marek Tarka and Technical Attache of the Polish Embassy in Stockholm, Mr. Tomasz Grzybkowski**.** OKG was represented by Annika Karlsson, communicator, and Emelie Johannesson and Thom Rannemalm, engineer working with the de-commissioning. SKB was represented by the communicators Maria Fornander at Clab, Eva Häll at Äspö Hard Rock Laboratory and Stefan Bergli at the Canister Laboratory. The municipality of Oskarshamn was represented by Mr. Ted Lindquist, Marketing Director and coordinator for the association of Swedish Municipalities with Nuclear Facilities.

Subjects for the study visit:

The municipality of Oskarshamn is involved in the BRILLIANT project through a special cooperation agreement between KTH and Oskarshamn. Oskarshamn is involved in its capacity as the owner of Nova Center for University Studies, Research and Development (Nova). The municipality of Oskarshamn and Nova hosted the following activities for the visit:

- Reactor O3.
- Interim Storage of all Swedish spent fuel.
- Äspö Hard Rock Laboratory (500 m under the ground), which is a model of the geological disposal site.
- The Canister Laboratory.

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

Project leader: **Waclaw Gudowski, KTH Royal Institute of Technology**
Project member: **Caroline Oscarsson, Nova Center for University Studies Research and Development**

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 the Oskarshamn facilities including their research and educational potential.

During two weeks in June 2016, 39 international students from 15 countries participated in an intensive course devoted to the handling and management of spent nuclear fuel. The course was taught 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 supported by the **University of Illinois at Urbana–Champaign**, and the European Master in Innovative Nuclear Energy program **– EMINE**.

Figure 7-24. *Mr. Wieslaw Tarka, Ambassador of Poland and Eva Häll, SKB.*

Figure 7-25. *Brilliant visitors at Encapsulation Laboratory.*

Figure 7-26. *Brilliant visitors at Äspö Laboratory.*

Figure 7-27. *Brilliant visitors at Äspö Laboratory.*

The course consisted of a combination of classroom lectures, field excursions and field exercises. The unique feature of the course is that the students visit **Clab** (an interim storage for spent nuclear fuel), the Laxemar Site (study area for bedrock and surface geology), the **Äspö Hard Rock Laboratory** (research laboratory for geological spent nuclear fuel disposal), and the **Canister Laboratory** (development center for spent fuel encapsulation technology).

The prerequisite for this course is a Bachelor of Science in natural science or in a relevant technical subject. The students of 2016 were pursuing degrees in nuclear engineering, environmental engineering, or geology. The course provided a comprehensive introduction to all aspects of managing spent nuclear fuel with a strong emphasis on geological sitting of a deep repository. Special guest lectures from Tsinghua University in Beijing and from Institute of Modern Physics in Lanzhou, China were a new exciting development in 2016.

All course lectures of 2016 were recorded and are available on the internet via a following link:

https://mediasite.neutron.kth.se/Mediasite/Catalog/catalogs/sh262v-june-2016

The final report form this Summer Course containing links to recorded lectures and lecture presentations can be downloaded from:

https://www.dropbox.com/s/t7bc2yppj619z8p/Summer_Course_SH262V-Report-2016.pdf?dl=0

Figure 7-28. *Group photo at the Äspö laboratory.*

Figure 7-29. *Emine students at Äspö Hard Rock Laboratory.*

Figure 7-30. Group photo at Äspö Island.

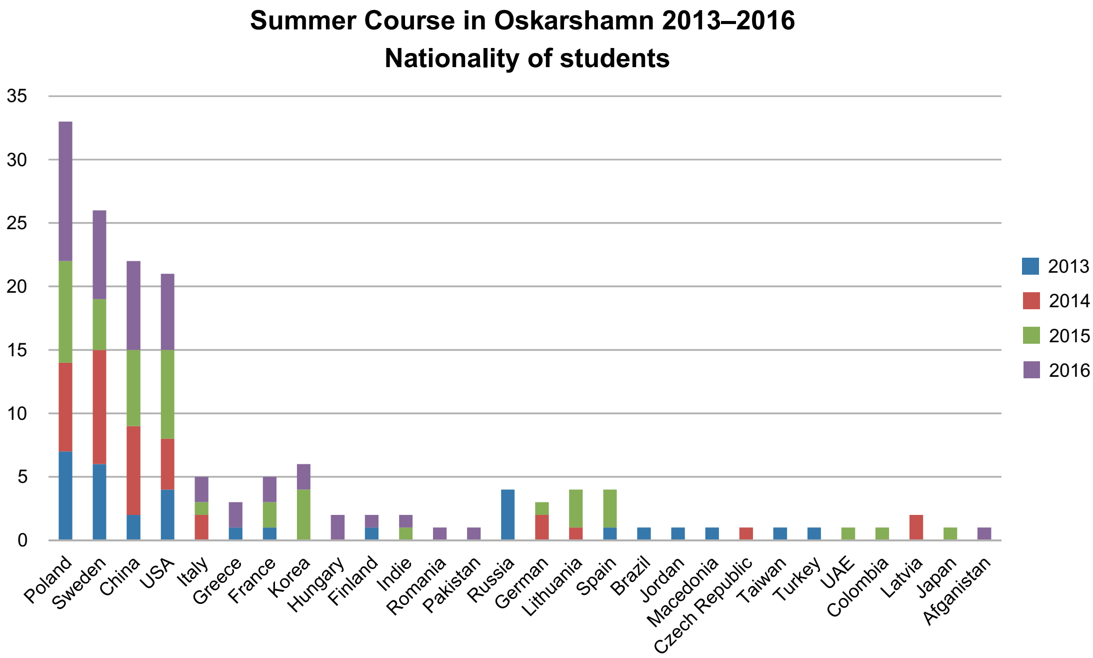

Figure 7-31. Nationality of the students of the summer course during the years 2013–2016.

7.8 The spin off effects from Nova FoU work

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

- **University education:** International Master's education in the field of nuclear technology and geological storage.
- **Research education:** PhD and post doctoral education .
- **Research:** Water management in regional scale to decrease the pollution to the sea according to new EU directives. Understanding of the fundamental geochemical processes in groundwater.
- **Technical development:** New technology to enhance heat extraction from large depths for geothermal use in large scale industrial plants. Study rock weaknesses and corrosion problems underground. Development of new characterization techniques to be used for tunnel construction projects. Establishing a center for friction steer welding.
- **Commercialisation:** Identification and commercialisation of research results in research projects.
- **Environmental technique:** Scientific support to the remediation of the harbour in Oskarshamn.
- **Development:** Support the further development of the SKB laboratories.

7.9 The Nova FoU progress

The actual situation at Nova FoU by the end of year 2016 was:

- 31 ongoing scientific projects representing a value of 52 million SEK
- 129 researchers
- 8 domestic and international universities
- 3 public organizations
- 3 research institutes
- 2 companies
- 52 scientific publications

The progresses of Nova FoU in terms of development of projects during the last seven years are shown in Figure 7-32.

7.10 The Nova FoU Steering Committee and personnel

Nova FoU steering committee

Mats Ohlsson, Coordinator External Relations, Äspö Hard Rock Laboratory, SKB (Chairman)

Peter Wikberg, Research Manager, SKB

Catherine Legrand, Pro-Vice-Chancellor, Linnaeus University

Rolf Persson, Municipality Chief Executive, Municipality of Oskarshamn

Bengt Karlsson, Rector, Nova Center for University Studies, Research and Development

Margareta Norell Bergendahl, Professor, KTH Royal Institute of Technology

Personnel

Marcus Laaksoharju, Chief coordinator

Anna Rockström, Coordinator

Caroline Oscarsson, Administrator

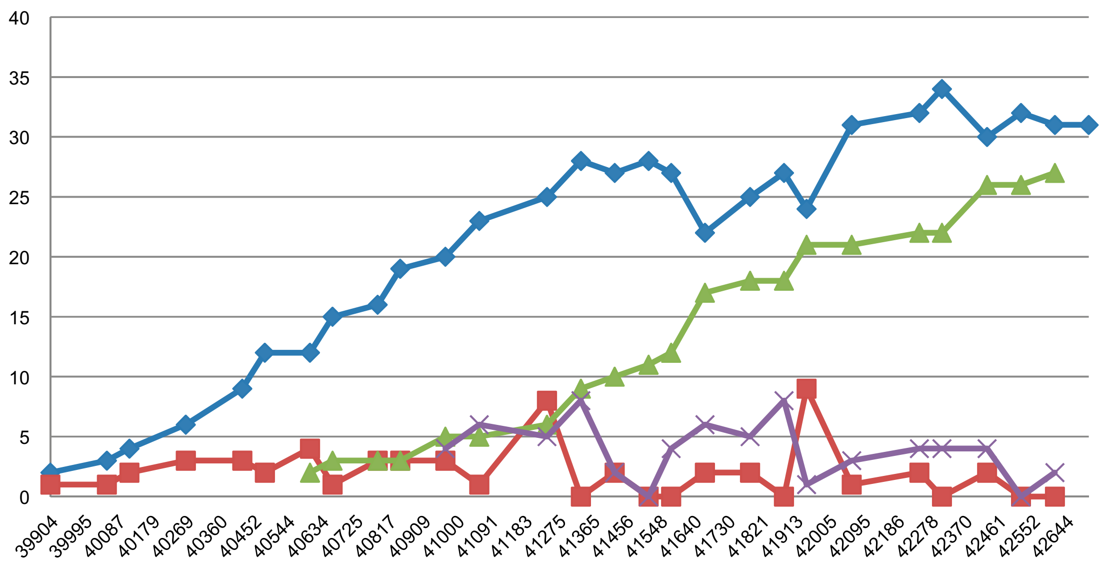

Figure 7-32. *Development of projects at Nova FoU during the last six years. X-axes show date and y-axes the number of projects. Blue curve = on-going projects, green curve = finished projects, red curve = to be approved, magenta = projects for evaluation.*

8 SKB International

8.1 Background history

SKB organised NWM, Nuclear Waste Management, at a department in SKB in order to manage international requests for consultations and transfer of methodology and technology in an efficient way. The international operation was in 2001 transferred to a separate company, SKB International Consultants AB, a wholly owned subsidiary of SKB. The name was changed in 2010 to SKB International AB. SKB International is the commercial arm of SKB and cannot draw any funds from the nuclear waste fund as the mother company SKB. SKB International offers technology, methodology and expert resources to international clients. SKB International has access to all expertise, experience and technologies that SKB has acquired and developed in its programme. SKB International provides services to organisations and companies in spent nuclear fuel and nuclear waste management and disposal and hence provides the opportunity to save time and cost and minimise risk. SKB International is committed to the safe disposal of spent nuclear fuel and radioactive waste generated in the operation and decommissioning of nuclear power reactors. The company has full access to SKB's experts, operating facilities, laboratories and intellectual property. SKB International's services are based on the know-how and hands-on experience accumulated by SKB in the development and operation of the Swedish nuclear waste management system.

SKB International makes available SKB's special purpose vessel m/s Sigrid at times she is not involved in SKB's programme. m/s Sigrid is roll on – roll off, lift on – lift off vessel with XX3 classification allowing transports of the highest class of radioactive cargo.

SKB International's main areas of operation are:

- Consulting services
- Technology transfer
- Laboratory services
- Transports with m/s Sigrid

8.2 Support and services related to Äspö

Äspö HRL is a unique research facility and there are only a few like it in the world. Almost 500 metres underground, SKB conduct experiments in collaboration with Swedish and international experts. The facility includes also the Äspö Village at surface with office spaces, different laboratories, an exhibition hall, etc.

Äspö HRL enables us to study the interaction of bentonite clay and copper canisters with the rock in realistic conditions. Here experiments are made to identify the role of the rock as a barrier. This can, for instance, concern how the rock slows down the movement of radioactive substances or how microbes affect conditions at this depth. It is possible for other organisations to carry out their own research and experiments at the Äspö HRL. This can be organised through SKB International.

8.2.1 The following facilities are available at Äspö HRL:

Underground facility with available experiments sites (Figure 8-1)

The underground part of Äspö Hard Rock Laboratory consists of a 3 600 metre long tunnel. It starts on the Simpevarp peninsula, where the Oskarshamn nuclear power plants are located.

Under Äspö, the main tunnel descends in two spiral turns down to a depth of 460 metres. Along the main tunnel there are connecting tunnels and niches where experiments and tests are conducted. In total, the tunnels are about five kilometres long. From Äspö Research Village there is also an elevator for passenger transport down into the underground tunnel system.

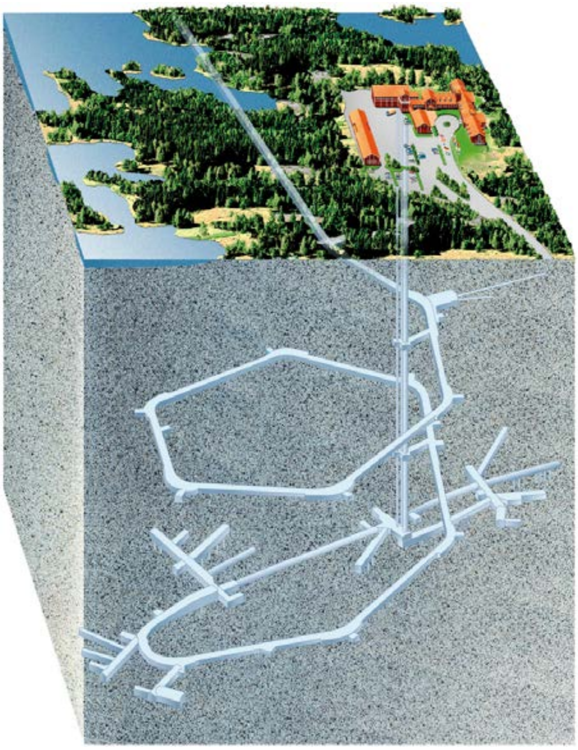

Figure 8-1. *Äspö HRL underground tunnel system.*

Bentonite laboratory (Figure 8-2)

The Bentonite Laboratory has been in operation since 2007. It includes two stations where the emplacement of buffer material at full scale can be tested under different conditions. The laboratory has also been used for continued testing of different types of backfill material and the further development of techniques for the backfilling of deposition tunnels. A wood frame mock-up of a deposition tunnel in full scale in the laboratory has been used in such testing.

Other equipment in the laboratory includes an Eirich bentonite mixer with a load capacity of 1 000 kg to allow mixing of bentonite with desired water ratio, and a press for production of extruded bentonite pellets.

Water chemistry laboratory (Figure 8-3)

The Chemistry Laboratory was built in the late 1990's. The main purpose is to perform the sampling and analyses on water samples collected in streams, lakes and boreholes in the surrounding area and the tunnel. In combination with groundwater flow, groundwater composition is of great importance for repository performance in both the short and long term. Before the site investigations started in 2002, a decision was made to accredit the chemistry laboratory. This was fulfilled in 2003. The laboratory serves all of SKB and its projects, not only Äspö HRL. In 2011 new laboratory areas was built and this makes it possible for external organisations to use the laboratory for sample preparations and other laboratory work while performing experiments at Äspö HRL.

Material science laboratory (Figure 8-4)

There are many current and future challenges regarding the bentonite buffer and backfill materials related to long term safety assessment, as well as industrial scale quality control. 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.

Wet chemical methods such as cation exchange capacity (CEC) and exchangeable cations (EC), X-ray diffraction (XRD) for the determination of crystalline solids, X-ray fluorescence (XRF) spectroscopy for elemental compositon, Fourier Transformed IR (FT IR) spectroscopy for detailed analysis of the clay mineral structure and amorphous material, and UV/Vis for the CEC method are examples of equipment.

Figure 8-2. *Äspö HRL Bentonite laboratory.*

Figure 8-3. *Äspö HRL Chemistry laboratory.*

Figure 8-4. *Äspö HRL Material science laboratory.*

Borehole deviation facility (Figure 8-5)

Drilling in conjunction with construction and operation of a repository for spent nuclear fuel at Forsmark requires careful control of borehole geometry in various applications. Foreseen pilot holes for deposition tunnels, up to 300 m long, where the boreholes are required to stay within the tunnel perimeter calls for careful control of the drilling process. This requires development not only of drilling methodology but also of instruments and methodology for providing the necessary steering and successive verification of borehole geometry. To this end SKB has devised a facility where indirect deviation measurements can be verified relative to the known geometry of a simulated borehole on ground surface.

The 300 m long near horizontal simulated borehole was constructed during 2013 on the Äspö island. The equipment consists of a tube anchored to the rock. The tube, which essentially follows ground surface topography, has been carefully surveyed geodetically. SKB use the facility to test borehole deviation equipment of different types, including magnetic tools, gyro based tools.

Office space (Figure 8-6)

The Äspö village accommodate office space in a unique and lovely environment for up to 100 people with access to conference rooms, video connections, internet, and other support and equipment necessary for an efficient working place.

8.2.2 SKB International can customise following services:

Participation in SKB's experiments

SKB is using Äspö HRL for testing and verifying different technical solutions for the KBS-3 method at full scale under realistic conditions. In this report several experiments and demonstrations gives examples of activities which can be followed or joined by other organisations.

On the job-training

Possible to arrange specific on the job-training activities for competence building of other organisation's staff.

Access to field data from 1986 up until today

SKB has produced data from the site investigations around the Äspö island back in the mid 1980s, from the construction phase of the Äspö HRL between 1990 to 1995 and from activities accomplished up until today. Most of this field data can be available for other organisations, who perhaps have no access to own field data and would like for instance do site descriptive modelling.

Figure 8-5. *Äspö HRL Borehole deviation facility.*

Figure 8-6. *Äspö HRL above ground office buildings.*

Support to your organisation with tests and experiments

The staff at Äspö has long experience in planning, accomplishing and analysing tests and experiments. They are prepared to support other organisation which would like to perform own tests or experiments at Äspö HRL.

Workshops and training courses

SKB International has good experiences in arranging customised workshops and training courses in different topics. Experts from SKB covering different disciplines, e.g. long term safety, site investigations and selections, public relations, construction of URL, etc can be involved.

Äspö International partnership

SKB International offers a unique partnership to organisations where they can get information from SKB's ongoing work accomplished at Äspö HRL. Meetings and workshops with SKB experts are annually organised specially for the partners. At these occations partners get good insite in the work and experiences SKB has developed over 40 years. The partners can also follow the work and activities on site at Äspö.

A specific web based site, the Äspö International Web Portal, is available for the partners. Information about the Äspö HRL, including the Äspö village with the Bentonite, the Chemistry and Material Science laboartories as well as the underground laboratory is presented. Also accomplished, ongoing and planned projects/experiments are presented. This gives the partners great possibilities continuously to follow planned and ongoing work and also to prepare for own experiments.

Field data measured from the site investigations of the Äspö HRL during 1986 to 1990, field data from the construction of Äspö HRL during 1990 to 1995 and extensions done at site and in the underground facility accomplished until today.

8.3 Activities and support during 2016

Äspö International partnership

For the Äspö International partners SKB International arranged different events during 2016. Three ***topical workshops*** were organised, two of them regarding development of borehole sealing of investigation boreholes drilled from the surface. In the third workshop SKB presented SKB's development of Site Descriptive Modelling, SDM.

The specific ***Äspö International Web Portal*** was updated with more detailed information about the Äspö facility, the ongoing and planned projects, etc. New animations presenting different experiments were uploaded at the web portal.

The annually ***Technical Information Meeting***, TIM, presented the latest updates from the technical development work accomplished. Examples of topics covered at the meeting were:

- Overall Äspö information
- Buffer and backfill development
- KBS-3H project
- Tunnel production
- Concrete caissons test

One of the Äspö International partners started to do own hydromodelling based on Äspö field data, which they received during autumn. Interest from the other partners to get similar data and do own modelling was raised.

Training course

During late autumn a customized training course in planning, construction and operation of an underground research laboratory was organised.

8.4 Contact information

Are you interested in our assistance or do you need more information? Just contact us and we will help you out.

Mr. Magnus Holmqvist, President, Phone +46 70-641 18 28, email: magnus.holmqvist@skb.se
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More information available at:

www.skbinternational.se

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SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

skb.se

Arkitektkopia AB, Bromma, 2017