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Äspö Hard Rock Laboratory Annual Report 2020

SVENSK KÄRNBRÄNSLEHANTERING AB

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Äspö Hard Rock Laboratory
Annual Report 2020

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 2020 is given below.

Äspö Site Descriptive Modelling (SDM)

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 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.

Research projects and development of 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 practices 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 Long Term Test of Buffer Material (LOT) project aims at studying possible alteration of the bentonite as a result of the hydro-thermal evolution, both with respect to mineralogy and to sealing properties. The LOT test series includes seven test parcels, which all contain a heater, central tube, clay buffer, instruments and parameter controlling equipment. Two test parcels were dismantled in 2019, and analysis and reporting was carried out during 2020.

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 2018 the test programme of Lasgit continued a phase of prolonged "hibernation" with monitoring of the natural and artificial hydration of the bentonite buffer. During 2020 a Gas Migration Test and a Full Canister Test was carried out and subsequently, the dismantling of the experiment started.

A project series is ongoing with focus on *System design of buffer and backfill*. During 2020 full scale, in situ tests of early THM processes in the buffer have been performed.

Work on concrete barriers. In order to verify that the suggested design solutions for a planned extension of the Final Repository for Short-Lived Radioactive Waste (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. In order to demonstrate that SKB is able to construct the concrete caissons in accordance with requirements under current prerequisites a development program comprising a number of different development and verification steps has been initiated. This development program includes the steps from material development through casting of a representative section of a concrete caisson in the Äspö Laboratory and monitoring of its properties.

Borehole sealing. A large number of investigation boreholes have been drilled in both the area for the planned Spent Fuel Repository in Forsmark and for the Final Repository for Short-Lived Radioactive Waste (SFR). A project was ongoing during 2020 with the objective to optimize the sealing of SKB's investigation boreholes in Forsmark.

Bentonite material studies. SKB has developed methods and techniques for acquisition and quality control of bentonite for a long time. The long-term safety requirements on the bentonite are quantified into a number of parameters; swelling pressure, hydraulic conductivity, shear strength, thermal conductivity and limitations in sulphide, total sulphur and carbon (harmful substances).

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 2020 the second concrete cylinder containing specimens of zinc, aluminium, stainless steel and carbon steel was retrieved and analysed.

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 outer test section was retrieved during 2011 after approximately eight years of water uptake of the buffer and backfill. The monitoring of the inner section will be continued at least until 2022.

The *Alternative Buffer Materials (ABM)* project was started in 2006 with the purpose to evaluate different bentonites as possible buffer candidates. The ABM project consists of a combination of field experiments at the Äspö HRL and laboratory studies of the bentonites performed at a variety of laboratories, including both SKB and external partners. The ABM experiment at Äspö HRL is in a monitoring phase.

SKB and Posiva have been co-operating on a programme for the *KBS-3 Method with Horizontal Emplacement* (KBS-3H). During 2020 decision was made to not continue development of KBS-3H. The Multi Purpose Test at Äspö HRL is still being monitored, but with no plan for a retrieval.

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. The experiment is in monitoring phase.

Transport system and development of installation equipment

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

During 2020, a project aimed at designing the equipment for backfill installation has been active at the Multi-purpose test facility at Äspö.

Development of excavation techniques

In the Äspö HRL different techniques for excavating the underground openings of a spent fuel repository have been developed and tested since the start of the HRL. Although the strategy is to rely on commercially available techniques they have to be tested and, in some cases adapted, to the specific requirements for the repository.

The plans to construct and later, during operation, expand the deposition areas rely on detailed knowledge of the geotechnical and geoscientific traits of the Forsmark site. This knowledge is needed in order to secure that the deposition area is constructed where requirements from post-closure safety can be met. Investigation methods are developed at Äspö as part of the tools needed to acquire this knowledge.

During 2020 the following experiments and projects concerning excavation techniques were ongoing:

- Mechanical excavation.
- Drilling of deposition holes.
- Investigation methods for ramp and shafts.

Äspö facility

The Äspö facility comprises both the Äspö Hard Rock Laboratory and the Research Village with laboratories. The main goal for the operation of the Äspö facility is to provide a facility which is safe and available for working and visiting. 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. The target on high service function and customized availability for projects and external customers was well met in 2020 despite great rock maintenance work and several parallel experiments.

In *the Multipurpose test facility* different methods and techniques for installation of pellets and blocks in deposition tunnels are tested, and work on buffer and backfill is performed. Several projects have performed activities in the facility during 2020.

As a part of the needed infrastructure, a *Material science laboratory* has been established at Äspö, with focus on material chemistry on bentonite properties and key-competence development. The key focus areas are long term safety related research and development of methods for quality control of the bentonite buffer and backfill materials. The laboratory is used in a number of projects and activities including technological development in the material science projects, and for various research studies such as the analysis of long-term field experiments such as LOT and Alternative Buffer Material.

The Water Chemistry Laboratory at Äspö HRL is accredited according to ISO17025 and perform the sampling and analyses on water samples collected in streams, lakes and boreholes in the surrounding area and the tunnel. For the moment the Chemistry Laboratory can perform 14 different analyses of water samples.

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. 2020 was a different year for everyone, and only 338 persons did visit the Äspö HRL before it was closed in mid-March. The total number of visitors to SKB's facilities in both Oskarshamn and Forsmark/Östhammar was just 1 082 persons during 2020.

Future use of Äspö HRL

SKB is conducting work with the intent to seek alternative possibilities for adaptation of the Äspö Hard Rock Laboratory into a top level national research- and innovation infrastructure. The work is being spurred both by an active external interest in the future use of Äspö HRL and by a strategic vested interest.

Together with LTU Business, SKB has elaborated a strong business case for Äspö HRL which was presented for a potential new owner in the fall 2020. The first proposal was met with great interest and complementary information has been added successively in the ongoing dialogue. SKB is looking forward to initiate negotiations with the invited potential future owner of Äspö HRL. The core of the proposed business case is based on SKB's potential need of long-term access to the underground facility throughout the 2020s and maybe even longer. A favourable starting point for a fruitful long-term collaboration.

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.

Due to the pandemic in 2020 and hard restrictions to travel, all events for our Äspö International partners at Äspö HRL were cancelled. Instead SKB International arranged three webinars with the latest updates from the technical development work at Äspö HRL at the annual ***Technical Information Meeting***, TIM.

Sammanfattning

Äspölaboratoriet i Simpevarp i Oskarshamns kommun är en viktig del i SKB:s arbete med utformning, byggande (och drift) av ett Kärnbränsleförvar. Ett av de grundläggande skälen till SKB:s beslut att anlägga ett underjordslaboratorium vid Äspö 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 2020.

Äspö Site Descriptive Modelling (SDM)

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 disciplinerna.

Programmet för hydromonitering utgör en grundsten i Äspö HRL's hydrogeologiska undersökningar, och stödjer de 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.

Forskningsprojekt och barriärutveckling

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 Kärnbränsleförvar. 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.

Projektet *Långtidstest av buffertmaterial (LOT)* syftar till att studera möjliga förändringar i bentoniten som ett resultat av hydro-termisk evolution, både sett till mineralogi och tätningsegenskaper. LOT-försöket inkluderar sju uppvärmda testpaket. Två testpaket återtogs under 2019. Analyser, utvärdering och rapportering genomfördes under 2020.

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 2018 fortsatte en förlängd fas av vila, med monitering av den naturliga och artificiella bevätningen av bentonitbufferten. Under 2020 genomfördes ett gastransportförsök (Gas Migration Test) och ett försök med trycksättning av hela kapseln (Full Canister Test). Därefter påbörjades brytningen av experimentet.

En serie av projekt pågår med fokus på *Systemkonstruktion av buffert och återfyllnad*. Under 2020 genomfördes fullskaleförsök in situ för att studera tidiga THM-processer.

Betongbarriärer. För att verifiera designen inför den planerade utbyggnaden av Slutförvaret för kortlivat radioaktivt avfall, SFR, har ett forskningsprogram initierats. Detta inkluderar steg från materialutveckling till gjutning av en testsektion av en betongkassun i Äspölaboratoriet.

Ett stort antal undersökningsborrhål har borrats både i områdena för det planerade Kärnbränsleförvaret och Slutförvaret för kortlivat radioaktivt avfall (SFR). Ett teknikutvecklingsprojekt kring *Förslutning av borrhål* pågår med målet att optimera förslutningen av SKB:s undersökningsborrhål i Forsmark.

Materialstudier av bentonit. SKB har utvecklat metoder och tekniker för inköp och kvalitetskontroll av bentonit under en lång tid. Kraven på långsiktig säkerhet för bentoniten har kvantifierats till ett antal uppmätta parametrar.

I projektet *"Concrete and Clay"* är syftet att öka förståelsen för processer i samband med nedbrytning av låg- och medelaktivt avfall i en betongmatris, nedbrytning av betongen självt genom reaktioner med grundvattnet och växelverkan mellan betong, mark och angränsande material som bentonit och den omgivande berggrunden. Under 2020 återtogs och analyserades den andra betongcylindern som innehöll prov av zink, aluminium, rostfritt stål och kolstål.

I Prototypförvaret pågår en demonstration av den integrerade funktionen hos förvarets barriärer. Prototypförvaret utgör dessutom en fullskalig referens för prediktiv modellering av Kärnbränsleförvaret 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. Den yttre sektionen bröts och kapslarna återtogs under 2011. Övervakningen av den inre sektionen kommer fortsätta till minst år 2022.

Försöket *Alternativa buffertmaterial (ABM)* startades 2006 med syftet att utvärdera olika bentonitmaterial som möjliga kandidater till bufferten. ABM-projektet består av en kombination av fältexperiment och laboratorieförsök på ett flertal laboratorier både hos SKB och externa parter.

Ett forskningsprogram för ett *KBS-3-förvar med horisontell deponering* (KBS-3H) har genomförts som ett samarbetsprojekt mellan SKB och Posiva. Under 2020 togs beslutet att inte fortsätta med utveckling av den horisontella metoden. Viss övervakning av MPT-testet fortgår vid Äspölaboratoriet men det finns ingen plan att öppna och återta försöket.

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.

Utveckling av transportsystem och installationsutrustningar

SKB utvecklar teknik och metoder för deponering och installation av barriärerna i Kärnbränsleförvaret. Totalt omkring 200 olika system och produkter kommer att behövas och såväl standardiserad som modifierad eller nyutvecklad teknik kommer att användas.

Nyutvecklad eller modifierad utrustning provas primärt vid Äspölaboratoriet och Kapsellaboratoriet i Oskarshamn där väl anpassade testmiljöer finns.

Under 2020 har ett projekt som tar fram design för utrustning för återfyllnadsinstallation genomfört provningsaktiviteter i testhallen vid Äspölaboratoriet.

Utveckling av bergbyggnadsteknik

Vid Äspölaboratoriet undersöks olika typer av tekniker för att konstruera de speciella underjordsmiljöer som krävs för Kärnbränsleförvaret. Detta arbete har pågått allt sedan byggnationen av Äspölaboratoriet. Även om strategin är att använda kommersiellt tillgänglig bergbyggnadsteknik så behöver vissa moment och metoder testas och i flera fall anpassas till de specifika kravställningar som gäller för Kärnbränsleförvaret.

Planeringen för att bygga och senare driva Kärnbränsleförvaret baseras på detaljerad geoteknisk och geovetenskaplig kunskap om egenskaperna hos slutförvarsplatsen Forsmark. Dessa kunskaper behövs för att säkerställa att deponeringsområdet byggs på sätt som möter kraven på säkerhet efter förslutning. Som ett led i detta utvecklas ett flertal undersökningsmetoder vid Äspölaboratoriet vilka kommer att användas under slutförvarsbygget i Forsmark.

Under 2020 bedrevs följande experiment och projekt avseende bergbyggnadsmetoder:

– Utredningar avseende mekanisk tunneldrivning.
– Borrning av deponeringshål.
– Undersökningsmetoder för ramp och schakt.

Äspölaboratoriet

I *Äspöanläggningen* ingår både det underjordiska berglaboratoriet och Äspö forskarby. Huvudmålet för driften av Äspöanläggningen är att tillhandahålla säkra och tillgängliga testmiljöer och även kunna ta emot besökare. Under 2020 nåddes målet på en hög servicegrad trots omfattande bergunderhållsarbeten och flera projekt som bedrevs parallellt.

I *Testhallen* provas olika metoder och tekniker för installation av pelletar och block i deponeringstunnlar och studier av erosion av buffert och återfyllningsmaterial utförs. Flera projekt har haft aktivitet i Testhallen under 2020.

Ett *Laboratorium för Materialstudier* har etablerats vid Äspö, med fokus på materialkemi för bentonitlera och utveckling av nyckelkompetenser. De största fokusområdena är metodutveckling för kvalitetskontroll av bentonit som ska användas som buffert- och återfyllnadsmaterial. Laboratoriet nyttjas för ett flertal projekt och aktiviteter som teknikutveckling i Materialprojektet och för studier så som analyser av långtidsförsök som LOT och ABM.

Vattenkemilaboratoriet vid Äspö är ackrediterat enligt ISO17025 och genomför provtagningar och analyser av vattenprover insamlade från vattendrag, sjöar och borrhål i omgivande områden och Äspötunneln. För nuvarande kan Kemilaboratoriet utföra 14 olika analyser på vattenprover.

Det huvudsakliga målet för enheten *Kommunikation Oskarshamn* är att skapa en allmän acceptans för SKB, vilket görs i samarbete med andra avdelningar inom SKB. 2020 var ett annorlunda år för alla och endast 338 personer besökte Äspö innan laboratoriet stängde för besök i mitten av mars. Totalt besökte bara 1 082 personer SKB:s anläggningar i Oskarshamn och Forsmark/Östhammar under 2020.

Framtida bruk av Äspö HRL

SKB bedriver ett utredningsarbete med avsikt att söka alternativa möjligheter till omställning av Äspölaboratoriet till en nationell forsknings- och innovationsinfrastruktur i världsklass. Utredningsarbetet sporras dels av ett aktivt omvärldsintresse för Äspölaboratoriets framtida användning dels av ett strategiskt egenintresse.

Tillsammans med LTU Business har SKB utarbetat en stark affärsmodell för Äspölaboratoriet. Under hösten 2020 presenterades prospektet för en tilltänkt ny ägare. Det första förslaget möttes med stort intresse och mer information har tagits fram för efterföljande dialoger. SKB ser fram emot att under kommande år inleda förhandlingar med en potentiell ny huvudman för Äspölaboratoriet. Kärnan i affärsförslaget är att SKB har behov av tillgång till en underjordsmiljö under hela 2020-talet, och potentiellt ännu längre. En bra startpunkt för givande och långvarig samverkan i Äspö.

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.

På grund av pandemin med besöks- och reserestriktioner ställdes alla evenemang in för våra Äspö International partners. Istället genomfördes det årliga Technical Information Meeting (TIM) i form av tre webinar där SKB presenterade nyheter från pågående utvecklingsprojekt.

Contents

1 General

The Äspö Hard Rock Laboratory (HRL) is a unique research facility that extends to a depth of 460 metres in the Swedish bedrock. For more than 35 years, this site has been central for the development of safe methods for final disposal of spent nuclear fuel.

At Äspö HRL, the Swedish Nuclear Fuel and Waste management Co (SKB) has built up a large part of the knowledge that is now being used in the detailed design and preparations for the construction of a Spent Fuel Repository in Forsmark, as well as experience that will be used during the construction phase and future operation of the repository.

It is fair to say that 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 planning for design and construction of deep geological repositories for radioactive waste.

The Äspö HRL is not only an underground laboratory. On the surface lies Äspö Research Village with laboratory areas for accredited hydrochemical analyses, research activities and advanced bentonite clay examinations. Furthermore, there is a large testing hall, including an overhead crane, which is used as a multipurpose facility for various technical developments.

Well worth noting, SKB is today offering Äspö as an open resource for both national and international customers within wide-ranging sciences.

This report summarises the main accomplishments and initiatives carried out during 2020.

1.1 Background

Äspö HRL is located in the south east coast of Sweden, on the island Äspö, 25 kilometres north of Oskarshamn. It was in SKB's Research, Development and Demonstration (RD&D) Programme 1986 that SKB first presented the idea of a new underground research facility. 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.

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 ramp 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 system is connected to the ground surface through a hoist shaft and two ventilation shafts. Thanks to the 20-passenger elevator, easy access to the underground laboratory is offered from the office building at the Äspö Research Village.

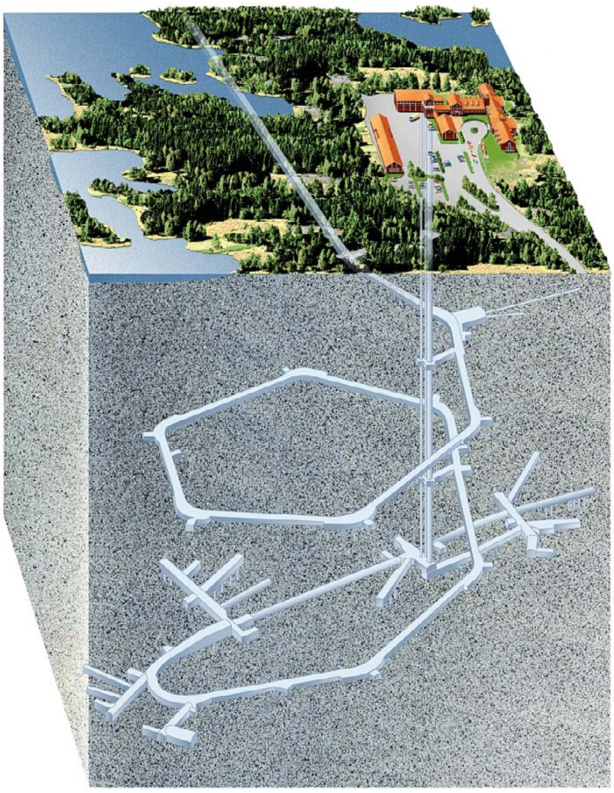


Figure 1-1. *Overview of the Äspö HRL facilities.*

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 construction 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.

The Operational phase began in 1995. A preliminary outline of the programme for this phase was given in SKB's RD&D Programme 1992. Since then the programme has been revised every third year and the detailed basis for the period 2020–2025 is described in SKB's RD&D-Programme 2019 (SKB 2019).

After the start of operation in 1995, experiments began gradually to investigate how the engineered barriers (canister, buffer, backfill and closure) of the Spent Fuel Repository could be designed and managed in order to provide optimal functionality and safety. 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 post closure 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 future 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.

SKB's technical development is now focused on improved rock excavation technologies and design, manufacturing and installation of the engineered barriers, including several steps of quality controls.

Tests are also performed to investigate, in detail, the initial performances of the engineered barriers subsequent to installation. All practical means of constructing a repository and emplacing the canisters with spent fuel are dealt with at the laboratory. This work also includes the development and testing of methods for use in the characterisation of a suitable repository site as well as the operative investigation methods to be used during construction of the underground openings.

Furthermore, Äspö HRL will be used by SKB to prepare the extension of the Final Repository for Short-Lived Radioactive Waste, the SFR at Forsmark. Specifically, the construction and control methods of casting concrete barrier caissons is demonstrated in large scale under realistic conditions.

In addition, research projects are carried out for future analyses of post closure safety for SFR and SFL (the Swedish repository for Long-Lived Radioactive Waste) focused on studies of interactions between different types of barrier materials relevant to these repositories and for different types of materials that are representative of low- and intermediate-level waste.

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 as 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 Spent Fuel Repository 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 yet fully reached. 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. Technology development is still ongoing for certain issues.

Goal number 3 has been reached completely.

Goal number 4 related tasks will continue at Äspö HRL at least until 2024. SKB has recently made a clear statement to open the Äspö facilities for a broader range of activities in the future and thus invite new stakeholders and projects. Accordingly, a new goal has been set for Äspö, namely that the underground laboratory can continue in a renewed constellation after SKB has completed most of its operations in 2024.

1.3 Organization

The Äspö HRL is included in the department Research and Development (R) at SKB. The Research and Development department comprises four units; Repository Technology (RD), Encapsulation Technology (RI), Site Modelling and Monitoring (RP) together with Research and Post-closure Safety (RS).

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 deposition tunnels, production and installation methods for the engineered barriers, transport and logistics as well as all necessary quality control methods.
- Develop, manage 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 that additional research and development activities can use the underground laboratory in the future.

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

- *Technology Development (RDT)*, 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.
- *Operations and technical support (RDD)*, responsible for the operation and maintenance of the Äspö HRL offices, workshops and underground facilities and for development, operation and maintenance of supervision systems. The group is also responsible for the preparations and practical coordination of projects undertaken at the Äspö HRL, providing services (design, site selection, installations, measurements, field equipment, monitoring systems etc) and workers safety to the experiments.
- *Chemistry (RDK)*, responsible for water sampling and accredited chemical water analysis and bentonite material analysis. The group coordinates all activities inside the research laboratory.

Each major research and development task, ordered by SKB and carried out in Äspö HRL, is organised as a project or assignment led by a Project Manager reporting to the client organisation. Each Project Manager is assisted by an on-site coordinator with responsibility for coordination and execution of project tasks at the Äspö HRL. The professional staff at the site office provides technical and administrative service to the projects.

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. SKB International is responsible for the Äspö International Joint Committee (IJC), which during last year consisted of five external member organisations; BMWi, RWM, NUMO, CRIEPI and JAEA. The committee is responsible for the coordination of the experimental work arising from the international participation.

1.4 Allocation of experiment sites

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

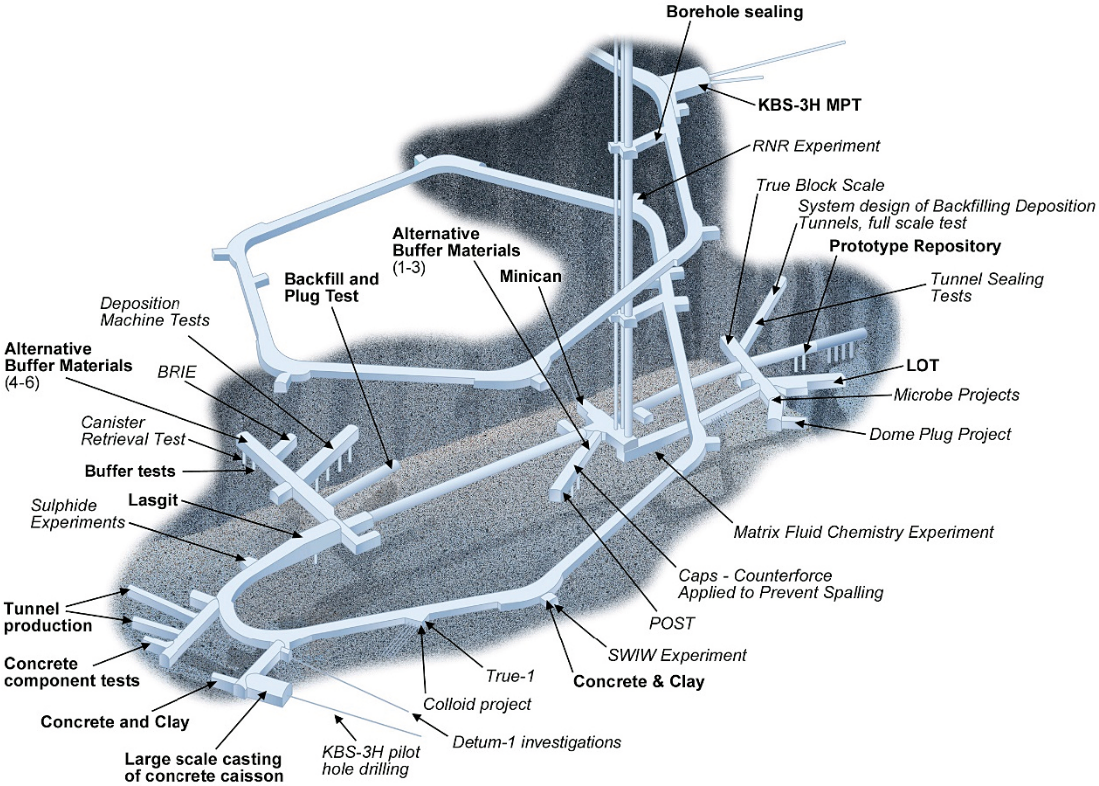


Figure 1-2. *Allocation of experiment sites from −220 m to −460 m level. Ongoing experiments in bold text.*

1.5 Reporting

The plans for research and technology development during 2020–2025 are described in SKB's RD&D-Programme 2019 (SKB 2019a).

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 general achievements during 2020.

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.

1.6 Structure of this report

The achievements obtained at Äspö HRL during 2020 are in this report described in six chapters:

- Äspö site descriptive modelling (SDM) – geoscience experiments, analyses and modelling to increase the knowledge of the surrounding rock.
- Research projects and development of engineered barriers – experiments, analyses and modelling to increase the knowledge of the repository barriers under natural conditions, demonstration of technology for, and function of, important engineered parts of the repository barrier system.
- Transport system and development of installation equipment – developing of technologies for the final disposal of spent nuclear fuel.
- Development of excavation techniques – demonstration and control of technologies for excavation, drilling and investigations.
- Äspö facility – laboratories, operation and maintenance, communication activities and future plans.
- SKB International – services and support related to Äspö HRL.

2 Äspö site descriptive modelling (SDM)

2.1 General

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 work will result:

- in a modern and updated site descriptive model and comprehensive quality checked data, updated with all available data until the end of 2016 and summarized in public report,
- in further understanding of the geological, hydrogeological and groundwater chemical conditions and processes in the rock mass at Äspö HRL,
- in testing of the developed methodology for iterative and integrated modelling,
- in further development of the modeling methodologies.

Added value of the work is to:

- develop the geoscientific model by using the same means, methods and resolution as is intended for the facility part scale models intended to be developed during construction and operation of the planed Spent Fuel Repository in Forsmark,
- train the staff at Äspö and Forsmark to learn and further understand modelling tools, software packages and methodology concerning conceptual and deterministic modelling methodology.

2.2 Geology

Efforts to obtain an updated version of the Äspö site model, as a multidisciplinary modelling project involving geology, hydrogeology and hydrogeochemistry, has been ongoing since 2016. The geological keystone of the model comprises deterministic geometries for rock domains and deformation zones, currently with draft versions of property tables describing the modelling procedure and the details of individual intercepts.

The model volume covers the laboratory with its immediate surroundings, down to a depth of –600 m, whereas individual domains and zones and have a minimum size constraint of approximately 300 m. Totally there are 13 rock domains and 23 deformation zones. While details in terms of thickness, orientation and to some extent location of deformation zones that originally were defined in the Laxemar SDM (SKB 2009) have been changed within the Äspö model volume, the overall position and connectivity are maintained. The predominant Äspö shear zone, that partly intersects the laboratory, has been separated into several branches inside the model volume.

The current versions of the domains and zones are, along with supporting documentation, basis for an ongoing process of interdisciplinary integration, aiming to provide the necessary feedback to finalise the geometries. After completion, the Äspö site model is intended to provide a dynamic basis for the various geoscientific experiments in the laboratory. In addition, it will serve as a framework for more highly resolved modelling in parts of the facility, as well as providing input to the ongoing development of modelling methodology to be used during the construction of the final repository for spent nuclear fuel in Forsmark.

The status of the model will be presented at the EGU General Assembly 2021, with an aim to complete the geometries of domains and zones shortly afterward. Reporting is currently planned to 2022.

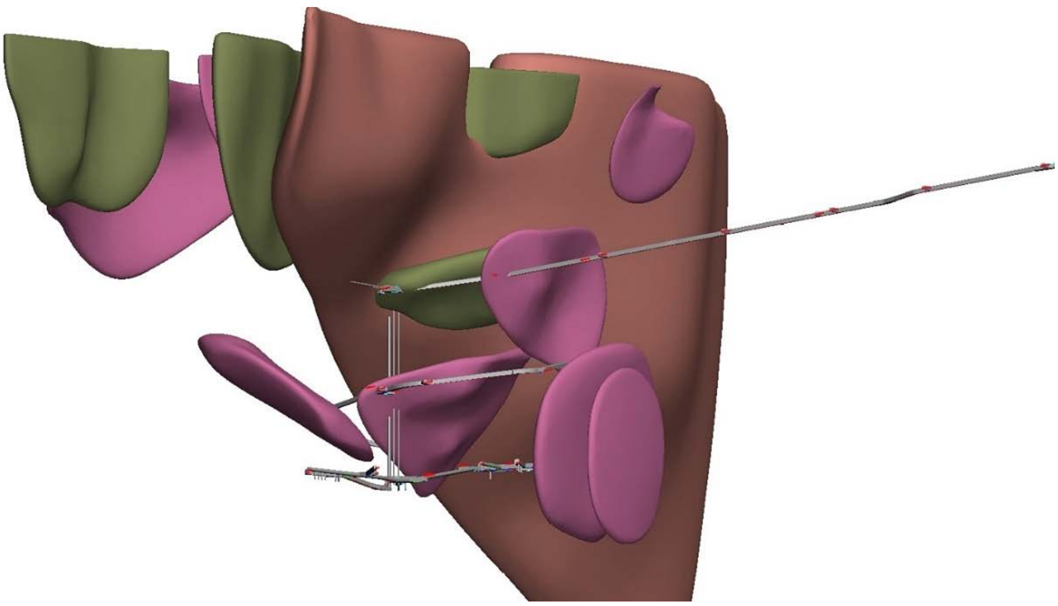


Figure 2-1. Three-dimensional model view of the rock domains within the Äspö model volume relative to the underground part of the laboratory.

2.3 Hydrogeology

The hydrogeologic activities at Äspö HRL comprised on updating of the Äspö site descriptive model, operation and maintenance of the hydrogeological monitoring system as well as hydrogeological expert support to experiments and projects at the Äspö HRL. The hydrogeological expertise at Äspö was also utilised in support of other projects within SKB. The modelling and monitoring work is described below, experiments and projects are reported under their own heading elsewhere in this annual report.

2.3.1 Äspö Site descriptive modelling

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, Figure 2-2.

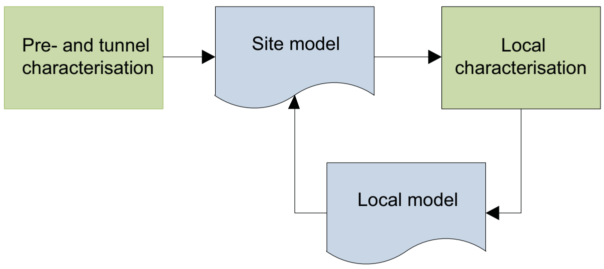


Figure 2-2. Evolution of local- and site descriptive model.

The main features are the inclusion of data collected from various experiments and the adoption of the modelling procedures developed during the Site Investigations at 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 site descriptive model and modelling are to:

- Maintain and develop the understanding of the hydrogeological properties of the Äspö HRL rock.
- Support of experiments and measurements in the hydrogeological field.
- Maintain and develop the expertise and methodology for site descriptive modelling.

Experimental concept

The concept is to recurrently compile and evaluate new hydrogeological data along with the previous data as a base for revising and updating the modelling/model and the geoscientific understanding of the site. Additionally, the modelling exercise is developing the internal expertise in site descriptive modelling.

Results

The hydrogeological component of the Äspö SDM progressed with the data compilation and evaluation as well as finalization of the hydrogeological parameter assignment to the rock and deformations zone units of the single hole interpretations. The methodology was established and executed for K-value assignment to single hole rock units and deformation zones.

2.3.2 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 law when granting the permission to execute the construction works for the tunnel. A staged approach of monitoring has been adopted according to Figure 2-3. Monitoring initiated as part of the pre-investigation for the site selection process. Upon completed characterisation boreholes were retained for long term monitoring in support of establishing a baseline. The monitoring system is also utilised for characterisation during construction and to develop site descriptive models.

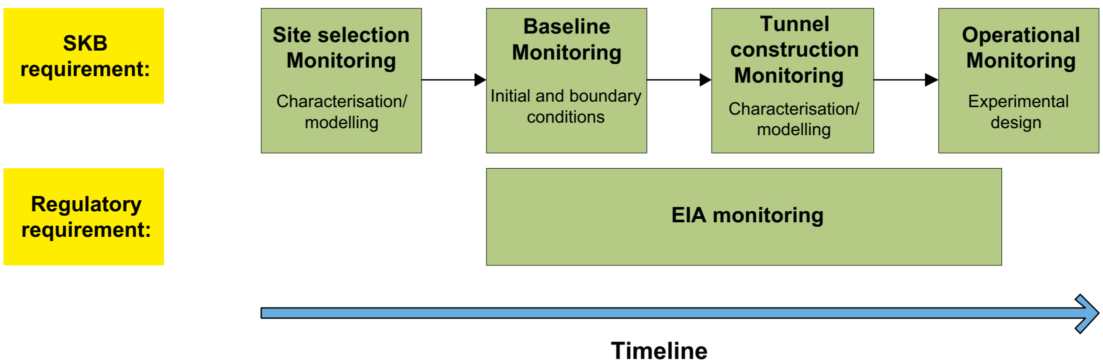


Figure 2-3. *The staged approach of monitoring at Äspö.*

During its operational phase the laboratory houses a number of different research experiments which are conducted simultaneously at different locations throughout the tunnel system. 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,
- means to set initial and boundary conditions for the experiments and models,
- direct data to experiments,
- means to minimize hydraulic disturbances between experiments.

The monitoring of water level in surface boreholes started in 1987 and the construction of the tunnel started in October 1990. The tunnel excavation began to affect the groundwater level in many surface boreholes during the spring of 1991. A computerised Hydro Monitoring System (HMS) was introduced in 1992 and the first pressure measurements from tunnel drilled boreholes were included in the HMS in March 1992.

Objectives

The purpose with the monitoring is to:

- Provide base data for tunnel drainage processes and impact on its surrounding i.e. environmental impact.
- 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/pressure with actual head/pressure.

Experimental concept

The monitoring system relies on about 1 500 measuring points of various hydrogeological variables distributed in space.

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

Results

The monitoring system is continuously maintained and data collected. The hydrogeological monitoring system has functioned well and the monitoring points in the tunnels were maintained.

The monitoring system has provided continuous support for the experiments and projects in their planning and execution and for the tunnel activities operations.

Quality control of data is performed at different levels and scope; weekly, semi-annually 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 quality assurance and control issues.

Annual monitoring reports for year 2019 were issued for groundwater and surface water respectively (SKB internal, restricted reports).

Work on improving the monitoring methodology was undertaken with particular focus on needs for the planned nuclear waste repository at Forsmark.

2.4 Geochemistry

Background

A general understanding of the current hydrogeochemical conditions in deep crystalline bedrock is crucial when predicting future changes in groundwater chemistry.

Through different experiments and projects undertaken in the tunnel, additional data is collected and deeper understanding is gained, for example in groundwater composition, origin and evolution in the area, together with active major processes, primarily flow/mixing related, in order to explain the groundwater chemistry and its distribution.

Objectives

The major aims of the site descriptive modell and modelling are to:

- Maintain and develop the understanding the groundwater composition and origin in fractures at Äspö HRL.
- Maintain and develop the knowledge of applicable measurement and analysis methods.
- Support of experiments and measurements in the hydrogeochemical field to ensure they are performed with required quality.
- Provide hydrogeochemical support to active and planned experiments at Äspö HRL.

Experimental concept

The concept is to recurrently compile and evaluate new hydrogeological along with the previous data as a base for revising and updating the modelling/model and the geoscientific understanding of the site. And develop the internal expertise in site descriptive modelling.

Results

The hydrogeological component of the Äspö SDM progressed with the data compilation and evaluation.

2.4.1 Hydrochemistry monitoring program

Background

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 and sea water.
2. The near surface environment: regolith aquifer (i.e. soil tubes).
3. The deep environment: water-bearing fracture network (i.e. surface- and tunnelboreholes).

The monitoring program is designed as monthly to annual sampling campaigns depending on the type of aqueous environment. Surface waters are collected from permanent meteorological stations, and temporary stream and sea stations. Near surface waters are collected, through pumping, in soil tubes 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 and 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 hydro-geological system. Additionally, the monitoring program provides data for external research organisations.

Results

All analytical data from 2020 are quality assured and stored in SKB database. In addition to the usual analyses during 2021, also Fe isotopes will be performed. Sampling of dissolved gases and gas isotopes will soon be added to the program.

3 Research projects and development of engineered barriers

3.1 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.

Furthermore, research projects are conducted in order to develop the knowledge of the repository barriers and their function in the long-term perspective.

It is important that research, 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. There are also ongoing projects at Äspö that primarily are comprised of laboratory work in the bentonite research laboratory and the chemistry laboratory.

The experiments focus on different aspects of engineering technology and performance testing and are in line with what is addressed in SKB's RD&D programme.

During 2020 the following experiments and projects concerning the engineered barriers were ongoing, either in active or in monitoring stage:

- System design of buffer and backfill.
- Development of concrete barriers.
- Borehole sealing.
- Bentonite material studies.
- Prototype repository.
- Concrete and clay.
- Alternative buffer materials.
- KBS-3 method with horizontal emplacement.
- Large scale gas injection test.
- In situ corrosion testing of miniature canisters.
- Long term test of buffer materials.

These projects are described in the following sections.

3.2 System design of buffer and backfill

Background

For detailed design of the deposition area, the designs of buffer and backfill should be updated to allow for efficient and robust installation. Decisions on new excavation method and new cross sections for deposition tunnels mean that the design of backfill must be adapted to new conditions.

A well-balanced and site-adapted design of buffer and backfill is vital both in order to achieve a robust installation and to meet the requirements for ensuring post-closure safety. The project will evaluate if the buffer design can be based on buffer blocks installed as block segments. As part of this evaluation, the project comprises a full-scale, in situ test of the early THM-processes of a buffer installed with segmented buffer blocks. This test was installed during September and October 2019 and dismantled and evaluated during the spring in 2020.

The design work also includes a revision of the buffer pellet design. As basis for this design, experimental testing was carried out in Äspö's Multi-Purpose Facility during 2018 and 2019. The pellet design work was reported in Annual Report 2019.

Objectives

The purpose of the full-scale buffer test is to better understand and model the buffer's early thermal, hydraulic and mechanical evolution. The gained knowledge and updated models will be used to better plan the installation sequence for the buffer in deposition holes with different water inflows.

The results from the test and subsequent modelling will also be a part of the evaluation of the buffer concept with segmented buffer blocks.

Experimental concept

The early THM processes in a buffer installed as segmented blocks were studied in full scale in the CRT deposition hole at Äspö. The experimental concept is described in more detail in Nord et al. (2020).

Test design: The test comprised the buffer blocks installed in 34 layers and a full-scale canister with a heater generating 1 700 W (see Figure 3-1). The layers were built by block segments according to Figure 3-1. The gap between the block and the deposition hole walls was filled with roller compacted pellets. The buffer had access to water from natural water-bearing fractures in the deposition hole wall. The uppermost top layer was covered with an insulated, diffusion-tight lid. The lid allowed for measurements of the top layer level and visual inspections through drilled holes.

Material: The bentonite material used for both blocks and pellets was a naturally sodium dominated clay from Wyoming, USA.

Instrumentation: The test was instrumented with around 130 thermoelements and 15 RH sensors. The thermoelements were placed in the buffer and the surrounding rock. All instrumentation was placed in 4 perpendicular directions. No sensors were placed in or near the joints between blocks.

Monitoring: The THM processes were foreseen to cause deformation both axially and radially. Therefore, the top surface level was measured at least weekly. Sensor data was logged every 15 minutes. The function of the heater and the sensors' function were monitored continuously.

Sampling and analysis: The test was sampled during dismantling and analysed for water content and density. The sampling covered the buffer in both axial and radial direction. Sampling of blocks was performed by core drilling while the pellet filling was sampled manually. Directly after core drilling the samples were protected by sealing them in marked plastic bags.

It was expected that there would be an increased accumulation of water in the bentonite closest to the capsule top. For this reason, extra samples were taken from two of the highest ring blocks, R20:1 and R20:5.

All analyses of water content and density were performed at SKB's chemistry laboratory at Äspö concurrently with the ongoing dismantling and sampling.

Test time: The test ran for 90 days in order to cover the maximum installation time for a deposition tunnel with margin.

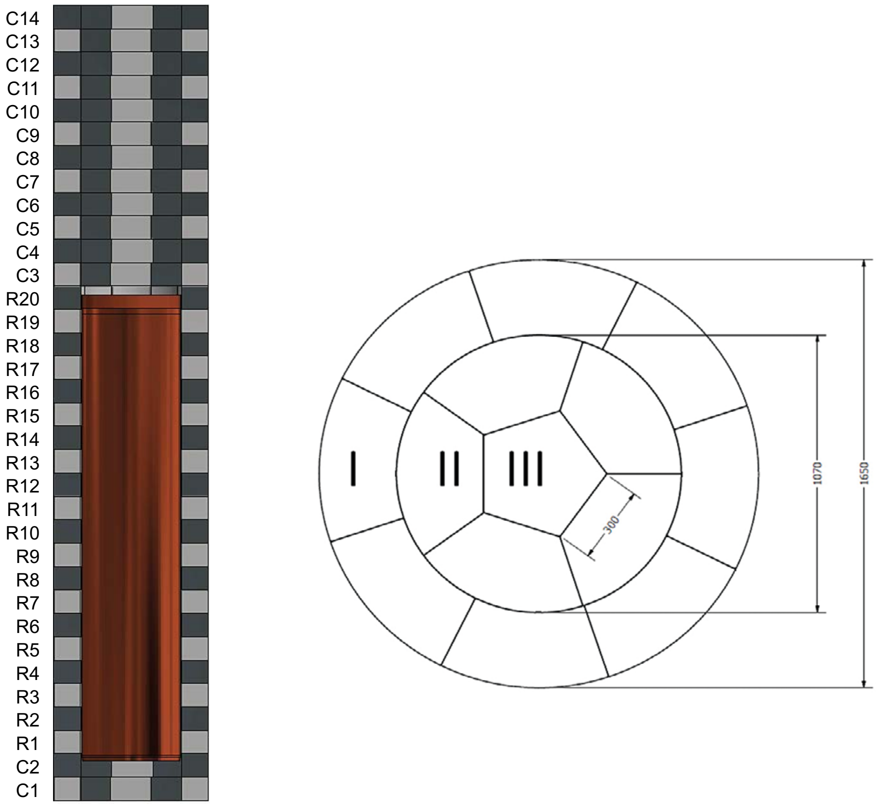


Figure 3-1. *Test design. Left: Block layers and canister. Right: Block layer design Type (I) Outer block, (II) Inner block and (III) Centre block.*

Results

The results are reported in more detail in Nord et al. (2020).

Observed cracks in the buffer

At the dismantling of the test, cracks in the buffer blocks were observed in practically all parts of the buffer. An example of observed cracks in the buffer around the canister is shown in Figure 3-2. Most of these cracks went through the entire block i.e. from the inner surface of the blocks towards the pellets filled outer gap. It is not clear whether the cracks were caused by drying of the inner part of the buffer blocks, by water uptake of the buffer from the rock surface in the deposition hole or of both. Although the observed cracks were in some cases quite wide, they are not likely to have affected the redistribution of the water in the buffer as the gaps between the individual blocks were much wider and thus affected this process to a greater extent.

Figure 3-2. *Observed cracks. Left: Cracks in the buffer surrounding the canister. Right: View of buffer above the canister.*

Displacement of block layers

Measurements of the vertical coordinate for the individual block layers were made both at installation and at dismantling of the test. The measurements were made at 8 locations on top of each block layer. From these data it was possible to determine an average vertical coordinate for each layer and from this data calculate the average height of the layers both at the start and after the test. By comparing these two data sets it was possible to calculate the changes in position for each individual section, see Figure 3-3. A positive value implies a displacement upwards of the block layer. The plot is indicating that small displacements were observed up to mid height of the canister i.e. at the level of the block layer R10 while above that level positive displacements were observed. The displacements are caused by redistribution of water in the buffer.

The density and water content of the whole buffer

A summary of data from all the analysis of the water content and density in the four directions (079, 169, 259 and 349 degrees respectively) are shown in Figure 3-4 and Figure 3-5. The initial water content of the buffer blocks was about 16 % and for the pellets filling 12 %. The dry density for the block sections around the canister were at the installation about 1 751 kg/m^3. For the block sections above and below the canister the corresponding dry density was about 1 710 kg/m^3.

The figures indicate that the water uptake was relatively axisymmetric. There was an increase of the water content close to the top of the canister which indicates that there has been a condensation of water at that region of the buffer. Furthermore, there was a drying of the buffer close to the canister surface from about 500 mm below the top of the canister to the bottom of the canister. This is also valid for the block section on which the canister is standing. All of the pellet filling had taken up water.

The density plots are indicating decreases in the dry density of the buffer at locations of water uptake and an increase of the dry density at those parts of the buffer where a drying has occurred.

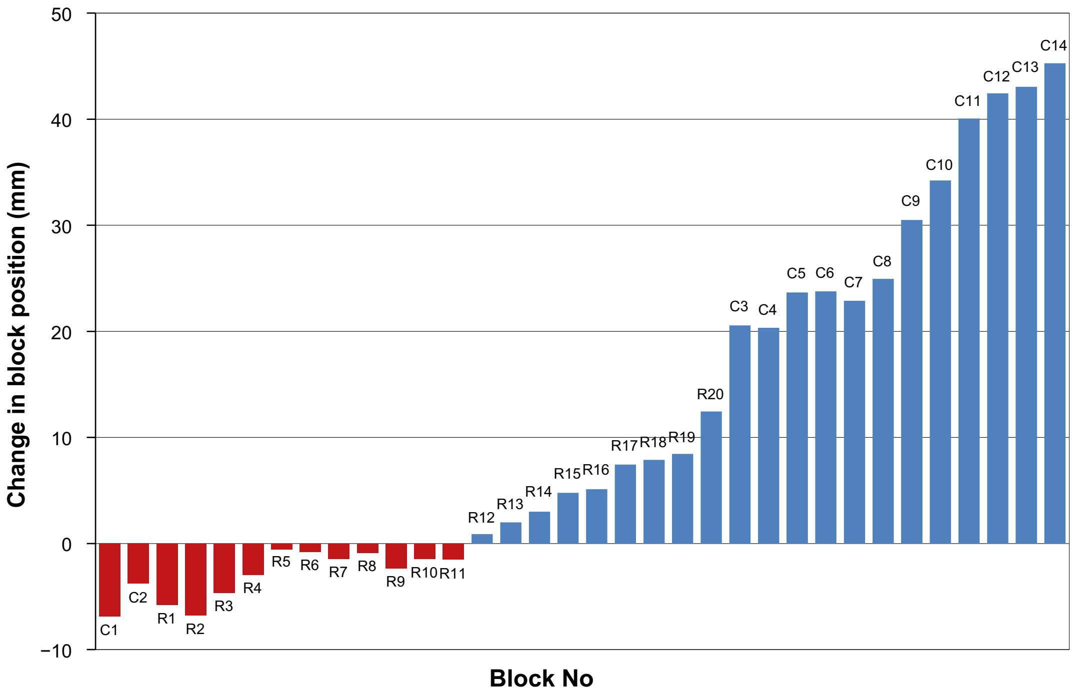


Figure 3-3. *The average displacement of the different block layers. The measurements were made in 8 positions.*

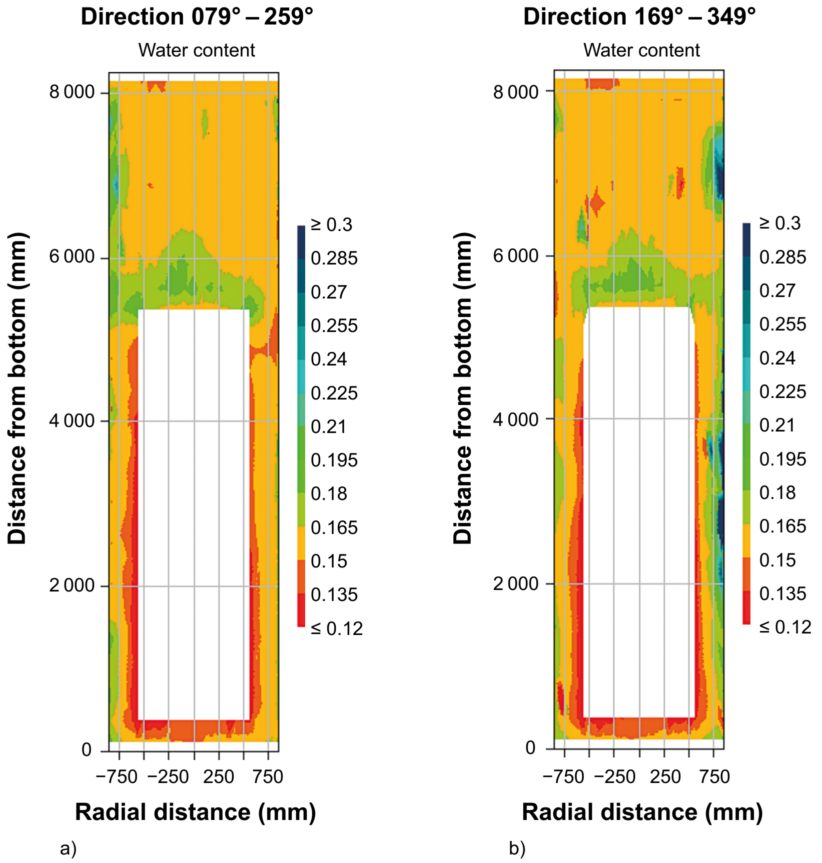


Figure 3-4. *Water content for the buffer a) in section 079°–259° and b) in section 169°–349°.*

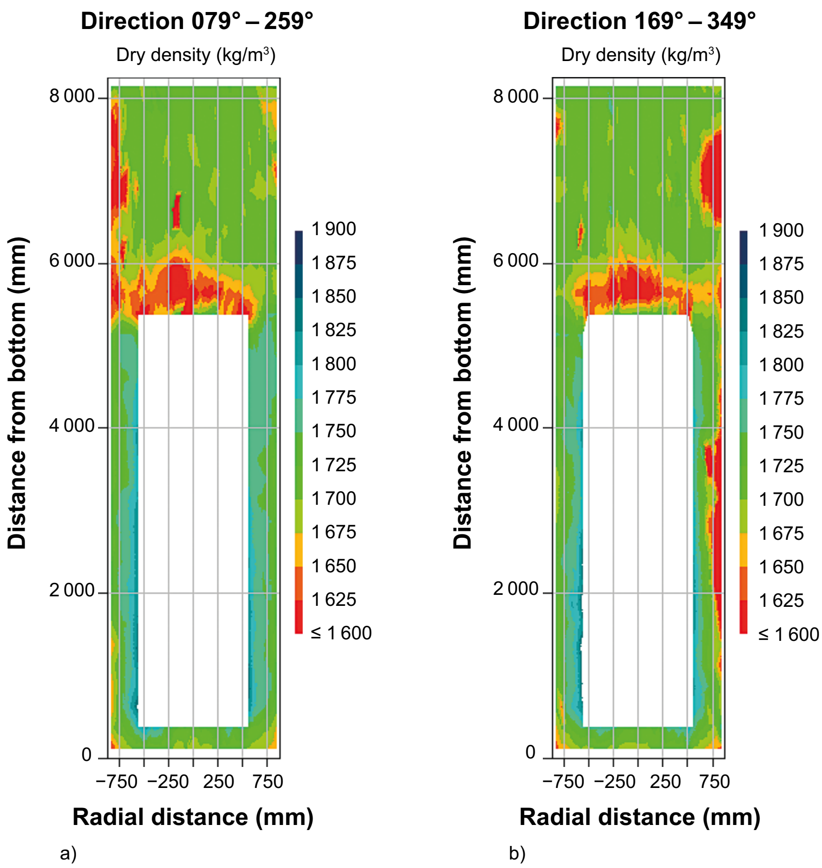


Figure 3-5. *Dry density for the buffer a) in section 079°–259° and b) in section 169°–349°.*

Evaluation

The test in this project had the purpose to find out how a buffer with segmented blocks behaves in the short term during the installation period before the backfill is installed on top of the buffer. Since this test has been done with segmented blocks, which has more air-filled gaps than the previous reference design, very little experience of the THM (Thermal-Hydraulic-Mechanical) behaviour is available. A test made on the reference design, reported in Luterkort et al. (2017), was used to compare the design for segmented buffer with the design with ring shaped and cylindrical blocks, see Figure 3-6 where it is compared to the design with segmented blocks.

The major difference between the solid block design and the design with the segmented blocks is the introduction of gaps between the blocks. It is known that air filled gaps can transport a lot of water and accelerate drying (Luterkort et al. 2017). This drying will affect the thermal conductivity and the swelling of the buffer, especially in the short term.

The focus of this evaluation will mainly be to do a qualitative comparison between the tests and describe the differences between the two tests and how the gaps between the blocks affect the system and if this could in any significant way affect the requirement fulfilment. The most important purpose with this comparison is to show that the buffer with segmented blocks do not differ too much from the solid block design on a deposition hole scale.

The main overall conclusion is that there are no major differences between the two types of buffer blocks, segmented or ring shaped/solid blocks, regarding the THM (Thermo-Hydro-Mechanical) behaviour during the installation phase. The evaluation is presented in its entirety in Nord et al. (2020).

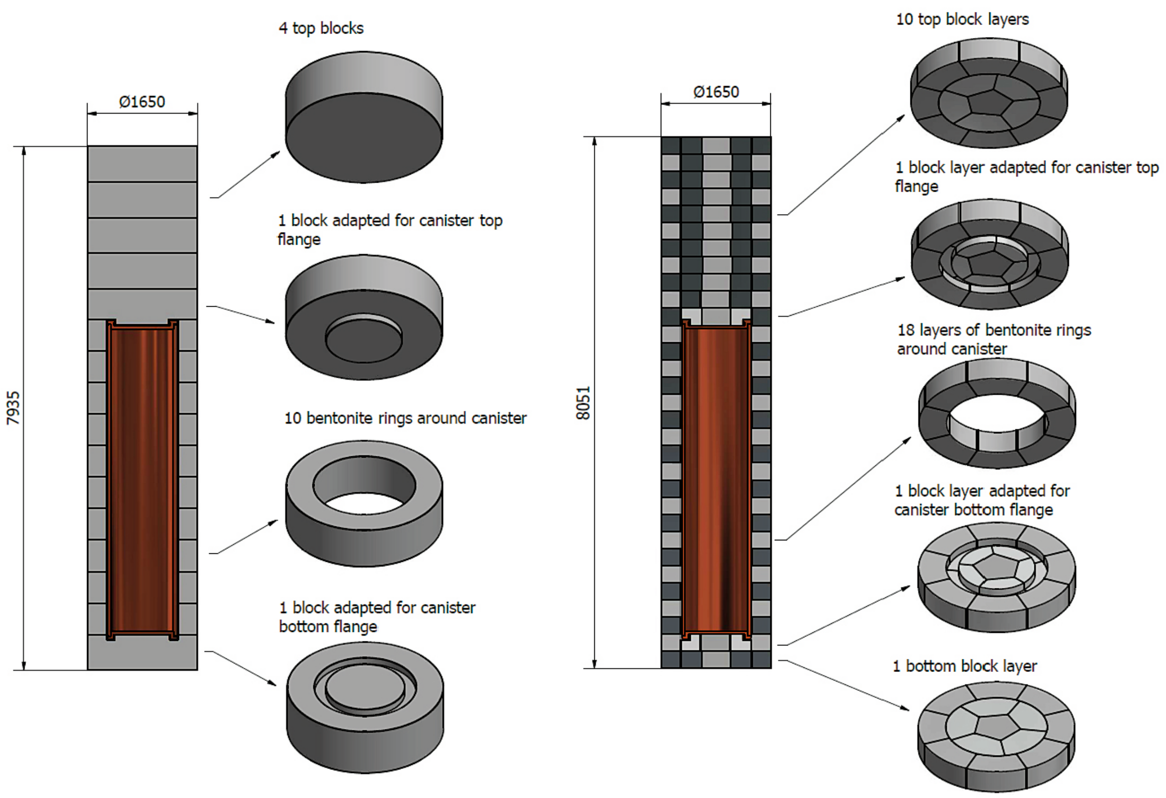


Figure 3-6. *Illustration of the differences between the two test designs.*

3.3 Concrete barriers

Background

The final repository for short-lived radioactive waste, SFR, located in Forsmark, has been in operation since 1988 and has been operated since 1 July 2009 by Svensk Kärnbränslehantering AB, SKB. The repository is located in rock vaults 50–120 meters below the sea bed of the Baltic Sea, and stores waste from Swedish nuclear power plants as well as from health care and industry.

The existing facility is designed for final disposal of mainly operational waste from the Swedish nuclear power plants. At present, an extension of the repository is being planned to facilitate disposal also of the waste that will arise during the dismantling of the Swedish nuclear power plants, SFR3. In this extension, a waste vault for intermediate level radioactive waste, 2BMA, comprising 13 caissons made from unreinforced concrete will be included, Figure 3-7.

In order to demonstrate that SKB is able to construct these concrete caissons in accordance with requirements under current prerequisites a development program comprising a number of different development and verification steps has been conducted. This development program has included the steps from material development through casting of a concrete caisson with all the design elements of the full-scale caissons in the future 2BMA in the Äspö Hard Rock Laboratory and monitoring of its properties.

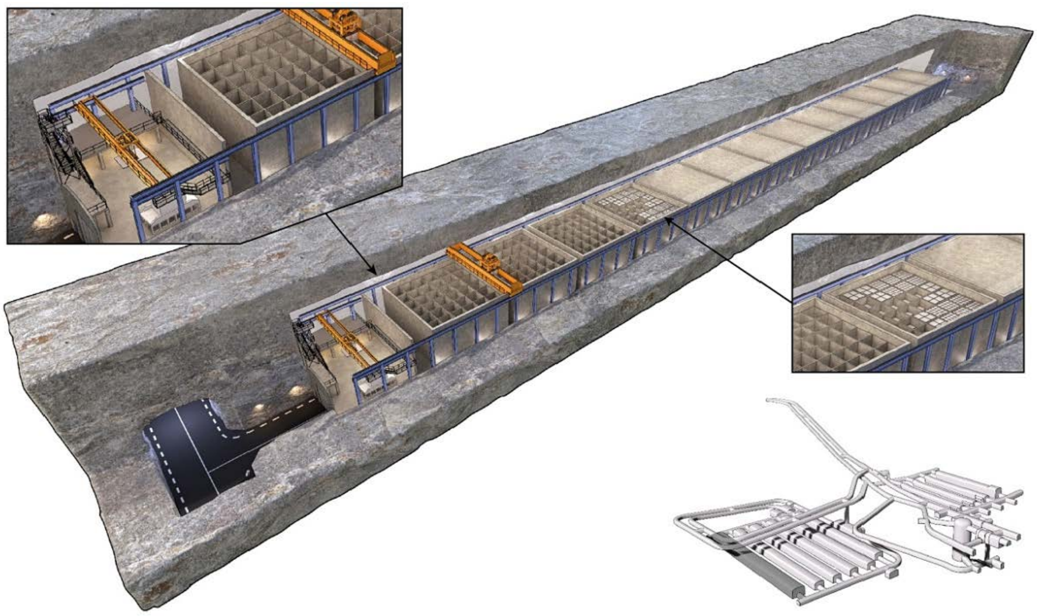


Figure 3-7. *The waste vault for intermediate level radioactive waste, 2BMA.*

Objectives

The main objective of this development programme is to demonstrate that SKB is able to construct the concrete caissons in accordance with requirements under current prerequisites.

Experimental concept

The initial program included the following main steps:

- Characterization of the bedrock in the area of the future SFR3 and identification of suitable quarries that can be used for production of concrete aggregates to be used during the material development work. See Lagerblad et al. (2016) for further details.
- Material development, including laboratory work, up-scaling to production scale, transport simulations and pump tests. See Lagerblad et al. (2017) for further details.
- Casting of a representative section of a concrete caisson in the Äspö HRL according to the reference method valid at that time as well as according to a more standardised method and long-term monitoring of its properties. See Mårtensson and Vogt (2019) for further details.
- Casting of a concrete caisson according to the new reference design adopted in 2017 in the Äspö HRL and long-term monitoring of its properties. See Mårtensson and Vogt (2020) for further details.

After finalisation of the four initial steps, the following needs for additional work were identified and initiated.

- Method for formwork construction including choice of protective tubes for the tie rods as well as materials and methods for filling the holes in these tubes after dismantling of the formwork.
- Method for construction of the inner walls.

Results

During 2020 the main focus has been on investigations of methods for formwork construction and in particular on finding a suitable type of protective tubes for the tie rods as well as material and method for filling of these tubes after dismantling of the formwork.

As a first step and in order to identify the most suitable grout and mixing ratio, concrete tubes were filled with different types of grout using a Spray-boy equipped with a hose and a steel tube that could be inserted into the hole in the concrete tube, Figure 3-8.

Four weeks later, the tubes were segmented and visually inspected, Figure 3-9.

As shown in Figure 3-9, the grout had a very low porosity and the tubes were homogeneously filled with no signs of separation of the grout or other imperfections.

The second part of this work comprised casting a wall-section with a large number of concrete tubes and investigations of the production capacity of the tested methods. The wall-section, Figure 3-10, contained a total of 40 concrete tubes or other concepts for keeping the formwork together.

A couple of weeks after casting, the concrete tubes were filled with grout and after an additional number of weeks ∅ 100 mm cores were extracted from the wall.

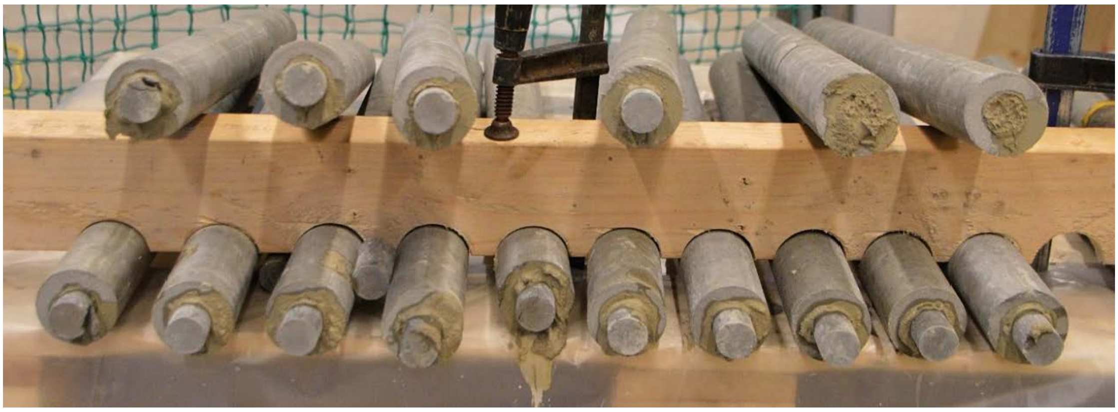


***Figure 3-8.** Grout-filled concrete tubes from the initial laboratory investigations.*

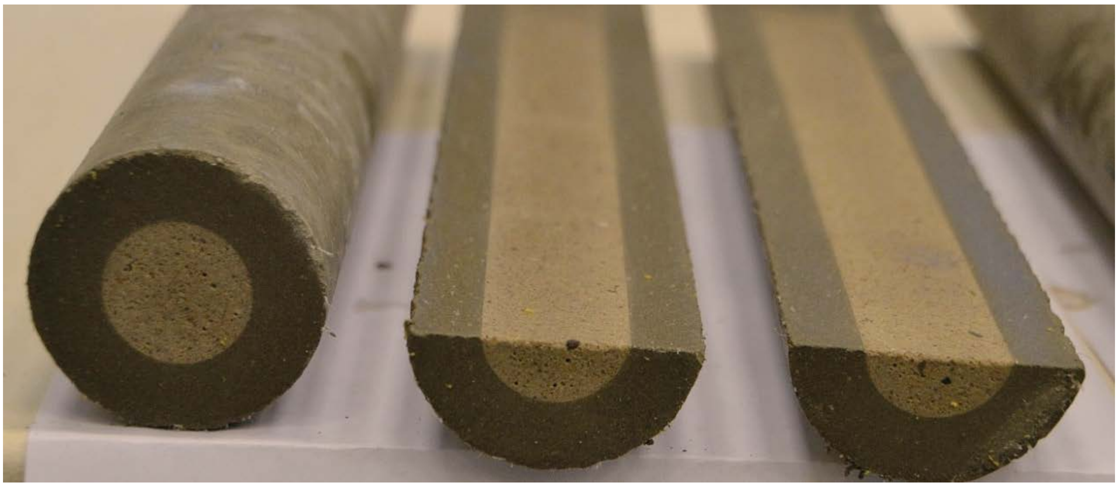


***Figure 3-9.** A grout-filled concrete tube after segmentation.*

***Figure 3-10.** The wall after that all tubes have been filled with grout.*

The cores were segmented in the same manner as the cores from the lab tests and visually inspected. As shown in cross sections in Figure 3-11, the tubes are completely filled and without any visible pores or other imperfections.

Finally, measurements showed that the hydraulic conductivity of the filled tubes were similar to that of the concrete used to cast the wall. The conclusion from this work is therefore that the tested materials and methods are suitable for use in the construction of the concrete caissons in 2BMA.

Figure 3-11. *Inner part of grout-filled tube, also showing the cement plug (top image) and cross section of a grout filled tube inside the concrete core.*

3.4 Sealing of boreholes

Background

A large number of investigation boreholes have been drilled in both the area for the planned Spent Fuel Repository and for the Final Repository for Short-Lived Radioactive Waste (SFR) which are both located in Forsmark in Östhammar municipality. While some of these boreholes will be used for monitoring during the construction others need to be sealed before the start of the construction of the above ground facilities and the start of the excavation work.

The current reference method for sealing these investigation boreholes was to install highly compacted bentonite plugs in sections of the borehole according to the "sandwich" concept. Though being way more efficient than the predeceasing method, it's still highly complicated and some components are sensitive to proper measurements of the boreholes in order to work properly. The requirement of a drill rig also makes the method quite costly.

With the current method of installing the sandwich concept, is the bentonite sections, concrete and the copper bridge plugs installed by a drill rig. The concrete is hoisted inside the drill pipes and ejected at depth, while the copper bridge plug requires an axial load in order to expand and seal against the borehole wall. The bentonite section is placed in the borehole using a drill rig, though is not dependent on the amenities that a drill rig comes with.

The sand, that is the main component in the "sandwich concept", is installed gravity fed from surface by using a funnel with a valve which is used to limit the installation rate. The installation rate is required to be limited, or there might be a risk of the sand forming friction plugs in the borehole. The installation rate also affects the installed density. The sand used is a fine to medium coarse sand, and there had been questions regarding the potential erosion of the sand in junction with fractures with high flow rates.

Objectives

The main objectives with the project are:

- Look into the potential erosion of the sand at fractures with high flow rates.
- To look into optimizing the installation and components; with a focus on trying to make the installation less dependent on the use of a drill rig.
- To describe a method for borehole that are not of a vertical nature.

Except for the objectives mentioned above, it has also been a goal to perform an inventory of all boreholes together with a classification and planning and performing the delivery of the technology to the user. This work is, however, still ongoing.

Experimental work

Tests of a newly designed cooper bridge plug were conducted at the Multi-Purpose Facilities at Äspö. This was developed in-house and tested in various stages at Äspö, and later the concept has been published[1] as a research disclosure. The new copper bridge plug is part of the installation optimisation, and a step on the way to get to a drill rig free installation.

Claytech performed erosion studies on various types of sands, the tests results had us conduct installation tests of the same sands in order to make a proper decision of which grain size distribution to use on the sand in the borehole sealing.

The installation tests were conducted in the Multi-Purpose facilities at Äspö. The sand was installed inside simulated boreholes in the form of a steel pipe. The rate of installing the sand was controlled and the density was measured. The pipe was then exposed to extreme vibrations by hitting it with a mallet. This is to get the maximum density and estimate the worst-case scenario of self-compaction over time or due to seismic activity.

[1] *Self-inflating bridge plug*. Research Disclosure in www.researchdisclosure.com, database number 675053. Published in the July 2020 paper journal.

Results

The results of the experiments conducted at Äspö is that the preferred sand has changed to a slightly coarser version. This sand showed little to no substantial erosion during the erosion test conducted by Claytech, and the properties of it installed had comparable properties to the previously used sand. Quite a lot of work resulted in a small revision of the reference method. The test also highlighted the discrepancy between the maximum density and the installed density, something that needs to be considered during the designing of the sealing, as the bentonite has to continue to work and possibly fill the void that is formed by the sand self-compacting.

The more interesting piece of work the last year is the new bridge plug. This is a self-expanding bridge plug is made as a replacement of the current mechanical bridge plug. The new bridge plug, is in the shape of a traditional packer, but rather than being made from rubber, it's made from copper. Copper was used for several reasons, but mainly is it a material that SKB got a lot of knowledge of on how it behaves over a long time in the environment that is a borehole, it also has one of the best ductile properties of metals, which is a preferred property for a permanent packer.

The bridge plug is then not activated by pressure applied by a gas or fluid, like its conventionally done, but rather utilize a non-explosive demolishing agent. This a cement like product that is mixed with water and the endothermic reaction produce a slow pressure increase up to a maximum above 80 MPa. Depending on the design of the bridge plug, temperature etc., the "activation time" can be so that the bridge plug inflate after a time. With the current design, at room temperature, it took around 3–4 hours for the pressure to increase enough to deform the copper and let the bridge plug to seal against the borehole wall, see Figure 3-12.

The 4 hours at room temperature will translate to longer time in a cold borehole, and therefor will give the installer plenty of time to place the bridge plug at the right location before it locks in place. And as it is not activated from the surface are you able to put several in series, or install them at the same time as you install bentonite.

Figure 3-12. *A cross-section of the self-inflating bridge plug for borehole sealing. The new bridge plug is shaped similar to a conventional packer, though it's made from copper rather than rubber. The bridge plug is not inflated by the use of a fluid or a gas, but rather uses a non-exploding demolishing agent. This produce a solid high pressure that deforms the copper wall to seal against the wall of the borehole, in the picture simulated with a steel pipe.*

The initial benefit of the new bridge plug is that it is less dependent on the borehole diameter than the predecessor. The new bridge plug also forms around uneven surfaces, which reduces the requirements of the surface being clean and perfectly round. The prototype of the self-expanding bridge plug has a theoretical working diameter span of 74–90 mm for the borehole, that can be compared to the old which had a range of 76 +/− 1 mm.

The bridge plug will also support axial loads, and the prototype was able to take 10 tons, located inside a smooth steel pipe, with an inner diameter of 76 mm, without displacement. This is beneficial as it will then be able to hold back the swelling pressure of the bentonite, allowing for shorter, or possibly totally eliminating, the concrete sections in the "sandwich concept".

As this new bridge plug doesn't need a drill rig to be activated by an axial load, and that it could possibly replace the concrete sections, means that the need for a drill rig is just the essential function of placing the components at the right depths. With further development could the installation of borehole sealings be totally drill rig free, which would reduce planning time, cost and simplify the install.

There is also the possibility to look into the bridge plug as a watertight section for boreholes that are located far from the repositories, simplifying the installations of those even further as well.

Now, this new bridge plug is still under development and testing, and there are still a few things to sort out before it will be possible to draw use of its full potential.

3.5 Bentonite material studies

Background

SKB has developed methods and techniques for acquisition and quality control of bentonite for a long time (Svensson et al. 2019).

The long term safety requirements on the bentonite are ensured by a number of technical design requirements (TDRs). The following TDRs are considered; a dry density yielding a certain swelling pressure, hydraulic conductivity and shear strength and thermal conductivity as well as limitations in sulphide, total sulphur and organic carbon (harmful substances) (Posiva SKB 2017a).

In order to develop in-house knowhow, improve flexibility and make cost-efficient bentonite sampling and characterisation, SKB has opted to set up its own laboratory at Äspö.

Different methods will be needed at different stages of the future process. Three different characterisation levels are currently suggested, see Table 3-1.

The extensive material characterisation is essential for the approach of an adaptive buffer and backfill design, where the dry density and water content of the blocks and pellets are adjusted based on the material characteristics (Kronberg et al. 2020), in order to fulfil the in situ requirements and allow for efficient industrial production.

Both the listed methods and characterisation levels will be updated when more experience and statistics are available. Characterisation level 1 is aimed at basic acceptance data that can be measured relatively quickly. Characterisation level 2 is more time-consuming and provides the basis to develop an adapted design. Characterisation level 3 is directly connected to the quality of the final blocks and should confirm the components quality.

Table 3-1. Characterisation methods under development at the Äspö material laboratory.

Level	Parameter	Comment
Characterisation level 1		**Level 1 should provide basic acceptance data**
1a	Water content (water/dry mass) Granular size distribution	1a) Includes process steering parameters.
1b	Chemical composition (XRF)	1b) Includes methods aimed at confirming acceptable homogeneity in the material.
	Swelling pressure, quick	
	Cation Exchange Capacity (CEC)	
	Combustion analysis, (C_{org}, S_{tot}, $S_{sulfide}$)	Currently external
Characterisation level 2		**Level 2 should provide the basis to develop an adapted design**
	Hydraulic conductivity and swelling pressure	
	Exchangeable cations (EC)	Currently external
	Mineralogical composition (montmorillonite) XRD	
	Grain density	Currently external
	Compaction properties	
	Unconfined compression strength	
	Thermal conductivity	
Characterisation level 3		**Level 3 should confirm the component quality**
	Pellets, dimensions and abrasion resistance	
	Block dimensions, weights and visual inspection	Under development

A large benefit in establishing analysis methods for the suggested parameters at Äspö and in SKB's central management system is that when a laboratory is built in Forsmark, the methods will already be available in the management system and verified in the Äspö laboratory and it will be possible to apply plenty of knowledge and routines from Äspö to establish selected methods in a new facility.

Planning and objectives

During 2020 SKB has initiated planning for a continuation of the previous material science projects.

The main objectives will be to continue the development of the measurement technology and the material knowledge needed for implementing the TDRs.

Focus will be on refining existing methods and procedures and further assessing and detailing the amounts of sampling and analyses needed at the repository scale.

3.6 Large Scale Gas Injection Lasgit19

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 to 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. During 2020 a Gas Migration Test and a Full Canister Test was carried out and subsequently, the dismantling of the experiment started.

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 (see Figure 3-13). 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.

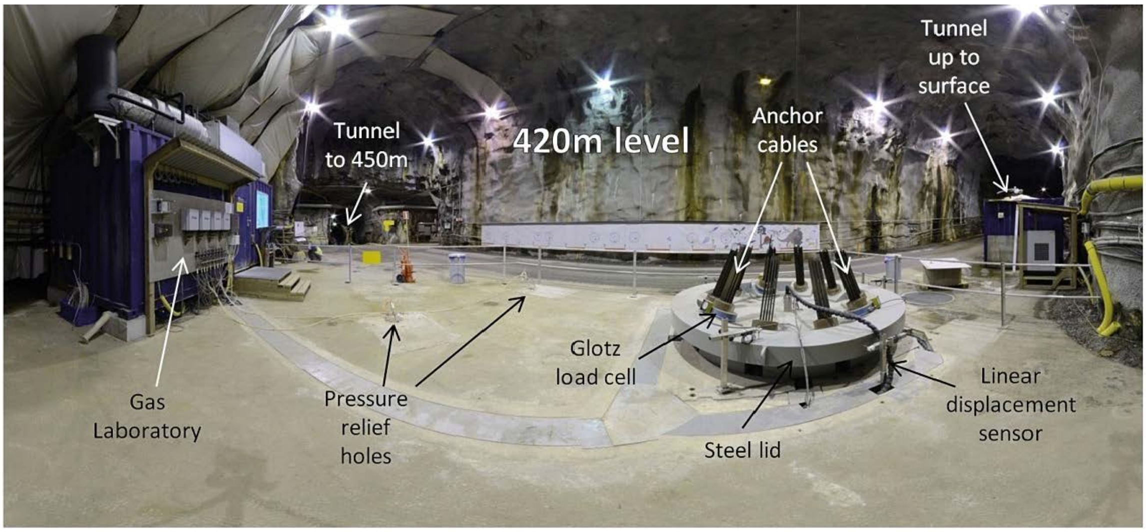


Figure 3-13. *The Large scale gas injection test at the −420 m level in Äspö HRL.*

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 groundwater and injected water. The saturation and equilibration of the bentonite was monitored by measuring pore pressure, total pressure and suction at both the buffer/rock interface and key locations within individual clay blocks. The hydration phase provided an additional set of data for (T)HM modelling of water uptake in a bentonite buffer. The test was dismantled during 2020.

Gas migration test 2019–2020

One outstanding uncertainty from basically all gas migration tests in bentonite that have been performed is the effect of the upstream gas volume. A small upstream volume means that there will be a rapid decrease in gas pressure when the gas is released through the bentonite. All earlier gas migration tests in Lasgit have been performed with an upstream gas reservoir of a few litres. Lasgit was originally equipped with a valve in the bottom of the canister where the entire void of the canister (> 1 m^3) could be released. This valve is called the Full Canister Test (FCT).

As a part of the dismantling of Lasgit it was decided to try to do a gas migration test in the FCT valve. There were doubts that the test would actually work. The FCT valve is on the bottom of the canister. It is operated using an air feed. The valve had been in situ for nearly 15 years. Water was accidentally pumped into the canister early in the test. The function of the valve was an unknown. At the beginning of the gas pressurisation, all pore pressure sensors in Lasgit showed a rapid pressure increase and then a slow decay. This was an indication that the copper canister was inflated by the internal gas pressure. Readings on the pressure sensors close the FCT valve indicated that water was expelled through the valve. This confirmed that the valve was open, but also that water had leaked into the canister. The question was now if it would be possible to expel all water within a reasonable time. The pressure in the canister was kept at a value slightly above 7 MPa. In the end of November 2019 there were indications that the water around the FCT valve was expelled and that gas could start to migrate through the bentonite. This was the final confirmation that the FCT worked as planned. Figure 3-14 shows the pressure decay in the Lasgit canister for the first ~200 days.

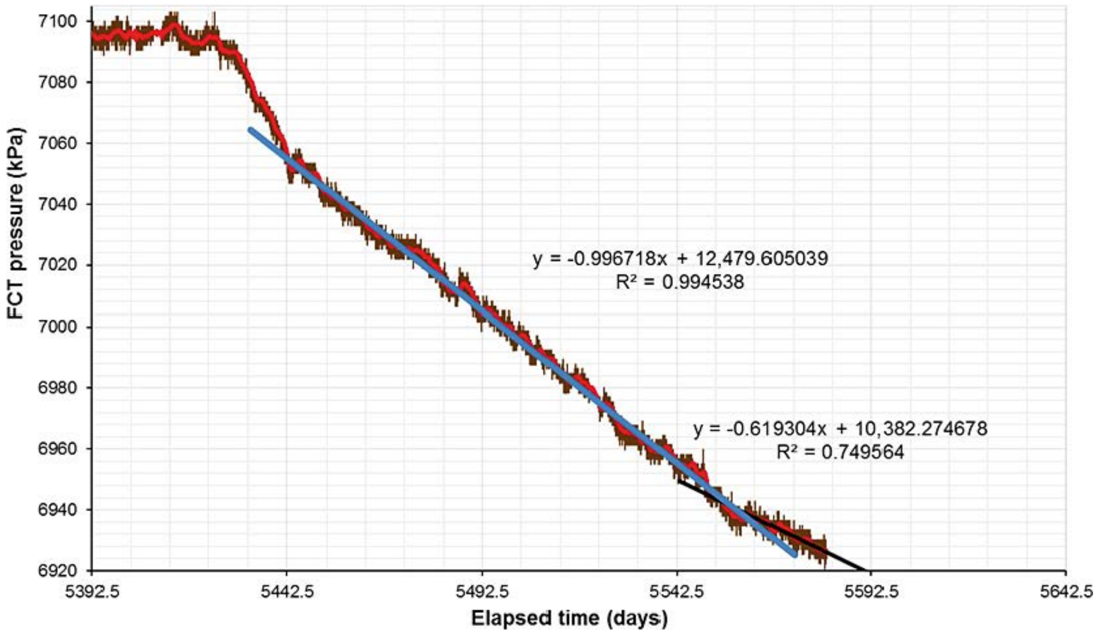


Figure 3-14. *Pressure decay in the Lasgit FCT.*

The pressure decay indicates a constant flow rate of gas. The rate does however seem to change at certain given times. The first gas breakthrough occurs at around day 5 330. At Day 5 442 there is a kink in the curve and the rate changes to a lower value. The same seems to happen at around day 5 560. This could be interpreted as closing of pathways in the bentonite.

The overall conclusions from the FCT are:

- The observations from small scale experiments are also seen in a large-scale tests with a large upstream gas volume.
- Gas can penetrate a bentonite barrier without any harmful effect on the barrier properties.
- The gas seems to move through a (limited) number of pathways. The pathways seem unstable and may open and close during a breakthrough event.

The results from Lasgit confirms the view taken in safety assessments from the 1990s to present. Gas generation from corrosion of the iron insert is not a major issue in a KBS-3 type repository in fractured rock.

Dismantling and sampling

Dismantling of the experiment started in September 2020 by loosening the anchor cables and removing the steel lid that can be seen in Figure 3-13. The last step before the first bentonite layer could be reached was to lift the large concrete plug underneath the steel lid.

Sampling of the bentonite was done by core drilling according to a template with a specific drilling pattern. From each drilling position, cores were drilled through the bentonite layers that were approximately 0.5 m thick. From each core, two samples were sent to the Äspö HRL for analysis of water content and density. Activities from the dismantling are illustrated in Figure 3-15.

At the end of 2020, layer R5 was reached. Sampling of remaining bentonite and lifting of the canister is planned to the beginning of 2021.

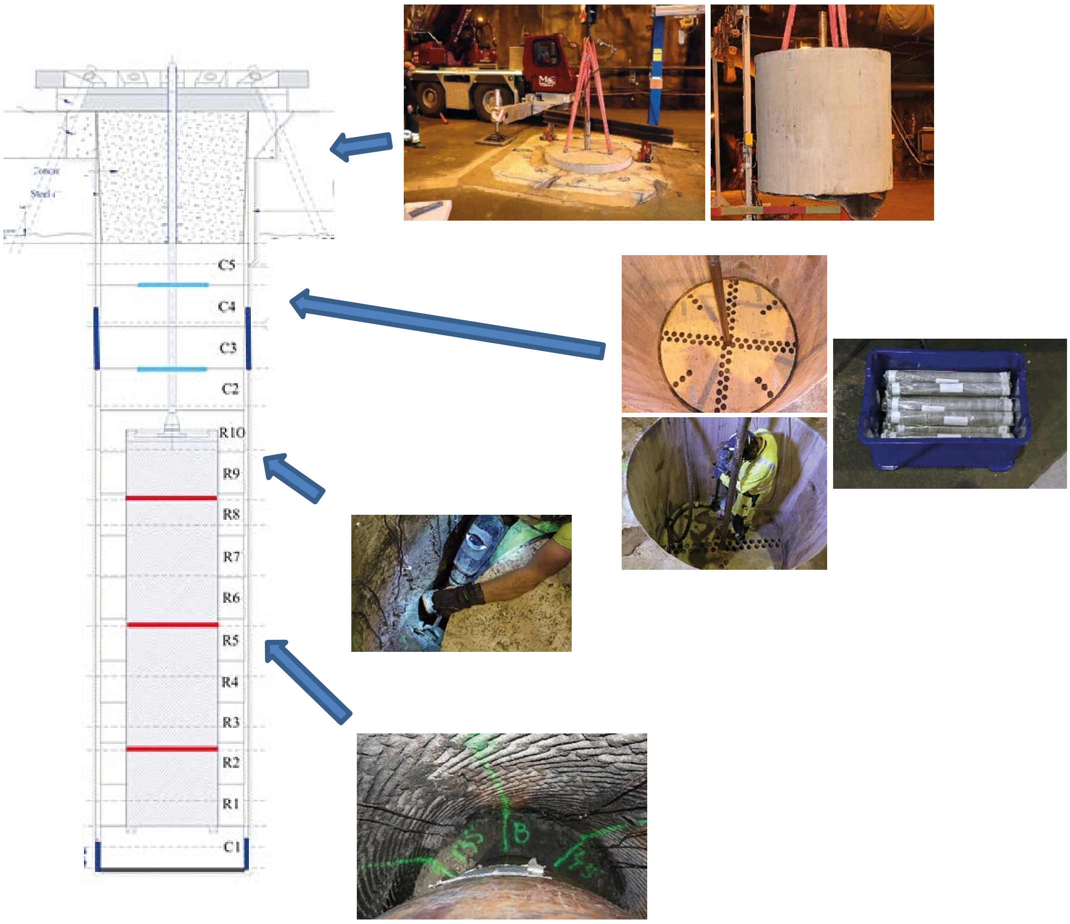


Figure 3-15. *Lasgit deposition hole with activities during dismantling and sampling.*

3.7 Long term tests of buffer material

Background

Comprehensive research and development work have been carried out during the last thirty years in order to determine the basic behaviour of unaltered bentonite material. The results have been reported in technical reports, scientific articles, and models concerning both unsaturated and saturated buffer conditions. The models are believed to well describe the function of an unaltered MX-80 bentonite buffer after water saturation with respect to physical properties, e.g. swelling pressure, hydraulic conductivity and rheological behaviour.

In a HLW repository, there will be a temperature increase and a thermal gradient over the bentonite buffer as a result of the decaying spent fuel. Original water in the bentonite will thereby be redistributed parallel to an uptake of water from the surrounding rock. The Long Term Test of Buffer Material (LOT) project aims at studying possible alteration of the bentonite as a result of the hydro-thermal evolution, both with respect to mineralogy and to sealing properties.

Objectives

The general objectives in the LOT test series may be summarized in the following items:

- Collect data for validation of models concerning buffer performance under quasi-steady state conditions after water saturation, e.g. swelling pressure, hydraulic conductivity and rheological properties.
- Check of existing models concerning buffer degrading processes, e.g. mineral redistribution and montmorillonite alteration.
- Check of existing models concerning cation diffusion in bentonite.

• Check of calculated data concerning copper corrosion, and collect information regarding the character of possible corrosion products.

• Collect information, which may facilitate the realization of the full-scale test series, e.g. the Prototype project, with respect to preparation, instrumentation, retrieval, subsequent analyses, evaluation and data handling.

Experimental concept

The LOT test series can be described as a multi-task experiment in which relatively small test parcels are exposed to field conditions at Äspö Hard Rock Laboratory (HRL). The experiment includes a total of seven test parcels, Table 3-2. Each test parcel consists of a central copper pipe with an electrical heater inside. Prefabricated ring-shaped bentonite blocks are placed around the copper pipe. The test parcels were placed in a vertically drilled 4-meter-deep borehole in granitic rock, 450 meters below ground surface at Äspö HRL, Figure 3-16.

Table 3-2. Test programme for the LOT project.

Type	No	max T (°C)	Controlled parameter	Time (years)	Remark
A	1	130	T, [K^+], pH, am	1	Reported, (Karnland et al. 2000)
A	0	120–150	T, [K^+], pH, am	1	Reported, (Karnland et al. 2011)
A	2	120–150	T, [K^+], pH, am	6	Reported, (Karnland et al. 2009)
A	3	120–150	T	20	Reported, (Sandén and Nilsson 2020), (Johansson et al. 2020)
S	1	90	T	1	Reported, (Karnland et al. 2000)
S	2	90	T	20	Reported (Sandén and Nilsson 2020), (Johansson et al. 2020)
S	3	90	T	> 20	Ongoing

A = adverse conditions, S = standard conditions, T = temperature, [K^+] = potassium concentration, pH = high pH from cement, am = accessory minerals added.

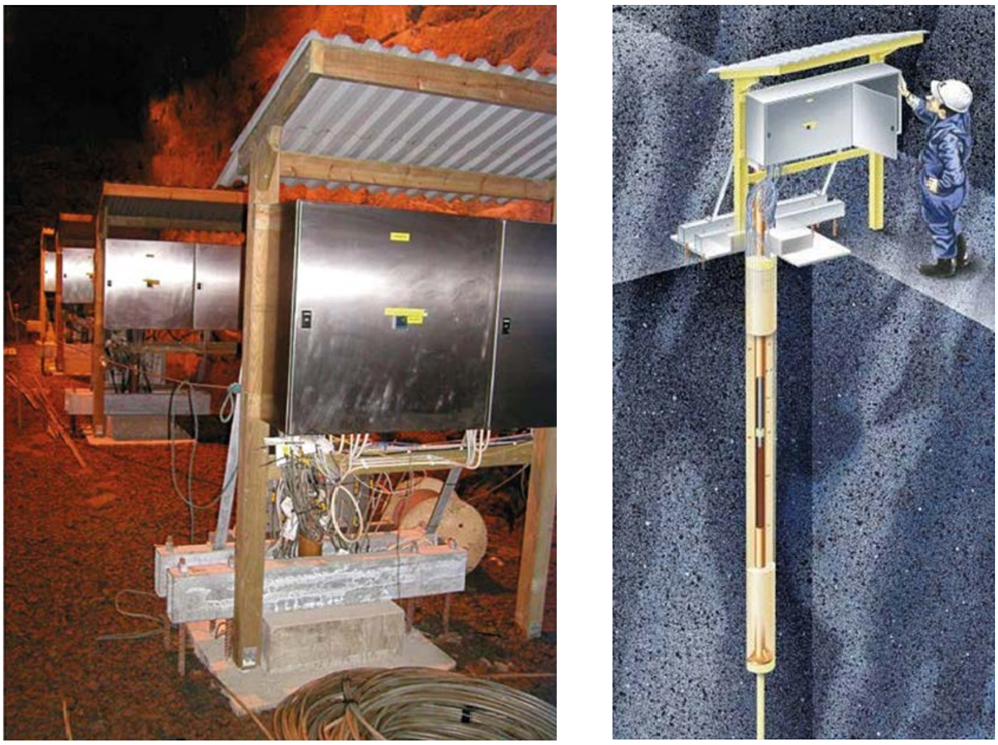


__Figure 3-16.__ Left: Photo of the test site in the Äspö HRL. Right: Schematic drawing of a LOT test parcel after installation. Reproduced from Sandén and Nilsson (2020).

Different types of instruments were placed in the bentonite, measuring total pressure, pore pressure, relative humidity and temperature.

Several test parcels, also contained equipment used for special measurements: Co-60 tracer doped plugs placed in one block to study radionuclide migration in compacted bentonite, copper coupons which can be used to quantify total corrosion with accurate methods (i.e. gravimetric analysis), which is not possible for the large copper pipe.

After exposure to field conditions for a defined period, a test parcel is extracted by overlapping drilling outside the original borehole, and the whole test parcel is lifted and transported to a laboratory where it is divided. Material from defined positions in the parcel and reference material are thereafter examined by well-defined tests and analyses in order to provide data for the different objectives.

The dimensions of the test parcels were kept considerably smaller, especially the diameter, compared to a KBS-3 deposition hole in order to:

- shorten the water saturation period and thereby have saturated condition during a substantial part of the test period,
- achieve a higher temperature gradient over the buffer material,
- facilitate sampling, i.e. release and lift the exposed test parcel in one piece.

Results

Introduction

Two test parcels, S2 with standard conditions (max 90 °C) and A3 with adverse conditions (max 120–150 °C) were dismantled during 2019. The installation, monitoring, dismantling and initial bentonite analyses are reported in Sandén and Nilsson (2020).

During 2020, more detailed analyses of the bentonite from both parcels has been initiated and will be reported in the coming years, for example: X-ray diffraction (XRD), X-ray fluorescence (XRF), Cation Exchange Capacity (CEC), Exchangeable Cations (EC), Scanning Electron Microscope/Energy Dispersive Spectroscopy (SEM/EDS), μ-RAMAN spectroscopy, Combustion analysis, Inductively Coupled Plasma – Atomic Emission Spectrometry (ICP-AES), Infrared spectroscopy (IR), swelling pressure, hydraulic conductivity, shear strength, Co-60 and Mössbauer analysis.

The copper coupons and central copper pipe have also been analysed during 2019–2020 and the results are reported in Johansson et al. (2020).The following result section is to a large extent a short exert from that report.

The LOT setup provides an opportunity to characterise corrosion products, evaluate corrosion depth and to make a conservative analyse of the corrosion morphology with respect to localised corrosion. While it provides several possibilities, it should be noted that the LOT experiments main objectives relate to the buffer and thus it has inherent limitations as a corrosion experiment. There are uncertainties with respect to how much air that was enclosed at the time of installation. The centre copper heater pipe, which is too large for the evaluation of mass loss is not made of SKB's reference material and its surface was not characterised regarding surface topography or deposits before the start of the experiment. Another limitation is that the electro-chemical near field environment of the experiment has not been measured. The copper coupons allow gravimetric mass loss analyses, but have not been pre-characterised microscopically, i.e. their starting topography is not available.

Sampling and analysis

The copper pipe was extracted by removing the surrounding bentonite and the extraction of the coupons was done carefully using wooden hand tools. Figure 3-17, shows the pipe and coupons together with the bentonite. The coupons were emplaced in bentonite block no. 22 and 30 both in S2 (4 pcs) and in A3 (4 pcs). All 8 coupons were found undamaged during the dismantling. Further details of dismantling and sampling are reported in Sandén and Nilsson (2020).

Figure 3-17. *Upper picture, a piece of the extracted copper pipe. Lower picture, an example of the extracted copper coupons.*

The copper pipe was made of a standard deoxidised copper quality (SS 5015-04), containing 99.85 % Cu and 150–400 wt-ppm P. The samples examined herein were taken from bentonite blocks 21 to 23 from each of the two test parcels, with ca 50 mm margin into blocks 20 and 24. The samples were thus ca 400 mm long. A spare pipe (also SS 5015-04) that had been kept in a non-heated storage since the installation of the LOT experiments has been analysed as a reference material regarding its content of O and H.

The coupons were made of SKB's reference material for the KBS-3 canister, i.e. oxygen free phosphorous doped copper (Cu-OFP), containing less than 5 wt-ppm oxygen and 30–70 wt-ppm phosphorous. The coupons had dimensions 60 × 15 × 1.5 mm, and had one milled and one polished side.

Corrosion products on the coupons were analysed using X-ray diffraction (XRD) and scanning electron microscopy (SEM) with energy dispersive scattering (EDS). One coupon from each test parcel was also cross-sectioned and examined using SEM-EDS and high-resolution transmission electron microscopy (HR-TEM). Gravimetric analysis was made to evaluate the average corrosion depth on three coupons from each test parcel. Finally, light optical microscopy (LOM) was used to examine the surface topography of the coupons before and after the removal of the corrosion products done in the gravimetric analysis.

Corrosion products on the pipe samples were analysed using SEM-EDS. The elemental composition of the material near the surface of the pipe samples were analysed using glow discharge optical emission spectroscopy (GDOES) and the hydrogen content of the material was measured using Leco gas fusion analysis.

X-ray fluorescence spectroscopy (XRF) was used to measure the concentration of copper and other major elements in the bentonite clay near the copper surfaces. This was done in order to estimate the extent of corrosion on various parts of the copper pipes. Variations in the elemental composition of the bentonite samples were examined using SEM-EDS, and the mineralogical composition was analysed using powder XRD.

A summary of copper samples and analysis methods is presented in Table 3-3.

Table 3-3. Summary of copper samples and analysis methods used to study the copper in LOT parcel S2 and A3 (reproduced from Table 2-1 in Johansson et al. 2020).

Analysis methods											
Test parcel	**Description**	**ID**	**Material**	**XRD**	**SEM/EDS surface**	**SEM/EDS cross-sect.**	**TEM cross-sect.**	**Mass Loss**	**LOM**	**Leco H**	**GDOES**
A3	Coupon	I	Cu-OFP	X	X	-	-	X	X	-	-
A3	Coupon	J	Cu-OFP	X	X	-	-	X	X	-	-
A3	Coupon	K	Cu-OFP	X	X	X	X	-	X	-	-
A3	Coupon	L	Cu-OFP	X	X	-	-	X	X	-	-
A3	Pipe section	-	SS 5015-04	-	X	X	-	-	-	X	X
S2	Coupon	M	Cu-OFP	X	X	-	-	X	X	-	-
S2	Coupon	N	Cu-OFP	X	X	X	X	-	X	-	-
S2	Coupon	O	Cu-OFP	X	X	-	-	X	X	-	-
S2	Coupon	P	Cu-OFP	X	X	-	-	X	X	-	-
S2	Pipe section	-	SS 5015-04	-	X	X	-	-	-	X	X
Ref.	Spare pipe	-	SS 5015-04	-	-	-	-	-	-	X[a]	-
Ref.	Unexposed coupon	K	Cu-OFP	X	X	-	-	X	X	-	-
Ref.	Unexposed coupon	L	Cu-OFP	X	X	-	-	X	X	-	-

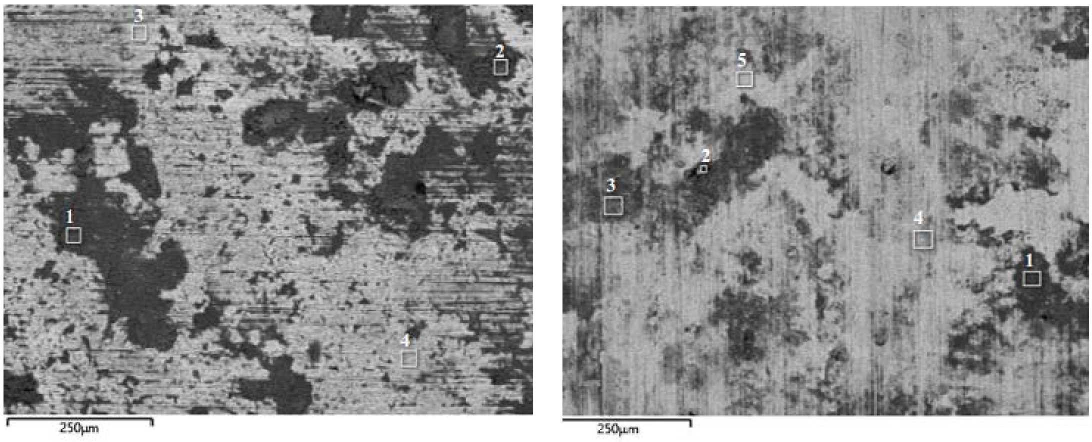
[a] For the spare copper pipe, the content of both H and O was analysed with Leco.

Examination of copper

This result section focuses on the copper coupons. All results including pipe data are provided in Johansson et al. (2020).

The expected corrosion products are Cu2O, Cu2S and possibly Cu2 (OH)3Cl. The copper in the bentonite is expected to be distributed with a steep profile, decreasing outwards from the copper surface. The selected methods provide surface examination, as well as analysis of some aspects of the bulk material. Furthermore, the selected methods provide both chemical and elementary data.

The SEM-EDS data was reviewed in two steps. First, analysis at 100× magnification was done for an area of a few mm^2 of each coupon, which gave an idea of the average elemental composition of the corrosion products and other surface deposit. It was observed that Cu and O were the most abundant elements on the coupon surfaces. Part of the O comes from the corrosion product Cu2O, while another part comes from SiO2 in the bentonite clay. The amount of S was generally low in comparison with O. Secondly, by looking at EDS data from spots of the surfaces at higher magnifications, see examples in Figure 3-18, there were a few observations of enhanced amounts of S at positions where the amounts of Ca (from CaSO4) and Fe (from FeS2) were very low, which indicates the formation of a CuxS corrosion product, something which was also confirmed via XRD analysis.



Element (At%)	1	2	3	4
O	61.90	61.58	28.00	31.34
Na	3.06	2.89	1.55	1.74
Mg	1.30	0.89	0.30	0.54
Al	8.73	5.30	1.44	1.62
Si	21.46	25.12	2.69	3.74
S	0.26	0.37	2.70	3.94
Cl		0.04	0.16	0.18
K	0.11	0.18		
Ca	0.42	0.16	0.20	0.38
Ti	0.03	0.08		
Fe	0.88	0.58		0.15
Cu	1.85	2.80	62.97	56.37
Total	100.00	100.00	100.00	100.00

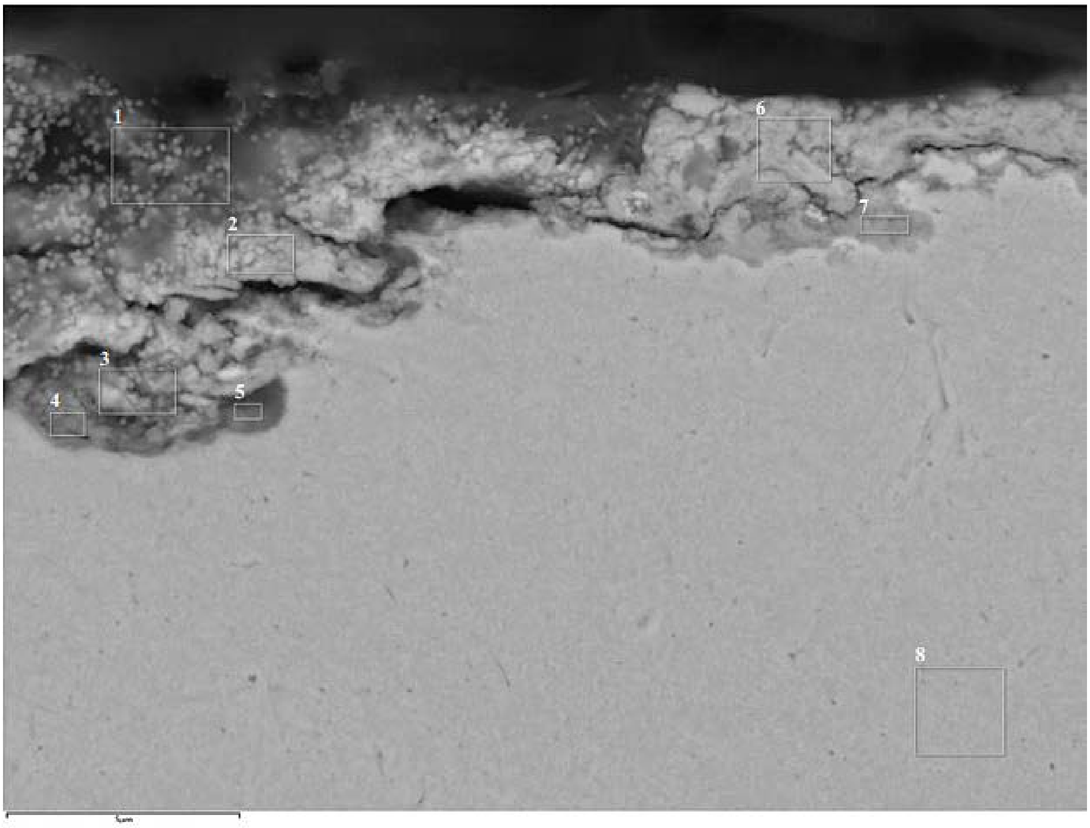
Element (At%)	1	2	3	4	5
O	61.78	51.58	53.07	35.29	11.44
Mg	1.36	1.33	1.25	0.80	
Al	7.57	7.89	6.15	3.60	0.59
Si	21.24	26.61	15.28	8.36	1.10
S	1.79	3.22	5.59	10.55	10.50
Cl	0.05		0.09	0.14	
K	0.05	0.15			
Ca	0.68	0.71	0.52	0.48	0.22
Fe	0.77	0.56	0.52	0.26	
Cu	4.69	7.94	17.54	40.51	76.15
Total	100.00	100.00	100.00	100.00	100.00

Figure 3-18. *SEM micrographs with associated EDS analysis results. Copper coupons A3/I (left) and S2/P (right). Magnification x 300 (reproduced from Figure 3-10 in Johansson et al. 2020).*

Prior to evaluating the mass loss of the corrosion coupons, it was decided to save one coupon from each test series in order to examine the corrosion product and morphology in cross-sections. The coupons A3/K and S2/N were chosen for this purpose and were cut before being cast in epoxy resin and polished. The polished cross-sections were then examined under the SEM and the elemental compositions of the surface and corrosion products were analysed with EDS. Figure 3-19 shows an example of the appearance of the corroded interface in cross-sections and the corresponding EDS analysis results. The cross-sections revealed roughly corroded interfaces with small pits densely distributed over the surface. The pits and surface defects observed in the micrographs were found to be less than 10 µm deep.

In order to further examine corrosion products or deposits found to have a higher content of S, TEM was applied on FIB cut lamellae from the A3/K and S2/N coupons. The investigation revealed the presence of small particles near the copper surface inside the pits (example in Figure 3-20). These particles were found in the clay near the copper surface. Closer to the copper surface, a more compact and ca 250 nm thick layer was found. From the EDS analysis, the sulfur rich particles and layers appear to have Cu:S ratios close to that of Cu2S. Further analysis of the layers and nanoparticles, using the selected area electron diffraction (SAED) technique indicated the existence of Cu2S on both coupons, as well as Cu2O on the S2/N coupon.

Summarising the data, Cu2O is found on all surfaces and Cu2S can only be found in relatively small amounts.



Element (At%)	1	2	3	4	5	6	7	8
O	37.48	22.01	25.20	18.03	12.26	13.93	4.65	0.45
Mg	1.88	0.38	0.62	0.34				
Al	7.88	1.68	1.90	0.71				
Si	20.12	3.98	4.58	1.75	0.52	1.99		
S	11.49	13.43	10.10	4.52	1.98	16.17	0.89	
Cl	0.10	0.26	0.30			0.22		
Ca	0.46							
Cu	20.59	58.27	57.29	74.66	85.25	67.69	94.96	99.55
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Figure 3-19. *SEM image of coupon A3/K in cross-section, with associated EDS analysis results. (reproduced from Figure 3-13 in Johansson et al. 2020).*

To evaluate the mass loss for the corrosion coupons the principle method of repeated pickling according to standard SS-EN ISO 8407:2014 was used. Initial weights of the coupons were obtained by Clay Technology before the start of the LOT experiments. The corroded specimens were chemically cleaned, removing the corrosion products by pickling. Repeated pickling is typically needed to remove all corrosion products. The specimen is weighed after each cleaning treatment and the procedure is repeated until the mass loss between two treatments is very small, and comparable to the mass loss of a reference specimen. Both the metal and the corrosion products determine what chemical cleaning solution is suitable to use.

After the initial pickling procedure, the mass-loss of five of the coupons corresponded to corrosion depths between ca 1 µm and 1.3 µm, while for coupon S2/P the corrosion depth was only 0.5 µm. Since coupon S2/P still appeared stained after the pickling, further attempts were made to remove the staining and possibly increasing the mass-loss. This was done by first pickling in H2SO4 for a total of 14 minutes, then electrolytic cleaning according to SS-EN ISO 8407:2017 (method E.3.1) for a total of 12 minutes (at one minute intervals) for each side of the coupon. The additional cleaning steps resulted in an additional mass-loss of coupon S2/P corresponding to ca 0.2 µm corrosion (Table 3-4).

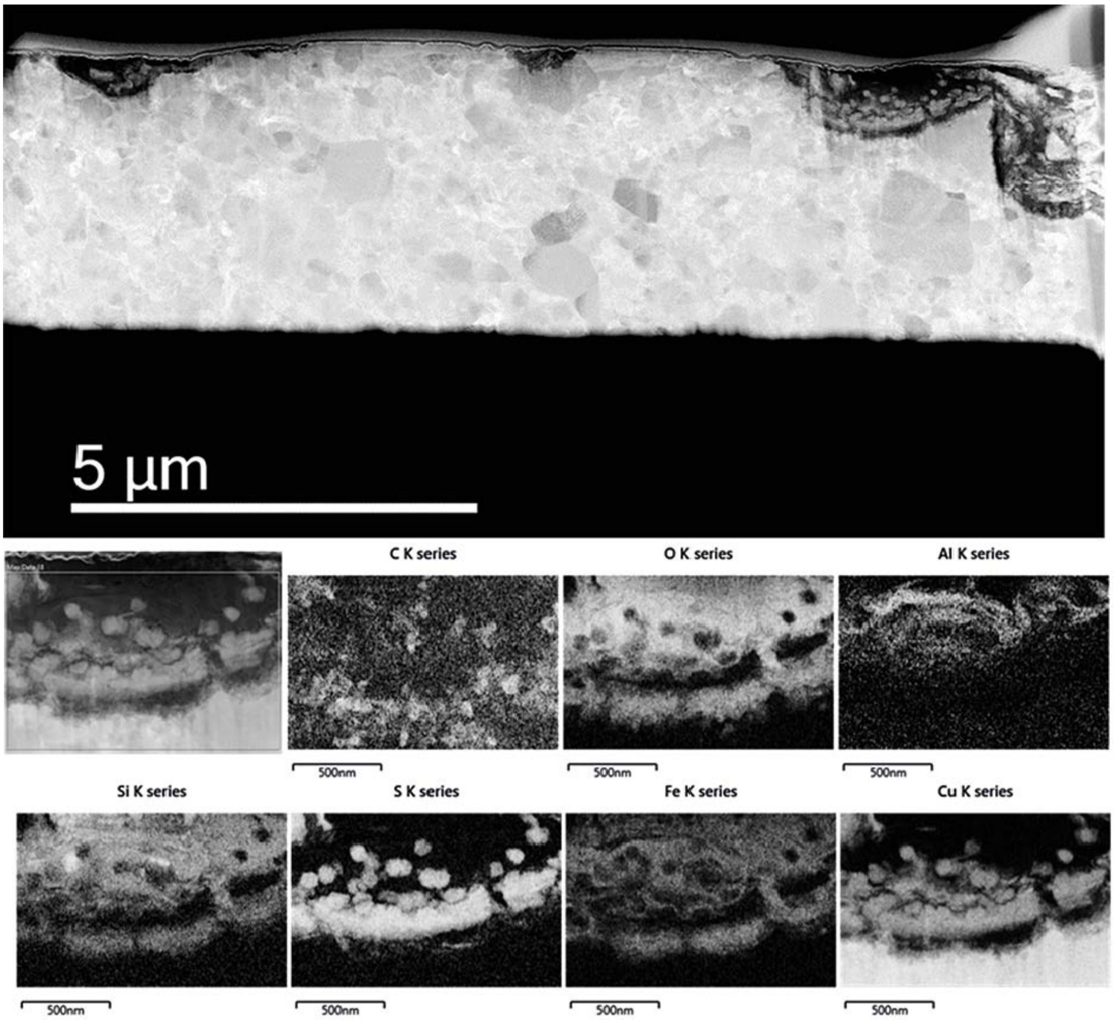


Figure 3-20. EDS maps of FIB cut lamella from coupon A3/K (reproduced from Figure 3-15 in Johansson et al. 2020).

Table 3-4. Mass loss and corrosion depths of the copper coupons (reproduced from Table 3-2 in Johansson et al. 2020).

Coupon	Mass loss		Corrosion		
	g	g/m^2	g/m^2, yr*	µm/yr*	µm
Pickling ref.	0.0006	0.2094	-	-	-
Ref L	0.0016	0.6458	0.0323	0.0036	0.072
Ref K	0.0035	1.3945	0.0697	0.0078	0.156
A3/I	0.0172	8.4885	0.4244	0.0477	0.954
A3/J	0.0234	11.5041	0.5752	0.0646	1.292
A3/L	0.0181	8.9252	0.4463	0.0501	1.002
S2/M	0.0217	10.7183	0.5359	0.0602	1.204
S2/O	0.0238	11.7589	0.5879	0.0661	1.322
S2/P	0.0088	4.3310	0.2165	0.0243	0.486
S2/P**	0.0105	5.2037	0.2602	0.0292	0.584
S2/P***	0.0120	5.9307	0.2965	0.0333	0.666

* Integrated corrosion rates are calculated for the whole exposure period of 20 years.

** Coupon S2/P was further pickled in H_2SO_4 for 14 minutes.

*** Coupon S2/P was further electrolytically cleaned for 12 minutes in KCl according to E3.1 in SS-EN ISO 8407:2014.

The surface topography of the coupons was examined by optical microscopy before and after removal of corrosion products by pickling. All pits and surface defects deeper than 6 µm were measured. Selected areas of 0.5 cm^2 were analysed before and after pickling in order to estimate the pit density or distribution of pits.

The topography is expected to be fairly rough caused by initial O2 corrosion, for the full-scale KBS-3 configuration probabilistic models predicts pits of up to a few hundred µm, while previous field experiments have shown < 100 µm (Febex).

In LOT the surface was rough with small pits in all places and near coalescence, with a maximum depth on the coupon of 25 µm (60 µm after the corrosion products were removed). A tendency for more and deeper pits after removal of the corrosion products was noted, this could be that the pickling method could have affected the topography of the copper surface. However, it is also possible that pits measured before pickling may have been obscured by surface deposits, i.e. corrosion products and bentonite clay. Inspection of cross-sectioned samples of the central copper pipe with SEM, similarly revealed pits up to 25 µm deep. It should be noted that pits in the order of tens of µm may have been present from the beginning since they were not pre-characterised.

Copper in bentonite – pipes

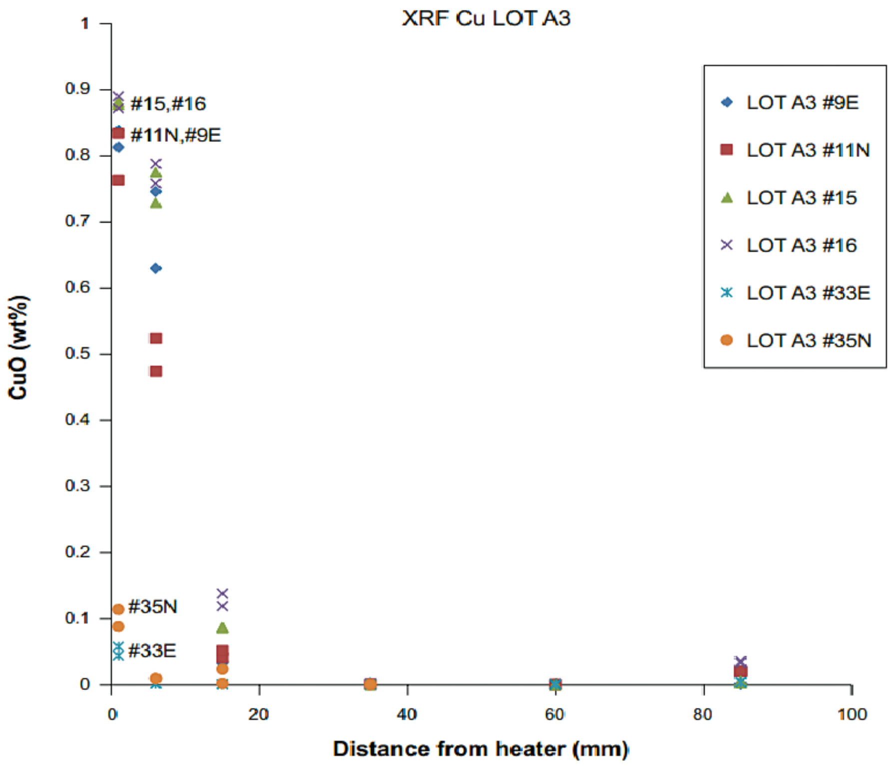
By analysing the copper content of the bentonite, it was possible to estimate the extent of corrosion (average corrosion depth) on the copper pipes. Profiles of the copper concentration in the bentonite near the copper surface was determined using XRF. Figure 3-21 shows results of the "CuO" (wt%) as a function of the distance to the heaters.

Since the determination of corrosion from the copper concentration profile in the bentonite is not a standardised method, the method was cross-tested on the bentonite that had been in contact with the copper coupons, for which corrosion could be determined by standardised gravimetric methods.

The data was used to estimate corrosion depths on different parts of the copper heater pipes in LOT A3 and S2. The estimated corrosion depths are in the range of 0.2 – 13.8 µm for LOT A3 and in the range of 0.2 – 4.8 µm for LOT S2, Table 3-5.

In the LOT A3 experiment the"CuO" concentrations were higher in the central part of the experiment (block #9–16; higher temperature) compared to the more peripheral blocks (#33–35; lower temperature). It was also observed that the"CuO" concentrations in S2 were lower than in the warmer A3. These observations indicated that the" CuO" concentrations were higher in bentonite that had a history of a higher temperature during the experiment. This could be interpreted as due to chemical kinetics, the corrosion reaction rate was higher at increased temperature, and hence hotter parts consumed a larger part of the installed oxygen in the experiment, resulting in more extensive corrosion in those areas. Additionally or alternatively, the hotter parts were desaturated for a longer time period compared to the colder parts, enabling more air corrosion.

Further details, XRF and SEM, on the copper in the bentonite is presented in Johansson et al. (2020).



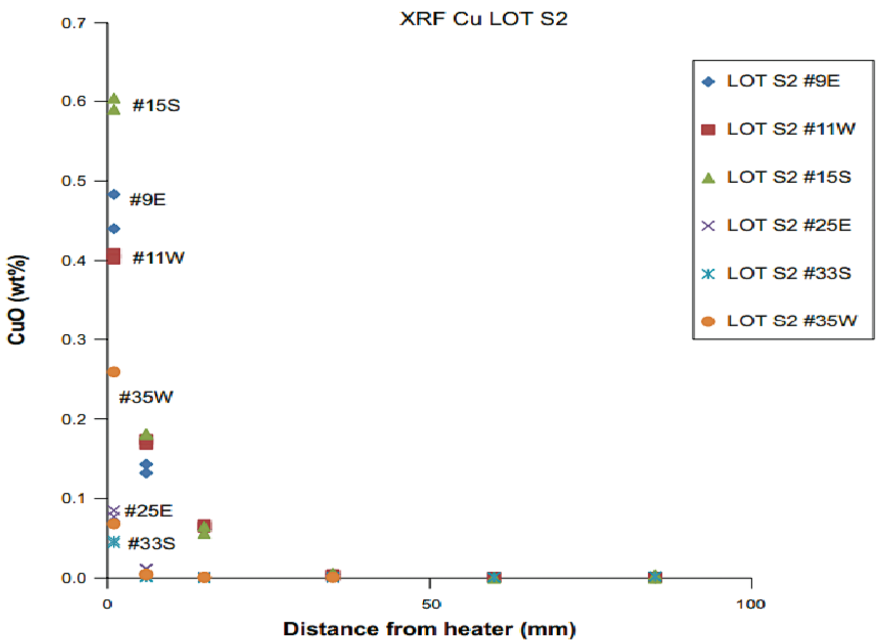


Figure 3-21. *Upper A3 and lower S2, "CuO" (wt%) as a function of the distance (mm) from the heater pipe in LOT, (reproduced from Figures 3-33 and 3-34 in Johansson et al. 2020).*

Table 3-5. Estimated corrosion depths on different positions of the copper heater pipes in LOT A3 and S2, based on the copper content in the bentonite. (reproduced from Table 3-19 in Johansson et al. 2020).

Block	Estimated corrosion depth (µm)
LOT A3 #9E	11.02
LOT A3 #11N	8.91
LOT A3 #15	12.82
LOT A3 #16	13.80
Average hot region A3	11.64
LOT A3 #33E	0.18
LOT A3 #35N	0.61
Average cold region A3	0.40
LOT S2 #9E	3.94
LOT S2 #11W	4.26
LOT S2 #15S	4.81
Average hot region S2	4.34
LOT S2 #25E	0.38
LOT S2 #33S	0.15
LOT S2 #35W	0.52
Average cold region S2	0.35

Implications of LOT S2 and A3 on SKB's corrosion analyses

The strength of field experiments like LOT is that they are carried out in an environment similar to the repository, at least during some period of the physico-chemical development of the repository. At the same time, the complex environment is also a weakness since it is hard to interpret field experiments with respect to individual processes. Field tests like LOT can mainly be used to evaluate the "larger picture" of the corrosion model.

The data and observations from LOT give support for and does not bring about any revision of SKB's conceptual corrosion model which is still applicable for the analysis of the repository's long-term performance.

A quality review of the recent LOT work, with focus on copper, has been carried out by the Swedish Radiation Safety Authority during 2020–2021 (Strömberg et al. 2021) a work in which the authority also let an external consultant undertake a review of the LOT S2 and A3 project. In brief, the results from the experiments are deemed to be reliable and of high quality, and in line with what can be expected from the established knowledge on the copper corrosion processes just after repository closure.

3.8 Concrete and Clay

Background

In the present SFR and future repositories for low and intermediate level radioactive waste, SFL and SFR 3, interactions will occur between the barriers (mainly comprising different forms of cementitious materials but also bentonite clay) and the waste. These interactions will affect the barrier´s 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.

Objectives

The objective of this project is to increase the understanding of the processes occurring in repositories for low and intermediate level radioactive 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.
- Interface reactions 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 (four packages) and 150 bentonite blocks (5 packages) containing materials representative for low- and intermediate-level waste which are deposited in the bedrock in the Äspö Hard Rock Laboratory.

As a complement to the field-scale experiments, also reference experiments have been prepared. These comprise different types of materials representative of low and intermediate level radioactive wastes 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 field-scale experiments. The experimental concept is further described in Mårtensson (2015).

Results

Retrieval and Analyses of a concrete cylinder with metal specimens

During 2020 the second concrete cylinder containing specimens of zinc, aluminium, stainless steel and carbon steel was retrieved and analysed, Figure 3-22.

The analyses (Kalinowski 2020) focused on studies of corrosion of aluminium and zinc and the composition and distribution of the corrosion products in the concrete adjacent to the metal specimens.

The relative humidity in the concrete cylinders were between 92 and 93 % indicating that sufficient water had been available for the corrosion process.

Visual inspections of the surface of the metal specimens showed obvious signs of corrosion of the Zn and Al specimens, Figures 3-23 and 3-24, whereas the different steel specimens were virtually unaffected.

Figure 3-22. *Lifting of the concrete cylinder with metallic specimens (left) and the specimens prior to shipping (right).*

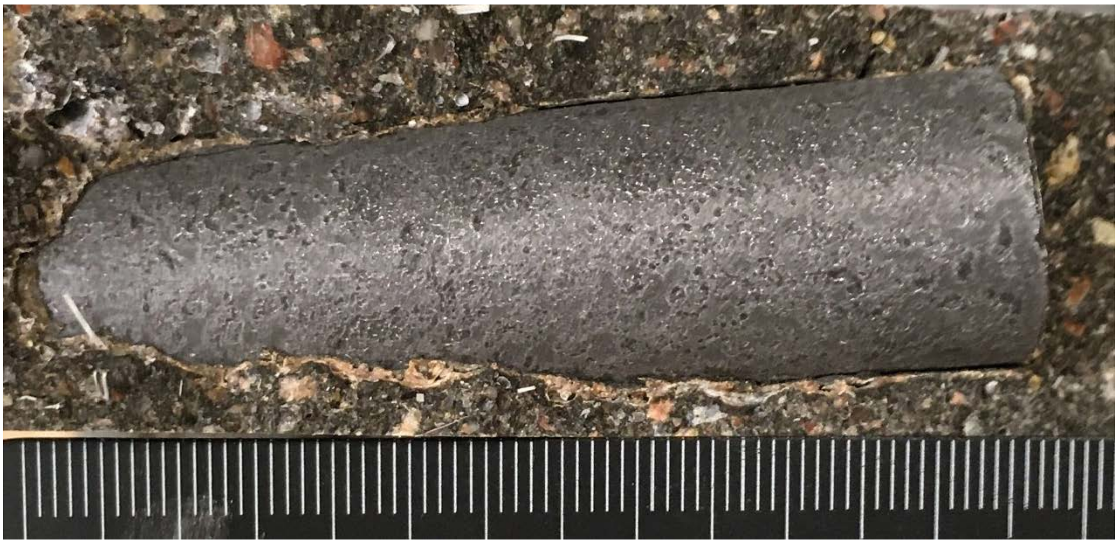


***Figure 3-23.** The surface of an aluminium rod which has been deposited in the bedrock under wet conditions for a period of about 10 years showing the presence of a thin crust of whitish corrosion products extruding into the concrete (Kalinowski 2020).*

***Figure 3-24.** The surface of a zinc specimen which has been deposited in the bedrock under wet conditions for a period of about 10 years (Kalinowski 2020).*

Microscopical investigations of the cross section showed that the thickness of the layer of corrosion products on Al was about 150–300 µm. The layers of corrosion products on the other metals were not thick enough to permit measurement. SEM studies also revealed the presence of small pores or voids just at the interface between the concrete and the Al and Zn specimens. These pores, now partially filled with corrosion products or secondary minerals, were probably formed during the casting of the specimen when hydrogen was evolved through a reaction between the yet wet concrete and the metal specimen. No pores were found in the concrete adjacent to the iron and steel specimens.

EDS analyses showed that corrosion products had diffused into the concrete. For Al and Zn increased levels were found up to 1 000 µm and about 400 µm respectively from the metal surface. However, for steel and stainless steel the concentration of Fe was close to the background level of Fe in the concrete already at the interface between concrete and metal.

When comparing the results from this work with those from those previously summarised in SKB (2016) it is clear that the corrosion rate during the five-year period has been extremely low for all types of metals included in this study. The conclusion is therefore that corrosion of grouted metals mainly occurs during grouting when the reaction with the wet grout can be vigorous but that corrosion rate is very low once the grout has hardened even for metals with an expected high corrosion rate in alkaline environments.

3.9 Projects in a monitoring phase

This section describes experiments that have been previously installed in the underground laboratory and are still in a monitoring phase.

3.9.1 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, a major project which started in 2011 and was finally reported by Svemar et al. (2016), was made in cooperation with Posiva. Furthermore, the following organisations were participating and co-financing the work with the dismantling; NWMO (Canada), ANDRA (France), BMWi (Germany), NDA (United Kingdom), NAGRA (Switzerland) and NUMO (Japan). The evaluation and reporting of the retrieval of the outer section started during 2013 and was published in January 2016 (Svemar et al. 2016).

Objectives

The main objectives for the Prototype Repository are to:

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

Experimental concept

The test is located in the bottom 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 3-25. 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 (Svemar et al. 2016). The inner section will be opened and retrieved 2023–2024.

Goudarzi (2021) is the latest available sensor data report (no 31) for the Prototype Repository and presents measurements from 2001-09-17 to 2020-01-01.

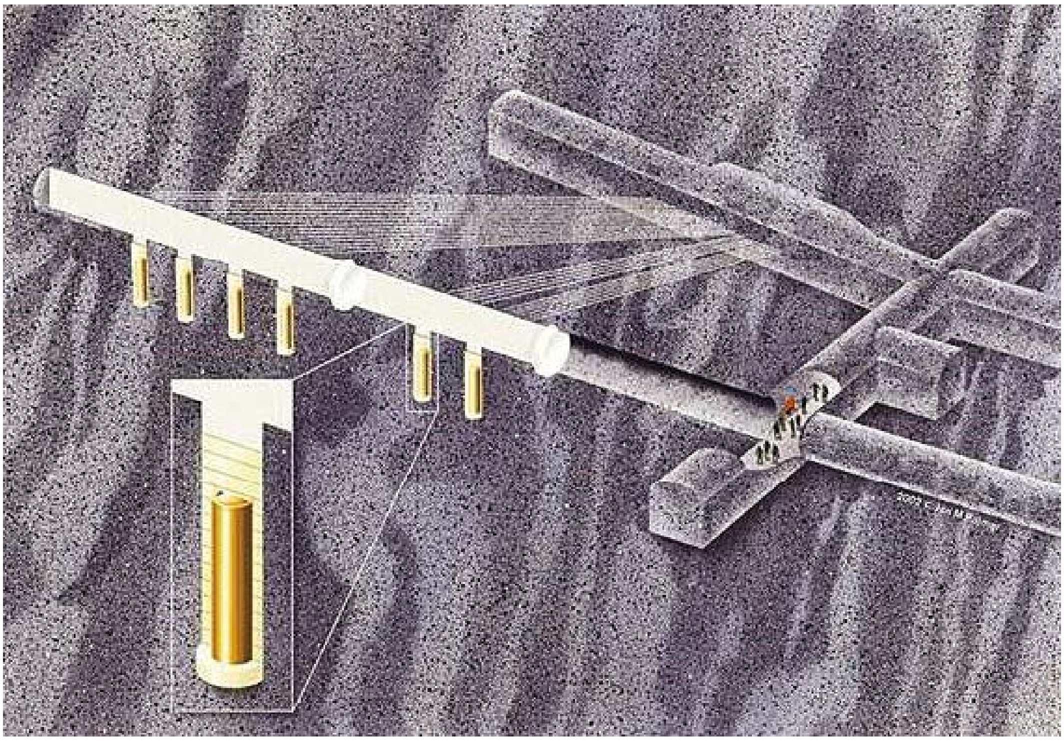


Figure 3-25. Schematic view of the layout of the Prototype Repository (not to scale).

3.9.2 Alternative Buffer Materials

Background

The Alternative Buffer Materials (ABM) project was started in 2006 with the purpose to evaluate different bentonites as possible buffer candidates, as up this point mainly the Wyoming MX-80 bentonite had been in focus.

Objectives

The objectives are to (i) characterise different bentonites regarding composition and properties, (ii) to evaluate their long term performance during realistic conditions, and (iii) to identify and study processes that may occur in the bentonite buffer during special conditions.

Experimental concept

The ABM project consists of a combination of field experiments at the Äspö HRL and laboratory studies of the bentonites have been performed at a variety of laboratories, including both SKB and external partners.

The field tests include more than ten different compacted bentonites, typically heated at 130°, the bentonite block outer diameter is 3 dm, and the central heater has a diameter of 1 dm and the heater material is iron-based. The selection of bentonites corresponds to typical commercially relevant bentonite types as well as scientifically more exotic variants.

In recent years the ABM project has been partly overlapping with other SKB-projects called the material science projects (Svensson et al. 2017). In the ABM project the focus is on the scientific difference between the bentonites composition and performance, while in the material science projects the focus is much more on the technical industrialisation process on how to industrialise the analytical and sampling techniques in order to achieve an effective quality control of buffer and backfill bentonites.

Results

In 2006 three experiments were started (ABM 1–3) and in 2012 three additional packages were installed (ABM 4–6). The ABM1 was excavated in 2009 after 2½ years of heating in the rock (e.g. Svensson et al. 2011, Svensson and Hansen 2013), and in 2013 the ABM2 was excavated after 6½ years of heating (e.g. Svensson 2015). The bentonites in ABM1 and ABM2 were typically highly ion exchanged and equilibrated with the Äspö ground water, making the distribution of ions in the different blocks more even, and the salt content typically also increased somewhat. Precipitates (e.g. Ca carbonates/sulphates and NaCl) and iron corrosion products typically formed locally. The integrity of the montmorillonites was typically fairly intact, with only some minor formation of trioctahedral smectite (saponite/ferrosaponite) very close to the corroding iron heater, however, with no expected impact on the buffer performance (Svensson 2015).

Since the start annual ABM-meetings has been held for discussing results and collaboration between the many international groups, and every year a number of presentations of the different groups have been held on a selection of international clay conferences, making the ABM experiment a very important and central experiment for bentonite long term performance studies, as well as Round Robin tournaments with the purpose of investigating and increasing the performance of selected laboratory analytical techniques.

In 2017 the ABM5 was excavated. The ABM5 experiment was different from the others, as it was water saturated at a lower temperature of 80°, and during its final year it was heat shocked at 150 – 200° in order to study effects from temperatures much higher than the expected boiling point (as a higher design temperature of the buffer would be economically very beneficial if possible). The ABM5 bentonite blocks were upon excavation highly fractured due to the very high temperature (Figure 3-26), detailed analyses of the blocks are to be performed in the coming years.

Figure 3-26. *Highly fractured bentonite blocks from the very high temperature experiment ABM5 excavated in 2017.*

3.9.3 KBS-3 Method with Horizontal Emplacement (3H Multi Purpose Test)

Background

In 2001, SKB published a RD&D programme including KBS-3H, an alternative repository concept with horizontal emplacement of canisters. The system design phase of the programme was concluded in 2017 (Posiva SKB 2017b). All development of KBS-3H have been made in close cooperation between SKB and Posiva.

Objectives

The final goal of the KBS-3H System Design phase was 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 would be possible to do.

A major part of the system design phase was to test and in full scale demonstrate the main KBS-3H components in a partial deposition drift configuration, the Multi Purpose Test (MPT) at Äspö HRL.

Experimental concept

In the KBS-3H concept, the canisters are placed in long horizontal deposition drifts, see Figure 3-27. 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 1 850 mm, and they have a slight upward inclination (2 ± 1°), which is why water is removed from the drifts by gravity along the bottom of the deposition drift during installation. The Supercontainers and the bentonite blocks installed in the drift stand on parking feet between which the inflow water can flow out of the drift. The gap between the Supercontainer and the drift wall is 44.5 – 48 mm.

The Multi Purpose Test (MPT) is a full-scale demonstration of the KBS-3H reference design. The test is conducted without heating and includes the main KBS-3H components in a partial deposition drift configuration. The test installation was carried out according to the Drainage, Artificial Watering and air Evacuation (DAWE) procedure and the system behaviour has been monitored through in situ instrumentation. The MPT is affiliated with the LucoeX project and was partly funded by the European Commission.

A total of 227 sensors were initially installed in the MPT. Pintado et al. (2017) is the latest published data report for the Multi Purpose Test and it includes measurements from December 7, 2013 to December 31, 2015.

In 2020, SKB and Posiva decided to put hold on continued development of the KBS-3H horizontal emplacement method to focus on the licensing of the KBS-3V. Consequently, there is no plan to dismantle and retrieve the MPT.

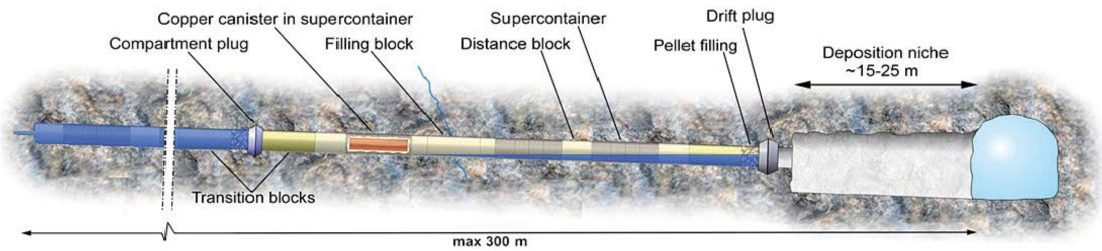


Figure 3-27. *KBS-3H reference design DAWE with its main components; the plugs with their transition zones, the Supercontainers, and the distance and filling blocks. The illustration shows an ongoing artificial water filling procedure of the second compartment.*

3.9.4 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 assessment of the release of radionuclides from the canister in a failure scenario. After a 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 assessment. 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 are 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 3-28), 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, Eh, is being monitored using a combination of metal oxide, platinum and gold electrodes.

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

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

Water samples are taken regularly from the support cages as weel as from the boreholes to monitor the development of the local water chemistry. The experiments will remain *in situ* for several years, after which they will be retrieved, dismantled and the evolution of the corrosion front inside the canister will be analysed. Further details on experimental concept are presented in Smart and Rance (2009).

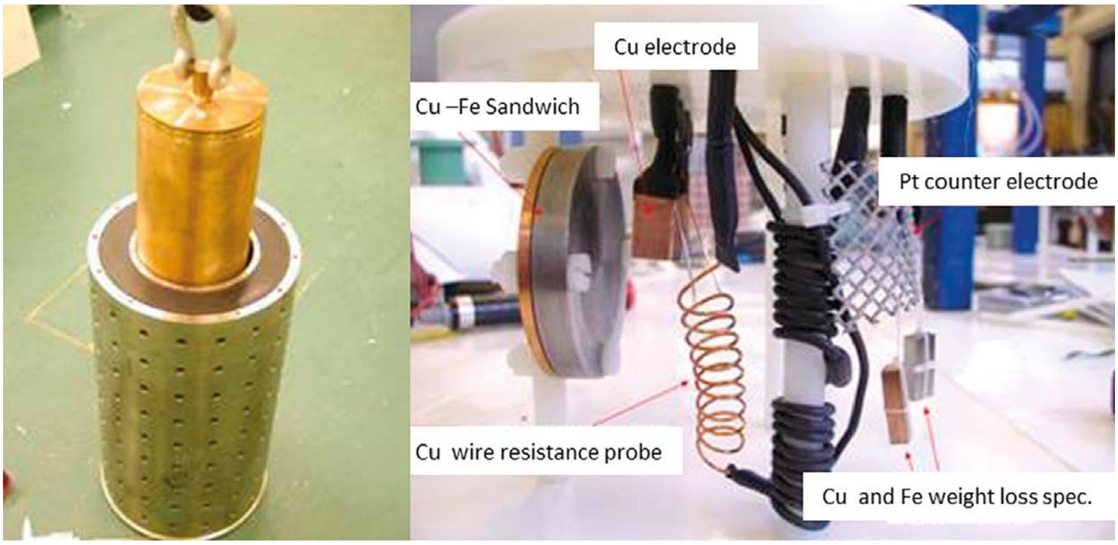


Figure 3-28. *Model canister being lowered into support cage containing bentonite pellets in annulus (left). Test electrodes inside support cage around model canister experiments (right).*

4 Transport system and development of installation equipment

4.1 General

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

Assessment has been made of when the production of machines must begin and when they need to be completed, as well as whether production of prototypes is necessary. The number of objects and affiliated information are due to change since the specifications are working documents.

Newly developed and modified equipment are primarily tested at Äspö HRL and the Canister Laboratory in Oskarshamn. At these sites, facilities suitable for testing are available.

During 2020, a project aimed at designing the equipment needed for backfill installation has been active at Äspö, see Figure 4-1. The project is described in the following sections.

4.2 Backfill installation equipment

According to SKB's KBS-3V method canisters of copper with spent nuclear fuel will be deposited, surrounded by a buffer of bentonite clay, in deposition holes drilled vertically in the sole of tunnels in granite rock. The deposition tunnel is planned to be backfilled with blocks and pellets of bentonite clay. A well-executed installation, together with the properties of the material, ensures that the backfill fulfils its functions towards post-closure safety. The tasks can be performed mainly by standard equipment but some modifications will have to be made.

Figure 4-1. *Prototype equipment for installation of backfill.*

A modular chassis concept has been developed in earlier projects, Figures 4-2 and 4-3, partly conducted as a joint effort together with a heavy transporter manufacturer. The choice of manufacturer Cometto Industries depended on the design parameters of the universal chassis, they already produced a transporter called EMT (Electrical Modular Transporter) which fitted the design profile and they were willing to produce a customized version. It has a payload of approximately 20 tonnes and is battery powered.

The issue with having a platform only powered by battery has been addressed and the conclusion was that it is possible with minor modifications to adapt a hybrid solution into the EMT to make it more versatile for use in a final repository.

The concept of using a robot for the installation of the backfill was tested at a large-scale test in 2014 with promising but not completely satisfactory results, see Figure 4-3.

Objectives

The ongoing project Concept for Installation of Backfill is now about to reach the point of final testing of the system for installation of backfill composed by components that are identical or similar to those planned to be used in a final repository for spent nuclear fuel. The objective of the project is to produce a prototype of a working concept for installation of backfill and the result should be considered as a validation of the subsystem Backfill.

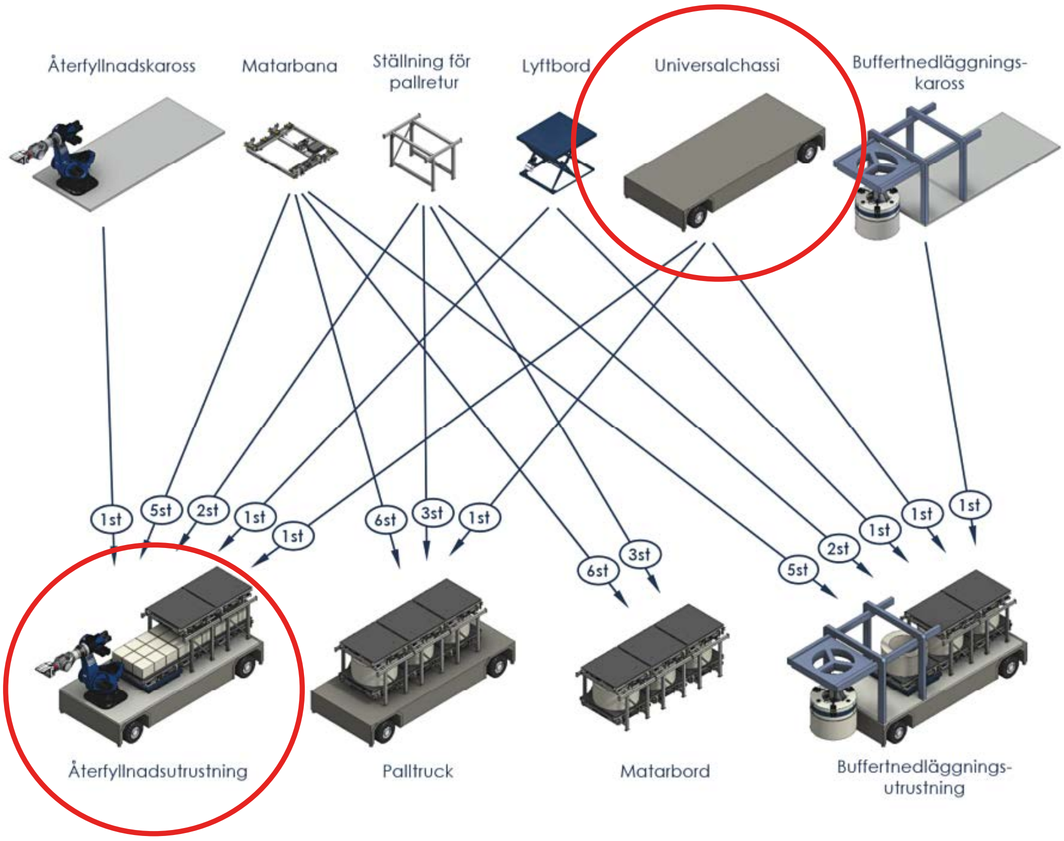


Figure 4-2. Modular chassis concept, with parts used for installation of backfill circled.

Figure 4-3. Earlier version prototype stacking blocks in a full scale test in the Multipurpose test facility. Tests were also performed in the underground laboratory.

Covid-19 delayed first the delivery of the prototype chassis from the supplier in Italy, and then also the commissioning. The remaining work before the final tests consists mainly of software development, converting, integrating and further developing software from earlier projects.

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.
- A navigation system which enables the equipment to validate its route.
- An automated machine control system which in this case emulates the commands from an operator using a remote control.

Results

When the concept was tested the previous time in 2012–2014 the results were promising but not completely satisfactory. The concept needed some more development, and since then the tunnel cross section area of the reference design has also changed.

Development and testing of the two different sets of pellet handling equipment was performed with satisfactory results during 2020. The prototype chassis, a modified EMT, was delivered and commissioned, and SAT was performed, Figures 4-4 and 4-5. Assembly, mounting of robot transport equipment and pellet handling equipment was performed and the comprehensive conversion and further development of the software was initiated during 2020.

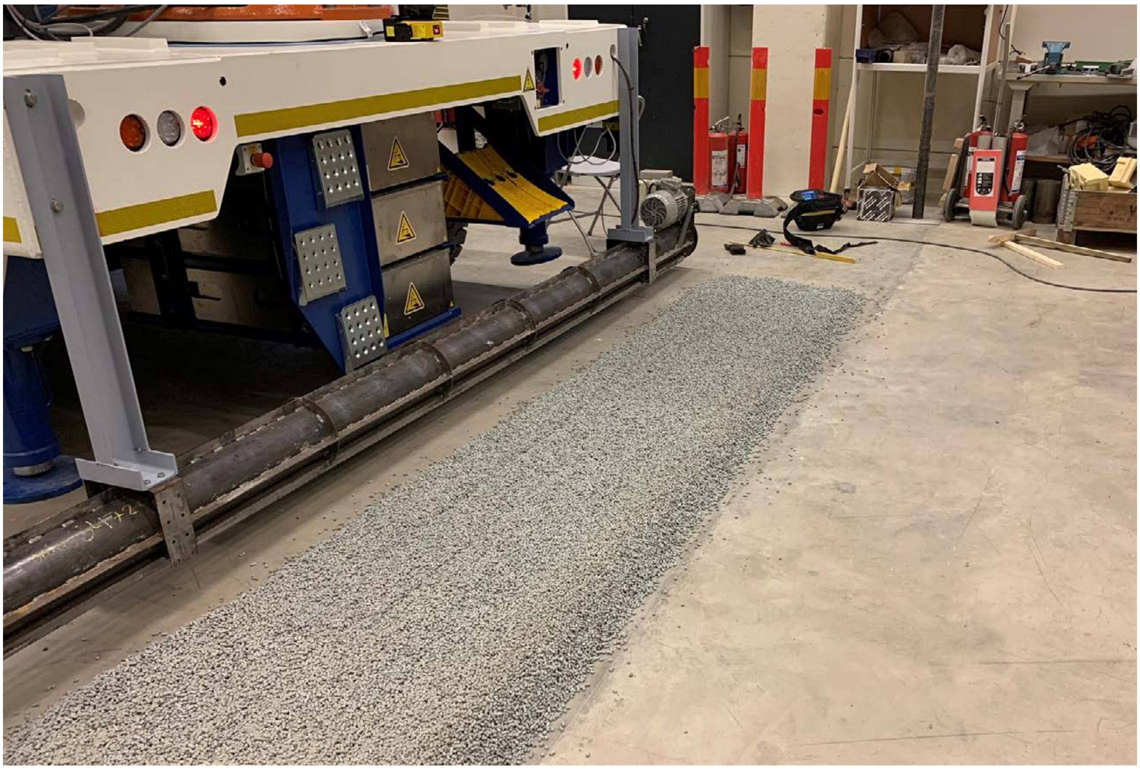


***Figure 4-4.** Equipment for installation of pellets on the tunnel floor.*

***Figure 4-5.** Equipment for installation of backfill. The chassis with the robot, the vacuum tool for handling of blocks, the transporters and the equipment for the installation of a pellet bed on the tunnel floor mounted. Mainly the comprehensive work with converting, integrating and developing the different software to make it compatible.*

5 Development of excavation techniques

5.1 General

In the Äspö HRL different techniques for excavating the underground openings of a spent fuel repository have been developed and tested since the start of the HRL. Although the strategy is to rely on commercially available techniques they have to be tested and, in some cases adapted, to the specific requirements for the repository.

The plans to construct and later, during operation, expand the deposition areas rely on detailed knowledge of the geotechnical and geoscientific traits of the Forsmark site. This knowledge is needed in order to secure that the deposition area is constructed where requirements from post-closure safety can be met. Investigation methods are developed at Äspö as part of the tools needed to acquire this knowledge.

During 2020 the following experiments and projects concerning excavation techniques were ongoing:

- Mechanical excavation (desk study only).
- Drilling of deposition holes.
- Investigation methods for ramp and shafts.

5.2 Drilling of deposition holes

Background

SKB has followed Posiva's development work for deposition holes, where Posiva has drilled ten vertical experimental holes in Onkalo, distributed between two demonstration tunnels (Railo et al. 2015, 2016). The deposition holes were drilled with a prototype machine of type Rhino HSP500 manufactured for the purpose. SKB has previously drilled around 15 deposition holes in the Äspö HRL with a different machine during 1998–1999 (Andersson and Johansson 2002).

There is still a need for further development and evaluation of the drilling of deposition holes with the improved prototype machine. A new project started during 2019 at Äspö HRL and the first results from the testing in field will be received during 2021.

The principle layout of a vertical deposition hole is a diameter of 1 750 mm and depth of circa 8 000 mm, a sketch seen in Figure 5-1.

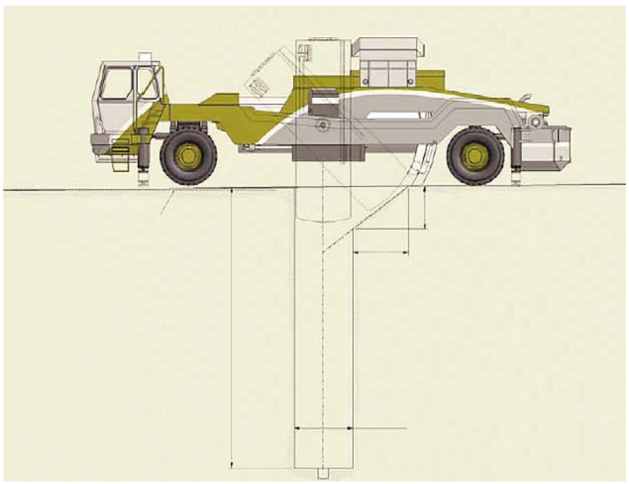


Figure 5-1. *Cross section of a reference design KBS-3 deposition hole.*

Objectives

SKB has hired Posiva's prototype machine for drilling deposition holes, see Figure 5-2, to evaluate functions and if possible further develop the equipment, including an attempt to have it CE-certified. Subsequently SKB will drill a new series of experimental holes at Äspö HRL at the −410 m level.

In addition to evaluating the development of the machine, drilling of deposition holes will be a good opportunity to update and expand SKB's experience in drilling of deposition holes as this has not been done in some time. The drilling activities will also give improved basis for calculations on cost for wear on drilling equipment.

SKB's updated requirements for the buffer and deposition hole geometry have to be incorporated by the project. The geometry of the deposition hole, with its narrow tolerances, interacts with the configuration of the buffer. The buffer blocks must be possible to install in the holes and the buffer system must be configured with the proper density to protect the canister in post closure safety analysis.

Experimental concept

Results

Initially, in a workshop above ground, an inventory list of the machine was compiled and status of each component has been evaluated and commented. The project team has systematically performed mechanical maintenance of the machine based on the evaluation list. After that a new electrical transformer was installed and the machine was started. Following weeks extensive testing of all the functions on the machine was carried out.

One of the results of the testing was that problems were identified with the software and also some electrical components. New parts were ordered and exchanged.

Furthermore, the project prepared the installation of media, such as electric and water distributions, at the work site. On the planned drilling site (Tunnel TASN) a lot of preparation work was done. A concrete slab was cast on the tunnel floor and all necessary media was installed including three large sedimentation tanks to handle and clean the process water.

Working with heavy equipment underground is always a major risk, thus the project also conducted risk assessment and implemented activity plans (work routines) in the work preparations.

Finally, the project transported the machine down to the −410 m level in the underground laboratory where it was established at the work place TASN, see Figure 5-3.

Figure 5-2. *Prototype machine of type Rhino HSP500.*

Figure 5-3. Transport of the machine to the test tunnel TASN.

The project is now in the realisation phase, with all test plans in place, and is ready to start drilling deposition holes in the middle of 2021.

5.3 Investigation methods for ramp and shaft

Background

Detailed studies are necessary to characterize and document the Forsmark bedrock before the production of the Spent Fuel Repository so that it is constructed in accordance with conditions in the bedrock, and construction requirements regarding rock can be verified.

During autumn 2016 it was decided that technology project DETUM-1 should be discontinued and the remaining work within DETUM's subproject *Methods and Instruments (M & I)* would be transferred into the new project KBP5003 Methods for investigations, for further development. The project was to complete technology development of methods for investigations for the Spent Fuel Repository accesses (ramp and shaft) in accordance with established list of investigation equipment. Developed methods will ensure that the detailed investigations efficiently provide the data required for the safety assessment and the repository construction with regards to cost and time. The project was to develop documentation for methods that will guide the performance of investigations in the Spent Fuel Repository (ramp and shaft). During 2020 the KBP5003 project was closed although the output target was not fully reached. The remaining work was transferred to the organizational unit *Site modelling and monitoring* for completion.

Output targets

The target is to ensure that all survey methods, document management and instruments needed to implement detailed investigations for the Spent Fuel Repository accesses are presented, described, quality assured and approved when it is time for the operational programs being submitted to the Swedish Radiation Safety Authority, this in connection with the application to commence construction of the Spent Fuel Repository.

Results

Geology

A digital system, RoCS, has been developed by SKB for geological mapping of underground openings (tunnels, shafts and niches, etc.). The basis for the system is a photogrammetric mapping record (3D model) upon which the spatial extent of various geological features is digitized. Geological properties of the digitized features are provided by studies of the rock surfaces of the underground openings.

For full application during construction of the Spent Fuel Repository, the recent development of the system has been focussed on demands from down-stream users and optimization of mapping routines. Introduced changes and adaptions of the RoCS mapping module have been tested continuously 2020 to provide feedback to software programmers. Further practical tests of the mapping system will be launched during 2021, including photogrammetry and remote mapping along parts of the TBM tunnel at Äspö HRL, as an analogy with the ramp of the Spent Fuel Repository.

As input to the generation of photogrammetric models of tunnel floors, setup and photography were tested in TASN at Äspö HRL during drilling of deposition holes, see Section 5.2. Testing of camera and light setups for photography of tunnel floors will continue during 2021.

Hydrogeology

A substantial body of work to identify and develop methodology and tools for surface based hydrogeological site investigations was produced at Äspö. These tools were subsequently applied in connection with the site investigations to identify the more suitable site for nuclear waste repository at Forsmark and Oskarshamn. Preparations are now underway to establish a suitable toolbox for tunnel based hydrogeological investigations to be applied in the ramp and shafts of the planned repository at Forsmark. These developments draws heavily on the previous work on surface based tools and on the work and experience undertaken at the Äspö HRL and its tunnel system. However, new methodologies/procedures are developed and old one adapted/revised for tunnel conditions.

Work undertaken during 2020 in this respect comprise a whole suite of hydraulic testing and monitoring procedures. The development work is on-going and will be tested at Äspö HRL, as completed, with site accepatance test scheduled to start in 2021.

Hydrogeochemistry

A method test for groundwater sampling for analyses of dissolved gas and isotopes in gases was initiated due to the need to establish suitable sampling method for non-vertical boreholes. Often encountered problems with the gas data are large deviation between analyses by different laboratories for some of the gases (especially nitrogen and hydrogen). Furthermore, total gas volumes also show variations within series of samples analysed by the same laboratory. During 2019–2020 has an equipment been tested and data evaluated from three borehole sections representing different ground water types and residence times for this purpose. The development work will continue and tested at Äspö HRL with the following strategy 2021; 1) sampling using cylinders connected in parallel 2) repeated sampling for dissolved gases and isotopes in gases included series of minimum three samples with different total pumped volumes.

6 Äspö facility

6.1 General

The Äspö facility comprises the Äspö Hard Rock Laboratory and the above ground Research Village.

The facility has been introduced in Chapter 1 where the historic background, goals for the laboratory together with its organizational structure were presented. Layouts of the facility can be found in Figures 1-1 and 1-2.

This section gives a deeper explanation of the purpose of all different parts of the facility and their outcomes during the year. Updated information is also available on communication activities and future strategies of the laboratory.

6.2 Multi-purpose test facility

Before building a Spent Fuel Repository, further studies of the behaviour of the buffer and backfill materials under different installation conditions are required. SKB has constructed the Multipurpose test facility at Äspö, designed primarily for studies of buffer and backfill materials. The laboratory has been in operation since spring 2007, and was previously called the Bentonite Laboratory. The name has been changed to reflect the breadth of research that is and can be performed in the facilities. The Multipurpose test facility enables full-scale experiment under controlled conditions and makes it possible to vary the experiment conditions in a manner which is not feasible in the underground laboratory.

The test facility, 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.

In 2020 experiments have been performed in the Multipurpose test facility within several projects as described in Chapter 3.

6.3 Material Science Laboratory

A research laboratory for bentonite analysis and experiments has been established on the Äspö facility, and is hosted by the department of Research and Post-closure Safety at SKB. The purpose of the laboratory is to act as a research and development infrastructure for bentonite investigations, supporting the research and technical development at SKB, including the very important competence build-up. The research laboratory is continuously evolving.

The laboratory is used in a number of projects and activities including technological development in (i) the material science projects, and for various research studies such as (ii) the analysis of long-term field experiments such as LOT and Alternative Buffer Material (ABM), (iii) chemical erosion properties of bentonite, (iv) microbiological activity of sulphate reducing bacteria (SRB) at unsaturated conditions, and (v) evolution of gases in bentonite during unsaturated conditions.

During 2020 highest activity was from microbiological activity of sulphate reducing bacteria (SRB) at unsaturated conditions, atmosphere tests (Figure 6-1), erosion tests (Figure 6-2), and bentonite material characterisation (e.g. Figure 6-3).

The work with bentonite material studies are further described in Chapter 3.5.

The infrastructure consists of equipment allowing handling, preparation, purification and analysis of bentonites, or investigation of important properties. This includes classical wet chemical analysis such as cation exchange capacity (CEC), exchangeable cations (EC), chemical reduction of iron (CBD), geotechnical measurements such as water content, density, swelling pressure and hydraulic conductivity, and solid state investigations using non-destructive techniques such as X-ray diffraction (XRD) for mineralogy, X-ray fluorescence (XRF) for chemical content, infrared spectroscopy for detailed investigations of the clay mineral crystal structure, and μ-raman spectroscopy for investigations requiring high spatial resolution. A very large glovebox is also available for anaerobic studies or sampling of oxygen sensitive field samples. Recent upgrades are more advanced equipment for wet milling of bentonite samples, and a small photo studio for improved documentation of samples and experiments.

Figure 6-1. *Deposition hole atmosphere test. Bentonite blocks, pellets and a copper heater are placed in a confined volume while oxygen, hydrogen and hydrogensulfide gases are monitored with time.*

Figure 6-2. *Experimental cell for measuring of chemical erosion of swelling clays. In this case the clay used is dialysed Nanocore at very low ionic strength in a 0.2 mm vertical fracture. The vertical placement show the impact from gravity on the sedimentation.*

Figure 6-3. *Naturally present smectite at −1 100 m level in the Kiruna mine. These swelling clay minerals are very similar to bentonite and this location is very promising for a natural analogue study.*

6.4 Water chemistry laboratory

History

The Chemistry Laboratory at Äspö HRL was built in the late 1990s. 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. The laboratory serves all of SKB and its projects, not only Äspö HRL.

The laboratory includes an on-site laboratory in Forsmark intended to aid the construction of the repository with sampling and water chemistry analysis for the site descriptive modelling. The information below concerns the work performed at Äspö.

The laboratory is certified in accordance with ISO/IEC 17025 Testing and calibration laboratories, and the overall certification was renewed by Swedac in June of 2021.

Analyses and equipment

For the moment the Chemistry Laboratory can perform 14 different analyses for water samples. Several of these analyses are accredited – pH, electrical conductivity, alkalinity, total organic carbon (TOC) and dissolved organic carbon (DOC), potentiometric measurements for chloride and fluoride, ion chromatography (IC) for anions such as chloride, bromide, fluoride and sulphate and UV/VIS spectroscopy for nitrogen as ammonia, sulphide and iron (Fe^{2+} and Fe^{tot}). The newest instrument is the Liquid Water Isotope Analyzer (LWIA) for determination of ^{18}O and ^{2}H and this analyse is also certified by Swedac since December 2019.

External laboratories are used for analysing cations (ex. sodium, calcium and sulphur), lanthanides and other trace elements, nutrient salts and isotopes such as ^{3}H, ^{34}S, ^{87}Sr and ^{37}Cl.

Performed activities

Once a year the Chemistry Laboratory performs a monitoring programme in the tunnel. At that time approximately 25 sections of different boreholes are collected and analysed at the laboratory. This programme has been ongoing since the tunnel was built in the 1990s and the data is used for modelling the groundwater in the HRL and understanding the area.

Quality control and quality assurance are performed every time an instrument is to be used. The results for both control samples and regular water samples are stored in a laboratory database (LabWare LIMS), see Figure 6-4. The chemistry laboratory has a useful and well described quality system for all the work that is done.

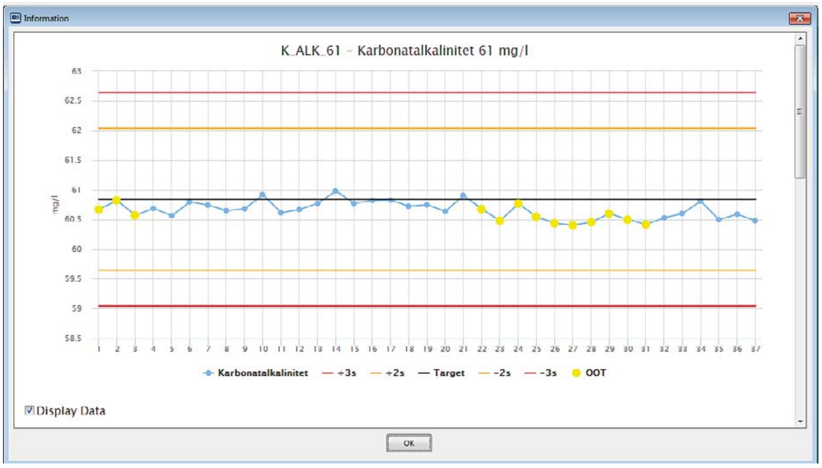


Figure 6-4. Example of control chart for the registration of control samples.

6.5 Facility Operation

Background and goals

The main goal for the operation of the rock laboratory is to provide a high service function and a customized availability for projects and external customers. The target was met well in 2020 despite great rock maintenance work and experiments.

The laboratories must also be safe for everyone who works or visits and for the environment. This includes preventative and remedial maintenance to ensure that all systems, such as drainage, electric power and lighting, ventilation, fire alarm systems, personnel monitoring systems and communication systems are always available in the underground laboratory.

Results

Äspö HRL has had a stable operation during 2020.

The independent rock inspection, carried out at the end of 2016, led to the execution of prioritised safety measures in different areas of the underground laboratory:

- Replacement of obsolete rock bolts.
- Exchange or addition of rock reinforcement networks.

The enhanced rock maintenance work has proceeded very well and all recommended activities from the major rock inspection were completed during 2020. Consequently, a new independent rock inspection was carried out in November 2020 with satisfactory results. The inspection suggests that ordinary systematic rock maintenance work can be carried out from 2021.

In addition to rock maintenance, the following major maintenance work has been carried out:

- Replacing of the mine-lift cable and subsequent adjustments of the elevator-operation.
- Upgrade or exchange of battery units for the uninterruptible power supply
- Several planned activities have been postponed due to the Covid-19 situation.

6.6 Communication Oskarshamn

The main goal for the Communication unit in Oskarshamn is to create public acceptance for SKB. This is achieved by presenting information and showing SKB's facilities and the RD&D work e.g. at Äspö HRL. The unit is responsible for visitor services at Clab and the Canister Laboratory as well.

The unit has a booking team which books and administrates all visits to SKB's facilities. The booking team also works for Oskarshamn NPP's service according to agreement.

External and internal communication activities carried out by the unit also range from local media relations, web and editorial work, school information and much more.

2020 was a different year for everyone, the Communication Oskarshamn unit included.

Before we closed our facilities for visitors in mid-March, 338 persons did visit the Äspö HRL and with the visitors to Clab and the Canister Laboratory included, it resulted in a total of 767 persons. The visitors represented the general public, students, professionals, politicians, journalists and international visitors.

The total number of international visitors to the Äspö HRL was 47. The international visits are mostly of technical nature, but increasing interest is shown regarding public acceptance of a geological disposal programme for high level radioactive waste.

The total number of visitors to SKB's facilities in both Oskarshamn and Forsmark/Östhammar was 1 082 persons.

Instead of the special summer arrangement "Upptäck underjorden" (Discover the underground) the Äspö nature trail was upgraded with new signs, a new footbridge and some handrail so we could invite the public, if not to the underground, so to the beautiful surroundings of the island of Äspö. The trail is 2 kilometres long and you find signs with information regarding the landscape, geology, birds, flowers and trees and so on while you walk. It is also prepared so that you can sit down and enjoy coffee or packed lunch. The nature trail was prepared already in the late 1980s and has been used for education, excursions etc.

The school information officer attended employer branding activities at selected Swedish universities, at first on site but later from digital platforms. She also, digitally, attended a special labour market day for all 7th graders in the Oskarshamn municipality and was part of "Innovation Camp" for second year students at the high school, arranged by "Ung Företagsamhet" (Young Enterprise) in cooperation with SKB and OKG.

The unit has been involved in regional work regarding Covid-19 communication arranged by the County administrative board.

During 2020 the Communication Oskarshamn unit consisted of seven persons.

6.7 Future use of Äspö HRL

SKB has continued to seek alternative possibilities for adaptation of the Äspö HRL into an open international research and innovation infrastructure. The initiative is spurred by an active external interest in the planning for the future use of Äspö HRL and by internal long-term strategic reasons. The efforts are focused on finding out if there are external organisations willing to individually or together with other parties take over the operations of the Äspö HRL. If such interest exists SKB will support the transfer of the ownership and the operations of the facility to a new owner. Otherwise, SKB will start to cease of the operations in the mid of 2020s.

In 2019 SKB identified and selected LTU Business as a strategic business partner. LTU Business supports customers develop innovations, business strategies and partnerships for a better future through adding leading methods, expertise and tools. LTU Business is a consulting company, owned by Luleå University of Technology (LTU), operating at the intersection of academia, business and government.

The collaboration with LTU Business has resulted in an increased understanding of Äspö HRL's business opportunities. Based on the new insights a strong business case was elaborated and presented for a potential new owner in the fall 2020. The first proposal was met with great interest and complementary information has been added successively in the ongoing dialogue. In 2021, next year, SKB will follow up with internal activities. The purchase price has to be decided based on a valuation of the facility. Mandate to initiate negotiations is needed as well.

In the beginning of 2020 a preliminary decommissioning study was initiated concurrently with the elaboration of the business case. The study resulted in insights of importance to consider in the future when planning the decommission of the facility if needed in the mid of 2020s. The study included an inventory of current permits and agreements for the current operations of Äspö HRL. A shortcoming in an agreement was identified and remedied.

Finally, SKB is looking forward to initiate negotiations with the invited potential future owner of Äspö HRL. The core of the proposed business case is based on SKB's potential need of long-term access to the underground facility throughout the 2020s and maybe even longer. A favourable starting point for a fruitful long-term collaboration.

7 SKB International

7.1 Background history

SKB organised NWM, Nuclear Waste Management, as 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 full access to SKB's experts, technology facilities, laboratories and intellectual property. SKB International's services are based on the knowhow and hands-on experience accumulated by SKB in the development and operation of the Swedish nuclear waste management system. 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 to 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 reactors. SKB International makes available SKB's special purpose vessel m/s Sigrid at times she is not occupied in SKB's programme. m/s Sigrid is roll on – roll off, lift on – lift off vessel with INF3 classification allowing transports of the highest class of radioactive cargo.

SKB International's main areas of operation are:

- Consulting services.
- Laboratory services.
- Training and competence development.
- Transports with m/s Sigrid.

7.2 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 space, different laboratories, a Multipurpose test facility, etc.

Äspö HRL enables SKB to study the interaction of bentonite clay and copper canisters with the bedrock in realistic conditions. Experiments are made to identify the role of the bedrock as a barrier. This can, for instance, concern how the bedrock slows the movement of radioactive substances or how microbes affect conditions at repository 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.

7.2.1 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

It is possible to arrange specific on the job-training activities for competence building of other organisations' staff.

Access to field data from 1986 until today

SKB has produced data from the site investigations of the Äspö island in the mid-1980s, from the construction phase of the Äspö HRL between 1990 to 1995 and from activities performed until today. Most of the field data can be made available for organisations, that may not have access to such data for the development of for instance methodology for site descriptive modelling.

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 genuine experiences in arranging bespoked workshops and training courses and events on different topics. Experts from SKB covering different disciplines, e.g. long-term safety, site investigations and selections, public relations, construction of underground facilities are a key component in securing high quality activities.

Äspö International partnership

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

A specific web-based site, the Äspö International Web Portal, is available to the partners. Information about Äspö HRL, including the Äspö village with the Chemistry and Material Science laboratories, Multipurpose test facility as well as the underground laboratory is presented. Also performed, ongoing and planned projects/experiments are presented. This allows the partners the opportunity to continuously follow planned and ongoing work and also to prepare for their own experiments.

Field data from the site investigations of Äspö HRL during 1986 to 1990, field data from the construction of Äspö HRL during 1990 to 1995 and the extensions made at can be made available.

7.3 Activities and support during 2020

Due to the pandemic in 2020 and hard restrictions to travel all events for our Äspö International partners at Äspö HRL were cancelled. Instead SKB International arranged three webinars with the latest updates from the technical development work at Äspö at the annual ***Technical Information Meeting***, TIM. The webinars covered the following topics:

- Techniques for tunnel production.
- Drilling of deposition holes.
- Development of borehole sealing.
- Material bentonite study.
- Technique for block and pellets production.
- Design of buffer and backfill.
- Granulated backfill.
- Dismantling of the LOT-experiment.
- Dismantling of Lasgit.

SKB presented planned activities at Äspö HRL for 2021 and the following years at the annual ***International Joint Committee meeting***, also in form of a webinar. SKB International launched a series of webinars for 2021 covering following topics:

- Data management during site investigations.
- Bentonite characterisation and adaptive design and manufacturing.
- Machine development.
- Modelling based on Äspö data.
- Sealing of investigation boreholes.

The ***Äspö International Web Portal*** was updated with updated in relation to ongoing SKB projects.

SKB International and SKB have organised scientific training courses, School of Geological Disposal, in 2018 and 2019. The training covered important issues governing nuclear waste disposal programmes. The course presented the planning and execution of a successful disposal programme based on the experiences gained by SKB during the past 40 years. Due to the pandemic in 2020 the planned training course with focus on Site Investigations was postponed.

7.4 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

Mr. Erik Thurner, Senior Advisor, Phone +46 70-577 27 25, email: erik.thurner@skb.se

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.

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