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Preface

The fundamental basis of geological disposal concepts for radioactive wastes is generally a multi-barrier system. Engineered barriers play a central role in this system ensuring the containment and long-term retardation of radionuclide release. Understanding the performance of engineered barrier systems (EBS) is therefore crucial to evaluate the safety of disposal concepts of radioactive waste in geological formations. Due to the complex interaction of thermal, hydraulic, mechanical and chemical (THM-C) processes in the EBS, a comprehensive scientific approach is required. EBS research programmes include a broad spectrum of laboratory and in-situ experiments. Findings of experimental studies are integrated into numerical codes for the simulation of coupled THM-C processes. Extrapolating the results of these two approaches from the transient phase to the long-term behaviour is always subject to uncertainty. These uncertainties need to be evaluated to clarify their significance for the safety function of the EBS and thus for the performance assessment of geological repositories.

The objective of the *International Conference on the Performance of Engineered Barriers* is to discuss, document and disseminate the current state of research on the performance of engineered barriers in geological repositories for high-level nuclear waste. As the 7th Framework EURATOM project PEBS (Long-term Performance of Engineered Barrier Systems) is nearing completion, the conference provides a platform to disseminate the outcomes of the project to the scientific community. The research results of the PEBS project play a central role; however, they are put in context through presentations of research results from other projects and activities.

Presentations are grouped in eight sessions, complemented by a poster exhibition. The conference is rounded up by a panel discussion with internationally recognized experts, aiming at providing a summary of topics relevant for the design of future R&D programmes in the field of engineered barriers.

The number and variety of submitted abstracts – more than 70 involved organizations from 19 countries – indicates the high international relevance of this field of research. We are very pleased about the strong interest in the conference and would like to wish all participants a successful conference and a pleasant stay in Hannover.

Annika Schäfers
PEBS Project Coordinator & Programme Committee

Sandra Fahland
Organizing Committee

The Project "Long-term Performance of Engineered Barrier Systems" (PEBS)

The 7th Framework EURATOM PEBS project (Long-term Performance of Engineered Barrier Systems) was initiated in 2010 to evaluate the barrier performance of clay-based EBS over time. The project approach includes experiments, model development and evaluation of the potential impact on long-term safety functions. The project aims are to

- deepen the knowledge and understanding of the THM and THM-C (thermo-hydro-mechanical and -chemical) evolution of the EBS system with time,
- provide a more quantitative basis for relating the evolutionary behaviour to the safety functions,
- clarify further the significance of residual uncertainties for long-term performance assessment.

The research results of the PEBS project are summarized and presented at the conference in four "Cases", which were identified to be of special interest:

1. Water uptake in bentonite buffer
2. EBS performance at temperatures above 100°C
3. HM evolution of the buffer
4. Impact of the geochemical evolution of bentonite barriers on repository safety functions

In addition to the scientific objectives, the dissemination of the essential results to the broad scientific community within the EC, China and Japan is an important aim of the project. The consortium uses its expertise for public information purposes and to promote knowledge and technology transfer through training.

The consortium involves 15 European organizations as well as the Beijing Research Institute for Uranium Geology and the Japan Atomic Energy Agency.

The research leading to these results has received funding from the Seventh Framework Programme of the European Atomic Energy Community (FP7/2007-2011) under grant agreement n° 249681.

Coordinator: Partners:

Acknowledgements

We would like to thank the members of the Programme Committee, who contributed their expertise and time to review the submitted abstracts, compose the conference programme and plan the panel discussion.

We equally thank the members of the Organizing Committee for all the effort they devoted for the organization of this conference.

Christophe Davies' contribution to the conference programme is highly appreciated. We especially thank Peter Wikberg for contributing to the programme with a keynote lecture and chairing the panel discussion. Furthermore we would like to thank Frédéric Bernier, Christophe Davies, Kari Koskinen, Nina Müller-Hoeppe and Klaus-Jürgen Röhlig for their participation in the panel discussion. The work of the session chairs is very much appreciated.

We thank all the authors for their contributions to the conference and the proceedings.

Our gratitude goes to the staff of the department of *Underground Space for Storage and Economic Use* and other colleagues at the BGR, who actively supported us during the months of planning and during the conference itself.

As the PEBS project is nearing completion, we would like to take this opportunity to thank the members of the PEBS consortium for their continuously excellent cooperation.

Programme Committee

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Gunnar Buckau – European Commission, JRC-ITU

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Overview on the Research Results of the PEBS Project

Water Uptake in the Bentonite Buffer – PEBS Case 1

Juan Carlos Mayor[1], María Victoria Villar[2], Pedro Luis Martín[2], Antonio Gens[3], Manuel Velasco[4]

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The main aim of the project PEBS (Long-term Performance of Engineered Barrier Systems) is to evaluate the sealing and barrier performance of the EBS with time. The focus is to study the processes in the early evolution of the repository system and to evaluate the impact of the processes on the long-term safety functions.

Water uptake in clay components in the EBS is one of the key safety-relevant processes that have been extracted in the framework of the PEBS project from the integrated assessment of the processes for four different repository concepts (France, Sweden, Switzerland, Spain). These key processes are formulated such that they are overarching and thus safety relevant for several disposal concepts.

It has been found in a number of laboratory, mock up and in situ tests that the progress of saturation at the later stages of hydration is lower than anticipated by the conventional coupled THM models. Three hypotheses have been examined to explain this discrepancy: existence of a threshold gradient in Darcy's law, thermo-osmosis phenomena, and evolution of bentonite microstructure during hydration. Numerical modelling has shown that each of these possibilities are capable of providing results in agreement with observations but, on their own, they are unable to identify with certainty what is the phenomenon (or combination of phenomena) underlying the observed slowing down of hydration.

The PEBS project has not been designed to establish experimentally the potential existence and effects of those three phenomena. However, the performance of THM modelling of the FEBEX mock up test conducted in the facilities of CIEMAT (Madrid, Spain) to cover the currently available long term observations gives some useful information on the effects likely to be associated with each one of the individual hypotheses. In addition, performance of long-term THM computations for design repository conditions will provide estimations of the potential significance or otherwise of those phenomena for safety assessment.

The context of the existing model uncertainty in the estimation of the resaturation times of the bentonite buffer has been however, from a long-term safety perspective, clearly improved – it can be stated that even though saturation is not yet fully achieved (e.g. after 15 years of resaturation of the FEBEX mock-up), the safety function assigned to the bentonite is achieved because a sufficient swelling pressure and hydraulic conductivity are already reached throughout the barrier at 85-90 % average degree of saturation.

The model uncertainty in the estimation of the resaturation times of the bentonite buffer is thus not important from a long-term safety perspective.

Acknowledgements: *The research leading to these results has received funding from the European Atomic Energy Community's Seventh Framework Programme (FP7/2007-2011) under grant agreement n° FP7-249681.*

EBS Performance at Temperatures above 100°C - PEBS Case 2

Irina Gaus[1], Lawrence Johnson[1], Klaus Wieczorek[2], Antonio Gens[3], José-Luis García-Siñeriz[4], Thomas Trick[5], Rainer Senger[6], Uli Kuhlman[6], Ann Dueck[7], María Victoria Villar[8], Olivier Leupin[1], Oliver Czaikowski[2], Benoit Garitte[1], Kristof Schuster[9], Juan Carlos Mayor[10]

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The 7th Framework EURATOM PEBS project (Long Term Performance of Engineered Barrier Systems) aims at providing in depth process understanding for constraining the conceptual and parametric uncertainties in the context of long-term safety assessment of the high levelwaste /spent fuel (HLW/SF) nearfield.

The performance of a bentonite barrier subjected to temperatures above 100°C (up to around 150°C) during the thermal phase of HLW/SF canisters under variable saturated conditions, and its relevance to clay-based disposal concepts, was investigated. While the characterisation of bentonite performance below 100°C is assumed to be largely established, the information regarding bentonite pellets at temperatures > 100°C, is less abundant.

As part of the PEBS project a review of potential property changes was conducted and options for improved process representation in the thermo-hydraulic-mechanical (THM) models were investigated. No indication exists that parameters change dramatically in the temperature range at hand; small changes are observed (e.g. regarding swelling pressure and hydraulic conductivity) but associated requirements are still expected to be met. Additional tests within PEBS regarding the mechanical properties showed small reduction in strain at failure for resaturated material exposed to high temperature (> 90°C). Existing THM modelling approaches were found similarly applicable as no phase change at 100°C is expected.

The early post-closure thermal behaviour was further elucidated by the HE-E experiment (Figure 1), a 1:2 scale heating experiment installed at the Mont Terri Rock Laboratory, which was designed and constructed as part of PEBS and initiated in June 2011. It characterises in detail the thermal conductivity at a large scale in both pure bentonite as well as a bentonite-sand mixture buffers, in the Opalinus Clay host rock. Column tests (50 cm) in the laboratory with similar materials and their modelling supported the interpretation of the HE-E in situ measurements. The HE-E experiment is especially designed as a model validation experiment at the large scale and subjects the EBS and the host rock to temperatures higher than in past in situ experiments using realistic heating rates while undergoing natural hydration from the low permeability Opalinus Clay host rock.

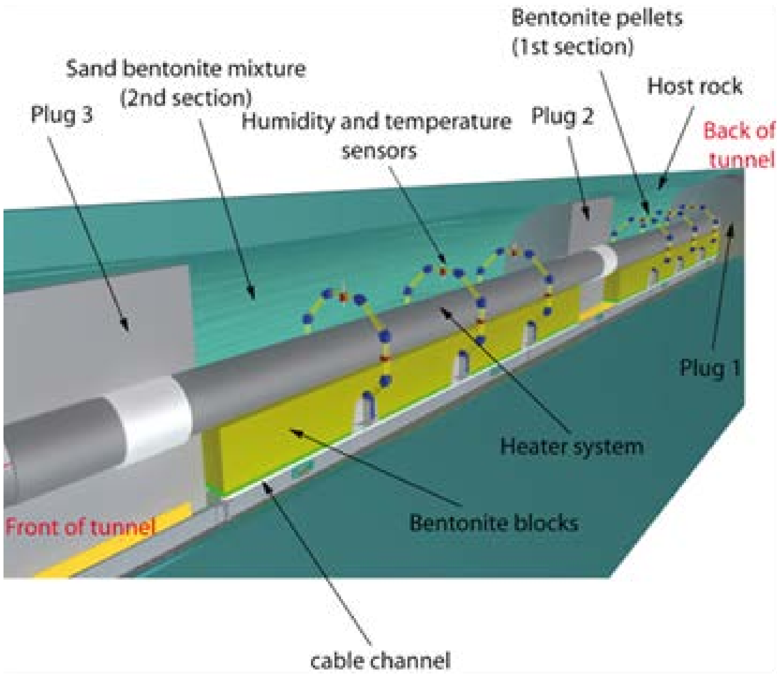

Fig. 1: Layout of the HE-E experiment at the Mont Terri URL.

The HE-E test showed that with the current TH(M) conceptualisations the very early dry phase can be reproduced adequately in terms of temperature evolution, while the modelling of the relative humidities illustrates the strongly coupled behaviour of the THM processes. Thermal overpressures in the Opalinus Clay are observed to be moderate and well reproducible. As the period of analysis within PEBS was limited to three years, further results from the experiment are expected in the years to come.

Good insight is required regarding the duration of the prevailing temperature in combination with the saturation state in the EBS in order to assess the potential impact of chemical and physical processes on the long-term EBS performance. Extrapolation calculations, both with TH and THM models at repository relevant conditions aimed at framing these conditions. The period in which part of the bentonite (a small ring close to the canister) is at temperatures above 100°C and fully saturated was modelled to be of the order of 30-180 years based on the selected parameter variations as part of the sensitivity analysis.

The integrated knowledge from the laboratory and URL experiences and their modelling mapped on the expected early EBS evolution at repository relevant conditions in a clay based host rock reduced significantly the uncertainties regarding the final state of the EBS when the safety functions are assumed to be in place.

Acknowledgements: *The research leading to these results has received funding from the European Atomic Energy Community's Seventh Framework Programme (FP7/2007-2011) under grant agreement n° FP7-249681.*

HM Evolution of the Buffer – PEBS Case 3

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The main aim of the project PEBS (Long-term Performance of Engineered Barrier Systems) is to evaluate the sealing and barrier performance of the EBS with time. The focus is to study the processes in the early evolution of the repository system and to evaluate the impact of the processes on the long-term safety functions.

The sealing ability is essential for the engineered clay barriers in all repository concepts. This is normally achieved by a swelling pressure and a low hydraulic conductivity. The swelling pressure may also impact the impact the barriers in the repository. The mechanical properties of the installed EBS, that may consist of a mixture of blocks, pellets and engineering voids, will be entirely different from the situation after full saturation. It is therefore important to understand:

1. The mechanical evolution during the saturation phase
2. The final situation after equilibrium

A good knowledge of the mechanical evolution is necessary to ensure that a given design is sufficient to meet the performance targets.

Results obtained from the PEBS project can be used to reduce the uncertainties in the mechanical evolution of the bentonite in future long-term assessments in a number of ways. A few examples are given here:

The EB experiment was a full-scale test for the demonstration, in a horizontal drift, of an emplacement technique of the clay barrier, using a granular bentonite material in the upper part of this barrier and bentonite blocks at the bottom. The test has been carried out in a 6 m long section of a niche excavated in Opalinus Clay of the Mont Terri underground laboratory. The results from the excavation showed that the high density blocks had expanded and compacted the low-density granulate material in the entire cross section of the test. This clearly indicates that density differences from the installations will be significantly reduced by the swelling of the bentonite.

Model testing has shown that the wetting process (slow or fast), expressed by use of the wetting/drying retention curves of the clay, has a significant impact on the level of remaining heterogeneity of the buffer system.

The FEBEX “mock-up” test is conducted in the facilities of CIEMAT (Madrid, Spain). The physical components of the test consist of five basic units: the confining structure, with its hydration system; the heating system; the clay barrier; the instrumentation; and the systems for data acquisition and for heater control. Despite the slow hydration of the test, the swelling pressure build up has been relatively rapid. The swelling pressure build up follows closely the hydration process.

Thermo-mechanically induced brittleness has previously been observed in the buffer material and further studies regarding the origin of brittleness is of importance to further understand the behaviour. The mechanical properties of bentonite are studied by laboratory tests as for example unconfined compression tests and swelling pressure tests. Small but significant lower strain at failure was measured in the material exposed to high temperature. A change was seen already after a few hours of exposure Changes were also seen in the PEBS series made on MX-80. However, no significant difference between materials heated before or after saturation was seen.

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Impact of the Geochemical Evolution of Bentonite Barriers on Repository Safety Functions - PEBS Case 4

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An important objective of the PEBS project is to analyse the findings of the experimental and modelling tasks with respect to the implications for the long-term performance and safety functions of the engineered barrier system (EBS). Four issues or “cases” of special interest were defined. This paper presents the main conclusions of Case 4 which is devoted to the effects of the geochemical evolution on the safety functions of the EBS.

The main uncertainties in the bentonite long-term evolution, especially regarding the thermally-induced mineral changes and the interactions at the canister/bentonite and bentonite/concrete interfaces were identified and analysed. This formal approach made it easier to integrate experimental and modelling results from the PEBS project and from other projects and relate them to the safety functions of the EBS. The most important safety function that could be impaired by the chemical effects is the limitation of advective flow. It has to be assessed that the chemical effects will not inhibit the low permeability and sufficient swelling pressure developing and being maintained in the buffer in the long term.

The main conclusions include:

- Thermally-induced mineralogical changes such as the cementation by silica precipitation and the illitization will be relevant mostly above 150 °C.
- The experiments on the interactions of corrosion products and bentonite indicate that: 1) The main properties of the bentonite remain unaltered; 2) There is a sequence of corrosion products, $Fe(OH)_2$(s) and magnetite being the end members; 3) Iron is sorbed by surface complexation while iron exchange is less relevant than iron sorption; and 4) Corrosion products penetrate a few mm into the bentonite. For the most part, the coupled THC numerical models reproduce the experimental data.

- The experiments on the interactions of bentonite and concrete show an altered layer of bentonite several millimetres thick (< 5 mm) which is cemented by the precipitation of new minerals in the pore space. A second layer of several centimetres of thickness may be also affected by changes in the concentrations of exchanged cations with an enrichment in exchanged calcium and a depletion of magnesium. Coupled THC(m) numerical models capture the main trends in mineral dissolution-precipitation. While there are still open questions regarding the conceptual geochemical model, the pore clogging processes, and the final parameters and properties of the altered zone, current models indicate that the thickness of the altered bentonite will be bounded.

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New Insights from In-situ Experiments in Clay-rich Formations

Outcome of the Dismantling of “EB” Experiment

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The Engineered Barrier Emplacement Experiment in Opalinus Clay or “EB” Experiment aimed the demonstration of a new concept for the construction of SF and HLW repositories in horizontal drifts, in competent clay formations. The project consisted on a real scale isothermal simulation of this construction method in the Opalinus Clay formation at the Mont Terri underground laboratory in Switzerland. A steel dummy canister, with the same dimensions and weight as the Spanish reference canister, was placed on top of a bed of highly compacted bentonite blocks, and then the upper part of the drift was buffered with a Granular Buffer Material (GBM) made from bentonite pellets. The used bentonite was the FEBEX one. The drift was sealed with a concrete plug having a concrete retaining wall between the plug and the GBM. Due to the short amount of free water available in this formation, an artificial hydration system was installed to accelerate the hydration process in the bentonite.

Since the end of the test installation the buffer was artificially saturated and the evolution of the different hydro-mechanical parameters was being monitored, both in the barrier and the rock. Relative humidity and temperature in the rock and in the bentonite buffer, rock displacement, pore pressure and total pressure were registered by means of different types of sensors. After 11 years of operation and with the barrier expected fully saturated, the experiment has been dismantled between the 19th of October 2012 and the 1st of February 2013.

The main objective of the dismantling of the EB experiment has been to know about the real status of the GBM used: degree of saturation, permeability, density, aspect, homogeneity, etc. It has been also important to check the status of the bentonite blocks that support the canister, the rock in contact with the buffer, with especial interest in the EDZ, and the degree of saturation of the concrete in the vicinity of the buffer (plug and blocks support). Therefore, the activities of the dismantling have been coordinated with a sampling programme intended to analyse parameters such as dry density, water content, permeability… in the laboratories of the different organizations collaborating in the project as well as in an on-site laboratory.

The aim of the proposed communication is to present the main facts of this operation and in particular the most relevant outcome in relation with the SF and HLW underground disposal concepts.

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Geophysical Long-term Monitoring within the PEBS Project and related HE-E- and EB-Experiment

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As part of the EC funded PEBS Project three geophysical long-term as well as one short lasting experiment were performed successfully in the related Heater Experiment (HE-E) and Engineered Barrier Experiment (EB) in the Mont Terri Rock Laboratory (Switzerland). In both experiments a dummy canister was emplaced in the Opalinus Clay (OPA) and bentonite or a sand-bentonite mixture was used for the proper sealing. The EB-Experiment started in 2001 and became part of the PEBS-Experiment in 2010. Several geophysical measurements were performed until 2003. The HE-E Experiment was initiated in 2010 and started in 2011.

The HE-E related experiments aim at the understanding of processes linked to the early evolution of a repository (early non-isothermal re-saturation phase) whereas the focus for the EB related experiments lies on later stages of evolution (isothermal, pressure recovery phase). The applied geophysical measurements are subdivided into the following tasks:

- Seismic monitoring of the early evolution of a sand-bentonite mixture and OPA in the HE-E Experiment (started March 2011, ongoing),
- Resumption of seismic monitoring of the evolution of the bentonite and OPA after 8.6 years and during the dismantling process in the EB-Experiment (resumption of seismic measurements in July 2012),
- Drilling of two pilot boreholes through the concrete plug in the backfill material of the EB-Experiment, take samples, perform geophysical borehole measurements and a hydro test (August 2011), and
- Geoelectrical monitoring of the evolution of the bentonite and OPA in the EB-Experiment during a controlled dismantling (September 2012 – May 2013).

Geophysical parameters as seismic velocities and geoelectrical resistivities react very sensitive to changes in materials as used in these experiments, OPA as host rock and bentonite or sand-bentonite mixture as backfill. In order to support the process understanding related to different stages of a real repository closure seismic and geoelectrical methods were used. The geophysical long-term monitoring was performed on a daily basis which results in a huge data set.

[1] With the help of seismic transmission methods over nearly three years within the HE-E Experiment the compaction/consolidation of the sand-bentonite backfill (65/35, MX80/sand) could be visualized very well. Furthermore, varying seismic parameters give very clear indications for the creation as well as the sealing of excavation damaged/disturbed Zone features (EdZ/EDZ) caused in the vicinity of the interface backfill-Opalinus Clay.

[2] Within the EB-Experiment seismic transmission measurements were resumed after a pause of 8.6 years. The extracted seismic parameters show the continuation of the sealing process in the EDZ and once again the stepwise creation of the EdZ/EDZ as a consequence of the dismantling process started in October 2012.

[3] In the run-up to the dismantling activities in August 2011 the drilling of two pilot boreholes was performed. In addition to the sampling of backfill material one borehole was used for seismic and geoelectrical borehole measurements. These measurements showed that the bentonite, which was emplaced ten years before and hydrated artificially, seemed to be homogenized in the inspected area.

[4] Furthermore, in July 2012 a circular geoelectrical array which was used for the initial characterization of the EB-niche with resistivity parameters and followed by two measurements after the closure of the niche, was reactivated for the daily monitoring. Resistivity data show a convincing inverse relation to the water content of the bentonite (FEBEX, Almería, Spain), which was surprisingly at first. The resistivity data show also EdZ/EDZ related features in the OPA caused by the dismantling activities.

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Sealing Materials used in the HE-E Test: Thermo-hydro-mechanical Characterisation

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The HE-E experiment is a 1:2 scale heating experiment considering natural resaturation of the EBS and a maximum heater surface temperature of 140°C. The experiment consists of two independently heated sections, where the heaters are placed in a steel liner supported by MX80 bentonite blocks. In one of the sections the granular material that fills the void between the heaters and the upper part of the gallery is MX80 bentonite pellets (B), whereas in the other is a 65/35 granular sand/bentonite mixture (S/B). Once emplaced the water content of the B material was 5.9 % and the average dry density was 1.46 kg/m^3. The average water content of the S/B mixture was around 4 % and the dry density 1.5 g/cm^3.

With the aim of complementing the information provided by the HE-E in situ test, CIEMAT has undertaken, in the framework of the PEBS project, the performance of two tests in cells simulating the conditions of the sealing materials used in the two sections of the *in situ* test. The laboratory tests are being performed in cylindrical cells of nominal internal diameter 7 cm and inner length 50 cm, which is the thickness of the GBM barrier in the *in situ* test. These cells have a heater at the bottom and a system allowing water injection on top. The initial conditions of the sealing materials inside the cells with respect to dry density and water content were the same as those in the *in situ* test. The temperature of the heaters placed at the bottom of the columns was increased to 100°C and then to 140°C during the heating phase. Hydration with Pearson water through the upper surface of the columns started after RH stabilisation inside the materials. The water intake the temperature and relative humidity (RH) of the materials at different positions were measured online during the tests.

The heating phase of both tests showed that the thermal conductivity of the dry materials is low, what causes a high thermal gradient near the heater, and low temperatures in the rest of the columns. Besides, the stabilisation of the temperature in these materials is very quick, being faster for material B than S/B. The movement of water in the vapour phase as a result of the thermal gradient was evinced by the sharp increase of relative humidity recorded by the sensors closest to the heater –followed by a continuous decrease– and the slower increase recorded in the upper part of the columns. The different permeability of both materials was made clear in the different pace and extent of this water redistribution process in the vapour phase, which was faster for the S/B mixture. Also the relative humidity gradient at the end of the heating phase was sharper in cell S/B, due to the lower permeability and higher water retention capacity of the bentonite pellets. The lower permeability of the pellets was again highlighted when hydration started, because the sensors started to record RH increases much later than in cell S/B. An average degree of saturation higher than 90 % was reached in cell S/B after 100 days of hydration, whereas after more than 400 days of hydration the average degree of saturation in cell B was only 50 %.

In addition, infiltration tests at room temperature have also been performed in order to check the effect of thermal gradient on saturation. These tests were performed in smaller cells (inner diameter and length 10 cm) in which the water intake and swelling pressure developed were measured online.

Acknowledgements: *The research leading to these results has received funding from the European Atomic Energy Community's Seventh Framework Programme (FP7/2007-2011) under grant agreement n° FP7-249681.*

Bentonite Buffer Material Production and Emplacement during the Full-Scale Emplacement (FE) Experiment at the Mont Terri URL

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The Full-Scale Emplacement (FE) Experiment at the Mont Terri underground research laboratory (URL) is a full-scale heater test in a clay-rich formation (Opalinus Clay). It simulates the construction, waste emplacement and backfilling of a spent fuel (SF) / vitrified high-level waste (HLW) repository tunnel as realistically as possible. The entire experiment implementation as well as the post-closure THM(C) evolution will be monitored using several hundred sensors. These are distributed in the host rock in the near- and far-field, the tunnel lining, the engineered barrier system (EBS) and on the heaters.

One of the main aims of this experiment, which is based on the Swiss SF/HLW disposal concept, is the optimization of the bentonite buffer material production and the investigation of emplacement procedures for realistic (underground) conditions.

Many important tasks, such as the excavation of a small cavern (completed in May 2011), the excavation of the experimental tunnel with a diameter of approx. 3 meters and a length of 50 meters (completed in September 2012) and the instrumentation of the rock in the 'far-field' (completed in April 2012), have already been executed successfully. The instrumentation of the rock in the 'near-field' is currently on-going and planned to be completed by until the beginning of 2014. The installation of the three heaters and the instrumentation within the tunnel will happen before and during the emplacement of the bentonite buffer. Finally the FE tunnel will be sealed off with a concrete plug and heating will be started by the end of 2014.

An interesting challenge in the coming months will be the production of the highly compacted bentonite blocks for the pedestals below the heaters as well as the production of a bentonite pellet mixture with the ideal properties for the backfilling of the experimental FE tunnel. Recent research confirms that the bentonite back-fill should consist of highly compacted bentonite granules (e.g. pellets) with a very broad grain size distribution, ideally a so-called Fuller-type distribution (Fuller and Thomson, 1907) in order to achieve an overall bulk dry emplacement density of at least 1,450 kg/m^3. This density will ensure a low porosity within the bentonite buffer and a low hydraulic conductivity as well as a sufficient swelling pressure.

Also challenging will be the construction of a prototype machine used for backfilling the horizontal FE tunnel. This prototype machine will transport, emplace and compress the GBM using five auger conveyors simultaneously. In order to control the machine parameters as well as the emplacement density several pre- and mock-up tests have been and will be conducted; first results will be presented.

Acknowledgements: *This experiment is part of the Mont Terri Project under the directorate of swisstopo. The initiator and lead organization for the experiment is NAGRA; ANDRA (France), DOE/LBNL (U.S.A), NWMO (Canada), GRS (Germany) and BGR (Germany) are participating in the FE Experiment.*

The engineering and demonstration components of the FE experiment are also part of NAGRA's participation in the EC co-funded 'Large Underground COncept EXperiments' (LUCOEX) project and therefore receive funding from the European Atomic Energy Community's Seventh Framework Programme (FP7) under grant agreement n269905.

Thermo-hydro-mechanical Characterisation of Samples Retrieved from the EB Test

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The EB experiment was run by ENRESA at the Mont Terri Underground Research Laboratory in Switzerland, starting in October 2000, with the aim of demonstrating that automated production of a Granular Bentonite Material (GBM) and its emplacement in the upper part of a clay barrier were feasible. The lower part of the barrier was composed by blocks of compacted bentonite. The test run under isothermal conditions (average temperature 16°C) for 10.5 years and started to be dismantled in October 2012. The GBM looked completely homogeneous and every void in the barrier had been filled. Samples of the GBM, the bentonite blocks and other materials were taken for analysis in the laboratory. The bentonite samples analysed at CIEMAT belonged to the sampling sections A1-25, CMT1, CMT2, E, B2 and CMT3. Their physical state was determined, as well as their porosity distribution, permeability, thermal conductivity and swelling capacity, among others.

The water contents determined in the laboratory ranged between 33 and 43 % and the dry densities between 1.42 and 1.24 g/cm^3, with a clear trend for the water content to increase towards the bottom part of the barrier. The blocks had water contents similar to those of the adjacent GBM, and their density had decreased from an initial value of 1.7 g/cm^3 to values close to 1.4 g/cm^3, similar to the average values found in the GBM. The degrees of saturation of the barrier ranged between 95 and 101 %. It is considered that the average pore water density in the barrier was close to 1.0 g/cm^3 due to the low average dry density of the bentonite. The basal spacings of the smectite indicate that 3 water layers were completely developed in the interlayer (values around or higher than 1.9 nm). The pore size distribution determined by MIP showed that during operation the GBM a macropore family with diameters around 13 µm that did not exist in the original material had developed. For the blocks, the average size of the macropores was slightly smaller. However, most of the porosity of the samples analysed belonged to the microporosity size (less than 2 nm).

The hydraulic conductivities measured in the GBM samples retrieved were in the range from $8 \cdot 10^{-12}$ to $2 \cdot 10^{-13}$ m/s, mainly related to the dry density of the samples. These values were determined using Pearson water as fluid. When comparing these values to those expected for untreated FEBEX bentonite of the same dry density permeated with deionized water, it was found that the values for the GBM were slightly above the theoretical ones. This can be attributed to the different salinity of the water used in the tests, since a higher salinity would increase permeability. Consequently, it is considered that the permeability of the GBM did not change during operation.

The suction of the samples was computed from the relative humidity and temperature measured with psychrometers in the laboratory in samples of the blocks and the GBM. The values obtained ranged between 2.1 and 4.7 MPa. The suction decreased with water content, and no difference could be found between the GBM and the blocks. The swelling capacity of the GBM samples was also tested. The preliminary results indicate that this is slightly below the values expected for untreated FEBEX bentonite. The thermal conductivity was measured on the blocks and in some GBM samples. The values obtained were between 0.95 and 1.33 W/(m·K), with a trend to find higher values in the GBM than in the blocks for samples of the same water content.

Geochemical Outcome of the Dismantling of "EB" Experiment

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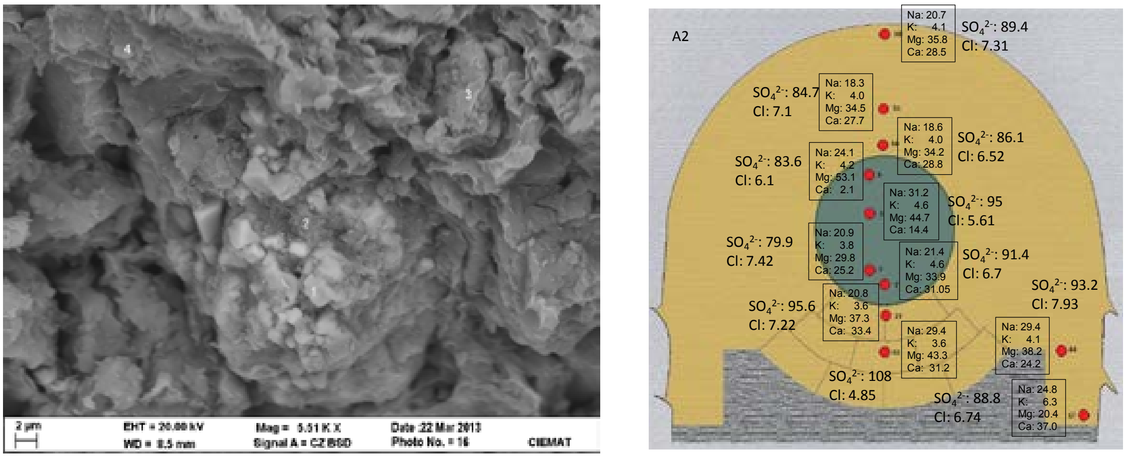
The Engineered Barrier Emplacement Experiment in Opalinus Clay or "EB" Experiment aimed the demonstration of a new concept for the construction of SF and HLW repositories in horizontal drifts, in competent clay formations. The project consisted on a real scale isothermal simulation of this construction method in the Opalinus Clay formation at the Mont Terri underground laboratory in Switzerland. The barrier was made of highly compacted bentonite (FEBEX bentonite, Spain) blocks, supporting a dummy canister; and granular bentonite pellets. The drift was sealed with a concrete plug. The whole system was artificially hydrated with Opalinus Clay pore water.

After 11 years of operation the experiment was dismantled between the 19th of October 2012 and the 1st of February 2013. Different water and rock samples were taken for analysing the possible mineralogical, geochemical and pore water chemistry changes in: a) the granular Buffer material (GBM) at different sections (A2, CMT2, CMT3), b) the bentonite blocks, and 3) the EDZ section, by analysing the Opalinus Clay-GBM interface.

The aim of this work is to present the main processes observed in the bentonite and Opalinus Clay samples. During more than eleven years of hydration with the high saline pore water of the Opalinus Clay, physico-chemical, geochemical and mineralogical alterations of the bentonite could have produced. Redistribution and neoformation of mineral phases, dissolution processes, changes in total absorption capacity (CEC) and crystallochemical changes in the smectite could have affected the physico-chemical and mechanical properties of the bentonite.

As preliminary results, corrosion processes due to SBR bacterias were observed in the GMB close to the contact with the front part of the canister (CMT2 section), where no geotextile material was placed. Here, a neoformation of pyrites (Figure 1a) was detected. However, in the other sections, no corrosion was observed due to the geotextile covering avoided the anodic/catodic processes between the carbon steel and the saturated bentonite. An increase of magnesium at exchange positions of the smectite particles was observed in all the sections (Figure 1b). Possible modifications of the crystallochemistry of the smectite particles are being analysed, due to increase of the magnesium content at octahedral positions in some samples.



a) b)

Fig. 1: a) Neoformation of pyrites (1) due to SBR bacterias (CMT2-023)
b) Distribution of soluble salts and exchangeable cations in the GBM samples at section A2

New Insights from In-situ Experiments in Crystalline Host Rock

The Bentonite Rock Interaction Experiment

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The Bentonite Rock Interaction Experiment (BRIE) is a field experiment which addresses the hydraulic interaction between the system components of compacted bentonite and near-field host rock composed of hard and fractured crystalline bedrock. This experiment is also addressed in a joint modeling task (Task 8) of the Äspö Task forces on Engineered Barrier Systems (EBS) and on Groundwater Flow and Transport of Solutes (GWFT).

Both the field experiment and the modelling have mainly addressed the importance of individual fractures for the hydration of the bentonite but also focused on an increased understanding of the possibility of matrix flow. Results from the in-situ field experiment; additional laboratory experiment and modelling indicate that the hydration is uneven and controlled by the main conductive fractures. Moreover, in-situ field experimental results indicate that the hydration from the matrix may be insignificant and that the axial spread of moisture within the bentonite could be controlling the hydration between the conductive fractures.

The experimental results have so far been hard to simulate with the independently determined laboratory values of matrix hydraulic conductivity. Hence the modelling indicates that the present understanding of flow through the matrix of a hard and fractured rock need to be further addressed in the future.

FEBEX In Situ Test
After 18 Years of Monitoring – Final Dismantling In 2015

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The FEBEX experiment at the Grimsel Test Site (GTS) consists of an in-situ full-scale engineered barrier system (EBS) test for the disposal of high level waste (HLW) performed under natural conditions. The experiment is based on the Spanish reference concept in crystalline rock in which the canisters are placed horizontally in drifts and surrounded by a clay barrier constructed of highly compacted bentonite blocks. It was initiated and led by Enresa in 1995 and has been one of the research subjects in three subsequent European projects. In 2008, a consortium consisting of SKB, Ciemat, Posiva, and Nagra (and since 2013 KAERI) undertook the continuation of the experiment under the project name FEBEXe.

Heating started in 1997 and since then a constant temperature of 100°C has been maintained, while the bentonite buffer has been slowly hydrating in a natural way. A total of 632 sensors were installed in the clay barrier, the rock mass, the heaters and the service zone to measure the following variables: temperature, water saturation, humidity, total pressure, displacement, water pressure. A partial dismantling and sampling of the EBS was carried out during 2002.

One of the main goals of the experiment, namely demonstrating the feasibility of handling and constructing the EBS, has been fulfilled with the construction and operation of FEBEX. Considering the need for a detailed understanding of early time coupled processes to assess the near field evolution – e.g. in terms of evolution of thermal conductivity of the partially saturated buffer; role of thermal convection; gas transport capacity of the near field (saturation history); geochemical evolution of the near field (e.g. iron/bentonite interactions) - the remaining part of the experiment was left intact. The second heater has been thus maintained at the same constant temperature since 1997, which makes FEBEX/FEBEXe the longest running experiment of its scale. After 18 years of operation it is planned to dismantle the experiment in 2015.

The long monitoring phase and the partial dismantling in 2002 show that the EBS has largely performed as expected and the major processes and couplings affecting the buffer saturation during the initial thermal period identified prior to the start of the experiment have been confirmed.

Much of the buffer is saturated and significant swelling pressures have developed close to the rock. The low permeability of the saturated bentonite close to the rock ensured a slow saturation and showed that inhomogeneity in rock properties have no influence on buffer saturation. In addition, the buffer inhomogeneity due to construction has played a smaller role than expected and a relatively uniform axisymmetric thermal, saturation and stress response controlled by the distance from the heater has been observed. Density gradients within the buffer have developed due to swelling from the hydration and drying and shrinkage near the heater. These density gradients were evident in the data from the partial dismantling in 2002 and they followed an axisymmetric saturation pattern, which was reproduced in equivalent laboratory tests (VILLAR et al., 2012) and was predicted by coupled models (GENS et al., 2009).

The role of 2nd order processes and couplings on saturation has become more important as the hydraulic gradients have reduced and has potentially been accentuated by the application of constant temperature at the heater surface. Such processes/couplings include: i) thermal osmosis; ii) threshold gradients for flow within the bentonite; and ii) the influence of evolution of porosity structure of the bentonite.

The FEBEX in situ dismantling project (FEBEX-DP) will provide a unique opportunity for sampling an engineered barrier and its components, that underwent continuous heating and natural resaturation for 18 years. The planning of FEBEX-DP was initiated at the end of 2013 with the following objectives:

- Characterisation of the key physical properties (density, water content) of the barrier and their distribution
- Characterisation of corrosion processes on instruments and coupons under evolving redox conditions and saturation states
- Characterisation of mineralogical interactions at material interfaces and potential impacts on porosity
- Further increasing understanding of the THM processes affecting the EBS through integration of the monitoring results and dismantling results

A large sampling and analysis programme is being developed, whereby additional partners are invited to participate in the FEBEX-DP project.

Borehole Plugging Experiment in OL-KR24 in Olkiluoto

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Posiva and SKB performed a joint borehole plugging experiment in 2005 in Olkiluoto, Finland. The experiment was performed in 76 mm drillhole called OL-KR24, an approximately 550 m deep investigation hole in a future shaft location in the ONKALO URCF. The used borehole closure materials in the plug were borehole backfill, which is dense bentonite cylinders in perforated copper tubes, and quartz concrete (Posiva WR 2006-35). The borehole backfill was produced as a 10-m-long section and below and above it is 5 m of quartz concrete (low-pH concrete). The borehole backfill was installed with drilling equipment from ground level approximately to the depth of 520 m. The remaining hole above the upper quartz concrete section was filled with regular concrete.

This year the OL-KR24 borehole closure materials were drilled in ONKALO from the shaft bottom in the level 455 m. The work was implemented by first opening the standard-concrete-filled section of the hole, which is about 50-60 m long drilling depth, then reaming it larger in four stages from the original size of 76 mm to the size of 146 mm and then overcoring the borehole backfill section. The overcoring was done as long sections that were cut to the lengths of the drill pipes (1.5 m) when lifted from the hole.

The aim of the project is to verify the performance of the borehole backfill. The outcome of the project has an impact on the design of the borehole closure as it would implicate how the borehole backfill has remained in place, swelled and isolated the section when installed as described. Samples of concretes were also collected for further studies.

The drilling project started in August 2013 and ended in September. The material investigations are planned to be done by the end of 2013.

Findings from the Retrieval of the Outer Section of Prototype Repository at Äspö Hard Rock Laboratory

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The Prototype Repository trial at Äspö Hard Rock Laboratory is a full-scale field experiment in crystalline rock at a depth of 450 meter. It consists of six deposition holes with copper canisters and MX-80 buffer and simulates conditions relevant for the Swedish KBS-3V concept for disposal of high-level radioactive waste in crystalline host rock. The gallery is divided into two sections and the corresponding two compartments of the deposition tunnel were backfilled with a mixture of bentonite and crushed rock and each sealed with a plug of concrete. The trial was installed during the period 2001-2003. In total, more than 1,000 sensors were installed to monitor total pressure, water pressure, temperatures, strains and displacements etc. Each canister contains electric heaters to simulate the residual effect from spent fuel. Natural wetting from the rock`s ground water of buffer and backfill has been ongoing until the end of year 2010 when the plug to the outer section was breached and 900 tons of backfill, 40 tons of buffer and two canisters were retrieved during 2011.

The scope of the retrieval of the outer section was to particularly study the following tasks:

1. At the installation of the buffer and the backfill the density and water content of the materials were known. It was expected that during the water uptake the water content and the densities of the materials would be changed. By extensive sampling of buffer and backfill an image of density and water saturation of buffer and backfilling could be produced after more than 7 years wetting. Important areas to specifically study were the interface between the buffer and the backfill and the interface between backfill and the rock surface of the tunnel.

2. During progress of the trial the buffer and the backfill has become saturated by water from the surrounding rock. Furthermore, it has been subjected to high temperatures during a long period. This can possibly affect both the geochemical and the hydro-mechanical properties of the buffer material. By extensive sampling and testing of the properties of the buffer material and compare the results from tests made on reference samples the possible changes in the buffer properties was studied.

3. Biological and chemical activity in the buffer and backfill has been measured during the progress of the trial by sampling of water and gas and during dismantling samples were taken to verify these measurements.

4. After removing the backfill, buffer and canister the rock in and around the deposition holes has been studied to observe changes, which possibly have occurred in the rock mass.

5. An extensive THM-modelling of the trial has been made. The purpose with this task is to compare modelling results with the findings from the measurements of the density and water content of the buffer and backfill.

An extensive examination program was performed during 2012-2013 and complete results are reported in beginning of 2014.

Investigating Gas Interaction in Laboratory and In-situ Experiments

Observations from Four Gas Injection Tests conducted in a Full Scale KBS-3v Setup; The Large Scale Gas Injection Test (Lasgit) conducted at the Äspö Hard Rock Laboratory, Sweden

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Up-scaling of observations from the laboratory to field scale is of fundamental importance, not least in the safety case for geological disposal of heat emitting radioactive waste. One of the key problems in “Rad Waste” is the fate of gas generated should the disposal canister be ruptured. Current knowledge pertaining to the movement of gas in initially saturated buffer bentonite used in engineered barriers is based on small-scale laboratory studies. These experiments have shown that gas penetration and subsequent flow is accompanied by local dilation of the buffer clay, which strongly affects porewater pressure and total stress acting within the clay.

While significant improvements in our understanding of the gas-buffer system have taken place, laboratory work has highlighted a number of uncertainties, notably the sensitivity of the gas migration process to experimental boundary conditions and possible scale-dependency of the measured responses. These issues were best addressed by undertaking a large-scale gas injection test or “Lasgit”.

Lasgit is a full-scale *in situ* canister test designed to answer specific questions regarding the movement of gas through bentonite in a mock KBS-3v deposition hole. The test is located at 420 m depth within SKB’s Äspö Hard Rock Laboratory (HRL) in Sweden. The objective of Lasgit is to provide quantitative data to improve process understanding and test/validate modelling approaches which might be used in performance assessment. The experiment has been in continuous operation since February 2005. The first two years (up to day 843) focused on the artificial hydration of the bentonite buffer. This has been followed by four campaigns of gas injection testing (Gas test 1, day 843 to 1,110; Gas test 2, day 1,385 to 2,019; Gas test 3, day 2,019 to 2,725; and Gas test 4, day 27,26 to present).

This presentation will focus on the main conclusions and observations derived from the four gas testing phases of Lasgit and compare these observations with the conclusions made from the laboratory studies. Many features of gas response are consistent between the laboratory and full-scale test, whilst there are a number of clear differences. The observed general coupling between gas, stress and porewater pressure at the repository scale is extremely important and can be explained through concepts of pathway dilatancy.

The behaviour seen in Lasgit is focussing further laboratory experimental work in order to understand the system in greater detail.

Interaction between Gas and Bentonite Seals: Small Scale In-situ Test in the Meuse/Haute Marne Underground Research Laboratory

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One experiment has been designed by the French national Agency for the management of radioactive waste (Andra) to understand the interaction between gas and bentonite seals use to close the tunnels within the repository (PGZ2 experiment).

1 PGZ2 layout

PGZ2 experiment is a set of a five horizontal boreholes drilled between two galleries to allow access from both sides and to avoid sensor equipment through the bentonite plugs (Figure 1). Two kind of materials have been tested: (i) pre-compacted bentonite plugs made with a mixture of MX80 and sand (70 %/30 % in mass), dry density about 1.6 g/cm^3 (boreholes PGZ1011, PGZ1012 and PGZ1013) (ii) pellets/powder mixture made with MX80 directly built in place (borehole PGZ1021), dry density about 1.54 g/cm^3. The resaturation of the bentonite plugs was only done by natural water from the host rock without any kind of water injection. In two boreholes gas has been injected during the resaturation phase of the plug to observe the perturbation induced by gas (in PGZ1011 during 70 days and PGZ1021 during 20 months). Other boreholes were used to see bentonite resaturation without gas injection to be able to estimate gas effects. In each borehole multiple pore pressure and total pressure sensors have been installed to follow as best as possible swelling pressure evolution and water saturation. PGZ1001 is equipped with multi-intervals completion to monitor pore water pressure between the GEX and GMR drifts.

2 Bentonite-sand mixture plug

Natural hydration of the bentonite-sand mixture was monitored in PGZ1012 and PGZ1013 boreholes. Thanks to mock-up test, the hydration scenario is that follow:

1. First, suction was applied during the steam phase via the moist air surrounding the plug. The duration of this phase was between a few hours and a few days.

2. As soon as part of the plug came into contact with the claystone the plug would hydrate more quickly. On the whole, the amount of water reaching the plug was sufficient to maintain the swelling pressure.

   - ✓ the total pressure first increased significantly (for 20 to 40 days) because of the water hydrating the outer layers of the plug. Most of the forces were applied axially due to the rigidity at the centre of the plug, whose state of saturation was close to its initial state. Then the total pressure decreased (for 10 to 30 days) as a result of the water re-balancing from the outer layers of the plug to the centre, which became increasingly plastic. Finally, total pressure increased again, indicating the uniform saturation of the plug and, therefore, the uniform swelling pressure.

The total duration to reach full hydration was approximately 500-600 days for PGZ1012 and PGZ1013 boreholes and the swelling pressure was 6.5 and 4.5 MPa respectively. The swelling pressure was set at 7 MPa. Swelling pressure equals to total pressure minus pore pressure.

For PGZ1011, gas (nitrogen) was injected at different pressure during the natural hydration of the plug (October 2009 to February 2010). The only difference for PGZ1011 concerns the pore pressure build-up which is slightly slower than the other bentonite-sand plug. The swelling pressure of this plug is closed to 5 MPa.

The gas injection test showed that the gas did not penetrate the plug (based on the gas pressures and flow rates tested), even though it was injected directly in contact with the plug. This indicates that all of the bentonite / stainless steel, packer / claystone and resin / claystone interfaces play a major role in the transfer of gas in this type of configuration. Thus, some of the gas migrates along the borehole, and this migration is clearly facilitated by its geometry. The borehole’s initial break-outs do not favour ideal contact between the rubber of the packers and the claystone, despite the convergence of the claystone around the packer.

In 2011, after full hydration, hydraulics tests were performed to get the water conductivity of the bentonite-sand plugs. All water conductivities were closed to 1 to $5 \cdot 10^{-13}$ m/s. Those values are in agreement with the target value based on dry density of bentonite-sand mixture. The gas injection test performed in PGZ1011 during hydration had no impact on the value of the water permeability.

3 Pure bentonite powder and pellets plug

In the borehole PGZ1021, gas (nitrogen) was injected at constant flow rate immediately after installation, on one of the surfaces of the fritted disc. This gas injection test started in April 2011 and was stopped in December 2012 (during 20 months).

Despite the gas injection, measurements taken in PGZ1021 are, on the whole, fairly close to those taken in the other compacted bentonite plugs (PGZ1011 to PGZ1013). The main difference is in the hydration period, which would be considerably longer than in the other boreholes. Furthermore, the hydration process appears to be more complex due to the granular texture of the core.

A quick gas test performed in November 2012 has shown that both plug faces are still connected to gas. In details, this test indicates that the centre of the plug is quite largely saturated but the peripheral zone is largely desaturated. Indeed, bentonite density is lower at the roof because of the mode of filling. It is likely that this area is the privileged pathway for gas flows.

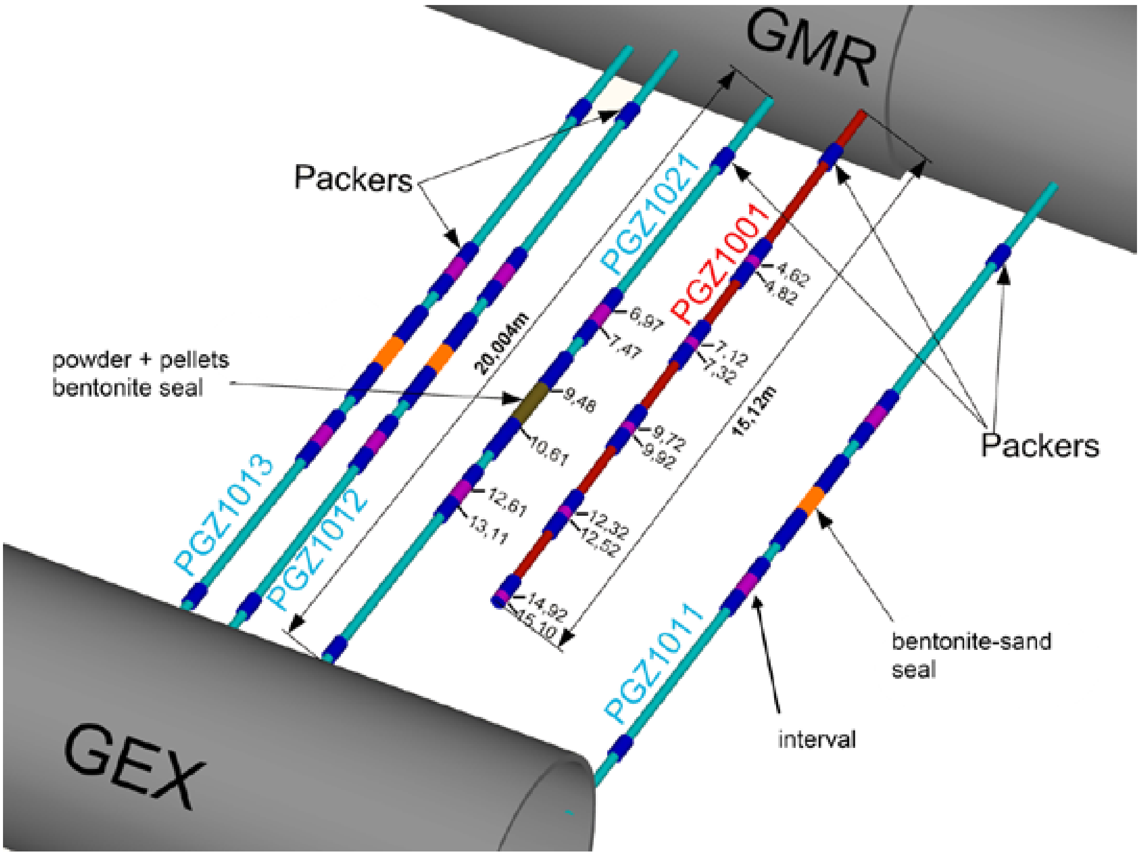

Fig. 1 : General layout of the small-scale gas-bentonite seal test : PGZ2 experiment

Hydro-mechanical Properties of Interfaces in Sealing Plugs constructed of Bentonite-Block Assemblies

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Deep underground repositories for radioactive waste generally rely on a multi-barrier system to isolate the waste from the biosphere. It consists of the natural geological barrier provided by the repository host rock and its surroundings, the waste container and an engineered barrier system (EBS), i.e. the backfilling and sealing of shafts and galleries to block any preferential path for radioactive contaminants. Bentonite emplaced in compacted block form is the preferred option for the clay buffer for most waste management organizations.

In assessing the performance of bentonite block masonries, in addition to the matrix properties of the sealing material, also technically related conductive discrete interfaces inside the sealing elements itself and to the host rock may have to be considered. They may act not only as mechanical weakness planes but also as preferential fluid pathways. For instance despite the assumed self-sealing capacity of bentonite during swelling inherent existing interfaces may be reopened during the unavoidable fluid pressure build-up due to gas production in the waste packages. Our lab investigations are aiming on a comprehensive hydro-mechanical characterization of interfaces in bentonite buffers, i.e. (1) between prefabricated bentonite blocks itself and (2) on mechanical contacts of bentonite blocks to the host rock, e.g. granite.

As reference material we used pre-compacted bentonite blocks (250 mm x 125 mm x 62.5 mm) consisting of a sand clay-bentonite mixture. The investigations comprise:

- Hydro-mechanical characterization of the initial “dry” bentonite-block properties, i.e. matrix strength, permeability and shear strength between interfaces;
- Pre-saturation of the bentonite blocks with long-term water injection tests in a new designed oedometer cell (duration of several month up to two years) with different sample constellations (block/block resp. block/host rock) under well controlled stress and swelling conditions;
- Characterization of the saturated state:
    - Gas injection tests on matrix samples and aggregates with interfaces (block/block, block/granite);

- Shear tests to quantify mechanical interface properties of pre-saturated bentonite blocks (block/block, block/granite) under well-controlled shear forces or displacements.

Our results document that despite existing interfaces the bentonite block assembly behaves during the saturation of the buffer not different than the homogenous matrix. This has been confirmed by gas injection tests on the former interface as well by shear tests. The outstanding observation is that our results convincingly demonstrate that interfaces between bentonite bricks may “heal” (not only seal) as it was physically verified by confirmation of cohesion after pre-saturation.

Swelling and Gas Injection Tests on a Sand Bentonite Mixture: Investigation on the Effects of Pore Water Chemistry

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Sand bentonite (S/B) mixtures are considered as backfilling materials for cavern plugs and repository seal in the Swiss concept for nuclear waste storage of low and intermediate level (L/ILW). One important aspect regarding the performance assessment of these repositories, in the long term, is the consequence on the performance of engineered barriers of the gas generated by microbial degradation of organic material and by anaerobic corrosion of the waste canister. The main aim of the repository plugs and the repository seals is to increase the gas storage and the gas transport capacity of the backfilled underground structures without compromising the radionuclide retention capacity of the host rock as well as the engineered barrier system. Initially the generated gas is evacuated by diffusion through the pore water, then, once the gas concentration exceeds the gas solubility, the pressure increases and other transport mechanisms may appear and become predominant (two-phase flow and gas breakthrough).

During the working life, the backfilling material is saturated with water coming from the surrounding host rock; therefore changes in the pore water salinity may happen and consequently the swelling capacity as well as transport properties of the bentonite-based material can be altered.

In this study a series of swelling and breakthrough tests were performed on a target S/B mixture in proportion 80/20 in dry mass. Tests were carried out on different dry densities of the mixture and by changing the osmotic suction of the pore water. The tests aimed at determining the relationship between the pore water composition, the swelling behaviour and the breakthrough pressure. Microstructural investigations were run in order to interpret the observed behaviours considering the porosity evolution upon osmotic suction variations. The obtained results showed that an increase of the osmotic suction produces a reduction of the swelling capacity and of the breakthrough pressure. This behaviour is associated with the reduction, or even a total lack, of the capacity of the bentonite to fill up the voids among the sand grains.

New Insights from Laboratory Experiments

THMC China-Mock-Up Test about the Buffer Material for HLW Disposal in China

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According to the preliminary concept of the high level radioactive waste (HLW) repository in China, the large scale China-Mock-up test, intended to study the Thermal-Hydro-Mechanical-Chemical (THMC) behavior of Gaomiaozi (GMZ) bentonite under relevant repository condition, is built. The experiment could demonstrate the technical feasibility, to evaluate THMC processes taking place within the compacted bentonite during the early phase of HLW disposal and to provide a reliable database for numerical modeling and further investigations.

The facility is designed as a vertical cylindrical tank of 900 mm internal diameter and 2,200 mm internal height, filled with compacted GMZ-bentonite with total dry density of 1,600 kg/m^3. A heater of 300 mm diameter and 1,600 mm length, which simulates the HLW canister, is placed inside the compacted bentonite blocks and pellets. The installed hydration system on the exterior surface simulates the supply of groundwater which is sampled at the depth of 500 m in Beishan site. More than 160 sensors have been installed within the experiment to measure the important parameters, including the temperature, pore pressure, relative humidity, water injection pressure and the total pressure.

The operational phase started on 1st April 2011. The temperature is increased progressively to 90°C which is the maximum temperature expected on the canister surface according the current disposal concept in China. Finally, the system was switched to the constant temperature control mode. In order to avoid potential damage to the sensors by a sudden saturation process, the hydration was initially controlled by a water injection rate which was increased gradually from 400 g/day to 1200 g/day in the first 800 days. The hydration is controlled by water pressure 0.2 MPa now and will increase to a constant pressure of 2 MPa with the water consumption rate decrease.

Based on the current recorded experimental data, several aspects are addressed in the paper, including the observed THM behavior of the compacted bentonite, the displacement of the electrical heater. The temperature of compacted bentonite had continuously increased and then keeps the constant temperature with the temperature of heater increased and constant temperature control. The saturation process of the compacted bentonite is strongly influenced by the competing mechanisms of drying effect induced by the heater and the wetting effect by the water penetration. As a result, the desiccation-saturation process

was observed in the zone close to the heater. An upward displacement of the heater was also noticed, which verified potential influence of buffer material on the stability of canister. The experiment is a valuable step in establishing the viability of the reference concept, and making progress in the understanding of the behavior of buffer material under THM coupled condition.

Keywords: Deep geological disposal, GMZ Bentonite, Thermal-hydro-mechanical behavior, China-Mock-up

Temporal Evolution of the Fe/FEBEX Bentonite System under Simultaneous Hydration and Heating – Results up to Seven Years

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Corrosion behaviour of the canister depends strongly on the evolution of environmental conditions (Johnson, 2008). Moisture conditions at the canister surface will dictate the mechanism and extension of the corrosion process. Deliquescence of salts and other impurities could favour the initialization of localized corrosion. Saline fronts are expected to be formed during the saturation of the clay barrier and chloride and sulphate could move by advective transport towards the metallic container due to the hydraulic and thermal gradients that will be established along the bentonite barrier, compromising canister performance. This work reports the results of an experimental programme designed to investigate the geochemical processes occurring at the canister/FEBEX bentonite interface during the pre-saturation phase. In the tests, a compacted bentonite block in contact with Fe powder was subjected simultaneously to constant hydration and heating, in opposite directions, in order to simulate both, the hydraulic and thermal gradients generated along the clay barrier.

Two of the six cylindrical cells assembled in August 2006 were dismantled during EU research project NF-PRO after 6 and 15 months of operation. The third and fourth ones were dismantled in the framework of the PEBS EU Project after 52 and 82 months of operation. A detailed sampling of the iron/bentonite interface and the iron itself was performed for geochemical characterization. In all cases, an advective movement of salts (Cl and Na, mainly) towards the heater was observed. Chloride was detected in corrosion products from the four dismantled cells. Initial precipitation of chloride seems to play a relevant role in the first stages of the corrosion process, as it helps to initiate it. In the four dismantled tests, Fe powder seems to undergo slight corrosion. Sequential dismantling of the cells allowed studying the influence of time and oxidation-reduction potential on the nature of the corrosion products. Different iron phases were found as a function of the test duration: Fe(III) oxides at shorter times and mixed Fe(II) / Fe(III) phases at longer durations. Goethite and hematite were the main corrosion products identified in the 6-month and 15-month tests, respectively. In the 52-month test, Fe(II) and mixed Fe(II) / Fe(III) phases were the prevailing corrosion products. After 82 months, a black thin magnetite layer was found coating most of the Fe powder. Fe-related mineralogical changes were not observed at the Fe/bentonite interface. However, distribution of exchangeable cations varied along the bentonite column, magnesium and sodium following complementary trends. Exchangeable sodium increases close to the hydration surface and drops near the interface, whereas magnesium decreases in saturated zones and increases near the heater. Results obtained in these tests will be completed after the dismantling of the last two experiments on-going at the moment.

Johnson, L. & F. King (2008): The effect of the evolution of environmental conditions on the corrosion evolutionary path in a repository for spent fuel and high-level waste in Opalinus Clay. J. Nucl. Mat., 379: p. 9-15.

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An Experimental Approach to Study the Long-term Alteration of Compacted Bentonite Affected by Cement Degradation and Iron Corrosion Products

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The aim of this study was to obtain evidences on the physical and geochemical processes occurring by the combined effects of cementitious materials from the concrete degradation and magnetite from steel corrosion on the bentonite barrier during disposal of radioactive waste.

The experiments try to reproduce the repository conditions prevailing from 1,000 to 3,000 years after emplacement. A lime mortar was used as a source of calcium and alkalinity presumed during concrete degradation at long-term. Besides, powder of magnetite was used as it is the end-member of the transformation of $Fe(OH)_2$ in the anaerobic corrosion of cast iron and C-steel. Either a natural FEBEX bentonite or a pre-treated sample depleted in exchangeable Mg and enriched in K was used. This later state characterizes the bentonite buffer placed at 12 cm from a long-term modeled bentonite-OPC concrete interface. Experiments, with both types of bentonite, were performed simultaneously in cylindric probes (50 mm diameter, 25 mm length), confined in a teflon sleeve/steel case cells. The probes were composed of cement mortar facing compacted bentonite, which is in contact with magnetite pressed powder. They were hydrated for 18 months at 60ºC and constant pressure through the mortar with an artificial Na^{+}-Ca^{2+}-SO_4^{2-}-type water obtained in the laboratory after the analysis of the Spanish reference clayey formation (Turrero et al., 2006).

After dismantling and sampling the probes, distribution of soluble ions was obtained by performing aqueous extracts in different parts of the cells. Exchangeable cations and mineralogy was studied in bentonite by different instrumental techniques. All the cells were fully hydrated in less than 3 months. Iron migration or any impact of the corrosion products in the bentonite was not noticeable. Both, mortar and magnetite acted as sinks of chloride and sulphate. Small quantities of Al-sulphates and carboaluminates, which can allocate chlorides, were determined near the mortar-bentonite interface. A calcium front was developed from the mortar towards the bentonite, in which C-S-H phases formed. Portlandite dissolved in mortar near the bentonite interface and the dissolution towards the hydration source was more extended in natural bentonite than in the pre-treated bentonite. Al penetrated in the mortar from the bentonite in accordance to the Al-sulfate phases. Mg concentrated at the interface with mortar in the natural bentonite, however, this was not observed in the pre-treated bentonite. The precipitation of Mg-phases in the natural bentonite may buffer the C-S-H front, which is more developed in pre-treated bentonite. This means that natural bentonite has potentially higher buffer capacity to attenuate the calcium alkaline front than the pre-treated one. A low porosity bentonite-mortar zone was experimentally created. This should be carefully studied in order to predict the further development of a diffusive alkaline alteration front through bentonite that could control the reduction of hydration or alkaline alteration at long-term.

Turrero, M.J. et al. (2006). Journal of Iberian Geology, 32, (2), 233-258.

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"Clay/Iron-Interaction"- Experiments on a Series of Bentonites

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Bentonites are suitable candidates as buffer and backfill materials in HLW-repositories. The main objective of this research was to enhance the understanding of the interactions of bentonite with iron in the near field of a HLW-repository. A target was to recognize the mineralogical interaction of bentonite with iron powder simulating the contact of bentonite with steel containers (by different "clay/iron-interaction"-experiments).

Compacted MX80 bentonite and Friedland clay were used as starting materials for clay/ iron interaction experiments in percolation systems. Iron was introduced in the system in two different forms. In one series of experiments metallic iron was added as powder to the bentonite and compacted to a raw density of 1.6 g/cm^3. In a second series of experiments iron was added only to the percolating solution in the form of $FeCl_2$ with different concentrations (0.1 – 10^{-4} mol/kg water in the solution). $FeCl_2$ was added to two high saline solutions an IP21- and a NaCl saturated solution. These experiments were conducted at three different temperatures (25°C, 60°C, 90°C).

XRD and TEM – EDX measurements were the major analytical techniques applied in this research. FT-IR and XRF analyses were used as additional tools for the characterization of the structure and composition of the smectites.

Smectite was the main phase and full expandable in all reaction products. Smectite has shown different octahedral Fe-amounts in the different reaction products (proofed by XRD, TEM-EDX and FT-IR). Also tetrahedral Si was different in the different reaction products (proofed by TEM-EDX and FT-IR). "Illitization" was found to be the main process of smectite alteration. This process was supported by the percolation design of these experiments. In several cases, smectitization was observed in case of highest degree of Fe^0-oxidation to Fe^{2+} and Fe^{2+}-oxidation to Fe^{3+}. It was overriding the removing of dissolved Si by percolation.

The alteration of smectite was mainly pH-driven because of high alkalic pH-value caused by Fe-corrosion.

The altered smectite has shown with increasing Fe-concentration ($FeCl_2$ between 0.1 and 10^{-4} mol $FeCl_2$ in solution) also three different types of modified properties for swelling pressure and permeability: (i) swelling pressure increased and caused a reduced permeability, (ii) swelling pressure is reduced and the permeability is also reduced and (iii) swelling pressure was constant and the permeability was increased. In first case, process was accompanied by reduced total charge of smectite in reaction products. The higher pressure and reduced permeability is controlled by the mineralogy of smectite. In the second case, XRD-data indicate a precipitation of Fe-oxides in the low temperatures experiments. Si-precipitation is assumed for high temperature experiments (90°C) indicated by TEM-investigations. Precipitation is cementing the smectite aggregates and reduces the permeability and also the swelling pressure. Expendability is reduced by cementation of smectite aggregates. Finally, in the last case a channel-formation due to increased cementation was identified as the reason for the observed behaviour.

Different mixed layer phases like kaolinite-smectite-vermiculite, berthierine-saponite, chlorite-vermiculite and cronstedtite-vermiculite were also identified as minor phases.

Mineralogical Characterization of all Samples of the Second ABM-Package and Implications for the Identification of Suitable and Less Suitable Buffer Materials

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The “alternative buffer material test” (ABM) performed by SKB in the HRL Äspö is the only up-scale experiment in which different bentonites are compared. 11 different materials are compared in different setups with different running time. Yet, the first package, ABM 1, was excavated and analyzed. The second package was excavated recently and samples are currently investigated by all project partners, including the section “technical mineralogy and clay mineralogy” of BGR. A few years ago BGR selected one block of each material of the first package of the ABM. CEC results proved that these samples were too few to understand the reactions, particularly the significant cation exchange. Furthermore, mineralogical differences as a slight Mg-increase (up to 3 wt.% MgO, XRF), some changes of the XRD d_{060} reflection, and the sporadic appearance of an IR band at 680 cm^{-1}, indicating trioctahedral domains, could not unambiguously be identified as material property since these changes may also be restricted locally. Therefore, BGR decided to investigate all blocks of the ABM-2 package. Four samples including the contact with the iron tube were collected for each block (without any vertical variation), ground, and analyzed with respect to the mineralogical composition (overall composition and position of d_{060}), the CEC including cation population before and after, the chemical composition (incl. C and S), and the possible appearance of the 680 cm^{-1} IR band. Results were also interpreted with respect to conclusion for distinguishing suitable from less suitable materials.

An Insight into the Water Retention Behaviour of MX-80 Granular Bentonite

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This study aims at investigating the microstructural evolutions of highly swelling MX-80 bentonite during cycles of wetting and drying. The use of MX-80 bentonite is foreseen in the radioactive waste repositories as compacted blocks or in granular form around the canisters. Bentonite will function as buffer under confined condition in the repository. An improved understanding of the water retention behaviour and the microstructural evolution of the buffer material is needed to predict and interpret the repository behaviour.

In this study, a new technique called 'Micro-cell' is presented to analyse the water retention and microstructural features of MX-80 granular bentonite. The Micro-cell is a constant volume cell used in combination with a dewpoint potentiometer to obtain the water retention curve. The technique provides an accurate evaluation of the the degree of saturation and air-entry value of highly swelling bentonite at a given compaction dry density. On the other hand, the Micro-cell provides representative samples for microstructural investigations by means of Mercury Intrusion Porosimetry analysis. Tested samples can be in fact freeze-dried directly in the device. In this way it is possible to investigate the microstructural evolutions of the saturated sample under a given swelling pressure and avoid porosity changes due to stress release. Experimental results are presented showing the hysteresis behaviour of the water retention curves of compacted MX-80 bentonite and the coupled role of the microstructure and the wetting-drying history. The microstructural analysis indicates in fact a significant change of the microstructure due to the hydration process starting at degree saturation close to one. The change of structure due to the saturation in constant volume conditions converts the initial double structure porosity of the compacted granular bentonite into a single mode pore size distribution. The collected results show how this change of porosity distribution affects the hysteresis water retention behaviour of the material for the next cycles of wetting/drying.

Geochemical Investigation in an Effort to Increase Bentonite Barrier's Thermal Load Capacity to Accommodate 32-PWR Dual Purpose Canisters

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Bentonite diagenesis at temperatures greater than 150°C is particularly important to the U.S. repository program, which is investigating solutions for disposal of approximately 140,000 MT of spent fuel. Clay-based buffer and backfill materials are important elements of alternative disposal concepts for clay, shale, or crystalline rock in the U.S., but waste packages could be larger and hotter than those being considered by international disposal programs. Hence, the performance of clays at temperatures of 150°C or higher in disposal environments is an area of active R&D. Mineral alteration, steam-induced swelling loss, silica precipitation, and smectite interaction with waste canisters are some of the more prevalent concerns regarding bentonite stability during heating and cooling stages. The focus of this experimental work is to expand our understanding on the hydrothermal stability of bentonite barriers under a range of geochemical, mineralogical, and engineering conditions.

Hydrothermal experiments were performed at 150 to 160 bars and temperatures up to 300°C for five to six weeks. Unprocessed Wyoming bentonite clay was saturated with a K-Ca-Na-Cl-bearing water (≈1,900 mg/L total dissolved solids) at a 9:1 water:rock mass ratio. The pH, K^+, and Ca^{2+} concentrations decreased during each reaction, while $SiO_{2(aq)}$, Na^+, and SO_4^{2-} concentrations increased. Precursor clinoptilolite underwent extensive recrystallization after six weeks at 300°C producing a Si-rich analcime in addition to authigenic silica phases. This zeolite alteration could promote a ≈2% loss in the total bentonite volume with an increase in silica concentration. Overall, it would appear that silica levels are controlled by the zeolite reactions and smectite partial dissolution. Even though zeolite and silica reaction kinetics have to be considered, the zeolite alteration appears to be restricted to the temperatures greater than 200°C. Additionally, pyrite decomposition is first observed at ≈210°C, producing available H_2S to further react with the metal plates promoting sulfide-induced corrosion.

There was no evidence of illite-smectite mixed-layering from any of the experiments conducted in this investigation. High Na^+ activity with a limited supply of K^+ appears to have significantly retarded smectite illitization. Maintaining an environment enriched with Na^+ or Ca^{2+}, while restricting K^+ availability might prevent or kinetically hinder smectite alteration at elevated temperatures and pressures. Additionally, the higher hydration

energies associated with Na^{+} and Ca^{2+} might help maintain swelling pressure if illitic layer charges were to develop after used fuel emplacement.

This work shows that host rock composition, bentonite composition, and groundwater chemistry are important factors in long-term bentonite stability for water saturated conditions at elevated temperature. Investigations of bentonite and other potentially suitable buffer or backfill materials will continue, with the objective to identify cost effective solutions that maintain low permeability, chemical stability, and swelling properties at temperatures of 150°C and greater.

Investigation of the Thermal Stability of Materials to be used in a High-Level Nuclear Waste Repository

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The decay heat of radioactive waste that is disposed of in an underground repository causes a temperature rise in the host formation as well as in the materials used for the construction of drift seals and borehole plugs. Increased temperatures induce structural and mineralogical changes in the materials which influence the permeability of the barriers. Due to the formation of cracks, flow paths can be generated, and the bond between the sealing material and the rock can be affected.

Comprehensive investigations were carried out to determine temperature limits for the host rocks, which were then used as design criteria for repositories and to specify maximum permissible temperatures for the waste packages. Thus, the design temperature of heat-generating waste disposed of in rock salt is limited to 200°C at the contact between the waste package and the host rock. The temperature of carnallitite is not to exceed 167°C. However, in the past, less attention was paid to the thermal stability of sealing materials considering the pressure dependence of dehydration processes.

With regard to cementitious materials it is generally assumed that the release of crystal water begins at temperatures above 105°C (atmospheric pressure), coupled with an increase in permeability of the contact zone. The bond strength begins to decrease at temperatures of approx. 120°C. First experiments indicate that the dehydration starts at lower temperatures in a saline environment due to the low water activity of salt solutions. However, the laboratory investigations focused on the thermal stability of magnesia binders, which are the most common material used for the construction of seals in salt mines. In the range of the primary rock temperature the reaction products of MgO and $Mg(OH)_2$ with $MgCl_2$-rich mix solutions are magnesium oxichlorides containing $Mg(OH)_2$, $MgCl_2$, and H_2O in the relation 3-1-8 or 5-1-8. In mass concrete structures magnesium oxichloride containing lower amounts of water, such as the 2-1-4-, 2-1-2- or 9-1-4-phase can occur.

The influence of thermal stresses was investigated on specimens stored at temperatures up to 180°C several months. Visual inspections of the samples prove the integrity of the material, although XRD analysis shows phase transformations, in particular the formation of oxichlorides, which are characterized by low crystal water contents. Dehydration begins at temperatures above approx. 90°C. With increasing temperature the crystal water content of the reaction products decreases.

The increase of the dehydration temperature with rising pressure was calculated based on the Clapeyron relation. The results were compared with the knowledge of the pressure dependence of salt mineral dehydration, as the structure of magnesium oxichlorides contains $MgCl_2 \cdot xH_2O$ comparable to carnallite and bischofite. XRD analyses were performed on samples that were saturated with $MgCl_2$-solution and stored in closed teflon boxes for at least one month.

It can be concluded that magnesia binders that contain no or thermally stable admixtures (e.g. halite) can be used in underground repositories if the temperature development does not exceed 130°C. Higher temperatures could reduce the hydraulic resistance of the seals. Hence, additional measurements are necessary for verifying the required material properties.

Alteration of Hydromechanical Behaviour of a Compacted Clay submitted to an Alkaline Fluid Circulation

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After the exploitation period, deep nuclear wastes repositories should be backfilled. Among other functions, the backfill will limit convergence of the galleries after the concrete lining breaks (i.e., after thousands of years). The backfill should also constrain bentonite seals during their hydration. Therefore, its long term hydromechanical characteristics are a key issue. Nevertheless, degradation of concrete lining of deep galleries could generate high-pH water that will diffuse into the backfill. Such fluid is likely to induce mineralogical and microstructural modifications of the backfill. The main objective of the study was to depict couplings between the hydromechanical behaviour of compacted clayey soil and the transformations induced by high pH water.

The purpose of the experiments was to reproduce the process of water circulation issued from the degradation of concrete lining through compacted material at the laboratory scale. Compacted samples made of crushed from Meuse-Haute Marne argillite (French underground laboratory site material) were subjected to the circulation of two types of water. The selected alkaline water was a portlandite-saturated solution (pH ≈ 12.4). To establish a reference point, some experiments were also performed with synthetic site water. After circulation, the samples hydromechanical characteristics were determined (i.e., shear strength, swelling properties, retention curve, saturated and unsaturated hydraulic conductivity). This was accompanied by investigations at the microscopic level to detect physicochemical processes induced by alkaline water or the site water (mercury intrusion porosimetry tests (MIP), scanning electron microscopy (SEM) and X-ray diffraction).

The first change induced by the circulation of alkaline fluid was the decrease of swelling properties of the compacted argillite. The SEM and MIP suggest that this could be related to the dissolution of the smectite, together with the formation of neoformed illite, a non-swelling clay. Opening of pores was also evidenced; this could be explained by the combination of the dissolution process and the neoformation of illite. Nevertheless, these processes did not significantly modified the hydrodynamic properties of the compacted argillite. Regarding shear strength behaviour, the circulation of alkaline fluid increased the friction angle of the compacted argillite, whereas the compressibility and stiffness remained almost constant. The microscale study showed that the alterations were located along the macropores, i.e., at the edges of the initial aggregates. Therefore, the surface roughness of the aggregates should have been modified by the circulation of the alkaline fluid, and particularly by the formation of the neoformed illite. Since the friction angle of illite is higher than that of smectitic-like clay minerals, the modifications of the shear strength could be attributed to the illite formation around the outer part of the materials' aggregates.

The results demonstrated that chemo-hydro-mechanical couplings occurred during the circulation of high-pH water and resulted in the modification of the material's mineralogy. Thus, these processes are likely to alter the sealing characteristics of a backfill constructed from compacted argillite in the very long term.

Direct Observation of Waterglass Impregnation of Fractured Salt Rock with Positron Emission Tomography

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Sealing with waterglass is one option of technical improvement of the geological barrier. The process of injection is rather involved, because it depends on the kinetics of reaction of the injected waterglass with salt and brines, on the nature of the fractures and the injection velocity. Generally, up to now only the final result of this impregnation could be tested with injection tests and tomographic methods.

We already applied PET process monitoring as laboratory method in a large number of studies of conservative and reactive flow, as well as diffusion experiments, in different geological materials. PET enables to observe the propagation of radiolabelled substances with ultimate sensitivity and with a reasonable spatial resolution of 1 mm. We now developed a method to observe the process of waterglass impregnation into salt rock with PET. Labelling of waterglass is possible by simply adding a small portion of [^{18}F]KF solution, with an activity of around 100 MBq. During the injection of the labelled waterglass into the salt rock we acquire a sequence of PET scans which yield a sequence of the spatial activity distribution in the sample. The activity per voxel is proportional to the volume fraction of waterglass.

The method was tested on small volumes of salt grit and a drill core, which was previously damaged with a geomechanical test and characterized with CT-imaging. These first examples were conducted at a low entry pressure, which limited the achievable depth of penetration and thus the achieved permeability reduction. However, PET-monitoring of the flow process before and after the waterglass injection showed significant alterations of the flow field.

Generally, this method is applicable also with other impregnation agents and matrices. Our approach, where we combine numerical process simulation based on CT-imaging with direct experimental process observation with PET is suited to improve fundamental process understanding and to verify the underlying assumptions and model codes.

Thermo-Hydro-Mechanical Behaviour of Unsaturated Buffer Materials: A Column-type Approach

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In the study of the behaviour of the buffer materials in engineered barrier system, the interaction between heat transfer, water flow, and swelling pressure have to be understood. The thermal, hydraulic flow and stress-strain behaviour take place within the clay barrier simultaneously and therefore are strongly coupled. This paper introduces a thermo-hydro-mechanical column to study one dimensional flow of water/moisture and heat as well as swelling pressure of the buffer materials. The column can apply hydraulic and temperature gradient along the column sample to simulate the in-situ behaviour of compacted unsaturated buffer materials. Temperature boundary condition at two ends of the column is controlled by means of a thermostat which allows controlling temperature from 0 to 80°C. For measurement of the variation of local thermal properties, water content, and moisture simultaneously during the testing process, the equipped sensors are installed along the column. Two load cells are installed at the top and the bottom of the column to measure swelling pressure of the buffer materials while water is supplied. The calibration for the devices considering temperature is also included. The transient relations of the unsaturated materials, i.e. between suction and water content or between thermal conductivity and water content, can be directly measured from the sensors installed along the column. The first test results with sand-bentonite mixture will be presented in this study.

Bentonite Buffer Material Saturating Simulation by Geotechnical Centrifuge

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Bentonite is one of several candidates for buffer material in radioactive waste depositories in Japan. During construction of the buffer material and emplacement of the radioactive waste, contact with groundwater is avoided by drainage. Operating tunnels are plugged after emplacement, allowing the buffer material to absorb groundwater, and then an effective engineered barrier is created. Many numerical analyses simulated this absorption, but there are few physical modeling studies.

Bentonite buffer material saturation tests were done on a geotechnical centrifuge and normal gravity with the same water pressure for the same numbers of hours. Compressed bentonite specimens which are 100 mm diameter and 20 mm height, were put into saturation test containers. Two kinds of initial dry density specimens were prepared; one was 1.6 Mg/m^3 as a proto type and 1.2 Mg/m^3 were as risk assessment. Water was streamed into the 1.6 Mg/m^3 specimens from the bottom with 0.64 MPa water pressure in 80 times gravity for 24 hours. The 1.2 Mg/m^3 specimens were injected with the same water pressure for 48 hours. Swelling pressures were recorded while the centrifuge tests and water content of each 4 mm layer were measured after the tests.

The water content distributions which were in 80 times gravity are the same as in normal gravity as the figure on the right shows. If water movement follows Darcy’s law, the saturation in 80 times gravity must be slower than in normal gravity. Therefore, the principle which is similar to diffusion exceeds the water movement found in Darcy’s law. It is concluded that the comparison geotechnical centrifuge test and the test in normal gravity is applicable to the bentonite buffer material groundwater movement study.

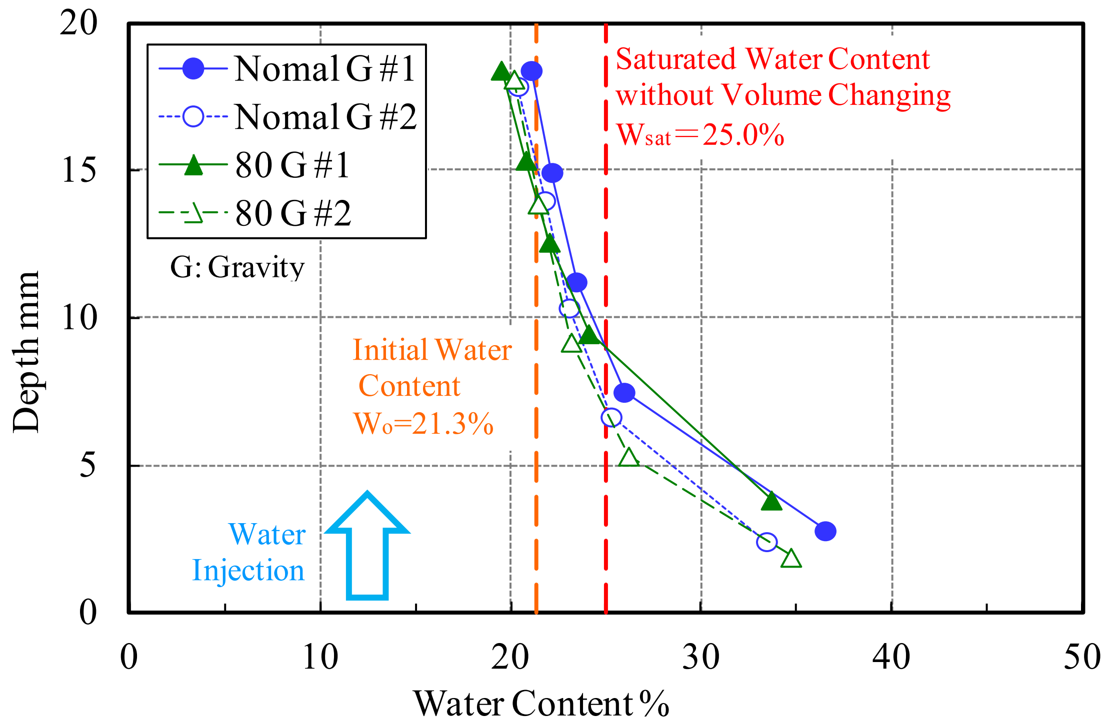

Fig.: Water Content Distribution after 24 hours: Initial Dry Density 1.6 Mg/m³

Cement Behaviour in Plug Sealing Storage Galleries – Numerical Comparison

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Czech concept of spent fuel and radioactive wastes disposal is based on deep geological repository made of underground galleries built in granitic host rock. In case of horizontal disposal, galleries would be sealed by concrete-bentonite plugs. However, presuming long term performance of deep geological repository (10^5 years at least), surrounding ground water would chemically alter the plug. Thus cement evolves chemically in time, forming for example high pH brine (pH > 12). Such a solution can impact the performance of bentonite components as well. As the plug tightness must be ensured, the use of low pH cements is envisaged. Low pH cements (pH < 11) would contain higher content of Silica and lower content of Calcium in comparison with ordinary highly reactive Portland cements.

In this context, this numerical study compares the chemical stability of concrete sealing plugs, the first one using ordinary Portland cement, the second one using low-pH cement mixture. Such two differing concrete mineral compositions are submerged in granitic groundwater. Two migration processes are envisaged: diffusive and advective mechanisms. Advection might be faster than diffusion depending on concrete permeability and the local flow.

The aim of this study is to interpret chemical degradation processes in practise, in order to improve selection of the appropriate mineral composition. Therefore starting from an initial mineral composition, we numerically observe water-cement interactions as well as the mineral evolution of concrete mixture. Important indicator of the system evolution will be the porosity of the concrete. Too high porosity may induce higher permeability. On the other hand too low porosity may induce mechanical cracks of the concrete.

Tab. 1: Mineral composition of two tested cement mixtures (% Vol)

Mineral	**Chemical Composition**	**Portland Cement**	**Low-pH Cement**
Calcite	$CaCO_3$	40 %	40 %
Portlandite	$Ca(OH)_2$	16 %	-
Remaining silica fume	SiO_2	-	3.4 %
Calcium-Silicate hydrates CSH1.6	$Ca_{1.6}SiO_{3.6}:2.58H_2O$	24 %	-
Calcium-Silicate hydrates CSH0.8	$Ca_{0.8}SiO_{3.6}:2.58H_2O$	-	46 %
Katoite	$Ca_3Al_2SiO_4(OH)_8$	6.5 %	3.9 %
Ferrihydrite	$Fe(OH)_3$	1 %	0.6 %
Hydrotalcite	$Mg_4Al_2O_7:10H_2O$	3.5 %	2.5 %
Ettringite	$Ca_6Al_2(SO_4)_3(OH)_{12}:26H_2O$	9 %	4.9 %

Table 1 indicates the initial mineral composition of two different cement mixtures. Cement mixture initial porosity is set to 30 %. 11 other secondary minerals are allowed to precipitate, including Tobermorite ($Ca_5Si_6H_{11}O_{22.5}$), more crystallised cement mineral, as well as different clay minerals. We use ToughREACT (LBNL reactive transport modelling code) coupled with Thermoddem (BRGM-developed Thermodynamic database) to simulate mineral evolution of a 1-dimension 2-m long cement plug for 200 years at a cm scale, subject to groundwater flow with pH 8, at 25°C.

"Rate of Alteration"-Experiments on a Series of Bentonites

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Bentonites are suitable candidates as buffer and backfill materials in HLW-repositories. An objective of these investigations was to explore the idea that bentonites have a specific dissolution potential (by "rate of alteration"-experiments).

The "rate of alteration" experiments were carried out as overhead-shaking batch experiments. Well characterized bentonites (9 from API-standard series, 12 from the BGR-collection and 4 others) were investigated in contact with deionized water (liquid/solid-ratio = 10/1) and with NaCl 1N solution (liquid/solid-ratio = 4/1) for 30 days.

XRD and TEM – EDX measurements were the major analytical techniques applied in this research. FT-IR and XRF analyses were used as additional tools for the characterization of the structure and composition of the smectites.

After the mineralogical characterization of original samples and of the reaction products of these experiments different degrees of alteration were recognized. Each approached smectite has shown a specific dissolution potential. This potential was identified by degree of "illitization" or smectitization for each sample (proofed by TEM-EDX, FT-IR). Bentonites with illite-smectite mixed layer phase in the original material have shown commonly smectitization. It seems that such mixed layer phases can buffer dissolved Si.

The following parameters were identified as driving forces for the mentioned specific dissolution potential: (i) original distribution of Al, Fe and Mg in octahedral sheet and (ii) Na/(Ca+Mg)-ratio in cationic composition of interlayer space.

Increasing octahedral Fe- and Mg-amounts are promoting a faster dissolution of smectite. Two types of dissolution behavior were identified for 21 different bentonites. High Na amount in interlayer space has acted in some cases as stabilizator (group A). In other cases Ca+Mg-cations in interlayer space stabilized the aggregates. These two groups are characterized by specific composition of octahedral sheet and by a specific signature in FT-IR-spectroscopy.

The Al-Fe ratio in the octahedral sheet influences the stability of the interlayer:

a. Al_{oct} > 1.4 and Fe_{oct} > 0.2 (per $(OH)_2$ O_{10}) favour delamination of quasicrystals. The swelling pressure increases by a co-volume process between the delaminated layers with higher numbers of quasicrystals for Na-dominant population of the interlayer space (Laird, 2006). The microstructural components including both small and large particles and parts of them have a very small ability to move and undergo free rotation. Such Na-montmorillonites are considered as stable phases and have only a low specific dissolution potential. They are „Sleepers".

b. Al_{oct} > 1.4 and Fe_{oct} < 0.2 or Al_{oct} < 1.4 and Fe_{oct} > 0.2 (per $(OH)_2$ O_{10}) promote demixing of monovalent and divalent interlayer cations (Laird, 2006). In the case of Ca and Mg-dominant interlayers, quasicrystal can break at Na-bearing interlayers and help to maintain the quasicrystal structure. Such Ca and Mg-montmorillonites can be also be taken as „Sleepers", because of their low specific dissolution potential.

It is assumed that the original composition of octahedral sheet is representing mainly the pH-environment during the formation of the smectite clay and therefore it serves as a geological fingerprint.

The specific dissolution potential of MX80 determined by "rate of alteration" experiments has shown comparable values to degree of alteration in tetrahedral sheet of "clay/iron-interaction" experiments. This observation indicates that the results of specific dissolution potential form "rate of alteration"-experiments could be transferred to processes in the "clay/iron-interaction"-experiments.

An Excel-based tool has been developed in order to estimate the specific dissolution potential and expected Si-precipitation of any bentonite. This tool can be used for the preselection of possible suitable bentonites for long-term stable barriers in repositories.

EMDD and the Effect of Salinity on Bentonite Properties

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Swelling pressure, hydraulic conductivity and diffusion results have been compiled from over 45 international published reports and journal articles on the properties of bentonite and bentonite mixtures. The data presented includes recent work on properties of the proposed 70:30 bentonite:sand shaft seal and includes data for Canadian conditions, including high salinity (160 g/L, 270 g/L).

The data is presented as a function of dry density (ρ_d) and Effective Montmorillonite Dry Density (EMDD). The EMDD concept was previously derived by Atomic Energy of Canada Limited to normalize bentonite testing results and to better describe the role of montmorillonite in clay behaviour, notably for swelling pressure and hydraulic conductivity.

As expected, the trends observed in the figures presented show with increasing dry density an increase in swelling pressure and a decrease in hydraulic conductivity and diffusivity. Apparent scatter in the figures are noticeably reduced when the swelling pressure, hydraulic conductivity and diffusion results are presented with the bentonite EMDD as opposed to bentonite dry density. The effect of salinity is also shown in the compiled data as increasing salinity reduces swelling pressure, and increases hydraulic conductivity. However the 70:30 bentonite:sand mixture retains useful properties consistent with prior expectations.

The NWMO will continue with its bentonite program, using pore water that simulates ground water condition in both sedimentary and crystalline geospheres. This data will aid in defining an acceptance criteria for bentonite materials for use in shaft sealing and buffer in the underground repository.

On the Electromagnetic Material Properties of Callovo-Oxfordian Clay Rock

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Safety solutions of management for all radioactive waste in order to protect the present and future generations from the waste risks is an essential need. The French National Radioactive Waste Management Agency (ANDRA – Agence Nationale pour la Gestion des Déchets Radioactifs) is in charge of long-term management of radioactive waste produced in France. ANDRA has been systematically studied the possibility of implementing an underground repository for high-level and long-lived waste in the underground laboratory (URL) in Bure/France (Meuse district, eastern Paris Basin, France) built during the early 2000's. The geological formation under consideration consists of a 130 m thick clay rock layer (Callovo-Oxfordian - COx clay rock) located at a depth of 500 m.

The absolute water content is a key state parameter for monitoring and prediction of Thermal-Hydraulic-Mechanical-Chemical and Radiological (T-H-M-C-R) processes in nuclear waste repositories since it drives radioactivity confinement. More precisely, monitoring of water content in the COx clay, host rock of the planed underground repository, enables to confirm and precise long-term radionuclide transfer models. High frequency electromagnetic (HF-EM) measurement techniques, i.e. time or frequency domain reflectometry (TDR, FDR), offer useful tools for quantitative estimation of water content in porous media. However, despite the efficiency of HF-EM methods the relationship between water content and electromagnetic properties needs to be characterized. Moreover, the high amount of swelling clay in the COx clay rock leads to dielectric relaxation effects which induce strong dispersion coupled with high absorption of EM waves.

Against this background, HF-EM material properties of a set of undisturbed and disturbed clay-rock samples were studied with network analyzer technique at frequencies from 1 MHz to 10 GHz in a water saturation range from 0.16 to nearly saturation. Experimental determined frequency dependent electromagnetic material properties were decomposed in the underlying dielectric relaxation processed based on a generalized fractional relaxation model under consideration of an apparent direct current conductivity assuming three relaxation processes: (i) a high frequency water process with relaxation times between 6 and 11 ps and two interface processes which are related to interactions between the aqueous pore solution and mineral particles such as (ii) adsorbed and hydrated water relaxation superposed with counter ion relaxation processes with relaxation times between 7.6 ns and 20.8 ns as well as (iii) Maxwell-Wagner effects with relaxation times > 100 ns.

Moreover, the HF-EM material properties were modeled based on a novel hydraulic-mechanical-electromagnetic coupling approach. The proposed model allows a quantification of free and interface water as well as a coupling to the electrical conductivity contribution in the aqueous pore solution. The complex relative permittivity was predicted with the approach as a function of water content or water saturation and porosity in reasonable agreement with experimental results in the frequency range of HF-EM applications around 1 GHz. The results clearly indicate the potential of HF-EM techniques for quantitative monitoring of physico-chemical state parameters in underground repositories in clay formations.

Investigations of Excavated Claystone as Backfill/Seal Material

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Crushed claystone produced by excavation of repository openings was investigated as backfill and sealing material for disposal of radioactive waste in clay formations, because of its many advantages such as chemical-mineralogical compatibility with the host rock, availability in sufficient amounts, low costs of material preparation and transport, and no or at least less occupancy of the ground surface with the excavated tailings. The raw aggregate with coarse grains is considered to be used for backfilling the repository openings and, in mixture with bentonite, for sealing the boreholes, drifts and shafts. The geotechnical properties of the excavated claystone from the URL at Bure in France and the compacted claystone-bentonite mixtures were comprehensively characterized at the GRS laboratory.

As backfill material, the coarse-grained claystone aggregate with grain sizes of less than 32 mm can be compacted from the initial porosities of 32-46 % to approximately 20 % as the applied stress increases to 12-16 MPa corresponding to the lithostatic stresses at a depth of ≈500 m. The compaction of the backfill material is mainly determined by applied mean stress, temperature, load rate or time, water content, and grain size. The compaction leads to a decrease in gas permeability down to $K_g = 10^{-19}$–10^{-21} m^2 at porosities of ϕ = 20–25 % and to a water permeability of $K_w = 10^{-19}$ m^2 at ϕ = 30 %. The values are close to that of the undisturbed clay rock ($K < 10^{-20}$ m^2 at ϕ = 15–17 %).

As sealing material, fine- and coarse-grained claystone aggregate were mixed with MX80 bentonite in different ratios. They were compacted by an axial load of 30 MPa. By application of the same energy, the dry density increases with the fraction of claystone in the mixture from 1.56 g/cm^3 for pure bentonite to 2.00 g/cm^3 for pure claystone aggregate. All the compacted mixtures exhibit favourable geotechnical properties with respect to their barrier functions:

- The water retention capacity of the claystone-bentonite mixtures increases with the fraction of bentonite. All the mixtures can take up large amounts of water from humid environment.
- Due to hydration, the compacted mixtures tend to expanding. The swelling capacity increases with the bentonite content. In confined conditions, hydration leads to a buildup of swelling pressure. Maximum swelling pressure amounts to 3 MPa for compacted pure claystone aggregate and to 8 MPa for bentonite.

- All the compacted mixtures show very low water permeabilities in the range of 10^{-19} to 10^{-20} m^2, close to the intact clay rock.
- Thermal properties of compacted claystone aggregate are dependent on the porosity and water saturation. The thermal conductivity increases from 0.8 $Wm^{-1}K^{-1}$ for dry state to 1.6 $Wm^{-1}K^{-1}$ for saturated case. The thermal properties of compacted claystone are comparable to those of compacted bentonite.

All the studied claystone-bentonite mixtures show favourable geotechnical properties with respect to their barrier functions and appear to be able to prevent the release of radionuclides from a repository into the biosphere.

Geochemical Behaviour and Stability of the Czech B75 Bentonite during Interaction with Water at 90°C

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The Czech B75 bentonite is a potential candidate material to be used as engineered barrier in a high-level radioactive waste (HLRW) repository. The B75 bentonite is classified as a natural non-activated Ca-Mg bentonite that comes from the Rokle deposit (Keramost, Obrnice, Czech Republic). This study presents the mineralogical and chemical composition of the B75 bentonite and water composition which is the result of long-term interaction with bentonite at 90°C. These data are crucial for assessment of bentonite stability and its performance during its use as an engineered barrier in HLRW deep repository.

The batch experiments were performed with the powdered B75 bentonite. Two types of solvents were used to prepare the bentonite-water suspension. It was demineralised water and natural groundwater from the granitic massif. The aim of this study was to check the impact of initial water chemistry on bentonite stability and final bentonite and water composition. The ratio of solid to liquid was 1:15 (66.67 g/L). The bentonite reacted with water in the covered glass beakers for 6 months at temperature 90°C. The samples of bentonite and water were analysed after 14, 28, 42, 56, 84, and 182 days. The mineralogical and chemical composition of bentonite and water chemistry was determined. The mineralogical composition was determined by X-ray diffraction analysis on random powders. The chemical analyses of the bulk bentonite suspension were performed and were complemented by determinations of cation exchange capacity (CEC).

Two bentonite layers with a different colour were formed after 14 days from the beginning of the experiment. The upper light brown layer was characterized by higher Fe_2O_3 content in contrast to the lower grey layer with higher FeO content. The X-ray diffraction analyses did not show any mineralogical differences. The bentonite material consisted of montmorillonite, illite, kaolinite, quartz, calcite/Mg-calcite, siderite, anatase, Fe-dolomite/ankerite. Although the mineral composition of the treated samples compare to the original bentonite was the same, quantitative changes were detected. The intensity of the carbonate peaks signalized decrease in the siderite content. In addition, there were visible subtle changes in the montmorillonite structural characteristics manifested by increase in the basal spacing. Supplementary XRD analyses are required to verify alteration of montmorillonite structure. The chemical composition showed minor changes in content of CO_2, Fe_2O_3 and FeO. The content of CO_2 decreased which is in accordance with decrease of the carbonate peaks intensity determined by XRD. The content of Fe_2O_3 increased with parallel decrease in FeO content with preservation of Fe_2O_3/FeO proportion between upper and lower layer.

Determined CEC values of the treated samples were slightly higher compare to the original bentonite. The relative concentrations of the exchangeable cations decrease in the row: sodium > calcium > magnesium > potassium. It can be concluded that used Czech B75 bentonite is stable during its 6 month interaction with water and that different initial water composition has no influence on its stability.

NUMERICAL MODELLING OF THERMO-HYDRO-MECHANICAL-CHEMICAL PROCESSES

Numerical Study of Thermo-Hydro-Mechanical Coupling Behaviors of GMZ Bentonite

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In this paper, a numerical study of a large scale China-mock-up test and several small scale THM-mock-up tests, with the purpose of investigating the performance of Gaomiaozi (GMZ) bentonite under THM coupled condition, is presented. In accordance with the reference concept of High Level Radioactive Waste (HLW) disposal in China, the facility is designed as a vertical tank, filled with compacted GMZ-bentonite. A heater, which substitutes the HLW canister, is placed inside the compacted bentonite blocks and pellets. The installed hydration system on the exterior surface is to simulate the intake of groundwater. A thermo-hydro-mechanical model is then presented to tackle the complex coupling behavior of GMZ bentonite. The model of Alonso-Gens is incorporated to reproduce the mechanical behavior of the GMZ bentonite under unsaturated conditions. With the proposed model, numerical simulation of the Mock-up test is carried out by using the code of LAGAMINE. The time variation of the temperature, saturation degree, suction and swelling pressure of the compacted bentonite are studied. In order to evaluate the influence of the thermo-hydraulic properties on the experiments, parametric studies are realized in the context. A mock-up test on compacted bentonite is performed for validation, the numerical results are compared with the experimental measurements. The results suggest that the proposed model is able to reproduce the mechanical behavior of the GMZ-Na bentonite, and to predict moisture motion under coupled THM conditions.

Keywords: Mock-up test; bentonite; thermo-hydro-mechanical coupled behavior

About Vapour Diffusion during Bentonite Re-Saturation

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The history of modeling bentonite re-saturation in the framework of repositories for radioactive waste began in the early 1980s. The first attempts to describe the process mathematically led to an empirical concept based on Fick's second law. This approach worked fine for isothermal problems at atmospheric pressure but failed for more complex conditions.

In the early 1990s the first THM-models, as we know them today, were developed to tackle this problem. For historical reasons a two-phase flow formulation was integrated as the hydraulic part of these models. However, as with the empirical "diffusion"-model this approach did again not represent the physical processes actually taking place. Usually, no difference between hydrated water in the interlamellar space and free water in the pore space is allowed in the framework of two-phase flow, the retention curve represents suction and not capillary forces and the concept of relative permeability developed for rigid porous media does not apply to re-saturating bentonite.

At the turn of the century GRS had performed an uptake experiment using water vapour as the source for re-saturation. It showed a water uptake that compared quantitatively rather well with experiments using liquid water. This observation led to a vapour diffusion model which explained re-saturation by binary vapour diffusion in the pore space and by hydration only. It was shown that a formal similarity of the mathematical formulation to the early empirical "diffusion"-model exists and that the "diffusion coefficient" used in the old models could actually be calculated based on a set of measurable quantities.

Having established the applicability of the vapour diffusion model to isothermal re-saturation at atmospheric pressure it was successfully extended to cope with the expected conditions in a repository for heat generating waste. It proved also to be applicable to bentonite-sand buffers. However, vapour diffusion alone does not explain certain phenomena during re-saturation under non-isothermal conditions. A diffusive migration process of interlamellar water based on the self-diffusion was incorporated in the model. The result was a double-porosity model for two diffusive processes – vapour diffusion in the pore space and diffusion of interlamellar water – that are linked by the process of hydration. This marks the present state of development.

The resulting code VIPER is thus basically simulating a diffusion-like - even if complex - phenomenon. In contrast, two-phase flow in the THM-codes is based on advection. However, the two-phase flow equations can be transformed into Richards equation if the influence of gas flow is neglected. The Richards equation can in turn be interpreted as a diffusion equation whose coefficient depends eventually on the degree of saturation and varies more or less, independently of the chosen equations of state, rather little in the range between 20 % and 80 % saturation. In effect the THM-codes therefore solve something like a diffusion equation as well.

Considering that the equations of state used in the classic THM-codes are not describing actual two-phase flow processes the conceptual model of VIPER appears to be physically better justified. As a consequence of successful modeling of complex non-isothermal problems it can be concluded that advective water flow in the re-saturating bentonite is debatable and that vapour diffusion plays an important if not a key role for the re-saturation of bentonite.

Model of Bentonite Swelling Solved as a Contact Problem

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We deal with a modelling of bentonite behavior during the saturation process in a high level waste repository. Our work is motivated by a potential damage of the bentonite barrier due to non-uniform swelling and the model problems are formulated based on the configuration of the BRIE experiment modeled as Task 8 within the Task Force on Engineered Barrier System (Bockgård, 2010). The swelling problem is an extention of the original modelling task of the water transport only.

The main challenge is how the gap between the rock and bentonite (often neglected in models) controls the swelling and the resulting stresses in bentonite. While in the fully confined case, the water inflow causes immediate build-up of the swelling pressure, in the real case the free swelling can occur in the first stage until the full contact between the bentonite and rock. Together with expected non-uniform water inflow (from a single fracture), the process can be quite complex.

We developed a solution by means of a contact problem, i.e. non-linear solution of stress-deformation problem with swelling, in a solution-dependent computational domain and boundary condition (either free surface or continuous material allowing only compression). We solve coupled problem of non-linear diffusion (Börgesson, 1985), which is equivalent expression of Richards' equation, and non-linear elasticity in standard multiphysics simulator ANSYS (Ansys, 2010). The swelling is defined as equivalent to heat expansion, with a coefficient dependent on water content according to literature data. The effective Young's modulus is also dependent on water content, with the decrease close to zero corresponding to the plastic state.

We compare two variants of water inflow which is controlled by both bentonite and rock (hydraulic conductivity and retention curves). We use simple 2D axisymmetric models with differences in the representation of the borehole vicinity. The first case is solved as a continuous coupled problem, so saturated bentonite directly affects surrounding rock matrix. The second one – more demanding coupled problem with contact behavior includes narrow gap between bentonite and rock and the fracture is the only way for bentonite hydration. The model requires some additional treatment to allow water transport across the gap.

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A Free Swelling Model of MX-80 Bentonite Implemented in Comsol

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This work proposes an elastoplastic model developed for the simulation of processes involving the free swelling of MX-80 bentonite. It uses a double porosity concept, considering a macrostructural and a microstructural level. The model includes the effect of a macrostructural destructuration when the free swelling process is advanced and the void ratio is high. This destructuration is caused by the swelling and delamination of the particle aggregates that compose the bentonite. The formulation proposed also includes a new approach to the calculation of the microstructural void ratio, as well as a new method to describe the kinetic mass exchange between micro and macrostructural water, considering that there may not be equilibrium between the two types of water. Both are based on the behaviour of bentonite aggregates, and are described by Navarro et al. (2013).

The constitutive model has been implemented in a multiphysics environment software. With this class of solvers, the user defines the governing equations and models for the behaviour of the system. The code takes automatic control of assembling and solving the system of equations. The user focuses on the physics of the problem, which allows for the coupling of almost any physical or chemical process that could be described through partial differential equations. The general form option of Comsol Multiphysics is used to solve the boundary value problems analysed. This way, the derivatives of all terms in the partial differential equations are computed by analytic automatic differentiation. This provides a great computing power. However, if there are variables defined through implicit relationships, their derivatives cannot be calculated. Thus, the iteration matrix cannot be defined, and the program fails. To solve this problem and be able to freely introduce elastoplastic models, a method based on multiphysics capabilities has been implemented and satisfactorily validated.

The model was used to analyse several free swelling tests and was found to yield suitable results. While there are still a number of aspects that need to be improved, the proposed formulation offers a unified approach to characterise the saturated and unsaturated behaviour of bentonites and the development of free swelling processes.

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Coupled THC(m) Models of Compacted Bentonite

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The strong interplays among thermal (T), hydrodynamic (H), mechanical (M) and chemical (C) processes during the hydration stage of a repository call for coupled THMC models of unsaturated compacted bentonite. Advanced multiple-continua THC(m) models for the clay barriers of the engineered barrier system have been developed within the framework of the PEBS Project by improving the existing models by: (1) Accounting for different types of waters such as free, adsorbed and interlayer waters in clays and different types of pores such as macropores, interaggregate and interaggregate pores in multiple-continua models; (2) Incorporating mechanical and geochemical couplings to account for changes in the porosity caused by swelling phenomena; and (3) Improvements in the chemistry of gaseous species such as O_2(g), CO_2(g) and H_2(g). These advanced multiple-continua THC(m) models have been implemented in INVERSE-FADES-CORE.

Here we report the testing of the THC(m) models with heating and hydration experiments performed on compacted FEBEX bentonite. Model results reproduce the measured cumulative inflow of the FEBEX mock-up test the for the last 14 years. The fit of relative humidity, however, shows some discrepancies possibly caused by some model limitations such as the consideration of a single porous space. The model has been tested also with temperature, water content, porosity and porewater chemical data from several nonisothermal infiltration tests performed by Ciemat on cylindrical samples (60 cm long and 7 cm in diameter) of compacted FEBEX bentonite with an inner length of were onstructed. The initial bentonite dry density is 1.65 g/cm^3. Tests were performed for the following durations: 6, 12, 24 and 92 months. The model reproduces the observed temperature, saturation degrees, porosities and chemical data. Geochemical predictions improve when changes in porosity caused by swelling are considered. The main sources of model uncertainties were identified.

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Numerical Modeling of Iron Corrosion and Interaction with Bentonite in Clay Formations

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In deep geological repositories bentonite is a possible Engineered Barrier (EB) to isolate the High Level Waste (HLW) from the biosphere. Bentonites are used for EB systems in HLW repositories because of their swelling ability which minimizes the permeability and their sorption capacity to retain radionuclides. Over time, the iron canister of the HLW corrodes and the interactions between the corrosion products and the EB modify the properties of the bentonite. This study focuses on (1) iron corrosion and precipitation of iron corrosion products, (2) the impact of corrosion products on the chemical and physical properties of the bentonite and (3) the interaction of the EB with the host rock. The aim is to model changes in porewater chemistry, mineral dissolution and precipitation as well as changes in permeability and porosity in order to assess the long term behavior.

The code TOUGHREACT [1] is used for the calculations with PetraSim as user interface [2]. The modeled system includes an iron canister, bentonite as EB and Opalinus clay as host rock. It is 1D and a timeframe of 10,000 years is covered. Due to low permeabilities the mass transport entirely takes place by diffusion. A constant temperature of 25°C and a completely water-saturated regime is assumed. After the closure of the repository the oxygen will be consumed rapidly and anaerobic conditions will prevail. The iron of the canister is represented by a cell of Fe(s). Corrosion is simulated with a dissolution rate of 1µm/year. The corrosion products are mainly magnetite as well as smaller amounts of other Fe-rich minerals.

The physical and chemical behavior of the bentonite (MX-80) is mainly controlled by the transformation of the montmorillonite, which is the main constituent (≈75 %). The initial composition of the MX-80 porewater, the Opalinus clay porewater and initial mineral compositions were taken from Nagra [3]. Dissolution and precipitation of minerals are kinetically controlled and the rates are taken from Palandri & Kharaka [4]. Due to a small diffusion coefficient of $1*10^{-11} m^2/s$, Fe-rich minerals precipitate close to the canister and decrease the porosity in the first cells of the model. The corrosion process also increases the pH temporary from ≈7 to higher values of ≈11.5 in the cells close to the canister. The precipitation of minerals can lead to a clogging of the porosity and retain radionuclides from the biosphere.

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Coupled Hydraulic-Mechanical-Chemical Modeling for Cement-Bentonite Barrier System (2) Mechanical Modeling of Bentonite Engineered Barrier in Consideration of Long Term Chemical Alteration

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For evaluation of the long term performance of engineered barrier in TRU geological repositories, it is important to consider the interaction among hydraulical, chemical and mechanical behavior of the barrier. According to the existing research, it is thought that the montmorillonite will be dissolved due to high pH leachate from cementitious barrier, and the part of dissolved montmorillonite will be deposited as other minerals of which densities are different. However, since the change of volume and mass of the soil particles was not allowed in the conventional soil mechanics, there was an inconsistency in the treatment of soil particles in the couple analysis between chemical and mechanical analysis.

For instance, in the case of alteration of the montmorillonite to analcime, the particle density of the montmorillonite is larger than analcime. When the alteration arises under constant total volume condition, swelling pressure decreases with decreasing of montmorillonite content and the volume of voids decreases with increasing of analcime. There is also the possibility that effective stress of buffer materials increases with increasing of analcime. Therefore, even if it is mechanical model, the consideration of the change of volume and mass of the soil particles is important to evaluate the long term performance of buffer materials.

In this study, mechanical model which can be considered the change of volume and mass of the soil particles due to chemical alteration was formulated. In the model, the montmorillonite content, the content and particle density of deposited minerals and so on are parameters. Since these parameters are common in chemical analyses of buffer, it is easy that chemical and mechanical analysis are coupled using this model.

As the first step of this study, in order to evaluate the effect of the chemical alteration on the mechanical behavior of buffer materials, the model was applied to the alteration of montmorillonite to analcime. As the results, the change of stress state of buffer materials with alteration of montmorillonite to analcime was calculated. It was found that although the montmorillonite content governs the mechanical behavior, the change of stress state also depends on the analcime content.

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Long-term THCM Simulations of the Interactions of Compacted Bentonite in Contact with Concrete and Carbon Steel in a HLW Repository in Clay

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The evaluation of the long-term performance of the engineered barrier system of a high-level radioactive waste repository requires the use of reactive transport models. Here we present a numerical model of nonisothermal unsaturated/saturated water flow and and multicomponent reactive solute transport in a HLW repository in clay according to the Spanish Reference Concept. The model domain was discretized with a 1-D axisymmetric grid. The model accounts for the saturation of the bentonite buffer with bentonite swelling and takes into account the variation of temperatures from 98ºC to the ambient rock temperature of 25ºC. The chemical system is defined in terms of the following primary species: H_2O, H^+, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2}-, HCO_3^-, O_2(aq), Fe^{2+}, Al^{3+} and SiO_2(aq). The model accounts for homogeneous reactions (acid-base, aqueous complexation and redox reactions) and heterogeneous reactions such as mineral dissolution/precipitation of calcite, gypsum/anhydrite, cristobalite, quartz, portlandite, brucite, ettringite, sepiolite, anorthite, C0.8SH, C1.8SH, magnetite, siderite, goethite, and $Fe(OH)_2$(s); cation exchange of Ca^{2+}, Mg^{2+}, Na^+, K^+ and Fe^{2+} using the Gaines-Thomas convention; and surface complexation reactions with three types of sites. Canister corrosion is modeled with a constant corrosion rate.

Model results indicate that canister corrosion causes a marked increase in pH and the concentration of dissolved Fe^{2+}. Most of the released Fe^{2+} diffuses from canister into the bentonite where it precipitates mainly as magnetite. The precipitation of corrosion products takes place in a narrow band of bentonite (< 7 cm) around the canister/bentonite interface and leads to a very significant decrease of bentonite porosity.

The pH in the bentonite increases also due to the dissolution of concrete minerals. The dissolution of the concrete minerals causes an increase in pH from neutral to up to 13 in bentonite buffer during all the simulation horizon. Once the CSH minerals in the concrete are exhausted, the pH decreases. The dissolution of silica minerals and the precipitation of secondary CSH minerals in the bentonite contribute to alleviate the effect of the hyperalkaline plume. Mineral precipitation can reduce the pore space in the bentonite close to the bentonite–concrete interface due to the diffusion of the hyperalkaline plume from the concrete. The hyperalkaline plume from the concrete extends to a distance of 0.7 m in the host rock over the time range of 1 Ma. There are no significant changes in the evolution of major ions of the porewater in the system, except Mg^{2+} due to the precipitation/dissolution of brucite and dolomite.

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Long-term THC Simulations of the Interactions of Corrosion Products and Compacted Bentonite in a HLW Repository in Granite

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The assessment of the long-term performance of the engineered barrier system of a high-level radioactive waste repository requires the use of reactive transport models. We present numerical models for the long-term hydrochemical evolution of the bentonite porewater in the bentonite barrier of a spent-fuel carbon-steel canister repository in granite. The model accounts for canister corrosion, the chemical interactions of corrosion products and bentonite, mineral dissolution/precipitation, Fe^{2+} and H^+ surface complexation reactions on three types of sorption sites and cation exchange reactions of Ca^{2+}, Mg^{2+}, Na^+, K^+ and Fe^{2+}. The model considers also the generation of H2(aq) which is allowed to diffuse through bentonite and the flow through granite which flushes the bentonite/granite interface. Long-term simulations (1 Ma) at a constant temperature of 25ºC were performed for the reference scenario and for a set of variant scenarios. Model results indicate that canister corrosion causes a marked increase in pH and the concentration of dissolved Fe^{2+}. Most of the released Fe^{2+} diffuses from canister into the bentonite where it precipitates mainly as magnetite. Precipitation of corrosion products takes place in a 7-8 cm thick volume of bentonite around the canister/bentonite interface and leads to a very significant decrease of bentonite porosity. Fe^{2+} also sorbs by surface complexation and undergoes cation exchange. Sorption plays a relevant role in the geochemical evolution of bentonite. The competition of Fe^{2+} and H^+ for the sorption sites near the canister/bentonite interface causes several sorption fronts which induce fronts on pH, Eh, Fe^{2+} concentration and mineral dissolution/precipitation. Prediction uncertainties were evaluated for the following model parameters: 1) The corrosion rate; 2) The effective diffusion coefficient D_e of dissolved species in the bentonite; 3) The water flow at the bentonite/granite interface; 4) The cation exchange selectivities and 5) The chemical compositions of the bentonite and granite porewater compositions. The latest improvements performed within the PEBS project include accounting for: 1) The thermal transient; 2) Smectite dissolution; 3) Magnetite kinetic and 4) Neoformation of Fe-clay minerals. Heat transport is solved and computed temperatures are used for updating temperature-dependent chemical parameters such as chemical equilibrium constants and activity coefficients. The dependence of corrosion rates on environmental and geochemical conditions such as temperature or pH has been analyzed. Long term simulations have been also performed allowing for the dynamic update of bentonite porosity to account for the possible pore clogging. Model predictions have been performed under more realistic conditions. The effect of model uncertainties on the long-term predictions of the EBS has been evaluated in a systematic manner.

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Numerical THCm Models of Bentonite Heating and Hydration Tests to study the Interactions of Compacted Bentonite with Concrete and Carbon Steel

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Here we present coupled THCM models of heating and hydration experiments performed at the Ciemat facilities to: (1) Study the interactions of concrete-bentonite and iron-bentonite under repository conditions and (2) Analyze how such interactions may affect the bentonite properties. These models were performed within the framework of PEBS with the INVERSE-FADES-CORE code. Several types of experiments were performed with different sample lengths and temperatures. The small corrosion cells include a 21 mm thick layer of bentonite and a 4 mm thick layer of Fe power. The FB3 test is 100 mm length which includes a 13 mm layer of Fe power in contact with the heater. The so-called double interface tests, 2-I tests, include a 3 mm thick layer of cement mortar which is in contact with the hydration system, an 18 mm thick layer of bentonite and a 2 mm layer of powder magnetite. The HB tests, on the other hand, include a 30 mm layer of concrete which is in contact with the hydration system and a 71.5 mm thick layer of bentonite. These experiments were modeled with a 1D THCM models. The chemical system is defined in terms of the following primary species: H_2O, H^+, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, HCO_3-, O_2(aq), Al^{3+} and SiO_2(aq). The model accounts for acid-base, aqueous complexation, redox reactions, mineral dissolution/precipitation of calcite, gypsum/anhydrite, cristobalite, and portlandite, brucite, ettringite, sepiolite, anorthite, C0.8SH and C1.8SH for the concrete-bentonite tests and magnetite, siderite, goethite, and $Fe(OH)_2$(s) for the bentonite-canister tests; cation exchange of Ca^{2+}, Mg^{2+}, Na^+, K^+ and Fe^{2+} using the Gaines-Thomas convention; and surface complexation reactions on three types of sites. Canister corrosion is modeled with a constant corrosion rate. Magnetite precipitation is controlled by a kinetic law depending on the mineral saturation degree. The experimental data show a sequence of corrosion products from the interface towards the heater. Bentonite canister interface models results indicate that: 1) The main properties of the bentonite remain unaltered; 2) There is a sequence of corrosion products, $Fe(OH)_2$(s) and magnetite being the end members; 3) Fe^{2+} is sorbed by surface complexation; 4) Fe^{2+} cation exchange is less relevant than Fe^{2+} sorption; and 5) Corrosion products penetrate a few mm into the bentonite. For the most part, simulations agree well with experimental data. The experiments on the interactions of bentonite and concrete show an altered layer of bentonite (<5 mm) which is cemented by mineral precipitation. A second layer (<3 cm) is affected by changes in the concentrations of exchanged cations. Coupled THCm numerical models capture the main trends in mineral dissolution-precipitation.

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Improvements in Performance Prediction

FEPs and their Designation in the Technical Proof of a Geotechnical Barrier´s Safety Function

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When building the safety case for a radioactive waste disposal facility, it is an internationally accepted approach to document features, events, and processes (FEP) in order to describe the initial state of a final repository system as well as the factors that may influence its future evolution. Features are properties or conditions that characterize the repository system or part of the system, e.g. the porosity or permeability of a sealing element, at a specified point in time. Events are impacts or changes, whose durations are short compared with the reference period for which safety has to be demonstrated, e.g. seismic events. Processes are incidents or changes that are effective during a relatively long time span compared with the reference period mentioned above, e.g. diapirism or corrosion. A collection of features, events, and processes, whose entity represents the knowledge available on a specific site, is called FEP catalogue. Because of the FEP collection´s relevance when building the safety case for a site, the Nuclear Energy Agency (NEA) created an international FEP data base and derived a general scheme for arranging the FEPs in a catalogue. This scheme is based on the experience of several repository projects as well as on different waste specifications and types of host rocks. It serves as a basis to create site-specific FEP catalogues. Within the scope of the “Vorläufige Sicherheitsanalyse Gorleben (VSG)”, special attention was paid to FEPs that may affect the safety function of the radioactive waste repository. To decide which FEPs are vital for the repository´s safety function, a safety concept must be available to specify the safety functions that may be affected.

The safety concept applied in VSG is based on the safe containment of the radioactive waste in a rock zone (CRZ) around the waste. Safe containment should be effective immediately after emplacement of the radioactive waste and be everlasting. Containment should be guaranteed by a barrier system whose components become effective successively and complement each other due to their time-dependent functional capability. Considering the safety concept, the geologic barrier as well as the shaft and drift seals play a fundamental role in containing the radioactive waste inside the CRZ. Thus, the FEP catalogue was reduced to so-called initial FEPs that may affect the integrity of the so-called initial barriers. The initial barriers “shaft seal” and “drift seals” are geotechnical barriers that are considered to be structures of civil engineering. When designing these kinds of structures, the relevant technical regulations and guidelines in force have to be taken into account. Technical regulations and guidelines define how to proceed in order to prove the safety functions of a geotechnical barrier and how to show compliance with the pertinent requirements. Currently, the method of partial factor design is mainly applied. When applying the partial factor design method, a FEP cannot be used directly. It must be restructured and linked to design situations, actions, and resistances in order to comply with the partial factor design method. In VSG, this step was exemplarily performed for the shaft seal Gorleben 1 and several drift seals. Although the Gorleben salt site was used as an example, the procedure to link FEPs to design situations, actions, and resistances can be transferred to other host rocks and is therefore important in practice.

Upscaling of Thermo-Hydrologic Phenomena from the Emplacement Tunnel to the Repository Scale

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Experimental observations are commonly integrated into numerical models to increase understanding of coupled processes taking place in the Engineered Barrier System (EBS) and ultimately provide predictions on the overall performance of the safety barrier in a high-level waste (HLW) geological repository. Due to their complexity, the assessment of such processes needs to be performed on different scales, wherein detailed analyses on the scale of the EBS provide the basis for the development and configuration of large-scale repository models.

The modeling study presented here aims to provide insights for upscaling from the EBS scale to the repository scale using a generic HLW repository design. For this, two three-dimensional numerical models were developed for simulating coupled flow and transport of water, gas and heat through the EBS and surrounding host-rock. The first model describes a single HLW emplacement tunnel using a detailed representation of the emplacement materials and geometry (i.e. canisters, buffer, liner, tunnel seal) and their corresponding volumes, interfacial areas, and thermal, hydraulic, and two-phase flow properties. The second model is developed on a larger scale to describe a HLW repository based on a generic configuration of emplacement-, operations-, and access tunnels, test facilities, and ventilation shafts emplaced in the host rock and surrounding rock formations. Owing to computational constraints, the level of discretization of the large-scale model is limited, meaning that geometry representations such as the EBS need to be simplified. This needs to be done in a fashion that enables large-scale repository models to capture observations made on the EBS-scale to make predictions on the larger spatial- and temporal scales. The relevant mechanisms therein include re-saturation of the buffer after emplacement and backfilling, the transport of heat from the HLW canisters through the buffer and into the surrounding host-rock, the thermal expansion and associated pressure buildup in the host rock, and the transport of waste-generated gas along the buffer material, through the operations and access tunnels and into the host-rock. The simulations of the thermo-hydrologic phenomena associated with the early post-closure period of a HLW repository require an iterative process in terms of upscaling the detailed configuration from a local-scale model of single HLW cavern to the repository-scale. From the repository-scale, the pressure- and temperature boundary conditions at the top of the models as well as associated with operations- and access tunnel need to be properly accounted for in the local-scale model. Comparison between the two models indicates the necessary considerations to adequately describe these mechanisms on the repository scale, that

include effective representations of the HLW tunnel, conceptualizations of vertical and horizontal connectivity between the buffer, operations tunnels and the host rock as well as scaling of the relevant anisotropic thermal-hydraulic properties.

Uncertainty and Sensitivity Analysis for Large-Scale Two-phase Fluid Flow Calculations

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Results from two-phase flow calculations conducted within the project “Preliminary Safety Analysis of the Gorleben Site (PSG)” indicate that shortly after the repository has been closed, radionuclide transport through seals occurs mainly via the gas phase. Moreover, results suggest that fluid flow behavior of the liquid and gaseous phases and transport of the radionuclides largely depend on the compaction properties of crushed salt backfill, i. e. rate of compaction and final porosity. Results also support the finding that factors controlling radionuclide release from the casks (corrosion rate and water content available for corrosion) play the major role for radionuclide transport. Although many calculations and parameter studies were performed, quantification of these parameters regarding their significance to radionuclide transport and to a radiological insignificance indicator (RII) was not possible.

In our project “Transition Phase” we analyzed processes which occur in a repository in a salt formation within the first 10,000 years, post-closure. Regarding the results from the project “PSG”, we want to quantify to which extent individual parameters contribute to the amount of radionuclides transported through the seals.

To achieve this goal we used uncertainty and sensitivity analysis on two-phase fluid flow calculations. The calculations were based on a full repository design. The varied parameters are, as indicated above: (1) final porosity of crushed salt (2) rate of compaction for crushed salt (3) water content per HLW cask and (4) rate of corrosion for HLW casks. Furthermore, parameter (2) had to be varied for 7 different material types in the repository. Therefore, altogether 10 model parameters were systematically varied. For these parameters, type and values of distribution were defined and used in the two-phase flow calculations. Statistically derived sample sets for parameters for 100 model runs were created and evaluated.

The results from the uncertainty analysis show, for example, that with a statistical certainty of 99 %, 90 % of the calculated results are below the relevant radiological insignificance index (RII < 1) for the given repository layout. Evaluation of sensitivity analysis is currently underway.

Probabilistic Performance Assessment of Repository and Geosphere Attributes Using a Detailed Three-Dimensional Groundwater Flow and Transport Model

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A probabilistic safety assessment (PSA) methodology was applied to a computationally intense three-dimensional (3D) numerical model of the transport of radionuclides from a hypothetical repository in a fractured granite geosphere. The model included a detailed representation of the geosphere, placement room engineered barrier system (EBS) and excavation damaged zone (EDZ). Simulations were conducted for a 1 Ma period and focussed on long term system performance in the period after a release from a defective container at 10,000 years post closure.

Previous safety assessments conducted by the Nuclear Waste Management Organization (NWMO) have used probabilistic safety assessments with simplified geosphere and repository transport models. Detailed deterministic finite-element models have been used to simulate flow and transport for a limited number of cases and a limited number of nuclides. This paper describes a proof-of-concept approach to conducting probabilistic simulations using detailed 3D numeric models. Existing numeric models used in a published case study for a conceptual repository in a hypothetical crystalline rock geosphere (NWMO, 2012) have been simplified and the modelling workflow automated to allow complete simulations to be executed under the control of a probabilistic sampling executive.

The basic scenario includes a water-supply well intersecting a large discrete fault or fracture that extends to repository depth. A defective container located within a placement room adjacent to the fracture supplies the radionuclide source-term. The placement room is geometrically correct and includes detailed representations of the planned EBS (room backfill, concrete bulkhead, bentonite room seal and access drift backfill). A single, non-sorbing radionuclide, Iodine-129, is used in the simulations. Geosphere, well, fracture, EBS and EDZ properties significant to radionuclide flow and transport were identified. The EDZ for the system consists of stress-relief zones with higher permeability surrounding all underground openings, as well as areas within the placement room where thermal damage is assumed to have occurred, with consequent increases in permeability in the near-field host rock.

Parameters are defined in terms of probability distributions, which are sampled under the control of an executive code. As a proof-of-concept project, the distributions have been designed to show a wide range in performance and do not necessarily represent ranges corresponding to or appropriate for the published study. In particular, although fracture location and dimensions (1 metre thick zone of enhanced conductivity) were fixed, fracture hydraulic conductivity was defined as a log-uniform distribution over the range 10^{-7} to 10^{-5} m/s. Similarly, the hydraulic conductivity of the rock mass around the repository was defined as a log-uniform distribution with a range of 10^{-13} to 10^{-9} m/s. Porosities were sampled using uniform distributions encompassing the expected range (0.001 to 0.005 for intact rock, 0.05 to 0.15 for fault/fracture).

Flow and transport simulations were conducted for each realization and model results extracted. Performance metrics are defined in terms of mass-flux: a) leaving the EBS, b) leaving the repository, c) uptake at the water supply well and d) discharge at surface. Results for all realizations are analyzed using graphical and stepwise regression techniques to indicate relative importance of system properties to defined safety assessment metrics.

Analysis of initial assessment results indicated that geosphere properties and well pumping rate have the most significant impact on the defined metrics at exposure points (well uptake and surface discharge), while placement room EDZ and EBS had virtually no impact on these metrics. Subsequently, two additional assessments fixed all geosphere and well variables at median values and focussed on near-field system performance (EBS and EDZ) to determine the relative importance of parameters describing these components. Results from these assessments confirmed that neither EBS nor EDZ parameterization had significant impacts on well uptake or surface discharge.

Repository performance should be evaluated with a holistic approach, ensuring that the individual components are viewed in context with the system as a whole. The methodology described here provides a framework for undertaking such analyses while still maintaining a realistic representation of both the geosphere and repository.

Design and Construction of Engineered Barriers

A General Overview of DOPAS Project and First Year Achievements for Full-Scale Demonstration of Plugs and Seals

Johanna Hansen

Posiva Oy, Finland

Fourteen nuclear waste management organisations and research institutes from eight European countries are participating in a technology development project for assessing tunnel plugging and sealing systems in geological disposal facilities for radioactive waste - the DOPAS project („Full-Scale **D**emonstration **O**f **P**lugs **A**nd **S**eals“). The project is built around a set of full-scale demonstrations, laboratory experiments, and performance assessment studies and is jointly funded by the Euratom‘s Seventh Framework Programme and European nuclear waste management organisations. The project is running from September 2012 to August 2016, and is being coordinated by Posiva Oy, the nuclear waste management company in Finland.

Five demonstration experiments will be partially or wholly implemented during the DOPAS project:

- Full-scale seal (FSS) by ANDRA and Nagra above surface in Saint-Dizier in France,
- Experimental pressure sealing plug (EPSP) by Rawra, CTU and UJV in underground Josef Gallery in Czech republic,
- Deposition tunnel dome plug (DOMPLU) by SKB and Posiva in Äspö Hard Rock Laboratory in Sweden,
- Deposition tunnel wedge plug (POPLU) by Posiva, VTT, BTECH and SKB in underground rock characterisation facility ONKALO (future spent fuel repository), Finland,
- Shaft seal (ELSA) by DBE TECH and GRS in Germany.

DOPAS project aims to improve the adequacy and consistency regarding industrial feasibility of plugs and seals to be used in different geological environments. The main challenges are related to: 1) site selection and construction technologies, 2) new material development, 3) in-situ instrumentation and performance assessment, and 4) quality and safety assurance.

The material development includes advances in cement-based and bentonite-based components used for plugs and seals. A comprehensive laboratory programme is required in order to ensure the specifications to be used in full-scale experiments. Low-pH cementitious materials have been developed in several projects for more than a decade, but still their use at full-scale requires modifications in mixes and laboratory verification of their properties before field use at a decametric scale. The production of bentonite components for large-scale tests requires understanding of manufacturing and emplacement processes, including quality assurance, storage and transport of the materials, ensuring achievement of planned design and accounting for the interactions between cementitious- and bentonite-based components in field conditions.

The DOPAS project with full-scale experiments provides the basis for future needs related to plug and seal technologies for nuclear waste management. Outcomes from the DOPAS project will be disseminated via a web site, public reports, papers and presentations at various conferences. Knowledge transfer will benefit from planned workshops and seminars as well as staff secondment.

Engineered Barrier System Design for the NWMO Mark II Used Fuel Container

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The NWMO is carrying forward two container concepts, the Mark I concept, in which the dimensions of the used fuel container are comparable to the KBS-3, and the Mark II concept in which the container has a diameter and length of roughly 0.6 m and 2.4 m, respectively. The Mark I container placement options are similar to those proposed by SKB for crystalline rock and NAGRA for sedimentary rock. However, due to the unique Mark II UFC design, alternative underground placement strategies are being investigated.

In addition, the NWMO is in the process of selecting a host community, and as such the DGR may be in either a crystalline or sedimentary geosphere. The specific rock properties in both geospheres are reasonably well understood, and the NWMO has estimates of ground water salinity and expects relatively slow groundwater in-flow conditions at repository level.

In support of the development of the Mark II 48 bundle used fuel container, an underground placement concept has been developed that is suitable for; both the expected crystalline and sedimentary geospheres; and buffer performance requirements.

Features of the proposed engineered barrier system for the Mark II container placement option include the following;

- Drill and blast excavated in-room placement for either rock type;
- Containment within a 100 % Highly Compacted Bentonite overpack and packaged in a shroud (buffer box) prior to transport underground;
- Placement of the buffer box in a stacked configuration in the placement room with the annular space on the floor and walls filled with well graded bentonite pellets and fines; and
- Spacer blocks to separate buffer boxes, so that thermal requirements are met for the surface of the UFC given the thermal conductivity of the host rock.

In support of developing the Mark II placement concept the NWMO is initiating studies in support of; pressing and shaping the unique bentonite blocks; constructing the buffer box outer shroud; confirming the thermal conductivity of the blocks and pellets under dry conditions; and handling of the packages in a radioactive underground environment.

Plan of Full-scale Experiment on Engineered Barrier System in Horonobe Underground Research Laboratory

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An important part of the safety assessments of near field in a geological disposal system of high-level radioactive waste consists an assessment of the coupled thermal - hydraulic - mechanical and chemical (THMC) phenomena. In order to validate the newly developed THMC model and to confirm the engineering technology, the in-situ experimental studies on the coupled THMC processes has been planned with a simulated full-scale engineered barrier at 350 m level gallery in Horonobe Underground Research Laboratory (URL), Japan (Fig.1). The geological formation in the URL area consists of mainly the Koetoi Formation (shallower formation) and the Wakkanai Formation (deeper formation) (Fig.2). Neogene tectonic activities of the region are folding, up-lifting/subsiding, denudation, faulting and small earthquake (swarms). The URL area has mechanically soft rock and saline groundwater with dissolved methane.

This study presents the plan of the full-scale experiment on engineered barrier system in Horonobe URL. A test pit with diameter of 2.5 m and a depth of 4.2 m will be excavated in the floor at 350 m level gallery in URL. An electric heater will be installed in an annulus with a diameter of 0.8 m and height of 1.7 m. The test drift will be backfilled with digging and bentonite mixture and will be closed by concrete plug. The heater surface will be maintained at lower than 100°C during the heating phase. A number of sensors will be installed in the buffer, the backfill and the surrounding rock mass during the test.

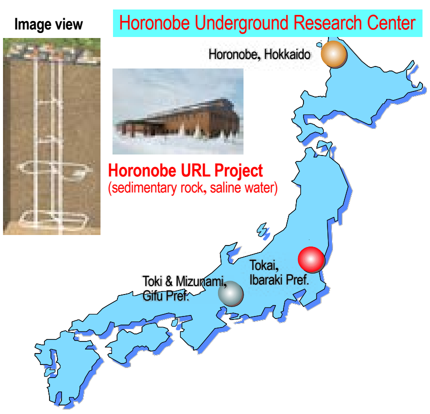

Fig. 1: Horonobe Underground southeast Research Laboratory

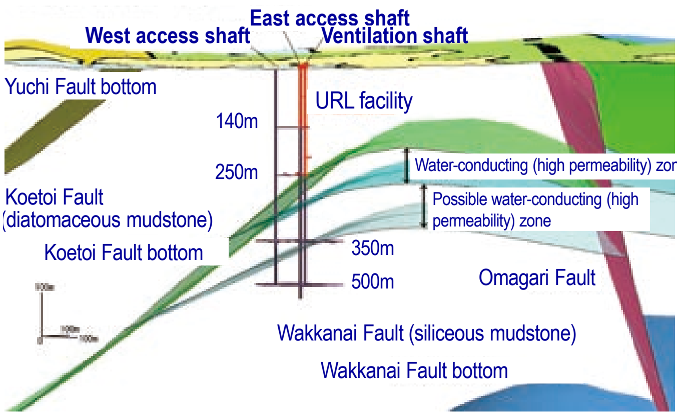

Fig. 2: Geological structure seeing from the direction of URL

Design and Construction of a Large-Scale Sand-Bentonite Seal in the Meuse/Haute Marne Underground Research Laboratory: NSC Experiment

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During the excavation of a shaft or drift, the rock properties around the underground openings could be altered due to the level of the ratio in situ stresses over strength of the rock. And even in some case, the rock mass could be fractured. One concern regarding waste disposal is that the associated disturbance and damage created in this area around these excavations might change the favorable properties of such formations and thus negatively impact the repository performance. To limit radionuclides migration along drifts and through the EDZ, seals will be implemented in drifts and shafts. These seals will be composed of swelling clay (mainly bentonite) core in between two concrete plugs. After natural hydration from the surrounding rock mass, the bentonite will swell and apply radial pressure against the drift wall.

In this context, ANDRA designs a large scale sealing experiment which is called NSC (French acronym for Noyau de SCellement) The main objective is to back analyze the equivalent permeability of the seal in place in order to check the efficiency of such seal. Before to reach this ambitious goal, numerous output will be provided by this experiment on the effect of the hydration of the seal: evolution of the permeability (at the interface seal/claystone and in the surrounding rock mainly the damaged zone), the pressure build up on the concrete plug. The experiment is not a demonstration of the seal emplacement technique. Lot of sensors has to be installed in the seal and around it and results have to obtain over a reasonable timescale. That implies that properties and emplacement of the seal could not be fully representative of the forecast seal.

For example, for the sealing material, three criteria were set at the beginning: (i) hydraulic conductivity at saturation equals to 10^{-11} m/s; (ii) swelling pressure between 1 and 3 MPa; (iii) reasonable time for hydration to reach fully saturation in some years. A first major step was the definition of this material and this was carried out by the CEA/LECBA. The finally chosen material is a mixture of Sand/Bentonite (MX80) in proportion 60 % and 40 % respectively in the form of brick (300 x 200 x 100 mm). With this S/B mixture, the permeability criterion is respected. For the other criteria, swelling pressure depends on the void ratio during the construction of the seal and the time for hydration depends on the number of the hydration membrane inside the S/B mixture.

It was chosen to put NSC experiment at the end of a drift of 4.6 m diameter (in GES drift see Figure 1), in order to be sure that flow goes preferential along the seal. The experiment is composed of 4 zones (Figure 1): injection chamber (zone 1), seal (zone 2), concrete plug (zone 3) and water thigh drift (zone 4). This seal is implemented in a drift of 5 m long and 4.6 m of diameter (inside the GES drift see Figure 1).

The injection chamber will be the upstream part during the performance test and the concrete plug will be the downstream part. To avoid leakage between the two faces of the seal, all instruments installed within the S/B sealing (sensors, hydration membranes and surrounding boreholes) must to be wired towards the injection chamber passing through the concrete plug in 2 tubes system that guarantees the test tightness. All the wires pass through 6 "instrumentation" boreholes between injection chamber and NRM niche. The detailed design of the instrumentation, delivery and installation are done by the joint venture Aitemin and Solexperts, except for the acoustic measurements into the concrete plug which are done by INERIS.

The monitoring instruments, which have been installed in the experiment, are divided in different cross sections. In the seal and at the interface with the concrete plugs (upstream and downstream), is composed of 319 sensors (humidity sensors: 64 capacitives, 64 psychrometers and 16 FDR; pore pressure sensors: 99; total pressure sensors: 76) and 6 hydration membranes. Between each hydration membrane, the thickness of the S/B seal is 1 m. The maximal distance inside the S/B mixture from hydration membrane is therefore equal to 50 cm. For this distance, the time for hydration is estimated at 3 years. So the second criterion is respected.

The hydration membrane at the interface between the concrete plug and the seal is divided into 12 independent areas (Figure 2). This specific design is for distinguish water fluxes from the near-field of the damaged zone, the interface between claystone and seal and water coming through the seal during the performance test.

The concrete plug (zone 3) will be monitored with deformation, displacement, temperature and acoustic sensors. Both concrete plugs of the zone 1 and 3 are dimensioned to a swelling pressure of 7 MPa. The chosen concrete is a low-heat concrete with no reinforcement.

The access gallery in GES (zone 4) is made watertight and a cut-off of 2 m depth will serve to inject water into the damaged zone around the drift (Figure 1). Indeed, scoping calculations were done with Bright code and showed that the ventilation into the access drift will desatured the damaged zone cross the seal. This desaturation will be harmful to get a full hydration of the S/B mixture. To counteract this effect, water will be injected into the cut-off.

Surrounding the GES drift (Figure 1), a total of 23 boreholes will be equipped with multi-packers systems to monitor pore pressure (19 boreholes) and the others (4) with extensometer. Into the multi-packers boreholes, hydraulic tests will be repeated to see the evolution of the hydraulic conductivity around the seal in respect to the swell of the S/B mixture.

The GES drift was excavated in 2012 and all the instrumentation inside GES drift and S/B mixture was installed during 2013. During the construction of the S/B seal, volume and mass of the S/B mixture was controlled. Those measurements were used to estimate the dry density of clay material in the seal and therefore estimate the swelling pressure. The estimated dry density of clay material and swelling pressure are closed to 1.45 kg/m^3 and 2.5 to 3.4 MPa respectively. The third criterion could be met.

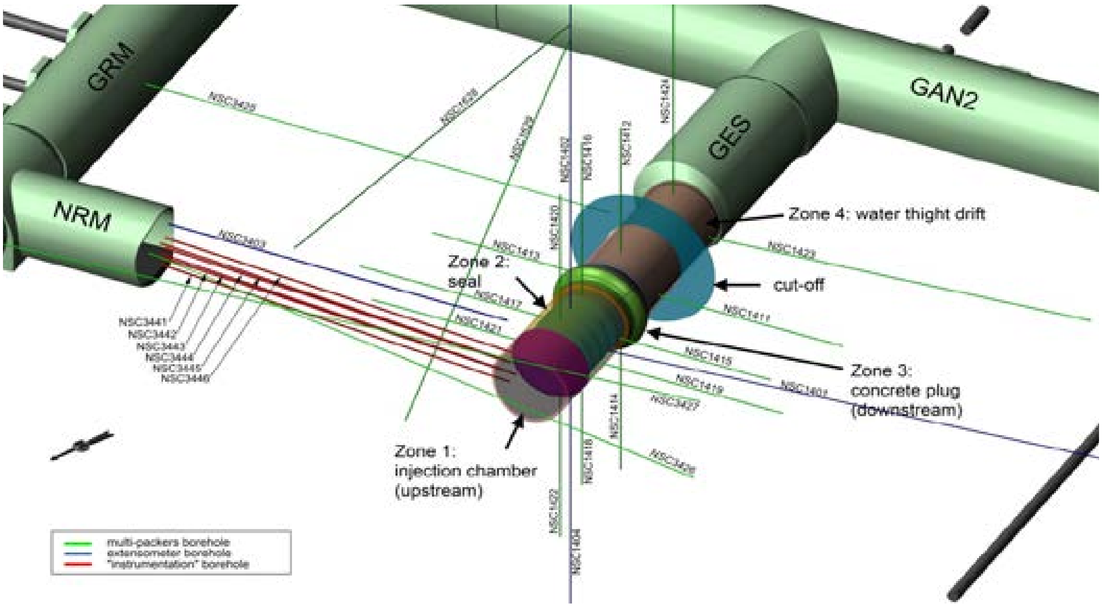

Fig. 1 : General layout of the NSC experiment in the Andra's URL

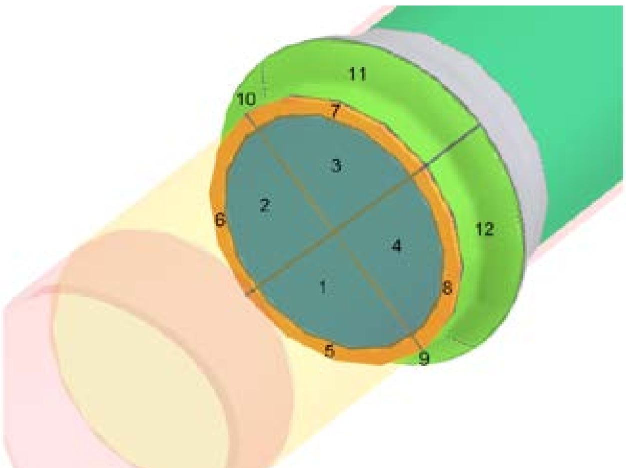

Fig. 2: Detailed layout of the membrane at the interface with the concrete plug (zone 3)

Preliminary Safety Analysis Gorleben – Design of a Bentonite Shaft Sealing Element

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One important aspect when designing a repository for heat-generating radioactive waste is the development of a sealing system for the geologic barrier whose perforation is unavoidable during construction.

Within the scope of the Preliminary Safety Analysis for the Gorleben site, a sealing system for a repository for heat-generating radioactive waste and spent fuel elements was developed. The sealing system consists of shaft and drift seals, which in turn consist of multiple functional elements. One vital functional element of the shaft seal is a sealing element that is made of bentonite and consists of multiple filter layers and bearings which is located near the overburden. After closure of the repository, this sealing element becomes immediately effective in case of brine inflow due to the swelling capacity of the bentonite.

The effectiveness of the bentonite sealing element is demonstrated by means of numerical calculations. Using the submodel technique, a calculation model could be developed that is able to represent all relevant processes for demonstrating the effectiveness of the shaft seal and, thus, the bentonite sealing element. The submodel for the bentonite sealing element includes the swelling process during the saturation phase and the creep processes in the salt. The saturation process is simulated by means of a coupled hydro-mechanical calculation.

For demonstrating the integrity for the bentonite sealing element, the following design criteria were taken into account:

- Criterion of effective fluid pressure

- Criterion of limited decompaction for the benonite.

In a first step, it was verified that a rotationally symmetrical submodel is sufficiently precise to represent all boundary conditions necessary for the demonstration. The hydraulic parameters of the excavation damaged zone (EDZ) and of the bentonite sealing element were then calibrated against the results of a large-scale experiment in Salzdetfurth. In addition to this, a suitable saturation regime was derived based on the results of said large-scale experiment and the fluid pressure was applied accordingly. Subsequently, the effectiveness of the sealing element during the design determining saturation phase, where the highest hydraulic gradients occur, was demonstrated.

The results verified the integrity of the sealing element and showed that its hydraulic resistance is as designed. Combined with the results of the large-scale experiment in Salzdetfurth, the effectiveness of the sealing element could thus be successfully verified from an engineering point of view.

New Progress in Crushed Salt Compaction for Shaft Sealing Elements

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For repositories in rock salt the use of salt based materials is very reasonable. In this case the most favourable material is crushed salt. For shaft sealing elements crushed salt may be used in filling columns. To limit the settlement of the filling column the crushed salt must be in situ compacted to a maximum of density.

The density of a compacted crushed salt filling column is dependent on the following parameters:

- Particle size distribution of the crushed salt,
- Particle shape of the crushed salt,
- Additives,
- Moisture content (additional water) and
- Compaction technology / specific compaction energy.

The influence of the particle size distribution and the particle shape is well known for the parameters of the Fuller-parable for continuous distributed mixtures. Binary or ternary mixtures with a gap grading particle size distribution are alternatives to continuous Fuller-mixtures. In this case the maximum grain size fraction must be more uniformly and has to be nearly to a spherical shape. Therefore a continuous mixture is more favourable, because crushed salt particles are usually different from spherical shape.

Butcher and Stührenberg demonstrated that crushed salt – bentonite mixtures are achieving lower porosities and lower permeability then pure salt mixtures without clay additives. For the sealing system of the shaft "Saale" (Teutschenthal mine) a support abutment with an in situ compacted crushed salt – clay mixture was created. Laboratory test showed, that a mixture of 85 % crushed salt (maximum grain size 100 mm) and 15 % Friedland clay powder with summary moisture content of 4.5 % is optimal to achieve a high density with a specific porosity of about 15 % by a specific compaction energy of about 2.65 MJ/m³. Popp et al. indicated that this mixture with the specific porosity of 15 % has an initial brine permeability of about $6 \cdot 10^{-17}$ m².

First field compaction tests in the Teutschenthal mine showed under real conditions, that the crushed salt has not equal size distribution and large particles cracked during compaction in result of point loading. The cracked particles induced a disturbed structure and consequently a decrease of density. Therefore the mixture must be further optimized during technical compaction tests.

Shaft sealing elements made from in situ compacted rock salt are an important topic in the ELSA-Project (Contract number 02E11193A under support of the BMWi - Federal Ministry of Economics and Technology). After the beginning of the project the following first results were received.

The rock salt - clay mixtures must have a strong constant particle size distribution. This demand is impossible to achieve with primary crushed or machine-cut salt. The mixture must be prepared with compatible particle fractions. From the production plant in the Sondershausen salt mine (company GSES) 4 rock salt fractions with a d_{50}-diameter of 6 mm, 2 mm, 0.5 mm and 0.2 mm were used for the optimisation of an ideal summary mixture with Friedland clay powder (d < 0.063 mm). Optimisation criterion is the Fuller-parable for a maximum particle size of 10 mm and a particle shape determined Fuller exponent of n = 0.3 (test range 0.25 – 0.35). The used percentages of the components were calculated with an optimisation program.

With new optimal mixtures dry densities up to 2.05 t/m³ (Fig. 1) could be reached, applying specific compaction energy of 7 MJ/m³. The air void content of the compacted salt-clay-mixtures varies between 2 - 4 % (Fig. 2), which is lower than in previous studies. Permeability values of the salt mixture probes will also be shown in the presentation.

In further research studies the transformation of the laboratory tests to a bigger scale is planned. The achieved results offer a good possibility to reach a very low permeability of the shaft barrier, which is nearly in the same dimension like rock salt.

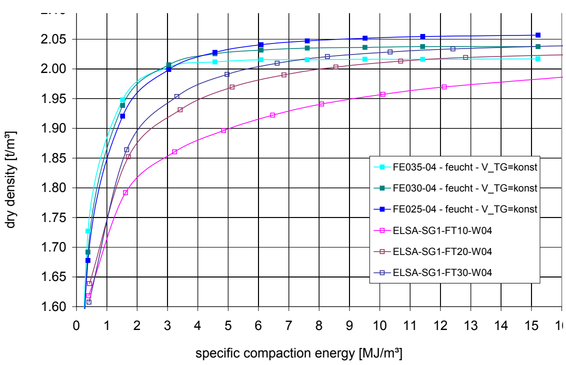

Fig. 1: achieved dry densities during compaction

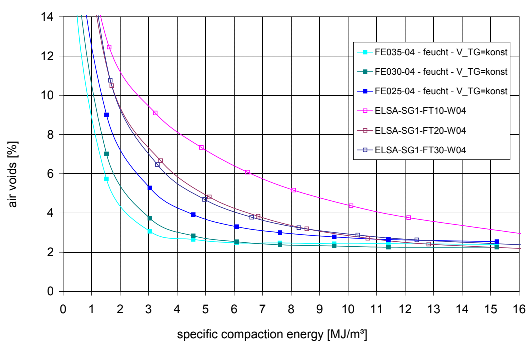

Fig. 2: remaining air void content during compaction

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Robust Natural Barriers: Parallel between CO_2 Geological Storage Oil & Gas Production and Radioactive Waste Disposal

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Underground storage and disposal, of radioactive waste as well as CO_2, requires a detailed understanding of the interactions between man-made structures and the perturbed rock formation. Whether at the scale of a borehole or shaft, or of larger subterranean structures, a key issue is how to prevent and mitigate releases by building and maintaining a hydraulic seal through impermeable rock formations. It is thus important to know the modes of failure of these seals and their robustness, i.e. their ability to re-establish hydraulic isolation after the cause of failure is removed. Cement is an essential type of engineered barrier in deep wells for oil, gas, CO_2 storage and geothermal power, sealing the annulus between steel pipe and the impermeable sections of the borehole, as well as in radioactive waste disposal with solutions presenting cemented boreholes, cement buffers and/or backfill.

In the case of boreholes, cement failure and therefore loss of integrity happens because a limited number of classes of vertically connected defects can form a leakage pathway through the cement: mud channels, chimneys and interface debonding (also called microannulus). The evolution of cementing technology over the past 30 years has reduced the incidence of the first two failure classes, but debonding persists as a high-frequency, low-impact leakage pathway that may affect ~20 % of wells worldwide. A notable feature of well integrity failures, however, is their dependence on local conditions, especially peculiarities of basin geology.

Recent studies from the oil & gas and CO_2 storage fields have started looking at the role that natural viscoplastic rock formation can play in providing, supporting and re-establishing zonal isolation. Whereas the role of halite has been the subject of theoretical studies and some experiments, especially in the Zechstein formation which is common in Northern Europe, creeping shales also hold promise as secondary barriers that can re-establish zonal isolation even after an initial failure.

Sparse evidence from wireline logs in many geological provinces has suggested for years that shales with high clay content creep and in 2009 a particular shale formation has been qualified as a barrier in the Norwegian North Sea. Recent data from a large-scale well study in France has confirmed that shale creep in specific formations can bridge the annulus and resist overpressures of up to 10 MPa. This geologic barrier fails smoothly, likely by debonding, and can re-seal the migration pathway after the cause of failure is removed; the radial stress exerted by creeping shales can also shut a microannulus, improving the performance of engineered barriers. Besides halite and shales, other lithologies exhibit viscoplasticity, for instance coal in the presence of CO_2. It is also possible that ice, and maybe permafrost, can behave as a robust annular barrier.

The paper will present the preliminary results of the above-mentioned studies and discuss how their results can be used while analyzing the performance of radioactive waste disposal. Geologic barriers can play an active role in the design and management of in-tunnel disposal (vertical, axial and radial boreholes), and should be considered as a primary – and basin-specific – factor when assessing long-term releases.

New Development of a Combined Abutment and Sealing Assembly made of Bitumen and Gravel

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The long-term safe closure of repository mine shafts requires mainly a long-term save sealing of the mine against penetrating and escaping fluids. According to the state of the art, sealing elements were built from mineral swellable bentonite. This bentonite sealing elements are structurally integrated into the supporting shaft backfilling. The shaft backfilling must be sufficiently stiff and reacts with a minimum of settlement due to loading. This ensures that the backfilled shaft is a sufficiently rigid abutment for the sealing element containing swelling bentonite.

To increase the level of safety several bentonite sealing elements can be combined according to the principle of redundancy. An even higher safety potential is achieved with the principle of diversely redundancy. Thereto sealing elements with different modes of action have to be combined.

While the sealing action of bentonite is based on its swelling properties, also a sealing by means of a hydraulic acting fluid can be achieved. These so-called hydrostatic sealings utilize the density-dependent buoyancy and the dynamic viscosity of the sealing liquid for a long-term sealing. The most famous materials for a hydraulic sealing are bitumen or bitumen-mineral suspensions (filled bitumen).

For shaft constructions bitumen or filled bitumen are used successfully for the past 5 decades as a hydrostatic acting sealing material in sliding shaft supports [1, 3, 5]. Due to this fact diversely redundant sealing systems of combined mineral and hydrostatic seals were planned for the future mine closures of the repositories Morsleben (shafts Marie and Bartensleben) and Konrad (shafts Konrad 1 and 2).

In particular the Morsleben repository will be the first repository for radioactive waste in Germany which will be closed under nuclear law. In the conceptual design study [4] to the closure of the Morsleben repository, a technology called “bitumenfilled gravel column” is intended as a hydrostatic seal. The concept of the “bitumenfilled gravel column” is deduced from the “stone-bitumen method”, a alternative asphaltic-core dam construction developed in Norway [2], which was successfully realized in several dam projects of the Norwegian water-power system.

The deduced concept describes a rigid gravel column, which corresponds to the state of the art in shaft closure, whose pore space is nearly void-free filled with bitumen or filled bitumen. Thus, this concept combines the functions “sealing” and “abutment” together.

In recent years extensive investigations, verifications and optimizations of the technological implementation of the concept “bitumenfilled gravel column” were carried out at the Technical University Bergakademie Freiberg. The focuses of this research were:

- a comprehensive material characterization and optimization of the materials to be used,
- Investigations on the use of additives to improve wetting of bitumen,
- Optimization of the implementation technology in half-scale experiments,
- Proof of the effectiveness of the hydrostatic sealing in half-scale experiments and
- Optimization of the implementation technology in a full-scale experiment.

Here, the results of the half-scale experiments will be reported.

To optimize the implementation technology half-scale casting experiments were carried out in heat-resistant borosilicate glass tubes (diameter 32.5 cm). In the tubes gravel columns were embedded up to 130 cm in length and sealed with 170 ° C hot bitumen or filled bitumen. Through extensive instrumentations with thermal sensors, a thermodynamic analysis of the system of hot bitumen and cold gravel were possible, while visual observations of the casting processes (Fig. 1) were carried out. Through a temperature-dependent volume balance the casting successes were evaluated using the determined remaining unfilled pore space, which was smaller then 0.5 Vol%.

For the proof of the effectiveness of the hydrostatic seal half-scale experiments were carried out in pressure cells (diameter 32 cm) under liquid pressures up to 2 MPa. In addition to long-term experiments for proofing the sealing capacity, short-term experiments for quantification of the time-dependent pressure variation in the bitumen filled pore space were performed. Although fluid pressure raises to 0.5 or 2.0 MPa were applied within one second and the propagation of the pressure wave within the bitumen-filled pore space in the gravel skeleton examined (Fig. 2). As a result, the hydrostatic sealing performance of the bitumen in the gravel pore space could be proofed.

Fig. 1: various stages of the casting process

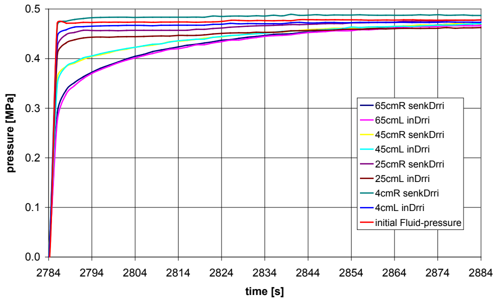

Fig. 2: measured pressure profiles at various positions in the sealing element

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Application of SHOTCLAY Method to Construction of Backfill and Clay Plug

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Authors have been researching the phenomena which will occur during saturation of buffer after closure of radioactive waste geological repositories. In the research, it was found that there was a possibility that the density distribution of the buffer generated by construction does not homogenize even if it swelled sufficiently. However, the conventional construction methods, such as in-situ compaction method and bentonite block emplacement method, generate the density distribution and/or gap between the rock and the bentonite material. The density distribution and the gap might cause piping and erosion in the early phase of bentonite saturation according to the water inflow.

SHOTCLAY method is the spraying method of bentonite which adjusted its water content in advance. Even if it is a narrow space such as the space between canister and rock, the homogeneous bentonite engineered barrier with high dry-density can be achieved. In case of spraying roughly crushed bentonite, the dry density is more than 1.6 Mg/m^3. In addition, this method can be applied to the construction of vertical wall and ceiling of bentonite in the engineered barrier system.

In this study, the construction test of backfill and clay plug was implemented by utilizing the characteristic of SHOTCLAY method. In the construction test of backfill, the various bentonites such as Kunigel V1 with silica sand, MX80 with silica sand, and Friedland clay were sprayed. As the results, the dry density of sprayed material increased with decreasing its montmorillonite content. Especially, it was found that Friedland clay is appropriate material for spraying. The dry density of sprayed Friedland clay was approximately 1.77 Mg/m^3 and its hydraulic conductivity was approximately 10^{-12} m/s.

In the construction study of clay plug, the plug was constructed in the small arch culvert with 1,800 mm height, 1,000 mm width and 2,000 mm thickness. The sprayed material was 70 wt% of Kunigel V1 and 30 wt% of silica sand. At first, the bentonite was sprayed upward against the crown of arch culvert. After the crown part, the bentonite was sprayed in circumferential direction. As the results, the bentonite which was sprayed upward against the crown of arch culvert did not collapse for several months. The dry density of the bentonite around crown part is approximately 1.55 Mg/m^3.

According to these results, it was found that SHOTCLAY method is appropriate to construction of backfill and clay plug. In this study, the control method to adjust the construction quality of SHOTCLAY method confirming the requirement of backfill and clay plug will also be described.

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Numerical Modelling of In-situ Experiments

Inverse Modeling of the FEBEX-In-situ Heating Experiment: Parameter Estimation, Extrapolation and Predictive Uncertainty Analysis

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This study is part of the PEBS WP 3.5 which is dealing with extrapolation of findings from the (relatively short term) experimental and their modeling efforts of the PEBS project. In this context, the long term evolution of heat as emitted by nuclear waste on the saturation behavior of the engineered barrier system (EBS) is simulated. The axisymmetric models are based on the Spanish repository concept – a proposal for disposal of spent fuel canisters surrounded by a high-density bentonite buffer in granite host rock. Rather than the coupled thermo-hydro-mechanical approach (THM) the computationally more efficient TH-code iTOUGH2 was applied, thus, neglecting mechanical processes as induced e.g. by bentonite swelling.

Prior to prediction, the involved model parameters were derived from inverse modeling of the FEBEX in-situ experiment at the Grimsel Test Site located in the Swiss Alpes. This 1:1 physical model of the mentioned repository concept provides pressure, temperature, and saturation data from a heating experiment measured in more than 600 installed sensors for a period of over 15 years.

The inverse modeling framework implemented in the iTOUGH2-code is based on Maximum Likelihood Estimation Theory and provides a state-of-the-art tool to carry out parameter estimation as well as sensitivity and uncertainty analysis. The inverse approach applied in this study differs from standard applications in that not only one single model can be run to simulate the experiment for the measurement period of 15 years. Rather, a series of models has to be maintained each representing one phase of the experimental setup, namely, (1) excavation and installation, (2) isothermal hydration, (3) first operational (heating) phase, (4) cooling down of first heater, (5) dismantling of first heater, and (6) second operational phase. The initial conditions being transferred in each case from the previous phase, the 6 models differ in geometry and boundary conditions but are driven by the same set of model parameters. The joint inversion of the whole set of measurement data results in parameter estimates of permeability, porosity, relative permeability and capillary pressure functions for both, host rock and bentonite buffer, so that model simulations are in good agreement with the observations. Moreover, uncertainty estimates of the resulting parameters are calculated in form of the parameter covariance matrix which has been applied in the following modeling steps in order to assess the uncertainty of long term predictions.

This type of modeling contributes to the understanding of the early behavior of the EBS system until full saturation is reached and the assessment of the impact of processes (such as chemical processes) which depend on the saturation state and its evolution in time.

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Modeling of the SEALEX In-situ Experiments-Performance Tests of Repository Seals

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The SEALEX project was built with specific focus on long-term hydraulic performance of sealing systems as part of the overall IRSN R&D program that provides the bases for scientific expertise on disposal safety. The SEALEX experiments are emplaced in the Tournemire Underground Research Laboratory (Toarcian argillites) via horizontal boreholes (diameter 60 cm) excavated from recent drift (2008). Each experiment consists of a bentonite based core mechanically confined at both ends, which represents a generic seal mock-up except for the artificial saturation system (porous filters located at both core ends) (Barnichon et al., 2012). A number of materials are being considered as seals; the current work focuses on clay cores built of pre-compacted disks composed of bentonite/sand mixture. In such layout, an annular technological void exists between the clay core disks and the surrounding host-rock. This gap with variable thickness is technically needed to facilitate the emplacement of the clay core into the borehole. This paper presents a preliminary analysis to examine the coupled hydromechanical behaviour of the first SEALEX in-situ test (PT-N1). The clay seal of test PT-N1 is made of 8 monolithic pre-compacted disks of 70/30 MX80 bentonite/sand mixture with an initial dry density of 1.97 Mg/m^3 and initial water content around 11 %. The annular technological void is estimated to 14 % (volume of void/volume of borehole). A coupled analysis has been performed using a 2-D model that includes the clay core, the annular void and the surrounding host-rock. The numerical analysis has been carried out using the finite element code CODE_BRIGHT (Olivella et al., 1994). A key feature in the simulation lies in the appropriate modeling of the bentonite-sand mixture hydro-mechanical behavior. The model parameters have been first calibrated against conventional laboratory tests (infiltration, swelling and suction controlled oedometer tests) and a 1/10th scale mock-up of PT-N1. A fundamental issue in modeling lies in properly representing the air-filled gap. As a first approach, the annular void is assumed to have a uniform thickness of 2.5 cm. The modeling results could be compared with the field observations. The models predict reasonably well the evolution of liquid saturation and axial swelling pressure at different points of the clay core. However, large differences are observed between the model predictions and the measurements in terms of radial swelling pressures evolution, related to the non-uniformity of the initial air-gap in the SEALEX experiments. Yet, the necessity to incorporate the effect of the gap with variable thickness forces the development of a model in 3- D.

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Scoping Computations for the Full-Scale Emplacement (FE) Experiment at the Mont Terri Underground Research Laboratory

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The Full-Scale Emplacement (FE) Experiment at the Mont Terri underground research laboratory (URL) is a full-scale heater test in a clay-rich formation (Opalinus Clay). It simulates the construction, waste emplacement and backfilling of a spent fuel (SF) / vitrified high-level waste (HLW) repository tunnel as realistically as possible. The entire experiment implementation as well as the post-closure THM(C) evolution will be monitored using several hundred sensors. These are distributed in the host rock in the near- and far-field, the tunnel lining, the engineered barrier system (EBS) and on the heaters.

One of the main aims of this experiment, which is based on the Swiss SF/HLW disposal concept, is the investigation of repository-induced thermo-hydro-mechanical (THM) coupled effects on the host rock and on the bentonite buffer as well as the validation of existing coupled THM models.

Many important tasks, such as the excavation of a small cavern (completed in May 2011), the excavation of the experimental tunnel with a diameter of approx. 3 meters and a length of 50 meters (completed in September 2012) and the instrumentation of the rock in the 'far-field' (completed in April 2012), have already been executed successfully. The instrumentation of the rock in the 'near-field' is currently on-going and planned to be completed by until the beginning of 2014. The installation of the three heaters and the instrumentation within the tunnel will happen before and during the emplacement of the bentonite buffer. Finally the FE tunnel will be sealed off with a concrete plug and heating will be started by the end of 2014. No artificial saturation is foreseen, thus the FE experiment aims to monitor the THM evolution over an extended time span. According to current planning, the heating and monitoring phase of the FE experiment at Mont Terri is envisaged to take at least 10 to 15 years.

First scoping calculations of the bentonite buffer and the host rock have been completed; these works have been carried out using CodeBRIGHT (Garitte, 2013), the multiphase flow simulator TOUGH2 (Ewing & Senger, 2012) and QPAC (Thatcher, 2013). With an initial heat output of 1,500 W per canister (according to the Swiss reference case) the first results of the FE experiment at Mont Terri indicate a temperature of up to 150°C at the heater surface and 60-80°C at the rock surface. Besides these predictions, first measurement results from the excavation of the experimental FE tunnel and the subsequent ventilation phase will be presented.

This experiment is part of the Mont Terri Project under the directorate of swisstopo. The initiator and lead organization for the experiment is Nagra; ANDRA (France), DOE/LBNL (U.S.A), NWMO (Canada), GRS (Germany) and BGR (Germany) are participating in the FE Experiment.

Acknowledgements: *The engineering and demonstration components of the FE experiment are also part of Nagra's participation in the EC co-funded 'Large Underground COncept EXperiments' (LUCOEX) project and therefore receive funding from the European Atomic Energy Community's Seventh Framework Programme (FP7) under grant agreement n269905.*

The Enhanced Sealing Project: Monitoring of a Full-Scale Composite Shaft Seal from 2009-2013 and Related Hydro-Mechanical Numerical Modelling

Deni Priyanto[1], David Dixon[2], Sim Stroes-Gascoyne[1], Radwan Farhoud[3], Petri Korkeakoski[4], Björn Nyblad[5], Jorge Villagran[6]

[1]AECL, Canada; [2]Golder Associates Ltd., Canada; [3]ANDRA, France; [4]Posiva, Finland; [5]SKB, Sweden; [6]NWMO, Canada

As part of closure activities, a full-scale shaft seal was installed in the access shaft at Atomic Energy of Canada's (AECL's) Underground Research Laboratory (URL). The primary purpose of the shaft seal is to limit the mixing of saline groundwater from the deeper regime, with the fresher, nearer-surface groundwater. In this respect, it is intended to function in the same manner as a shaft seal in a repository containing radioactive waste. The seal consists of a 6-m clay component sandwiched between 3-m-thick concrete components that are keyed into the access shaft walls (diameter ~5 m) (Figure 1). The seal is located where the shaft intersects a water-bearing fracture zone (FZ2), approximately 275 m below the ground surface. Construction of the shaft seal was completed as part of Canada's Nuclear Legacy Liabilities Program (NLLP). A jointly-funded monitoring project, called the Enhanced Sealing Project (ESP) was developed by AECL and is supported by the NWMO (Canada), SKB (Sweden), Posiva (Finland), and ANDRA (France). The purpose of the ESP is to monitor the thermal-hydraulic-mechanical (THM) evolution, including: temperature, hydraulic pressure, total pressure, water content, displacement and strain measurements of the seal and the rock immediately adjacent to it. The results of the ESP are of relevance to repository closure planning and important to our confidence in the functionality of shaft seals. Of particular importance is to evaluate the degree of isolation provided by the seal to the regions above and below its location. This can be examined through the water pressure difference across the seal (Figure 1). As of September 2013, the pressure difference continues to gradually increase (~320 kPa) and it is significantly greater than the hydrostatic pressure difference that would exist without the presence of seal (~60 kPa). This indicates that the seal is providing effective resistance to water transport across it. A hydro-mechanical (HM) finite element analysis was done to simulate the saturation of the shaft seal and its result is compared to the ESP data measured in situ.

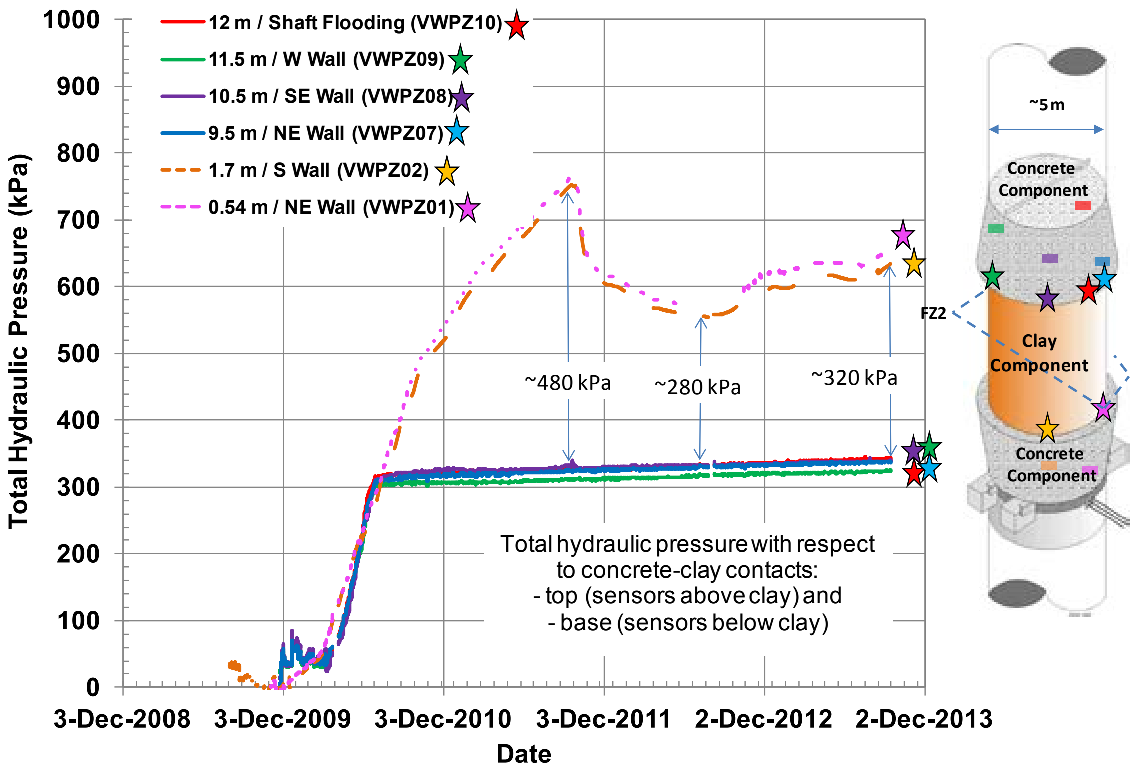

Fig. 1: Hydraulic Pressure Above and Below the Clay Component of the Seal

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Appendix

International Conference on the Performance of Engineered Barriers

Physical and Chemical Properties, Behaviour & Evolution

February 6-7, 2014
BGR, Hannover, Germany

Editors: A. Schäfers & S. Fahland
Organized by the PEBS project

Programme Committee: Wilhelm Bollingerfehr – DBE TECHNOLOGY GmbH, Germany
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General Rapporteur: Irina Gaus – Nagra, Switzerland
Klaus Wieczorek – GRS, Germany

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Day 1 – February 6, 2014	
	Welcome Words and Keynotes
09:00	Welcome *H.-J. Kümpel* (BGR)
09:10	Final Status of the Euratom FP7 Research and Training Programme in Radioactive Waste Geological Disposal and Outlook to the Future *C. Davies* (EC)
09:30	Implementing a Deep Geological Disposal System for Spent Nuclear Fuel in Sweden *P. Wikberg* (SKB)
	Overview on the Research Results of the PEBS Project *Chaired by S. Williams (NDA)*
10:00	PEBS Case 1 – Water Uptake in the Bentonite Buffer *J. C. Mayor, M. V. Villar, P.L. Martín, A. Gens (Cimne, UPC), M. Velasco*
10:20	PEBS Case 2 – EBS Performance at Temperatures above 100°C *I. Gaus, K. Wieczorek, A. Gens, J. L. García-Siñeriz, T. Trick, U. Kuhlman, A. Dueck, M. V. Villar, O. Leupin, L. Johnson (Nagra), O. Czaikowski, B. Garitte, K. Schuster, J. C. Mayor*
10:40	PEBS Case 3 – HM Evolution of the Buffer *P. Sellin (SKB), J. L. García-Siñeriz, A. Dueck, J.-C. Mayor, M. V. Villar, P. L. Martín, A. Gens, O. Kristensson, E. Alonso, I. Gaus*
11:00	PEBS Case 4 – Impact of the Geochemical Evolution of Bentonite Barriers on Repository Safety Functions *J. Cuevas (UAM), J. Samper, M. J. Turrero, K. Wieczorek*
11:20	Coffee break

INTERNATIONAL CONFERENCE ON THE PERFORMANCE OF ENGINEERED BARRIERS
FEBRUARY 6-7, 2014 - HANNOVER, GERMANY
PROGRAMME

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Day 1 – February 6, 2014

	Large conference room	Conference room (A14)
	New Insights from In-situ Experiments in Clay-rich Formations *Chaired by I. Gaus (Nagra) & T. Fujita (JAEA)*	**Numerical Modelling of Thermo-Hydro-Mechanical-Chemical Processes** *Chaired by K. Wieczorek (GRS) & E. Hardin (SNL)*
11:40	Outcome of the Dismantling of "EB" Experiment *B. Palacios, J. L. García-Siñeriz (AITEMIN), J.C. Mayor*	Numerical Study of Thermo-Hydro-Mechanical Coupling Behaviors of GMZ Bentonite *S. Cao, Y.M. Liu, L. Chen, J. Xie (BRIUG), Y. Li, L. Ma*
12:00	Geophysical Long-term Monitoring within the PEBS Project – HE−E- and EB−Experiment *K. Schuster (BGR), M. Furche, F. Schulte, T. Tietz, C. Czora and S. Sanchez Herrero, T. Fischer*	About Vapour Diffusion during Bentonite Re-Saturation *K.-P. Kröhn (GRS)*
12:20	Sealing Materials Used in the HE-E Test: Thermo-hydro-mechanical Characterisation *M. V. Villar (CIEMAT), P. Martín, R. Gómez-Espina, V. Gutiérrez-Rodrigo, J. Barcala*	Model of Bentonite Swelling Solved as a Contact Problem *I. Skarydova (University of Liberec), M. Hokr*

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12:40	Bentonite Buffer Material Production and Emplacement during the Full–Scale Emplacement (FE) Experiment at the Mont Terri URL *H. R. Müller (Nagra), B. Garitte, H. Weber, S. Köhler, M. Plötze*	A Free Swelling Model of MX-80 Bentonite Implemented in Comsol *V. Navarro, L. Asensio (Universidad de Castilla-La Mancha), Á. Yustres, J. Alonso, X. Pintado*
13:00	Lunch break, poster session and conference group photo	
14:30	**Investigating Gas Interaction in Laboratory and In-situ Experiments** *Chaired by P. Sellin (SKB) & J. Avis (Geofirma)* Observations from Four Gas Injection Tests Conducted in a Full Scale KBS-3v Setup; The Large Scale Gas Injection Test (Lasgit) Conducted at the Äspö Hard Rock Laboratory, Sweden *R.J.Cuss (BGS), J.F. Harrington, D.J. Noy, C.C. Graham, P. Sellin*	Long-term THCM Simulations of the Interactions of Compacted Bentonite in Contact with Concrete and Carbon Steel in a HLW Repository in Granite and Clay *J. Samper (UDC), A. Mon, L. Montenegro, A. Naves*

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	Large conference room	Conference room (A14)
14:50	Interaction between Gas and Bentonite Seals: Small Scale In-situ Test in the Meuse/Haute Marne Underground Research Laboratory *R. de La Vaissière (ANDRA), J. Talandier*	Numerical Modeling of Iron Corrosion and Interaction with Bentonite in Clay Formations *C. Hansmeier, G. Bracke (GRS), B. Reichert*
15:10	Hydro-mechanical Properties of Interfaces in Sealing Plugs Constructed of Bentonite-Block Assemblies *T. Popp, C. Rölke (IfG), K. Salzer*	Cement Behaviour in Plug Sealing Storage Galleries – Numerical Comparison *F. Wertz, P. Večerník, T. Černoušek (CVŘ)*
15:30	Coffee break	
15:50	Gas Injection and Swelling Tests on a Sand Bentonite Mixture: Investigation on the Effects of Pore Water Chemistry *D. Manca (EPFL-ENAC-LMS), A. Ferrari, L. Laloui*	Coupled Hydraulic-Mechanical-Chemical Modeling for Cement-Bentonite Barrier System (2) Mechanical Modeling of Bentonite Engineered Barrier in Consideration of Long Term Chemical Alteration *Y. Takayama, A. Iizuka (Kobe University), H. Ohwada, T. Ishii, I. Kobayashi*

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	Large conference room	Conference room (A14)
16:10	**New Insights from In-situ Experiments in Crystalline Host Rock** *Chaired by J. C. Mayor (ENRESA) & K. Birch (NWMO)*	**Improvements in Performance Prediction** *Chaired by L. Johnson (Nagra) & T. Popp (IfG)*
	The Bentonite Rock Interaction Experiment *M. Åkesson (Clay Technology), Å. Fransson, P. Vidstrand, A.Sjöland*	FEPs and their Designation in the Technical Proof of a Geotechnical Barrier´s Safety Function *N. Müller-Hoeppe (DBE Technology)*
16:30	FEBEX In Situ Test After 18 Years of Monitoring – Final Dismantling in 2015 *I. Gaus (Nagra), P.-L. Martin Martin, E. Thurner, M. Vahanen, S.-P. Teodori, F. Kober, J.-S. Kwon*	Upscaling of Thermo-hydrologic Phenomena from the Emplacement Tunnel to the Repository Scale *A. Papafotiou (INTERA Inc.), J. Ewing, R. Senger*
16:50	Borehole Plugging Experiment in OL-KR24 in Olkiluoto *T. Karvonen (Saanio & Riekkola Oy), J. Hansen*	Uncertainty and Sensitivity Analysis for Large-scale Two-phase Fluid Flow Calculations *I. Kock (GRS), S. Hotzel*

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	Large conference room	Conference room (A14)
17:10	Findings from the Retrieval of the Outer Section of Prototype Repository at Äspö Hard Rock Laboratory *L.-E. Johannesson (Clay Technology), P. Grahm, A. Sjöland, J. Hansen*	Probabilistic Performance Assessment of Repository and Geosphere Attributes Using a Detailed Three-Dimensional Groundwater Flow and Transport Model *J. Avis (Geofirma Engineering), M. Gobien*
17:30	Discussion	Discussion

18:30	Conference dinner *(Buses depart at 17:50 from BGR)*

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	Large conference room	Conference room (A14)
	New Insights from Laboratory Experiments *Chaired by M. V. Villar (CIEMAT) & K.-H. Lux (TU Clausthal)*	**Design and Construction of Engineered Barriers** *Chaired by J. L. García-Siñeriz (Aitemin) & G. Armand (Andra)*
08:30	THMC China-Mock-Up Test about the Buffer Material for HLW Disposal in China *Y.M. Liu (BRIUG), J. Wang, S.F. Cao, J.L. Xie, L.K. Ma, X.G. Zhao, L. Chen, Y.W. Li*	A General Overview of DOPAS Project and First Year Achievements for Full-scale Demonstration of Plugs and Seals *J. Hansen (Posiva)*
08:50	Temporal Evolution of the Fe/ FEBEX Bentonite System under Simultaneous Hydration and Heating – Results up to Seven Years *E. Torres (CIEMAT), M. J. Turrero, A. Escribano, R. Fernández, A. Ruíz, J. Cuevas*	Engineered Barrier System Design for the NWMO Mark II Used Fuel Container *K. Birch (NWMO), A. Murchison, M. Mielcarek, D. Marinceu, C. Hatton*
09:10	An Experimental Approach to Study the Long-term Alteration of Compacted Bentonite Affected by Cement Degradation and Iron Corrosion Products *J. Cuevas (UAM), R. Fernández, E. Torres, A. Escribano, A. I. Ruiz, M. Regadío, M. J. Turrero*	Plan of Full-scale Experiment on Engineered Barrier System in Horonobe Underground Research Laboratory *T. Fujita (JAEA), M. Nakayama, K. Tanai, Y. Sugita*

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09:30	“Clay/Iron-Interaction”- Experiments on a Series of Bentonites *H.-J. Herbert, J. Kasbohm (GeoEncon), N. Tan, L. Meyer, H. Thi Minh Thao, M. Xie*	Design and Construction of a Large-scale Sand-bentonite Seal in in the Meuse/Haute Marne Underground Research Laboratory: NSC Experiment *R. de La Vaissière (ANDRA), N. Conil, J. Morel, F. Leveau, C. Gatabin, J.L. Garcia-Sineriz, H. Habos, M. Rey, M. Piedevache, B. Helminger, C. Balland*
09:50	Mineralogical Characterization of all Samples of the Second ABM-package and Implications for the Identification of Suitable and Less Suitable Buffer Materials *S. Kaufhold (BGR), R. Dohrmann*	Preliminary Safety Analysis Gorleben – Design of a Bentonite Shaft Sealing Element *M. Breustedt (DBE Technology), N. Müller-Hoeppe*
10:10	An Insight into the Water Retention Behaviour of MX-80 Granular Bentonite *A. Seiphoori (EPFL-ENAC-LMS), A. Ferrari, L. Laloui*	New Progress In Crushed Salt Compaction For Shaft Sealing Elements *U. Glaubach (TU Freiberg), M. Hofmann, M. Gruner, W. Kudla*
10:30	Coffee break	

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Day 2 – February 7, 2014		
	Large conference room	Conference room (A14)
		Numerical Modelling of In-situ Experiments *Chaired by A. Gens (Cimne) & J. Stahlmann (TU BS)*
10:50	Geochemical Investigation in an Effort to Increase Bentonite Barrier's Thermal Load Capacity to Accommodate 32-PWR Dual Purpose Canisters *M. Cheshire (Los Alamos National Laboratory), E. Hardin, F. Caporuscio, C. Jove-Colon, M. K. McCarney*	Inverse Modeling of the FEBEX-in-situ Heating Experiment: Parameter Estimation, Extrapolation and Predictive Uncertainty Analysis *U. Kuhlmann (TK Consult), I. Gaus*
11:10	Investigation of the Thermal Stability of Materials to be Used in a High–Level Nuclear Waste Repository *H.-J. Engelhardt (DBE Technology), L. von Borstel, T. Schirmer*	Modeling Of The SEALEX In-situ Experiments-Performance Tests of Repository Seals *N. Mokni (IRSN), J-D. Barnichon*
11:30	Alteration of Hydromechanical Behaviour of a Compacted Clay Submitted to an Alkaline Fluid Circulation *O. Cuisinier (LEMTA), F. Masrouri, D. Deneele, N. Conil*	Scoping Computations for the Full-Scale Emplacement (FE) Experiment at the Mont Terri Underground Research Laboratory *B. Garitte (Nagra), H. R. Müller, T. Vogt, T. Vietor, K. Thatcher, R. Senger*

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	Large conference room	Conference room (A14)
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12:20	Panel discussion • What are the key remaining scientific-technical questions for engineered barriers? • How can programmes in early phases of development become involved in T&E, joint R&D, joint use of facilities and involvement in URL investigations? • How can activities contribute to common views across the EU on regulatory expectations, regulator methodologies, as well as review and assessment criteria? • How can activities contribute to clarity and thus to acceptance by stakeholders beyond the expert community and interest groups or organizations? *Chaired by P. Wikberg (SKB, Sweden)* *K. Koskinen (Posiva, Finland), K.-J. Röhlig (Clausthal University, Germany), N. Müller-Hoeppe (DBE, Germany), F. Bernier (FANC, Belgium), C. Davies (EC)*	
13:30	Concluding words *V. Bräuer (BGR)*	
13:45	Lunch	

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	New Insights from In-situ Experiments in Clay-rich Formations
P01	Geochemical Outcome of the Dismantling of "EB" Experiment *A.M. Fernández (CIEMAT), D.M. Sánchez-Ledesma, M.Sánchez, P. Galán, L. Gutierrez-Nebot, A. Melón*
P02	Thermo-hydro-mechanical Characterisation of Samples Retrieved from the EB Test *M. V. Villar (CIEMAT), R. Campos, I. Barrios, L. Gutiérrez-Nebot*
	New Insights from Laboratory Experiments
P03	Thermo-hydro-mechanical Behaviour of Unsaturated Buffer Materials: A Column-type Approach *T. Schanz, L. Nguyen-Tuan (Ruhr-Universität Bochum), W. Baille, S. Tripathy, M. Datcheva*
P04	Bentonite Buffer Material Saturating Simulation by Geotechnical Centrifuge *T. Mori (Obayashi Co.), H. Komine*
P05	"Rate of Alteration"-Experiments on a Series of Bentonites *N. T. Lan, J. Kasbohm (GeoENcon), H.-J. Herbert, H. Thi Minh Thao*
P06	EMDD and the Effect of Salinity on Bentonite Properties *G. Grégoire, K. Birch (NWMO), P. Gierszewski*
P07	On the Electromagnetic Material Properties of Callovo-Oxfordian Clay Rock *N. Wagner (Bauhaus-University Weimar), T. Bore, J.-C. Robinet, D. Coelho, F. Taillade, S. Delepine-Lesoille*

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P09	Geochemical Behaviour and Stability of the Czech B75 Bentonite during Interaction with Water at 90 °C *P. Filipská (Masaryk University), J. Zeman, D. Všianský, M. Honty*
P10	Slovak Candidate Bentonites for the Engineered Barriers: Review of Past & Ongoing Research at the Comenius University in Bratislava *R. Adamcova (Comenius University Bratislava), M. Galambos, O. Rosskopfova, A. Krajnak*
	Numerical Modelling of Thermo-Hydro-Mechanical-Chemical Processes
P11	Coupled THC(m) Models of Compacted Bentonite *J. Samper (UDC), A. Naves, L. Montenegro, A. Mon, B. Pisani*
P12	Long-term THC Simulations of the Interactions of Corrosion Products and Compacted Bentonite in a HLW Repository in Granite *J. Samper (UDC), A. Naves, L. Montenegro, A. Mon*
P13	Numerical THC Models of Bentonite Heating and Hydration Tests to Study the Interactions of Compacted Bentonite with Concrete and Carbon Steel *J. Samper (UDC), A. Mon, L Montenegro, J. Cuevas, R. Fernández, M. J. Turrero, E. Torres, A. Naves*
P14	Coupled Hydraulic-mechanical-chemical Modelling for Cement-Bentonite Barrier System (1) Purpose and Issues of the Study *H. Owada (RWMC), T. Ishii, I. Kobayashi, M. Takazawa, K. Yamaguchi, Y. Tajayama, A. Iizuka*

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P16	New Development of a Combined Abutment and Sealing Assembly Made of Bitumen and Gravel *U. Glaubach, M. Hofmann, T. Teichert, W. Kudla (TU Freiberg)*
P17	Application of SHOTCLAY Method to Construction of Backfill and Clay Plug *I. Kobayashi, K. Suzuki (*RWMC), *J. Eto, H. Asano*