Invited Paper https://doi.org/10.7733/jnfcwt.2018.16.2.137

Validation of Performance of Engineered Barriers in a Geological Repository: Review of In-Situ Experimental Approach

심지층처분장 공학적방벽 성능 실증: 현장실험적 접근법 검토

Won-Jin Cho* and Geon Young Kim
Korea Atomic Energy Research Institute, 111, Deaduk-Daero 989beon-gil, Yuseong-gu, Daejon, Republic of Korea

조원진*, 김건영
한국원자력연구원, 대전광역시 유성구 대덕대로989번길 111

(Received April 17, 2018 / Revised June 19, 2018 / Approved June 25, 2018)

The guarantee of the performance of the engineered barriers in a geological repository is very important for the long-term safety of disposal as well as the efficient design of the repository. Therefore, the performance of the engineered barriers under repository condition should be demonstrated by in-situ experiments conducted in an underground research laboratory. This article provides a review of the major in-situ experiments that have been carried out over the past several decades at underground research laboratories around the world to validate the performance of engineered barriers of a repository, as well as their results. In-situ experiments to study the coupled thermal-hydraulic-mechanical behavior of the engineered barrier system used to simulate the post-closure performance of the repository are analyzed as a priority. In addition, in-situ experiments to investigate the performance of the buffer material under a real repository environment have been reviewed. State-of-the art in-situ validations of the buffer-concrete interaction, and the installation of the buffer, backfill and plug, as well as characterization of the near-field rock and the corrosion of the canister materials are, also performed.

Keywords: In-situ experiment, Engineered barriers, Geological repository, Validation, Demonstration

*Corresponding Author.
Won-Jin Cho, Korea Atomic Energy Research Institute, E-mail: wjcho@kaeri.re.kr, Tel: +82-42-868-2852

ORCID

Won-Jin Cho	http://orcid.org/0000-0003-3063-9334	Geon Young Kim	http://orcid.org/0000-0001-5502-178X

심지층처분장 공학적방벽의 성능 보장은 장기처분안전성 측면에서 뿐만 아니라 심지층처분장의 효율적인 설계를 위해서도 매우 중요하다. 따라서 지하실험시설에서 수행되는 현장실험들을 통해 심지층처분장 조건 하에서의 공학적방벽 성능을 입증할 필요가 있다. 이 논문에서는 심지층처분장 공학적방벽의 성능을 실증하기 위해, 지난 수십 년 동안 전 세계에서 수행되어온 주요 현장실험의 현황과 그 결과에 대해 검토하였다. 먼저 심지층처분장의 폐쇄 후 성능을 모사하는 공학적방벽시스템의 열-수리-역학적 복합거동을 규명하기 위한 현장실험들이 분석되었다. 아울러 실제 심지층처분장의 환경에서 완충재의 성능을 조사하기 위한 현장실험들이 검토되었다. 완충재-콘크리트 상호반응, 완충재, 뒷채움재 및 플러그의 설치, 그리고 근계암반 특성과 처분용기 재질의 부식 현상을 규명하기 위한 현장실험들의 기술현황도 분석되었다.

중심단어: 현장실험. 공학적방벽, 심지층처분장, 실증, 입증

1. Introduction

A geological repository would be constructed in a bedrock at the depth of several hundred meters below the ground surface. The repository is expected to be of a room-and-pillar design, and high-level waste canister will be deposited in an array of large-diameter deposition holes drilled into the floor of disposal tunnel. The space between the canister and the inner wall of the deposition hole will be filled with a buffer material of compacted bentonite. When all deposition holes in a disposal tunnel are filled, the tunnel is backfilled with a compacted bentonite-sand mixture, and the entrance of the tunnel is plugged with concrete plugging material [1]. The canister, buffer, backfill, plugging and near-field rock are called engineered barriers because they are man-made barriers or their performance can be improved through artificial efforts.

An engineered barrier controls the dissipation of decay heat from the high-level waste to the surrounding environment to prevent an improper increase of the temperature in the repository. As the performance of the repository is affected by the temperature, keeping a proper temperature in the repository is an essential factor for the design of a geological repository. The engineered barrier also has a significant influence on the radionuclide release from the repository to the surrounding rock. Therefore, the validation of the performance of engineered barriers is very important for the design and long-term safety of a geological repository. At the initial stage of a research program for the validation of the performance of engineered barriers, validation is mainly carried out through laboratory works, which have essential limitations in that the experiments are done under unrealistic conditions on a small scale and in a short period. These limitations can be overcome by in-situ experiments carried out at a full scale or semi-full scale under realistic repository condition at an underground research laboratory. Therefore, in-situ experiments are of great importance for the efficient design of a repository and an improvement of public acceptance on the safety of high-level waste disposal.

In this article, the in-situ experiments to demonstrate the performance of engineered barriers of a repository that have been carried out at underground research laboratories around the world for the past several decades are reviewed, and their results are analyzed.

2. Underground Research Laboratory

There are many underground research laboratories around the world for R&D on the disposal of high-level waste. Several underground research laboratories where in-situ experiments for the performance of engineered barriers of a geological repository have been carried out actively are as follows (Table 1);

Table 1. Several underground research laboratories in the world

URL	Descriptions	Remarks
Grimsel Test Site	· Host rock: Granite · Location: Grimsel, Switzerland · Depth: 450 m	· Managing organization: Nagra · Operating since 1984
Mont Terri Rock Laboratory	· Host rock: Opalinus clay · Location: Mon Terri, Switzerland · Depth: 250~320 m	· Managing organization: Swisstopo · Operating since 1995
Aspö Hard Rock Laboratory	· Host rock: Granite · Location: Oskarshamn, Sweden · Depth: 460 m	· Managing organization: SKB · Operating since 1995
Exploratory Studies Facility	· Host rock: Tuff · Location: Yucca Mt. USA · Depth: 300 m	· Managing organization: US DOE · Operation from 1997 to 2009
ONKALO UCRF	· Host rock: Granite · Location: Eurajoki, Finland · Depth: 520 m	· Managing organization: Posiva · Operating since 2004
HADES URF	· Host rock: Boom clay · Location: Mol, Belgium · Depth: 225 m	· Managing organization: EURIDICE · Operating since 1984
KURT	· Host rock: Granite · Location: Daejeon, Korea · Depth: 100 m	· Managing organization: KAERI · Operating since 2006

2.1 Grimsel Test Site

The Grimsel Test Site (GTS) is one of two operating underground research laboratories in Switzerland. GTS is located in a granite at a depth of 450 m below the ground surface of Central Aar Massif in Switzerland. The main tunnels with a diameter of 3.5 m and a length more than 1,000 m were constructed from 1983 to 1984 using a tunnel boring machine (TBM), and extended in 1996 and 1998. Additional caverns were excavated using a conventional drill and blast technique [2,3].

2.2 Mont Terri Rock Laboratory

The Mon Terri Rock Laboratory (Mont Terri RL) is the other underground research laboratory in Switzerland, and is located in Opalinus Clay at a depth of 250 to 320 m below the ground surface. Mon Terri RL was constructed at the investigation tunnel of the National Highway N16 of Switzerland with a width of 4.6 m and a height of 4.5 m. The investigation tunnel was excavated using a conventional drill and blast technique, whereas the research tunnels were excavated using a hydraulic or pneumatic hammer, horizontal raise boring and large-diameter auger. In 1996, eight research tunnels with a width and height of 4 m and a length of 8 m were constructed, and in 1997, an additional 230 m long research tunnel with a width of 3.5 m and a height of 8 m was excavated. After that, several extension works were conducted [3,4].

2.3 Aspö Hard Rock Laboratory

The Aspö Hard Rock Laboratory (Aspö HRL) is located in granite at Aspö Island, Oskarshamn in Sweden. The main access tunnel expands in a spiral down from the ground surface to a depth of 460 m, and the total length of the tunnel is 3,600 m. The main part of the tunnel from ground surface to a depth of 400 m was excavated using a conventional drill and blast technique and the last 400 m long research tunnels with a diameter of 5 m was excavated using a tunnel boring machine (TBM). The facility was constructed from 1990 to 1995, and started operation in 1995 [5].

2.4 Exploratory Studies Facility

The Exploratory Studies Facility (ESF) was constructed at the site for the Yucca Mountain repository, Nevada in the USA. It is a 16 km underground network of inclined ramps, connection tunnels, and research tunnels with a total length of 8,000 m. The ESF is located in unsaturated tuff at a depth of 300 m, and the aquifer is 300 m below the ESF. The main ramp and tunnels are of a round shape with a diameter of 7.6 m. The research tunnels were excavated using conventional drill and blast technique from the ground surface to a depth of 60 m, and the rest was excavated by a tunnel boring machine (TBM) with a diameter of 7.6 m. The ESF was constructed in 1997 as an underground laboratory for the Yucca Mountain repository, and closed down in 2009 due to the suspension of the Yucca Mountain repository program [6]. US DOE makes constant efforts to continuing the resumption of the NRC licensing process for Yucca Mountain repository [7].

2.5 ONKALO Underground Characterization and Research Facility

The ONKALO Underground Rock Characterization and Research Facility (ONKALO UCRF) in Finland was constructed to collect data for the construction license of the spent fuel repository which was granted in November 2015, and its host rock is a granite. ONKALO UCRF has also been used to develop excavation and disposal techniques under the repository conditions. In the future, it will be used as a part of the final repository. The 5,500 m access tunnel expands in a spiral downward from the ground surface to a depth of 520 m, and its slope is -10 %. The main part of the tunnel from ground surface to a depth of 400 m has been excavated by the conventional drill and blast technique. The research tunnels are located at a depth of 420 m and 520 m, and the width and height of tunnel are 5.5 m and 6.3 m, respectively [8].

2.6 HADES Underground Research Facility

The HADES Underground Research Facility (HADES URF) is located at a depth of 225 m in a deep clay formation in Belgium. It was the first underground laboratory in Europe to study the possibility of geological disposal in clay, and was constructed in a Boom clay formation which is 100 m thick and its top is about 180 m deep. In the HADES URF, the first phase tunnels were constructed from 1980 to 1987, and the second phase tunnels were constructed from 1997 to 2002. Finally, in 2007, the PRACLAY gallery was constructed. The PRACLAY gallery is used for the large-scale PRACLAY Heater Experiment to study the effects of decay heat generated from high-level waste on the Boom Clay properties [9].

2.7 KAERI Underground Research Tunnel

The KAERI Underground Research Tunnel (KURT) is located at the site of the Korea Atomic Energy Research Institute (KAERI) in Daejeon, Korea, and its host rock is a granite. The length of the access tunnel is 345 m, and its slope up to 180 m from the portal is -10%. The total length of six research modules and the length of the connection tunnel are 165 m and 42 m respectively. Two research modules are located at 90 m, and the four research modules are located at 100 m below the ground surface. The access tunnel and research modules are all horseshoe shape, and their tunnel size is 6 × 6 m. The tunnels were excavated by a controlled blast technique. The access tunnel and two

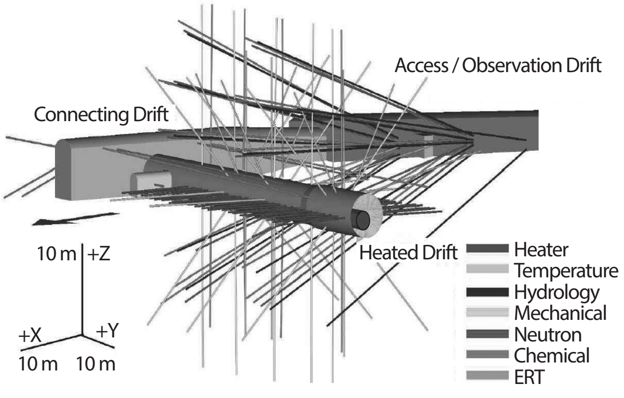

Fig. 1. Layout of the Drift Scale Test at the ESF.

research modules were constructed from 2003 to 2006, and the extension work for four research modules and the connecting tunnel was conducted from 2012 to 2014 [10].

3. In-Situ Experiments to Validate the Performance of Engineered Barriers

The in-situ experiments to demonstrate the performance of engineered barriers can be classified roughly into the following six categories based on their nature;

- Coupled thermal-hydraulic-mechanical behavior of the engineered barrier system
- Performance of buffer material
- Buffer-concrete interaction
- Installation of buffer, backfill and plug
- Characterization of the near-field rock
- Corrosion of canister material

3.1 Coupled Thermal-hydraulic-mechanical Behavior of the Engineered Barrier System

An in-situ experiment to study the thermal-hydraulic-mechanical (THM) behavior is one of the most important in-situ validations for the performance of the engineered barriers of a repository. The THM behavior occurred in an engineered barrier system is importance with regard to the design and safety of the repository, because it simulates the post-closure performance of the geological repository. Therefore this in-situ experiment has been carried out preferentially in many countries. The canister containing high-level waste is simulated using a electrical heater with the same thermal power, and the heater is installed in a deposition hole excavated into the host rock. The gap between the heater and the wall of the deposition hole is filled with bentonite buffer. The coupled THM interactions between the engineered barrier system and the rock due to heat generated from the heater and the groundwater intruded from surrounding rock are investigated. The changes in temperature, water content, and stress in the bentonite buffer and surrounding rock are measured. In some cases, only a heater is installed in the deposition hole without a buffer to measure the changes in temperature and stress in rock due to the heating, which is called a heater test. The major in-situ experiments that have been carried out up to the present are as follows;

3.1.1 Drift Scale Test

The Drift Scale Test (DST) was a large scale heater test conducted at the ESF to evaluate the coupled THM response of the potential repository host rock which is unsaturated tuff. Prior to the DST, a preliminary thermal experiment, the Single Heater Test (SHT) had been conducted at ESF from 1996 to 1997 [11].

In the DST, nine canister-sized containers with a length of 4.6 m, a diameter of 1.7 m, and a thermal power of 15 kW were installed in the test drift with a diameter of 5 m and a length of approximately 50 m. Considering the effects of heat generated from the adjacent tunnels, fifty 10 m long wing heaters with a total power of 210 kW were installed in the boreholes in both walls of the tunnel (Fig. 1) [12]. The DST was constructed during 1997. The heaters were turned on in December 1997, and turned off in January 2002. Then cooling lasted four years. The surface

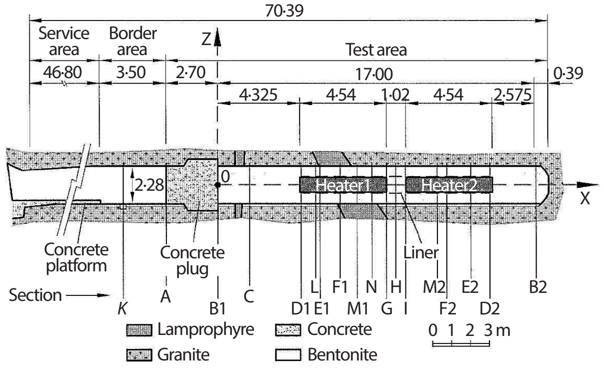

Fig. 2. Layout of the FEBEX in-situ experimental facility at the GTS.

temperatures of the rock mass surrounding the DST reached a maximum of about 200℃. A numerical analysis of the THM behavior of the near-field rock was conducted in the test scoping calculations [13,14] and in the Task B of the DECOVALEX III (1999~2003) [15-18] which is an international research project for THM processes in hard rock. The time-dependent displacement of rock mass in the borehole located at the midpoint of the longitudinal axis of the heater tunnel was calculated, and the change in fracture permeability was also predicted to investigate the variation of hydraulic properties around the heater tunnel. The calculated results were compared with the data measured from the in-situ experiment.

3.1.2 FEBEX

The FEBEX (Full-scale Engineered Barrier Experiment) is a full scale in-situ experiment conducted at GTS. The main objective of the FEBEX was to investigate the performance of the engineered barrier system at full scale for the Spanish spent fuel repository. In the Spanish repository concept, the spent fuel canister is deposited in horizontal large-diameter deposition holes drilled into the wall of the disposal tunnel. The space between the canister and the inner wall of a deposition hole is filled with compacted bentonite. As a complementary experiment under controlled boundary conditions, a mock-up test was conducted in CIEMAT at almost the same time [19].

For FEBEX, a 70 m long cylindrical horizontal deposition hole with a diameter of 2.28 m was excavated using a tunnel boring machine (TBM) in 1995. Two heaters with a total power of 4.3 kW simulating a spent fuel canister were installed in the deposition hole. The length and diameter of the heater were 4.54 m and 0.90 m, respectively. After backfilling with compacted bentonite block, the deposition hole was plugged with a 2.7 m long concrete plug (Fig. 2). The final dry density of bentonite after installation is 1.6 $Mg{\cdot}m^{-3}$. In the first operational phase (1996-2002), the heating started in February 1997 and ended in February 2002. During heating the heater temperature was maintained at 100℃ [20]. In the second operational phase (2002-2007), the excavation and dismantlement of section I including the first heater and surrounding bentonite buffer were completed in July 2002. A dummy steel cylinder with a length of 1 m was inserted into the buffer in place of the first heater. A concrete plug with a total length of 3 m was installed. During the dismantlement of section I, the second heater was operated continuously, and the samples obtained from the dismantlement of section I were analyzed to investigate the THM behavior occurred in the bentonite buffer [21-23]. Since 2008, heating had been continued to observe the saturation behavior under the name FEBEXe. The FEBEX-DP project completed the dismantlement of the second heater in August 2015 after 18 years of heating [24]. Benchmark modelling for the simulation of the THM behavior occurred in the engineered barriers during the first operational phase was performed by ten teams from six countries [25]. The modeling was capable of predicting the temperature distribution in an acceptable error range, and the hydraulic characteristics with a limited accuracy. However, there is a considerable difference between the total pressures predicted and those measured. The results from the second operational phase are being simulated in the DECOVALEX-19 project [26].

The major outcomes from the FEBEX project are summarized in the NAGRA's (Swiss National Cooperative for Radioactive Waste Management) report [27].

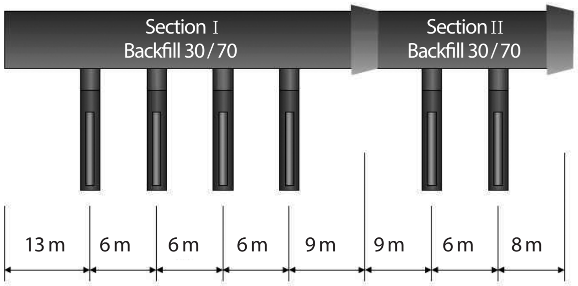

Fig. 3. Layout of the Prototype Repository at the Aspö HRL.

3.1.3 Prototype Repository

The SKB (Swedish Nuclear Waste Management Company) constructed the Prototype Repository at the Aspö HRL to demonstrate in full scale the Swedish spent fuel repository concept, KBS-3. The Prototype Repository was excavated using a tunnel boring machine (TBM) in the granite host rock at a depth of 460 m below the ground surface. The Prototype Repository has a tunnel with a diameter of 5 m and a length of 63 m, and is composed of two sections (Fig. 3). Six vertical deposition holes of a diameter of 1.75 m and a length of 8.3 m are drilled into the floor of the tunnel. Four holes are in an inner section (section I) with a length of 40 m, and two holes are in an outer section (section II) with a length of 23 m [28]. The center to center spacing between the deposition holes is 6 m. Two sections are separated from each other by a concrete plug. The cylindrical canister with a diameter of 1.05 m and a length of 4.83 m containing heaters to simulate the decay heat from spent fuel was placed in the deposition hole and surrounded by bentonite blocks with a final saturated density of 2.0 Mg·m^{-3}. The tunnel was backfilled with a mixture of bentonite and crushed rock (30:70), and plugged by a concrete plug. The installation of the inner section was completed in 2001, and the heating of the canister was started in September 2001. The backfilling and plugging were finished in December 2001. The outer section was installed in 2003, and the heating was started in May 2003.

In November 2004, the drainage of the tunnel was closed, and it increased the pressure in the buffer and backfill resulting in a failure of the heaters in canister 2. Therefore the drainage of the tunnel was reopened [28]. The outer section was dismantled in 2011 after approximately 8 years of heating. The outer plug and the backfill and buffer in the two deposition holes were dismantled [29,30], and the samples obtained were analyzed [31]. The results show that backfill was fully saturated, but buffer was not fully saturated in all parts. The hydraulic, mechanical, chemical and microbial characterizations of the buffer and backfill was reported [32,33], and the investigation of the canister showed damages to the cables [34]. The works for dismantling the outer section was described in a summary report [35].

The THM modelling of the Prototype Repository was performed by several teams [36-41]. These results indicated that the calculated temperature history agreed well with the measured data. For the degree of saturation, there was a considerable difference between the calculated values and the measured data at the locations closed to the heater. There was a large difference between the calculated values and measured ones for the total pressure, and the numerical model should be improved significantly. These results were similar to those from the modeling of the FEBEX. The second phase of the modelling work to simulate the outer deposition holes was started in 2010, and seven teams are participating the modeling [42,43].

3.1.4 HE-E Experiment

The HE-E experiment is a large-scale (1:2 scale) in-situ experiment to investigate the THM behavior of the ANDRA (French National Radioactive Waste Management Agency) near-field concept in the Opalinus clay at the Mont Terri RL [44], and was constructed from December 2010 to June 2011. Prior to the HE-E experiment, an in-situ heating experiment, HE-D was performed at the Mont Terri RL from October 2003 to December 2005 to enhance knowledge about the THM processes in argillaceous rocks [45].

The purposes of the HE-E experiment are to investigate the early non-isothermal resaturation period and its impacts on the THM behavior, and to validate the present

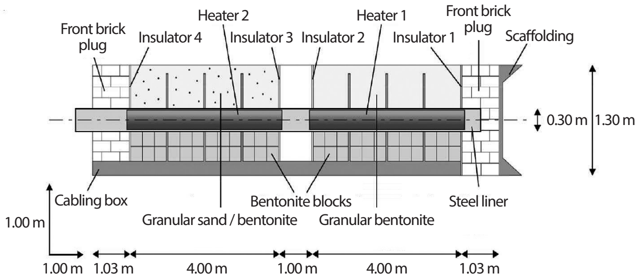

Fig. 4. Layout of the HE-E experiment at the Mon Terri RL.

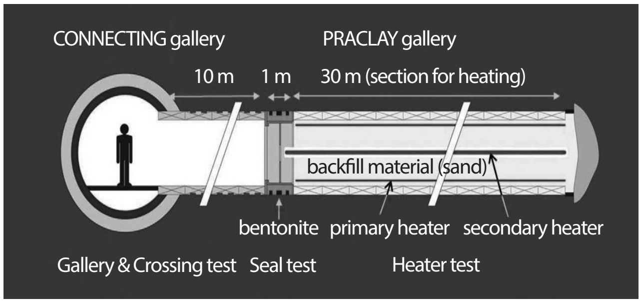

Fig. 5. Concept of the PRACLAY in-situ experiment at the HADES URF.

THM models. In addition, it is intended to upscale the thermal conductivity of the partially saturated buffer from the laboratory scale to the field scale. The experimental system is located in the horizontal deposition hole with a diameter of 1.3 m and a length of 50 m, and consists of two independently heated sections of 4 m each (Fig. 4). The heaters are placed in a steel liner supported by MX-80 bentonite blocks. Section I is filled with a 65/35 sand/bentonite mixture, and section II is filled with pure MX-80 bentonite pellets. The densities were about 1.45 $Mg{\cdot}m^{-3}$ for bentonite and 1.5 $Mg{\cdot}m^{-3}$ for the sand/bentonite mixture. The maximum temperature of the heater surface is 140℃.

The experimental results show that the distributions of temperature in the engineered barrier system and the Opalinus Clay agreed with those predicted. They also present a large temperature gradient in the engineered barrier system due to the low thermal conductivity of clay under dry condition, especially in the inner part of the buffer. A complex development in the humidity profiles was observed because of the differences in the water contents, material densities, two-phase flow and vapor diffusion. The vapor is driven out from the heater, most likely in a radial direction and a part of the increase in relative humidity at the interface between the engineered barrier system and the host rock can be attributed to a condensation of vapor. The groundwater inflow from Opalinus Clay occurs by diffusion, and the hydraulic pressure front progresses through the engineered barrier system. An important observation is that the measured temperatures and relative humidity in the bentonite and sand/bentonite mixture are dominated by the distance from the heater and not by the differences in the material properties, and this rapid homogenization can be explained by vapor movement [44].

3.1.5 PRACLAY

PRACLAY is a large scale in-situ experiment at the HADES URF (Fig. 5) [46]. PRACLAY is applied to investigate the effects of decay heat on Boom Clay, which is a candidate site for the high-level waste repository in Belgium [47], and consists of a Gallery & Crossing Test, Seal Test and Heater Test. The Gallery & Crossing Test is applied to demonstrate the feasibility of a crossing between an access tunnel and a disposal tunnel, and to characterize the hydraulic and mechanical behavior of Boom Clay. The Seal Test is to provide the hydraulic boundary conditions required for the Heater Test. In the Seal Test, the heated section of the tunnel and its surrounding excavation disturbed zone are isolated from the non-heated section. The Heater Test investigates the change in temperature, total pressure, pore pressure, and deformation of clay due to the heating. The Heater Test is performed under reasonably conservative thermal, hydraulic and mechanical conditions. This conservative approach is to make sure that the experimental results remain valid even if the design of geological repository is changed in the future. The PRACLAY tunnel was constructed in 2007, and the sealing system and the primary heating system were installed in 2010. The gallery was backfilled with sand, and the hydration was started in

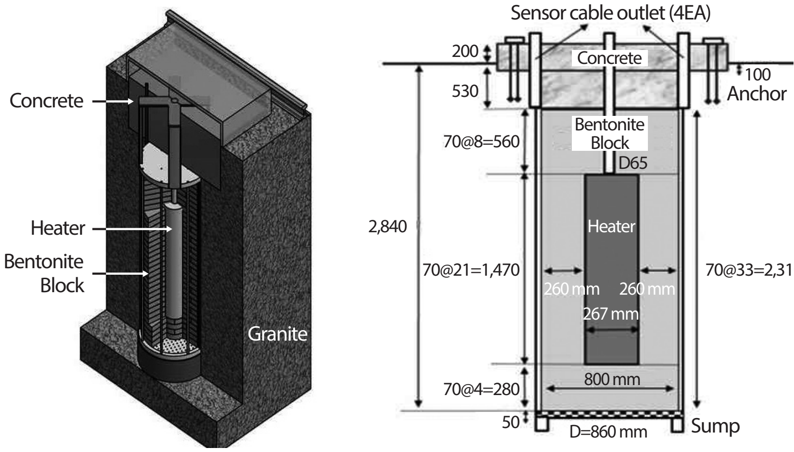

Fig. 6. Concept of the In-DEBS in-situ experiment at the KURT.

2011. The installation of a secondary heating system was completed in 2014, and the heating was started in 2014. The temperature at the interface between the lining and the Boom Clay was increased stepwise to 80℃. The heating will last for 10 years or more, and the experimental system will be dismantled and the stability of tunnel lining will be investigated in 2025 [48].

3.1.6 In-DEBS

The In-DEBS (In-situ Demonstration of Engineered Barrier System) which is the 1:2.3 scale of the Korea reference repository concept is an in-situ experiment being performed at KURT to investigate the THM behavior of the engineered barrier system installed in granite rock. Prior to the In-DEBS, a borehole heater test was performed at KURT from 2007 to 2011 to investigate the thermal properties of a rock mass and the thermal and mechanical behavior around the deposition hole [49]. In In-DEBS, a deposition hole with a diameter of 0.8 m was excavated into the floor of the tunnel at a depth of 100 m below the ground surface. The heater was surrounded by bentonite blocks with a dry density of 1.6 $Mg{\cdot}m^{-3}$. The heater, bentonite blocks, and measuring sensors were assembled in the OBPA (One-Body Pre-Assembly) in advance, and the OBPA was placed in the deposition hole by a crane (Fig. 6). The heating was started in July 2016 [50]. At present the temperature at the surface of the heater maintains 100℃, and the time-dependent change of temperature, relative humidity, total pressure and pore pressure in the buffer and rock are being measured.

3.2 Performance of Buffer Material

The in-situ experiments for the performance of the buffer material contains several experiments to investigate the long-term performance of a bentonite buffer under the geological condition of the repository.

3.2.1 Long Term Test of Buffer Material

The Long Term Test of Buffer Material (LOT) was an in-situ experiment carried out at the Aspö HRL to collect the experimental data and to validate the existing models for the performance of the buffer under real repository conditions. The buffer properties considered were the swelling pressure, hydraulic conductivity, rheological properties, mineral redistribution and montmorillonite alteration. In addition, the cation diffusion and survival of bacteria in bentonite were also investigated. The LOT consists of seven test parcels, which are exposed to the repository conditions for 1 to more than 10 years. The test parcel contains a heater, bentonite buffer and instruments, and was placed

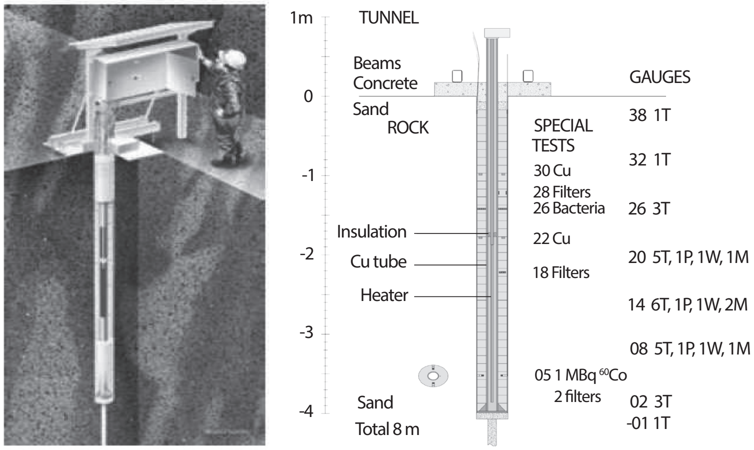

Fig. 7. Illustration of the Long Term Test of Buffer Material at the Aspö HRL (left) and the cross-section of S-type parcel (right).

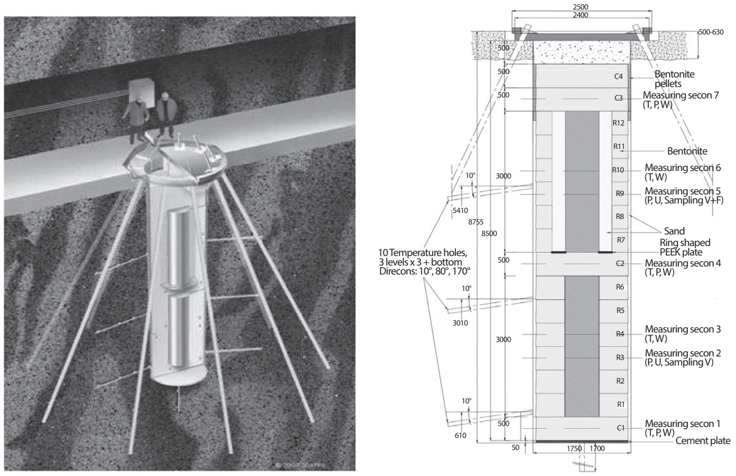

Fig. 8. Illustration and the cross-section of the Temperature Buffer Test at the Aspö HRL.

in the vertical boreholes with a diameter of 300 mm and a depth of 4 m (Fig. 7). The maximum bentonite temperature was maintained at 90℃ for the standard tests and 120 to 150℃ for the severe tests. The temperature, total pressure, pore water pressure and water content were measured during the heating period. At the termination of the tests, the parcels were extracted using over-core drilling. For the pilot tests (1 year tests), two parcels placed in the boreholes in 1996 were extracted after approximately 12 months of heating, and the bentonite material was analyzed [51].

The five parcels were installed in the boreholes in 2000 [52]. The first and the second parcel were recovered in November 2001 and January 2006, respectively. The physical and rheological properties of the exposed bentonite were analyzed [53,54]. The results showed that the observed mineralogical alterations are relatively low and these alterations did not change the physical properties significantly [55,56]. The development of model, particularly concerning the influence of concentration discontinuities on the ion transport through bentonite was performed. The three

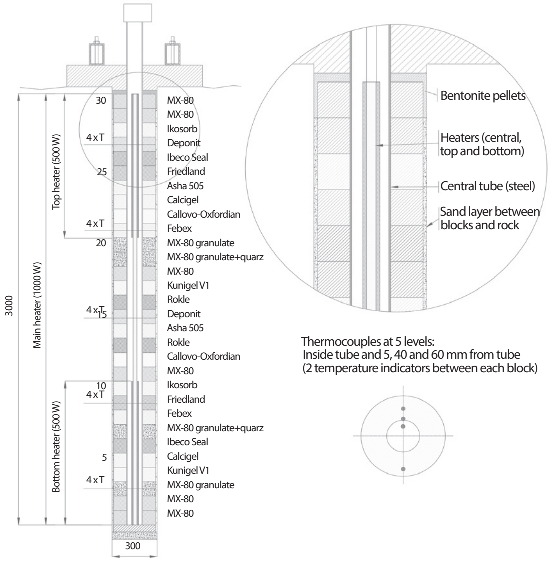

Fig. 9. Cross section of the Alternative Buffer Material test at the Aspö HRL.

remaining parcels have been running for more than 10 years [57], and no results have been reported since 2012.

3.2.2 Temperature Buffer Test

The purpose of the Temperature Buffer Test (TBT) is to improve the understanding and modeling for the THM behavior of buffers at high temperatures of above 100℃ [58]. The experiment was carried out at the -420 m level in the Aspö HRL. Two arrangements of heater and buffer were installed in a deposition hole with a depth of 8.5 m and a diameter of 1.76 m (Fig. 8). The lower heater was surrounded by the compacted MX-80 bentonite rings, whereas the upper heater was surrounded by a composite barrier with a sand shield and bentonite. The experimental system was installed at the beginning of 2003 [59]. The length and diameter of each heater was 3 m and 0.61 m, respectively. The thickness of the bentonite block was 0.5 m, and the slots were filled with sand or pellets. The power of each heater was 1,500 W for the first phase of ~1,700 days, and it was subsequently changed to 1,000 and 2,000 W for the upper and lower heater, respectively in the second phase of the last ~600 days. In the second phase, the temperature at the innermost part of the bentonite around the lower heater reached approximately 155℃. The dismantling was performed from October 2009 to April 2010 [60]. The bentonite samples were collected, and their water content and density were measured [61]. The hydraulic, mechanical and chemical investigation showed that no significant differences could be observed between the samples and the reference material [62]. Several THM modelling works have been carried out [63-67]. The final modelling task was resumed after the dismantling operation, and three modelling teams presented several results [68]. The validity of the material models was also assessed [69].

3.2.3 Alternative Buffer Materials

The main objectives of the Alternative Buffer Material test (AMB) were to examine the mineral stability and physical properties of the several candidate buffer materials, and to study the interaction between metallic iron and bentonite. In the ABM, eleven materials were examined under the repository conditions at a temperature of 130℃, and the laboratory analyses of the reference materials were also performed.

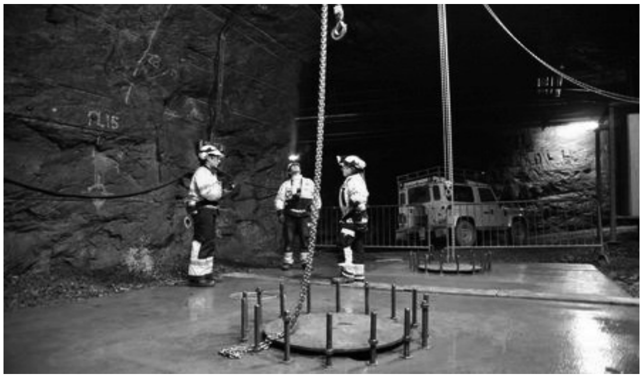

Fig. 10. Testing of Buffer Material at the ONKALO UCRF.

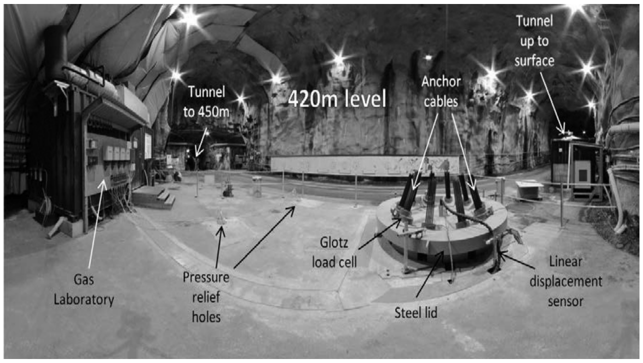

Fig. 11. Large Scale Gas Injection Test at the Aspö HRL.

The test parcels containing heater, central tube, compacted buffer blocks and instruments were placed in the vertical boreholes with a diameter of 300 mm and a depth of 3 m (Fig. 9). The slots between the buffer blocks and the wall of borehole are filled with sand. Three test parcels (ABM 1, 2, 3) were installed in December 2006, and parcels 1 and 2 were artificially wetted. The heaters in parcels 1 and 3 were activated from the beginning, whereas the heater in parcel 2 was activated after the saturation of the buffer. ABM 1 was retrieved in May 2009 [58], and the rock cores and the bentonite blocks were analyzed in the laboratory. The results showed that the degree of saturation was high at all positions of the test parcel, and the swelling pressure decreased slightly. In addition, the saturation with a Na-Ca type groundwater resulted in the replacement of some sodium in Na-bentonite by calcium [70]. The minor traces of trioctahedral clays were observed, as well as an increase of Fe(II)/Fe(I) associated with the oxygen sensitive phases [71]. Two parcels (ABM 4, 5) were installed in November 2012. The parcel ABM 2 was retrieved in April 2013 after about 6 years of heating [29], and the bentonite block samples were analyzed. The various precipitates and corrosion products were observed, and a much higher content of trioctahedral smectite was found compared to the cases of ABM 1 and the TBT [72]. However, the degree of trioctahedral smectite formation is currently not expected to have any significant impact on the buffer performance [30].

3.2.4 Testing of Buffer Material

The Testing of Buffer Material (TBM) which is the first bentonite in-situ test at the ONKALO UCRF was started in September 2011. The purpose of the TBM is to obtain more information about the bentonite buffer and to apply this information on a larger scale. Another important purpose is to test the techniques to install buffer under the repository conditions. Two boreholes have been drilled into the bottom of the tunnel (Fig. 10). A stainless steel canister surrounded by bentonite buffer was installed in the boreholes. The diameter and depth of the borehole were 0.8 m and 3 m, respectively, which are at a scale of 1:3 [73]. The boreholes were sealed with leak-proof covers anchored to the rock. The groundwater was supplied to one borehole, and not to the other. The purpose of the supply of groundwater is to investigate the effects of enhanced resaturation of the bentonite. The canister with a heating power of 600 W was installed in the hole, and the temperature of the canister was increased to 90℃. The temperature, humidity and pressure of the bentonite buffer were measured. The test was completed around 2016, and no results have however been reported up to now.

3.2.5 Large Scale Gas Injection Test

The Large Scale Gas Injection Test (Lasgit) is a full-scale

Fig. 12. Lowering the bentonite package into the deposition hole at the Aspö HRL.

in-situ experiment to investigate the gas transport through a bentonite buffer, and was carried out in the deposition hole located at a depth of 420 m in the Aspö HRL (Fig. 11) [74]. In Lasgit, a series of gas injection tests were performed in a full-scale KBS-3 deposition hole to improve the understanding of the gas migration through bentonite and to validate the numerical model for the performance assessment. A deposition hole with a diameter of 1.8 m and a depth of 8.5 m was drilled into the tunnel floor, and the full-scale KBS-3 canister without a heater was placed in the hole. Thirteen circular filters with variable dimensions were located on the surface of the canister, and the compacted bentonite blocks with high initial water content were installed in the deposition hole. The hole was capped by a conical concrete plug with a reinforced steel lid.

Lasgit consists of four operational phases, namely the installation phase, the hydration phase, the gas injection phase and the homogenization phase. The installation phase including the design, construction and emplacement of the infrastructure necessary to conduct the Lasgit was carried out from 2003 to early 2005. The hydration phase began in February 2005, and the buffer was saturated with the natural and injected groundwater. The gas injection test was started in 2007, and continued until 2013. The breakthrough of gas occurred at a pressure of 5,660 to 6,195 kPa, which were similar to the local stresses [29]. In 2013, after completion of the gas injection test, the experimental system was modified to investigate the suction of water in the buffer. Two-stage hydraulic constant head tests were conducted in eleven canister filters to determine the hydration state of the buffer. At present the natural and artificial hydration of the bentonite buffer is being monitored [75].

3.3 Buffer-Concrete Interaction

This in-situ experiment is to investigate the interaction between the bentonite buffer and concrete which is a material for grouting and plugging in the repository. The buffer-concrete interaction may have a significant influence on the long-term integrity of the buffer, grout and plug in the geological repository.

3.3.1 Concrete and Clay Project

The Concrete and Clay Project at the Aspö HRL aims to investigate the decomposition of waste form materials, the mineral alterations in the concrete and the transport of degradation products in bentonite. From 2010 to 2014, nine waste packages including concrete cylinders or bentonite blocks had been deposited at different locations in the Aspö HRL. From 2010 to 2011, four packages containing 12 concrete cylinders with a diameter of 0.3 m and a length of 1 m were deposited in two boreholes with a diameter of 0.35 m (Fig. 12). The slot between the concrete specimens and the wall of rock was filled with sand. In 2014, five packages containing 150 bentonite blocks with a diameter of 0.27 m and a length of 0.1 m were deposited. The specimens were prepared by ordinary cement and low-pH cement or pure bentonite and bentonite containing metallic powder or metal salt [76]. This project is expected to run for up to 30 years. The first retrieval of the waste package will occur after about 5 years, and the waste packages will then be retrieved at regular intervals and only a few will be left for

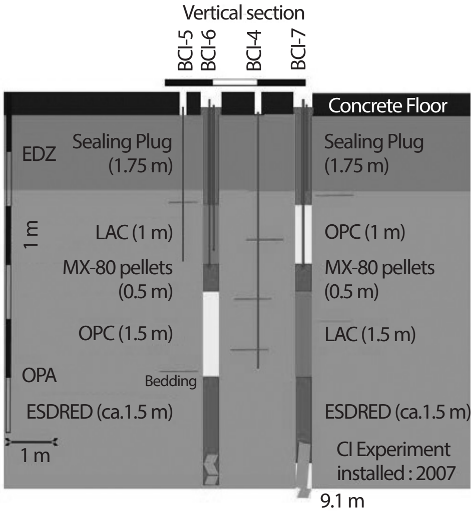

Fig. 13. Concept of the Cement-Clay Interaction Experiment at the Mon Terri RL.

the entire 30 year period [30]. All cylinders have now been stored at the Aspö HRL and the analyses will be performed in the future.

3.3.2 Low-pH Program

The purpose of the low-pH Program at the Aspö HRL is to develop low-pH cement products for a geological repository. These products will be used for the sealing of fractures, the grouting of rock bolts, a rock support and plugs for the tunnels. SKB has developed a low-pH concrete [77], and the in-situ experiment of low-pH concrete grout for the rock bolts was started at the Aspö HRL in 2009. A total of 20 rock bolts were installed, and these bolts were planned to be over-cored after 1, 2, 5 and 10 years to investigate the behavior of the low-pH concrete grout and the corrosion of the bolts. An in-situ experiment to study the corrosion behavior of steel in low-pH concrete was also started, and a total of 24 samples were prepared and placed in an open container at the Aspö HRL. The results for the rock bolt grout, the shotcrete and the corrosion of steel after one year of exposure were reported [78]. In 2013, three rock bolts were over-cored and analyzed to investigate the corrosion behavior of the bolts after almost five years of exposure under a repository environment. The results showed no signs of corrosion [75].

Six concrete blocks containing three steel bars each were also examined in 2013. The corrosion behavior of the steel bars in low-pH concrete and conventional concrete with or without chlorides was investigated. Due to the unclear results, it was decided to extend the period of the in-situ experiment. The next examination will be done in 2018 and, and its results will decide the schedule for the further investigation. The low-pH concrete was used for the construction of a full size plug to seal the deposition tunnel in 2013, and a monolith was also prepared at the same time using the low-pH concrete to investigate the long-term properties. Concrete cores taken from the monolith were analyzed to investigate the strength and the modulus of elasticity [79]. The concrete cores will be taken out and investigated every 2 or 3 years of exposure, and the investigation may be continued for a longer period of time if its results are interesting [30].

3.3.3 Cement-Interaction Experiment

The purpose of the Cement-Interaction Experiment (CI) at the Mont Terri RL is to investigate the spatial extent and time-dependent evolution of the chemical interactions between the cement and the Opalinus Clay/bentonite and the changes in porosity [80]. Two boreholes with a depth of 9.1 m each were drilled into the bedding of the Opalinus Clay. Each borehole was filled with multiple 1~1.5 m long sections of 2 types of low pH concrete (LAC and ESDRED), an ordinary portland cement (OPC) and an in-situ saturated natural Na-bentonite (MX-80) segment (Fig. 13). Sampling of the various cement-Opalinus Clay interfaces was carried out in 2009 and 2012 using an over-coring technique. The analysis of samples focused on the interface between one of the three different cement matrices (OPC, LAC, ESDRED) and the clay. The element distribution developed show complex patterns at the concrete-clay interface. Up to 6 chemically distinct zones were observed at the concrete side within 2~4 mm from the interface. Depending on the

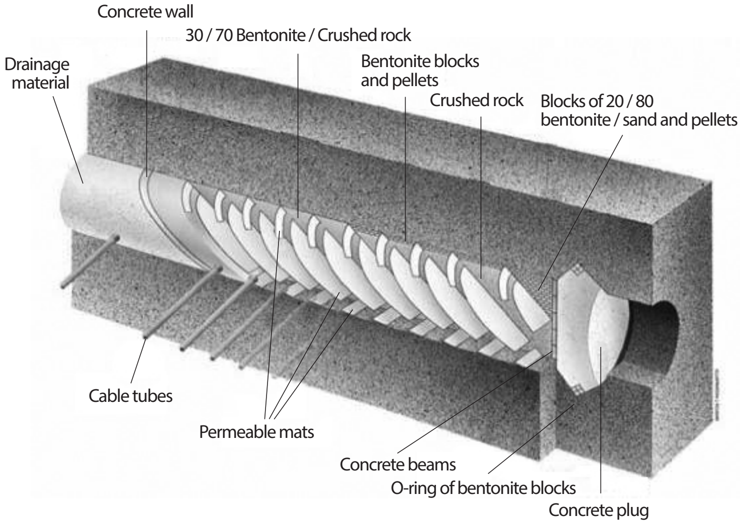

Fig. 14. Illustration of the Backfill and Plug Test at the Aspö HRL.

cement recipe, they included the zones with sulfur enrichment, the carbonated zones and the zones with strong Mg enrichment adjacent to the interface. The carbonated zones showed a 7% lower porosity than the undisturbed OPC. On the clay side of the interface, a single zone with increased Ca or Mg content was observed in the first 100 μm next to the interface. In the clay phases close to the OPC, Mg was depleted, and Na was enriched, whereas there were no changes in the porosity at all. The analysis of the samples from the second sampling is under way. The CI is expected to be continued for about the next 15 years.

3.4 Installation of Buffer, Backfill and Plug

This is to develop practical technologies to install the buffer, backfill and plug in a geological repository.

3.4.1 Backfill and Plug Test

The Backfill and Plug Test at the Aspö HRL was applied to test the characteristics of the backfill materials, the emplacement techniques and the performance of a full-scale plug. This test investigated the integrated function of the backfill and the near-field rock in the disposal tunnel and the hydraulic and mechanical functions of the plug. Prior to the Backfill and Plug Test, the single-hole hydraulic tests had been carried out in the selected boreholes to investigate the initial hydraulic characteristics and the hydraulic connection between the boreholes and the surrounding fractures [81].

A schematic illustration of the Backfill and Plug Test is shown in Fig. 14. The test tunnel with a length of 30 m was divided into three parts, namely, the inner part (six sections), the outer part (four sections), and the concrete plug. The inner part was filled with a mixture (30:70) of bentonite and crushed rock, and the outer part was filled with only crushed rock. Because the crushed rock was not swelled, and settled with time, a slot of a few centimeters was left between the top of the backfill and the ceiling of the tunnel. This slot was filled with a layer of highly compacted bentonite blocks to ensure a good contact between the backfill and the rock. The remaining voids between the bentonite blocks and the ceiling were filled with bentonite pellets. The preliminary tests showed that inclined compaction with a slope of about 35° should be applied to the entire cross section. The inner and outer parts are divided by drainage layers of permeable mats in order to supply hydraulic gradients between the layers and to study the flow

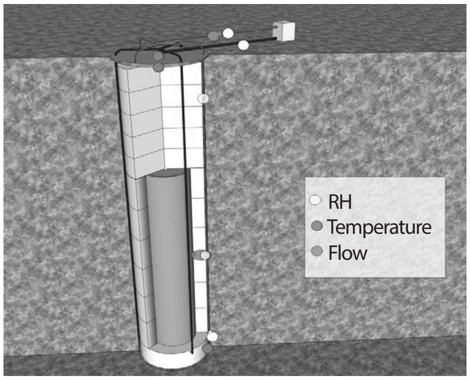

Fig. 15. Illustration of the System Design of Buffer Project at the Aspö HRL.

Fig. 16. The installation of the full-scale backfill at the Aspö HRL.

of water in the backfill and near-field rock. The outer part ends with a wall made of the prefabricated concrete beams to support the backfill temporarily before the installation of the plug. The plug was designed to resist the water flow and the swelling pressures of the backfill, and was equipped a 1.5 m deep triangular slot with an "O-ring" of highly compacted bentonite at the contact surface with rock. After the installation, the wetting of the backfill was started at the end of 1999. The water pressure was increased to 500 kPa and kept at 500 kPa until the backfill was saturated at the beginning of 2003. During 2003 the equipment was rebuilt for a flow test which had been conducted until 2005. The experimental data from 1999 to 2007 were reported in 2008 [82]. In 2010, it was decided to keep the project dormant for the coming years, and after then, the temperature, water pressure, water flow and total pressure have been measured [57]. However, the results have not been reported.

.

3.4.2 System Design of Buffer Project

In the SKB reference concept, the backfilling of the disposal tunnel is started when all deposition holes in the disposal tunnel are filled with a buffer. This means that the buffer is left for up to three months in a deposition hole before the backfilling of the tunnel. During this period, the buffer needs to be protected from drying and wetting to prevent the occurrence of crack or uplift in the buffer blocks. In the SKB reference design, the buffer is protected by a rubber sheet installed in the deposition hole until the backfilling. However, the test results [83] showed that the protection of the buffer did not work as well as intended, and as an alternative, controlling the environment in the deposition hole was suggested.

The purpose of the System Design of Buffer project carried out at the Aspö HRL is to ascertain whether controlling the environment in the deposition hole is efficient to protect the buffer [29]. Several activities for the System Design of Buffer project were performed in 2013 [30], and their results were reported [83-86]. To simulate the realistic situation, the experiment was done in a deposition hole using a canister with a heat power of 1700 W. The dehumidified air was led down to the bottom of the deposition hole through six tubes installed in the slot between the buffer and the rock wall to keep the relative humidity in the bottom of the deposition hole to 75%, and temperature and relative humidity sensors were installed (Fig. 15). The results showed that the applied method worked reasonably well up to 6 m from the bottom of the deposition hole as long as the flow rate of air though the system was high, but the top three to four blocks would probably need extra protection [30]. The second test for the installation of the buffer conducted in 2016 showed that the cracks occurred in the two top ring blocks. Therefore, it was concluded that the installation of the bentonite blocks and pellets in the deposition hole at the same time without a buffer protection could guarantee the performance of the buffer [75].

Fig. 17. The hardened concrete dome structure at the Aspö HRL.

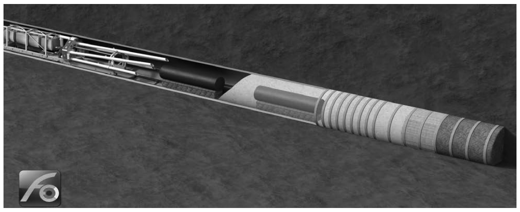

Fig. 18. Illustration of the Full-Scale Emplacement Test at the Mon Terri RL.

3.4.3 System Design of Backfill Project

The disposal tunnels are backfilled with pre-compacted bentonite blocks stacked on the bed of bentonite pellets. The slot between the bentonite blocks and the rock wall is filled with pellets. The purpose of the System Design of Backfill project at the Aspö HRL was to verify the efficiency of the SKB's reference backfilling method and to improve the backfilling concept [30]. Since 2010, studies on the system design, the production of bentonite components, and the installation equipment have been performed. In 2014, a full-scale backfill installation test with prototype equipment was carried out at the Aspö HRL. The tunnel with a length of 12 m located at a level of -450 m was filled with blocks and pellets. An installation robot and a wheel loader was used to install the backfill, and the control system was operated in semi-automatic mode. In total, 1,684 blocks weighing about 225 kg each, were installed, and 72,000 kg pellets were filled into the gap between the tunnel wall and the block stack using shotcrete equipment. The total mass of the pellets including pellets placed on the tunnel floor was 84, 500 kg (Fig. 16). The in-situ backfilling test was evaluated as successful from the viewpoint of the installation techniques and the control of the works. However, further work is needed to improve the efficiency of the work [87].

3.4.4 System Design of Plug Project

The plug of the disposal tunnel in the KBS-3V concept consists of an arched concrete dome, a bentonite seal and a filter zone. Furthermore, a backfill transition zone is introduced to moderate the swelling pressure from the backfill in the tunnel. The plug is made of low-pH concrete developed previously to avoid adverse effects on the bentonite [88].

The purpose of the System Design of Plug project is to examine the performance of the reference end plug of the disposal tunnel [30]. The end plug was demonstrated at a full-scale to prove its feasibility and controllability. The full-scale test, the Domplu (Dome plug) was carried out in the tunnel located at the -450 m level in the Aspö HRL. The height and width of the tunnel are 4.8 m and 4.2 m, respectively. The plug slot area was excavated to obtain smooth surfaces using a wire sawing technique in an octagonal shape [89]. The installation of the inner plug components began in late 2012 and was completed in early 2013. In March 2013, the concrete dome was installed (Fig. 17). The main goal of the Domplu is to determine the leakage through the plug under the design pressure of 7 MPa. The monitoring of the Domplu was started in September 2013, and the applied water pressure was however reduced to 4 MPa due to the leakage of water. Since February 2014, the water pressure has been fixed at about 4.0 MPa, and in September 2014, the recorded leakage rate was about 2.6 L·hr^{-1} which is well below the target leakage rate through the disposal tunnel plug. Furthermore, the leakage was believed to decrease further since the swelling pressure of bentonite seal had increased continuously [90], and the leakage rate in December 2016, decreased to 1.8 L·hr^{-1} [75]. The monitoring of the concrete dome showed that the dome was not fully released, and was partly bonded to the rock. This full-scale test demonstrated the feasibility of the construction of the dome plug [90].

3.4.5 Full-Scale Emplacement Test

The Full-Scale Emplacement (FE) Test is based on the Swiss disposal concept for spent fuel and high-level waste, and is being carried out at the Mont Terri RL. This in-situ experiment is intended to demonstrate the Swiss disposal concept and to test the THM model at a full scale [91]. The construction of the experimental tunnel with a diameter of 3 m and a length of 50 m was completed in September 2012. At the far end of the tunnel, only steel arches were used for rock support, whereas the rest of the tunnel was supported by shotcrete. In the experimental tunnel, three heaters with the dimensions similar to those of waste canisters have been placed on the top of the pedestals made of bentonite blocks, and the remaining space of the tunnel was backfilled with granular bentonite (Fig. 18). The sodium bentonite blocks with a dry density of 1.8 $Mg{\cdot}m^{-3}$ were used for the filling material of the tunnel as well as the pedestals below the three heaters, and the bentonite pellets with an average dry density of 2.18 $Mg{\cdot}m^{-3}$ were used to fill the slots. The overall target bulk dry density of the backfill was at least 1.45 $Mg{\cdot}m^{-3}$. A prototype machine to backfill the horizontal tunnels was manufactured and successfully operated. The heating phase started in late 2014, and early in 2015, the experimental tunnel was sealed with a concrete plug. With a heat output of 1,500 W per heater, the temperatures at the heater surface and the rock surface are 120 to 150℃ and 60 to 80℃, respectively. According to the present plan, the heating and monitoring of the FE Test will last at least 10 to 15 years [91].

3.5 Characterization of the Near-field Rock

3.5.1 Characterization of Excavation Damaged Zone (EDZ)

An excavation damaged zone (EDZ) is a zone around the tunnel where the rock properties and conditions have been changed owing to the excavation. As the EDZ has an influence on the groundwater flow characteristics as well as the stability of rock mass, the characterization of the EDZ is important for the performance of a geological repository. The magnitude of an EDZ and the degree of property change in the EDZ depend on the rock conditions and the method of excavation, i.e. whether by blasting or by the use of a tunnel boring machine (TBM). In general, the tunnel boring machine generates a smaller EDZ and a lesser change of property than blasting.

In the ZEDEX experiments at the Äspö HRL, the tunnels excavated using the normal smooth blasting, the blasting with low-shock explosive and the TBM were studied. For the tunnel using the drill and blast technique, the EDZ was observed at up to 1 m from the tunnel wall, and for the tunnel using the TBM, the EDZ was extended to a few tens of cm. However, no significant change of property in the EDZ was observed for both techniques [92]. In the FEBEX at the GTS, it was concluded that the properties in the TBM-induced EDZ is comparable to those of the undisturbed rock [93]. Liedtke [94] reported however that the permeability of a TBM-induced EDZ was three orders of magnitude higher than that of the undamaged rock in the Prototype Repository at the Aspö HRL. The size of the EDZ and the effects of excavation on the permeability are remarkable in a blast-induced EDZ. Martino and Chandler [95] reported that the blast-induced EDZ extended to a depth of 0.3 to 0.4 m, and the permeability increased by less than three orders of magnitude relative to that of intact rock. In the Stripa mine, Sweden and the Aspö HRL, the blast-induced EDZ was generated more than 1 m from the periphery of the tunnel and the permeability was increased by two to three orders of magnitude [96].

In the Kamaishi mine, Japan where the blasting was used, the EDZ had a extent of about 1 m from the tunnel wall, and the permeability in the EDZ increased two orders of magnitude compared with that of the undamaged rock at the floor of the tunnel, but a permeability change was not observed at the side walls of the tunnel [97]. The in-situ investigation on the sedimentary rock in the Tono mine, Japan showed that the permeability increased two orders of magnitude in the EDZ with a size of 0.5 to 1 m [98].

Fig. 19. EDZ09 Project at the ONKALO UCRF.

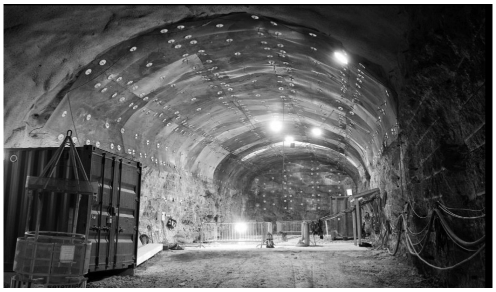

Fig. 20. POSE Project at the ONKALO UCRF.

In KURT, an in-situ experiment to investigate the characteristics and size of the EDZ was carried out. The results showed that the EDZ size was with the range of 0.6 to 1.8 m, and the value of the deformation modulus in the EDZ was about 40% of those in the undisturbed zone. The RQD (Rock Quality Designation) was decreased about 20% by the blasting within the range of 0 to 2 m [99]. The permeability in the EDZ seemed to be increased up to 2 orders of magnitude compared with that in the intact rock [100].

In the ONKALO UCRF, the EDZ09 project and related EDZ studies were carried out from 2008 to 2010 [101]. The purpose of the EDZ09 project was to improve the drilling and blast excavation method for the control of the EDZ (Fig. 19). The results showed that the EDZ is not continuous layer. The depths of the EDZ were within the ranges of 0.15 to 0.7 m, and the most common maximum depth is 0.3 m. The depth and extent of the EDZ on the floor were greater than those on the wall.

3.5.2 Characterization of Rock Mass Strength

In the Aspö HRL, the Pillar Stability Experiment had been carried out from 2004 to 2006. This was to demonstrate the prediction of the spalling in a fractured rock mass and the effect of swelling pressure on the propagation of micro-cracks in the rock mass close to the deposition hole. Two large vertical holes with a diameter of 1.8 m were drilled into the floor of the tunnel, and the distance between the holes is 1 m. To simulate the confining pressure in the buffer (0.7 MPa), an internal water pressure was given to one of the holes [102]. The pillar was sawn into five large blocks, which were removed from the experiment site during late 2004 and early 2005, and the experiment was successfully finished in 2006 [51]. The main results were that the low confinement pressures significantly affects the start of yielding, and the primary mode of the initiation and propagation of the fracture is extensional. In addition, no significant time dependency of the yielding process was observed [103].

In the ONKALO UCRF, the in-situ test to determine rock mass strength, the Posiva's Olkiluoto Spalling Experiment (POSE) has been carried out since 2010 [104,105]. The objectives of the POSE are the investigation of the in-situ spalling/damage strength of the Olkiluoto gneiss, the establishment of the state of in-situ stress at a depth of 345 m and a comparison between the prediction and measured data. In phase 1 (Pillar test), two deposition holes with a diameter of 1.52 m and a depth of 7.2 m were drilled by a tunnel boring machine (TBM) in 2010. The pillar between two holes is 0.9 m (Fig. 20). The configuration of holes was intended to cause the maximum excavation-induced stresses and the consequent damage to the pillar. Phase 2 (Pillar heating test) was conducted in 2011. One hole was heated by four heaters with a length of 7.5 m to increase the stresses around the experimental holes, and the other hole was backfilled with sand. The results showed that during the boring of the holes in phase 1, no damage except for three opened/sheared fractures was observed however, in phase 2, the heating induced a surface damage which was

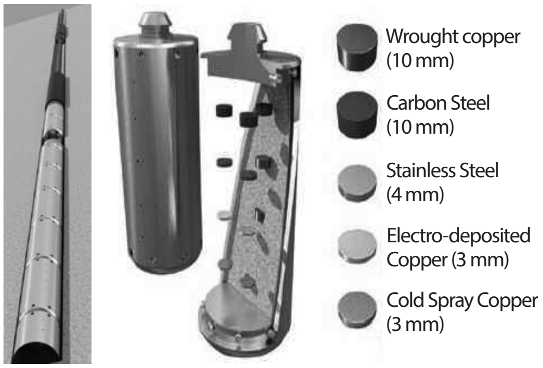

Fig. 21. Experimental layout of Material Corrosion Test at the GTS.

concentrated in the mica and rich layers around the holes, and the depths of the damaged zones were less than 100 mm. The depths and sizes of the damaged zones could be predicted relatively well using the thermomechanical and fracture mechanical analyses; however, the exact location of the damage was not defined due to the heterogeneity of the rock.

3.6 Corrosion of Canister Material

3.6.1 Material Corrosion Test

The Material Corrosion Test (MaCoTe) is an in-situ canister corrosion test carried out at GTS. The purposes of MaCoTe are to confirm the long-term anaerobic corrosion rate of carbon steel, stainless steel and copper in the compacted bentonite under geological repository conditions and to obtain experimental evidence for the inhibiting effect of the bentonite buffer on the microbial activity and the microbial-influenced corrosion. The in-situ experiment consists of a series of specially designed modules (0.3 m long) that are inserted into a vertical borehole with a length of 10 m and sealed with a double packer system. Each module contains 12 specimens embedded in the MX-80 bentonite with a dry densities of 1.25 or 1.5 Mg·m^{-3} (Fig. 21). The first eight modules were inserted into the borehole in September 2014. Retrieval of the module will be made at increasingly longer intervals, and the final two modules will be retrieved after 10 years. The corrosion rates of the samples, the mineral alterations at the interface between the specimen and bentonite, and the microbial populations in both the bentonite and the borehole water will be analyzed [106].

3.6.2 Corrosion Test of Miniature Canister

After a failure of the outer copper shell, the solid iron corrosion products may give an internal load to the copper shell which could lead to a deformation of the copper shell [107,108]. The main objective of the in-situ corrosion test of the miniature canister at the Aspö HRL is to obtain information on the evolution of the environment in a copper-cast iron canister when a failure of the outer copper shell occurs. In addition, it is intended to investigate the microbiological effects on the canister corrosion and degradation [30].

Since late 2006, five miniature copper-cast iron canisters have been exposed to the groundwater in the boreholes at a depth of 450 m in the Aspö HRL [109]. The miniature canister simulates the main features of the SKB reference canister. The cast iron canister has four holes simulating the fuel pin channels, and a bolted cast iron lid sealed with a Viton O-ring. The width of the annulus between the cast iron canister and the outer copper shell is < 30 μm. All canisters have one or more defects with a diameter of 1 mm in the outer copper shell. The canisters are mounted in electrically insulated cages, which contain bentonite clay with two different densities (Fig. 22). One miniature canister does not have any bentonite to investigate the effect of the direct groundwater flow on the corrosion. The cast iron and copper corrosion coupons are mounted inside the cages of each experiment and the corrosion behavior is monitored electrochemically. The boreholes are located in the region containing many fractures to supply the sufficient groundwater to the canisters. The corrosion potential and corrosion rate of the miniature canister, cast iron, and copper, the strain on the surface of two miniature canisters, and the hydrostatic pressure in the boreholes have been monitored continuously. After several years, they are retrieved and the evolution of the corrosion front in the canister are analyzed. The

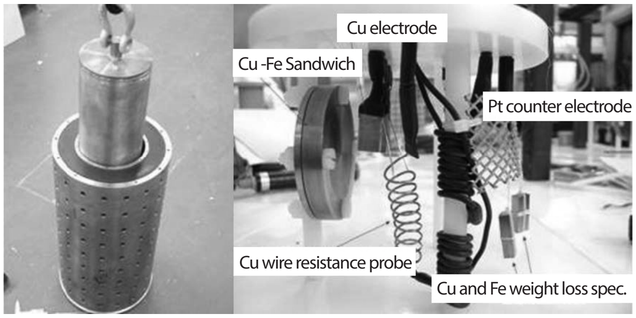

Fig. 22. Miniature canister for the Corrosion Test of Miniature Canister at the Aspö HRL.

miniature canister 3 was retrieved in 2011, and analyzed in 2013. The results containing experimental data until 2013 were reported [110-112]. The miniature canister 4 and 5 were retrieved and analyzed in late 2015 and 2016, respectively and the final results were reported in 2017 [113]. The remaining miniature canisters 1 and 2 are being monitored, but no results have yet been reported [75].

4. Conclusions

A validation of the performance of the engineered barriers in a high-level waste repository is very important to ensure the disposal safety and improve the disposal density in a geological repository. At the early stage of a research program, the validations are mainly carried out in laboratories, and however, they are converted into in-situ validations at an underground research laboratory with the progress of the research program. The advantage of the in-situ experiments is to overcome the laboratory work's limitation of the small scale, short-term and unrealistic experimental conditions. An in-situ validation is also necessary to improve the public acceptance on the reliability of the high-level waste disposal. Therefore, in many countries promoting a nuclear power program, various in-situ experiments to validate the performance of the engineered barriers have been carried out over the last several decades.

A comprehensive review of the state-of–the-art of major in-situ experiments to demonstrate the performance of engineered barriers in a geological repository for high-level waste has been given in this article. The review indicates that the in-situ experiments conducted to study the coupled thermal-hydraulic-mechanical (THM) behavior of the engineered barrier system have been carried out extensively around the world. Although valuable information has been achieved from in-situ experiments, the variation in the measured data originated from the differences of the engineered barrier system adopted in the repository design concept and the surrounding geological conditions has stimulated the necessity of a further in-situ research program. The numerical modelling of the THM behavior has shown considerably good results for the temperature in the buffer. However, there is a considerable difference between the mechanical stresses predicted and those measured, indicating the necessity of development of a robust model.

The most in-situ experiments conducted up to now to investigate the performance of a buffer material have been carried out at the Aspö Hard Rock Laboratory using several kinds of bentonite. However, the information obtained is restricted within the short-term behavior because the in-situ experiments are at the early stage, and more valuable information will be obtained with the future progress of the experiments. Other in-situ experiments on the buffer-concrete interaction, the application of a buffer, backfill and plug and the canister corrosion were started relatively late, and most experiments are progressing. For the near-field rock, the characteristics and size of the EDZ have been studied to a relatively large extent. However, the in-situ studies on the rock mass strength which has an influence on the long-term stability of the repository are scarce, and additional in-situ experiments are required.

The information and data from these in-situ experiments will contribute greatly to the efficient design, construction and closure of the repository, as well as the successful accomplishment of a high-level waste disposal project. Even though considerable achievements have been made through in-situ experiments on the engineered barrier performance, many technical problems remain unsolved.

Additional validation programs on the performance of engineered barriers in an underground research laboratory motivated by the above mentioned activities are expected. It is hoped that this article will stimulate researchers to conduct in-situ experiments for validation of the performance of engineered barriers.

Acknowledgement

This work was supported by Nuclear Research & Development Program of the National Research Foundation (NRF) grant (NRF-2017M2A8A5014857) funded by the Korean government (MSICT).

REFERENCES

[1] H.J. Choi, J.Y Lee, D.K. Cho, S.K. Kim, S.S. Kim, K.Y. Kim, J.T. Chung, M.S. Lee, J.W. Choi, and J.O. Lee. Korean Reference HLW Disposal System, Korea Atomic Energy Research Institute Report, KAERI/TR-3563/2008 (2008).

[2] National Cooperative for the Disposal of Radioactive Waste, “Grimsel Test Site Phase VI”, International Steering Committee Meeting, June 10-11, 2008, Swiss National Cooperative for Radioactive Waste Management.

[3] S. Vomvoris, I. Blechschmidt, T. Vietor, and H. Mueller, “NAGRA's Activities at the Grimsel Test Site and the Mont Terri Project: Update and Outlook”, High Level Radioactive Waste Management 2015, Charleston (2015).

[4] National Cooperative for the Disposal of Radioactive Waste, “The Mont Terri Rock Laboratory”, NAGRA Bulletin, 34, 24-35 (2002).

[5] Swedish Nuclear Fuel and Waste Management Company Aspö Hard Rock Laboratory- A Unique Place for Experiments and Research (2016).

[6] Department of Energy, Yucca Mountain Science and Engineering Report, U. S. Department of Energy Report, DOE/RW-0539-1 (2002).

[7] Department of Energy, Department of Energy FY 2019 Congressional Budget Request, U. S. Department of Energy Report, DOE/CF-0141 (2018).

[8] POSIVA. ONKALO URL Homepage, Accessed Jan. 2018, Available from: http://www.posiva.fi/englanti/; ONKALO Situation.

[9] F. Bernier, X.L. Li, and W. Bastiaens, “Twenty-five Years’ Geotechnical Observation and Testing in the Tertiary Boom Clay Formation”, Geotechnique, 57, 229-237 (2007).

[10] G.Y. Kim, D.S. Bae, J.Y. Lee, and J.H. Park. Establishment of Infrastructure in KURT for In-situ Demonstration, Korea Atomic Energy Research Institute Report, KAERI/RR-3886/2014 (2015).

[11] Y.W. Tsang, J. Apps, J.T. Birkholzer, B. Freifeld, M.Q. Hu, J. Peterson, E. Sonnenthal, and N. Spycher. Yucca Mountain Single Heater Test Final Report, Yucca Mountain Site Characterization Project, Lawrence Berkeley National Laboratory Report, LBNL-42537 (1999).

[12] R.E. Finley, S.C. Blair, W.J. Boyle, J.J. Danneels, R.N. Datta, N.Z. Elkins, J.T. George, E.F. Homuth, M.Y. Lee, W.L. Mark, T. Peters, M. Riggins, Y. Tsang, R.A. Wagner, D.J. Weaver, and R.M. Yasek. The Yucca Mountain Project Drift Scale Test, Sandia National Laboratory Report, SAND2000-2362C (2000).

[13] TRW, Drift Scale Test Design and Forecast Results, TRW Environmental Safety Systems Report, BAB000000-01717-4600-00007 Rev. 00 (1997).

[14] TRW, Characterization of the Drift Scale Test Block, TRW Environmental Safety Systems Report, RADD00000-01717-5705-00001 Rev. 00 (1997).

[15] Itasca Consulting Group, FLAC-Fast Lagrangian Analysis of Continua, Version 4.0 (2000).

[16] K. Pruess, C. Oldenburg, and G. Moridis. TOUGH2 User's Guide, Version 2.0, Lawrence Berkeley National

Laboratory Report, LBNL-43134 (1999).

[17] S. Olivella, A. Gens, J. Carrera, and E. Alonso, "Numerical Formulation for a Simulator 'CODE_BRIGHT' for the Coupled Analysis of Saline Media", Eng. Comput., 13, 87-112 (1996).

[18] French Atomic Energy Commission, CASTEM, An Objective Oriented Finite Element Method Framework (2000).

[19] P.L. Martin and J.M. Barcala, "Large Scale Buffer Material Test: Mock-up Experiment at CIEMAT", Eng. Geol., 81, 298-316 (2005).

[20] Empresa Nacional de Residuos Radiactivos S.A., Full-scale Engineered Barriers Experiment, Updated Final Report 1994-2004, ENRESA Technical Publication, 05-0/2006 (2006).

[21] A.M. Fernandez, N. Jockwer, and P.L. Martin. Evolution of the Chemical Parameters in the FEBEX In-situ Experiment, EC NF-PRO Project Report, D2.2.10 (2007).

[22] A. Gens, M. Sanchez, L.N. Guimaraes, E.E. Alonso, A. Lloret, S. Olivella, M.V. Villar, and F. Huertas, "A Full-scale In situ Heating Test for High-level Nuclear Waste Disposal: Observation, Analysis and Interpretation", Geotechnique, 59, 377-399 (2009).

[23] A.M. Fernández, A. Muurinen, E. Montarges-Pelletier, N. Jockwer, and P. Rivas, "Geochemical Processes in the FEBEX Bentonite after a Heating and Hydration In-situ Test in the Grimsel URL", Clays in Natural & Engineered Barriers for Radioactive Waste Confinement, 4th Int. Meeting, Nantes (2010).

[24] F. Kober, I. Gaus, S. Birkholzer, and S. Vomvoris, "18 Years of Heating a Full Scale EBS at 100℃ (FEBEX, Grimsel Test Site) and Possible Applications at Higher Temperatures ("hotFEBEX" at > 150℃)", Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, 6th International Conference, Brussels (2015).

[25] E.E. Alonso, J. Alcoverro, F. Coste, L. Malinsky, V. Merrien-Soukatchoff, I. Kadiri, T. Nowak, H. Shao, T.S. Nguyen, A.P. Selvadurai, G. Armand, S.R. Sobolik, M. Itamura, C.M. Stone, S.W. Webb, A. Rejeb, M. Tijani, Z. Maouche, A. Kobayashi, H. Kurikami, A. Ito, Y. Sugita, M. Chijimatsu, L. Börgesson, J. Hernelind, J. Rutqvist, C.-F. Tsang, and P. Jussila, "The FEBEX Benchmark Test: Case Definition and Comparison of Modelling Approaches", Rock Mech. Min. Sci., 42, 611-638 (2005).

[26] DECOVALEX-2019, Accessed Jan. 2018, Available from: http://decovalex.org, 2018. 1.

[27] G.W. Lanyon and I. Gaus. Main Outcomes and Review of the FEBEX In Situ Test (GTS) and Mock-up after 15 years of Operation, National Cooperative for the Disposal of Radioactive Waste Technical Report, 15-04 (2016).

[28] C. Andersson, I. Bárcena, N. Bono, L. Boergesson, P. Cleall, T. Forsmark, D. Gunnarsson, L.E. Johannesson, A. Ledesma, L. Liedtke, A. Luukkonen, K. Pedersen, I. Puigdomenech, R. Pusch, I. Rhén, T. Rothfuchs, T. Sandén, J.L. Sineriz, Y. Sugita1, C. Svemar, and H. Thomas, Full-scale Testing of the KBS-3V Concept for the Geological Disposal of High-level Radioactive Waste, Prototype Repository, EUR Final Report, EUR 21924 (2005).

[29] Swedish Nuclear Fuel and Waste Management Company, Aspö Hard Rock Laboratory Annual Report 2013, SKB Technical Report, TR-14-17 (2014).

[30] Swedish Nuclear Fuel and Waste Management Company, Aspö Hard Rock Laboratory Annual Report 2014, SKB Technical Report, TR-15-10 (2015).

[31] L-E. Johannesson, Prototype Repository, Measurements of Water Content and Density of the Excavated Buffer Material form Deposition Hole 5 and 6 and the Backfill in the Outer Section of the Prototype Repository, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-13-14 (2014).

[32] S. Olsson, V. Jensen, L-E. Johannesson, E. Hansen, O. Karnland, S. Kumpulainen, D. Svensson, S. Hansen, and J. Lindèn, Prototype Repository, Hydro-mechanical,

Chemical and Mineralogical Characterization of the Buffer and Backfill Material from the Outer Section of the Prototype Repository, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-13-21 (2013).

[33] J. Arlinger, A. Bengtsson, J. Edlund, L. Eriksson, J. Johansson, S. Lydmark, L. Rabe, and K. Pedersen, Prototype Repository, Microbes in the Retrieved Outer Section, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-13-16 (2013).

[34] U. Nilsson, Prototype Repository, Validation of Retrieved Sensors from the Prototype Experiment at Aspö Hard Rock Laboratory, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-13-31 (2014).

[35] C. Svemar, L-E. Johannesson, P. Grahm, D. Svensson, O. Kristensson, M. Lönnqvist, and U. Nilsson, Prototype Repository, Opening and Retrieval of Outer Section of Prototype Repository at Aspö Hard Rock Laboratory, Summary Report, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-13-22 (2016).

[36] R. Pusch, Comparison of Results from THMCB Modelling of Buffer, Backfill and Rock with Measured Data from Prototype Repository, Swedish Nuclear Fuel and Waste Management Company International Project Report, IPR-04-11 (2004).

[37] A. Gens, A. Ledesma, P. Pusch, and L. Borgesson, “THMC Processes in Engineered Barriers: The Experience from Febex and Prototype Projects”, Euradwaste’04 Conference, Luxembourg (2004).

[38] P.J. Cleall, T.A. Melhuish, and H.R. Thomas, “Modelling in the Three-dimensional Behaviour of a Prototype Nuclear Waste Repository”, Eng. Geol., 85, 212-220 (2006).

[39] H.R. Thomas and Y. He, “Modelling the Behaviour of Unsaturated Soil using an Elastic Constitutive Relationship”, Geotechnique, 48, 589-603 (1998).

[40] H.R. Thomas and P.J. Cleall, “Inclusion of Extensive Clay Behavior in Coupled Thermo Hydraulic Mechanical Models”, Eng. Geol., 54, 93-108 (1999).

[41] G.J. Chen and A. Ledesma, “Coupled Thermo-hydro-mechanical Modelling of the Full-scale In-situ Test Prototype Repository”, Geotech. Geoenviron. Eng., 135, 121-132 (2009).

[42] Swedish Nuclear Fuel and Waste Management Company, Aspö Hard Rock Laboratory Annual Report 2010, SKB Technical Report, TR-11-10 (2011).

[43] Swedish Nuclear Fuel and Waste Management Company, Aspö Hard Rock Laboratory Annual Report 2015, SKB Technical Report, TR-16-10 (2016).

[44] I. Gaus, B. Garitte, R. Senger, A. Gens, R. Vasconcelos, J-L. Garcia-Sineriz, T. Trick, K. Wieczorek, O. Czaikowski, K. Schuster, J.C. Mayor, M. Velasco, U. Kuhlmann, and M.V. Villar, The HE-E Experiment: Lay-out, Interpretation and THM Modelling, PEBS deliverable D2.2-11 and D3.2-2, NAB 14-053 (2014).

[45] C-L. Zhang, T. Rothfuchs, N. Jockwer, K. Wieczorek, J. Dittrich, J. Muller, L. Hartwig, and M. Komischke, Thermal Effects on the Opalinus Clay, A Joint Heating Experiment of ANDRA and GRS at the Mont Terri URL (HE-D Project), GRS Final Report, GRS-224 (2007).

[46] SCK/CEN. Geological Disposal: R&D for the Geological Disposal of Medium and High Level Waste in the Boom Clay (2008).

[47] W. Bastiaens, The HADES Underground Research Facility (2007).

[48] P.V. Marcke, P.X. Sillen, X.L. Li, G.J. Chen, A. Dizier, J. Leysen, I. Troullinos, J. Verstricht, and W. Bastiaens, “The PRACLAY Heater Test at URL HADES: Preparation of the Heater Switch-on”, Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, 6th International Conference, Brussels (2015).

[49] W.J. Cho, J.S. Kim, C. Lee, S. Kwon, and J.W. Choi, “In-situ Experiments on the Performance of Near-field for Nuclear Waste Repository at KURT”, Nucl. Eng. Design, 252, 278-288 (2012).

[50] Korea Atomic Energy Reseach Institute, HLW Long-term Management System Development: Establishment of Infrastructure in KURT for In-situ Demonstration and Long-term Investigation of Repository System Performance, Korea Atomic Energy Research Institute Report, KAERI/RR-4201/2016 (2017).

[51] O. Karnland, T. Sandén, L-E. Johannesson, T. Eriksen, M. Jansson, S. Wold, K. Pedersen, M. Motamedi, and B. Rosborg, Long-term Test of Buffer Material, Final Report on the Pilot Parcels, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-00-22 (2000).

[52] Swedish Nuclear Fuel and Waste Management Company, Aspö Hard Rock Laboratory Annual Report 2000, SKB Technical Report, TR-01-10 (2001).

[53] Swedish Nuclear Fuel and Waste Management Company, Aspö Hard Rock Laboratory Annual Report 2006, SKB Technical Report, TR-07-10 (2007).

[54] Swedish Nuclear Fuel and Waste Management Company, Aspö Hard Rock Laboratory Annual Report 2007, SKB Technical Report, TR-08-10 (2008).

[55] O. Karnland, S. Olsson, A. Dueck, M. Birgersson, U. Nilsson, T. Hernan-Hakansson, K. Pedersen, S. Nilsson, T. Eriksen, and B. Rosborg, Long-term Test of Buffer Material at the Aspö Hard Rock Laboratory, LOT Project, Final Report on the A2 Test Parcel, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-09-29 (2009).

[56] O. Karnland, S. Olsson, T. Sandén, B. Fälth, M. Jansson, T. Eriksen, K. Svärdström, B. Rosborg, and A. Muurinen, Long-term Test of Buffer Material at the Aspö HRL, LOT Project Final Report on the A0 Test Parcel, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-09-31 (2011).

[57] Swedish Nuclear Fuel and Waste Management Company, Aspö Hard Rock Laboratory Annual Report 2011, SKB Technical Report, TR-12-03 (2012).

[58] Swedish Nuclear Fuel and Waste Management Company, Aspö Hard Rock Laboratory Annual Report 2012, SKB Technical Report, TR-13-03 (2013).

[59] L-E. Johannesson, T. Sandén, M. Akesson, I. Bárcena, and J. García-Siñeriz, Temperature Buffer Test, Installation of Buffer, Heaters and Instruments in the Deposition Hole, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-12-02 (2010).

[60] M. Akesson, Temperature Buffer Test, Dismantling Operation, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-12-04 (2010).

[61] L-E. Johannesson. Temperature Buffer Test, Measurements of Water Content and Density of the Excavated Buffer Material, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-12-05 (2010).

[62] M. Akesson, S. Olsson, A. Dueck, U. Nilsson, O. Karnland, L. Kiviranta, S. Kumpulainen, and J. Lindén, Temperature Buffer Test, Hydro-mechanical and Chemical/Mineralogical Characterizations, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-12-06 (2012).

[63] H. Hökmark, A. Ledesma, T. Lassabatere, B. Fälth, L. Börgesson, J. C. Robinet, N. Sellali, and P. Sémété, "Modelling Heat and Moisture Transport in the ANDRA/SKB Temperature Buffer Test", Phys. Chem. Earth, Parts A/B/C 32, 753–766 (2007).

[64] M. Akesson, Aspö Hard Rock Laboratory, Temperature Buffer Test, Evaluation Modeling– Field Test, Swedish Nuclear Fuel and Waste Management Company International Project Report, IPR-06-10 (2006).

[65] M. Akesson, Aspö Hard Rock Laboratory, Temperature Buffer Test, Evaluation Modelling– Mock-up Test, Swedish Nuclear Fuel and Waste Management Company International Project Report, IPR-06-11 (2006).

[66] M. Akesson, Aspö Hard Rock Laboratory, Temperature Buffer Test, Evaluation Modeling, TBT_3 Mock-up Test, Swedish Nuclear Fuel and Waste Management Company International Project Report, IPR-08-09 (2008).

[67] M. Akesson, A. Jacinto, C. Gatabin, M. Sanchez, and

A. Ledesma, "Bentonite THM Behaviour at High Temperatures: Experimental and Numerical Analysis", Geotechnique, 59, 307-318 (2009).

[68] M. Akesson, D. Malmberg, L. Börgesson, J. Hernelind, A. Ledesma, and A. Jacinto, Temperature Buffer Test, Final THM Modelling, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-12-07 (2012).

[69] M. Akesson, Temperature Buffer Test, Final Report, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-12-04 (2012).

[70] D. Svensson, A. Dueck, S. Olsson, T. Sandén, S. Lydmark, S. Jägevall, K. Pedersen, and S. Hansen, Alternative Buffer Material. Status of the Ongoing Laboratory Investigation of Reference Materials and Test Package 1, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-11-06 (2011).

[71] D. Svensson, "Early Observations in a Large Scale 6 1/2 year Iron-bentonite Field Experiment ABM2 at Aspö Hard Rock Laboratory, Sweden", 50th Annual Meeting of Clay Mineralogical Society, Urbana-Champaign (2013).

[72] P. Svensson and S. Hansen, "Redox Chemistry in Two Iron-bentonite Field Experiments at Aspö Hard Rock Laboratory, Sweden: an XRD and Fe K-edge XANES Study", Clays Clay Min., 61, 566–579 (2013).

[73] E. Johansson, T. Siren, and K. Kemppainen, "ONKALO –Underground Rock Characterization Facility for In-situ Testing for Nuclear Waste Repository", 4th International Underground Research Laboratory Workshop, Montreal (2015).

[74] R. Cuss, J. Harrington, and D. Noy, Large Scale Gas Injection Test (Lasgit) performed at the Aspö Hard Rock Laboratory, Summary Report 2008, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-10-38 (2010).

[75] Swedish Nuclear Fuel and Waste Management Company, Aspö Hard Rock Laboratory Annual Report 2016, SKB Technical Report, TR-17-10 (2017).

[76] P. Mårtensson, Aspö Hard Rock Laboratory, Concrete and Clay, Installation Report, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-15-01 (2015).

[77] C. Vogt, B. Lagerblad, K. Wallin, F. Baldy, and J-E. Jonasson, Low pH Self Compacting Concrete for Deposition Tunnel Plugs, Swedish Nuclear Fuel and Waste Management Company Report, R-09-07 (2009).

[78] A. Bodén and S. Pettersson, Development of Rock Bolt Grout and Shotcrete for Rock Support and Corrosion of Steel in Low-pH Cementious Materials, Swedish Nuclear Fuel and Waste Management Company, Report, R-11-08 (2011).

[79] A. Mathern and J. Magnusson, System Design of Dome Plug, Experience of Low-pH Concrete Mix B200, Material Properties from Laboratory Tests and Full-scale Castings, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-14-26 (2015).

[80] A. Jenni, U. Mäder, C. Lerouge, S. Gaboreau, and B. Schwyn, "In-situ Interaction between Different Concretes and Opalinus Clay", Phys. Chem. Earth, 70-71, 71-83 (2014).

[81] J. Ludvigson, R. Nordqvist, L. Ekman, and K. Hansson, Aspö Hard Rock Laboratory, Backfill and Plug Test, Hydraulic Testing of Core Drilled Boreholes in the ZEDEX Drift, Swedish Nuclear Fuel and Waste Management Company International Project Report, IPR-09-01 (1999).

[82] R. Goudarzi, L-E. Johannesson, and L. Börgesson, Backfill and Plug Test, Sensors Data Report (Period 990601–070101) Report No. 14, Swedish Nuclear Fuel and Waste Management Company International Project Report, IPR-08-02 (2008).

[83] L-E. Johannesson, O. Kristensson, M. Akesson, P. Eriksson, and M. Hedin, Tests and Simulations of THM Processes Relevant for the Buffer Installation, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-14-22 (2014).

[84] B. Nyblad, D. Luterkort, and M. Lundqvist, Buffer

Protection for the Installation Phase, Design and Testing, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-13-51 (2014).

[85] L. Börgesson and J. Hernelind, Modelling of Bentonite Block Compaction Swedish Nuclear Fuel and Waste Management Company Progress Report, P-14-10 (2014).

[86] P. Eriksson, Basic Engineering of Buffer Production System, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-14-11 (2014).

[87] A. Arvidsson, P. Josefsson, T. Sandén, and M. Ojala, System Design of Backfill, Project Results, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-14-20 (2015).

[88] C. Vogt, B. Lagerblad, K. Wallin, F. Baldy, and J-E. Jonasson, Low pH Self Compacting Concrete for Deposition Tunnel Plugs, Swedish Nuclear Fuel and Waste Management Company Report, R-09-07 (2009).

[89] P. Grahm and R. Karlzén, System Design of Dome Plug, Experiences from Full-scale Wire Sawing of a Slot Abutment for the KBS-3V Deposition Tunnel Plug, Swedish Nuclear Fuel and Waste Management Company Report, R-14-24 (2015).

[90] P. Grahm, R. Malm, and D, Eriksson, System Design and Full-scale Testing of the Dome Plug for KBS-3V Deposition Tunnels, Main Report, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-14-23 (2015).

[91] H. Müller, T. Vogt, B. Garitte, S. Köhler, T. Sakaki, H-P. Weber, and T. Vietor, "The Full-Scale Emplacement Experiment– Implementation of a Multiple Heater Experiment at the Mont Terri URL", Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, 6th International Conference, Brussels (2015).

[92] S. Emsley, O. Olsson, L. Stenberg, H. J. Alheid, and S. Falls, ZEDEX- A Study of Damage and Disturbance from Tunnel Excavation by Blasting and Tunnel Boring, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR 97-30 (1997).

[93] B. Sabet, H. Shao, J. Autio, F. Elorza, I. Canamon, and J. Perez, "EDZ Assessment in the Febex II Project", in: Impact of Excavation Disturbed or Damaged Zone (EDZ) on the Performance of Radioactive Waste Geological Repositories, 137-142 (2005).

[94] L. Liedtke, "Spread of Contaminants in Excavation Disturbed Zone Based on Results of Hydraulic In-situ Tests in Jointed Rock", in: Impact of Excavation Disturbed or Damaged Zone (EDZ) on the Performance of Radioactive Waste Geological Repositories, 157-162 (2005).

[95] J. B. Martino and N. A. Chandler, "Excavation-induced Damage Studies at the Underground Research Laboratory", Int. J. Rock Mech. Min. Sci., 41, 1413-1426 (2004).

[96] R. Pusch and R. Stanfors, "The Zone of Disturbance around Blasted Tunnel at Depth", Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 29, 447-456 (1992).

[97] K. Sugihara, "Geological Disposal of High-level Radioactive Waste and the Role of Rock Engineering", Int. of Japan. Com. Rock Mech., 5, 19-24 (2009).

[98] T. Sato, T. Kikuchi, and K. Sugihara, "In-situ Experiments on an Excavation Disturbed Zone induced by Mechanical Excavation in Neogene Sedimentary Rock at Tono Mine", Central. Eng. Geol., 56, 97-108 (2000).

[99] S. Kwon, C.S. Lee, S.J. Cho, S.W. Jeon, W.J. Cho, and J. Kim, "An Investigation of Excavation Damaged Zone at the KAERI Underground Research Tunnel", Tunn. Undergr. Space Technol., 24, 1-13 (2009).

[100] W.J. Cho, J.S. Kim, C. Lee, S. Kwon, and J.W. Choi, "In-situ Experiments on the Performance of Near-field for Nuclear Waste Repository at KURT", Nucl. Eng. Des., 252, 278-288 (2012).

[101] S. Mustonen, J. Norokallio, S. Mellanen, T. Lehtimaki, and E. Heikkinen, EDZ09 Project and Related EDZ Studies in ONKALO 2008–2010, POSIVA Working Report, 2010-27 (2010).

[102] J.C. Andersson and A. Eng, Aspö Pillar Stability Experiment, Final Experiment Design, Monitored Data

and Observations, Swedish Nuclear Fuel and Waste Management Company Report, R-05-02 (2005).

[103] J.C. Andersson, Aspö Pillar Stability Experiment Final Report, Rock Mass Response to Coupled Mechanical Thermal Loading, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-07-01 (2007).

[104] E. Johansson, T. Siren, M. Hakala, and P. Kantia, ONKALO POSE Experiment- Phase 1&2: Execution and Monitoring, POSIVA Working Report, 2012-60 (2014).

[105] J. Valli, M. Hakala, T. Wanne, P. Kantia, and T. Siren, ONKALO POSE Experiment- Phase 3: Execution and Monitoring, POSIVA Working Report 2013-41 (2014).

[106] GTS, The Material Corrosion Test (MaCoTe), http://www.grimsel.com/gts-phase-vi/macote-the-material-corrosion-test/macote. 2018. 1.

[107] A.E, Bond, A.R. Hoch, G.D. Jones, A.J. Tomczyk, R.M. Wiggin, and W.J. Worraker, Assessment of a Spent Fuel Disposal Canister, Assessment Studies for a Copper Canister with Cast Steel Inner Component, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR 97-19 (1997).

[108] N.R. Smart, A.P. Rance, and P.A.H. Fennell, Expansion due to the Anaerobic Corrosion of Iron, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-06-41 (2006).

[109] N.R. Smart and A.P. Rance, Miniature Canister Corrosion Experiment- Results of Operations to May 2008, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-09-20 (2009).

[110] N.R. Smart, A.P. Rance, B. Reddy, P. Fennell, and R.J. Winsley, Analysis of SKB MiniCan Experiment 3, Swedish Nuclear Fuel and Waste Management Company Technical Report, TR-12-09 (2012).

[111] N.R. Smart, S. Rose, D. Nixon, and A. Rance, Metallographic Analysis of SKB MiniCan Experiment 3, Swedish Nuclear Fuel and Waste Management Company Report, R-13-35 (2013).

[112] N.R. Smart, B. Reddy, D. Nixon, A. Rance, and A.J. Johansson, Miniature Canister (MiniCan) Corrosion Experiment, Progress Report for 2008–2013, Swedish Nuclear Fuel and Waste Management Company Progress Report, P-14-19 (2015).

[113] A.J. Johansson, C. Lilja, L. Sjogren, A. Gordon, and L. Johansson, “Insights from Post-test Examination of Three Packages from the MiniCan Test Series of Copper-cast Iron Canisters for Geological Disposal of Spent Nuclear Fuel: Impact of the Presence and Density of Bentonite Clay”, Corros. Eng. Sci. Tech., 52, 54-60 (2017).