NAGRA'S ACTIVITIES AT THE GRIMSEL TEST SITE AND THE MONT TERRI PROJECT: UPDATE AND OUTLOOK

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ABSTRACT

Switzerland is in a unique position to host two operating underground research laboratories (URLs) in two different host rocks - the Grimsel Test Site (GTS) and the Mont Terri Project (MTP). GTS, which is owned and operated by Nagra, is situated in crystalline rocks in the Swiss Alps and has been in operation since 1984; the MTP takes place in the Mt. Terri rock laboratory, which is owned by the Republic and Canton of Jura and operated by the Swiss Geological Survey of the Swiss Federal Office of Topography (swisstopo), is situated in the Opalinus Clay and has been in operation since 1996. Nagra has been actively engaged in both URLs from the very beginning with experiment programs which are derived from the RD&D priorities and evolve as the geological disposal program advances.

Nagra's work performed at the Mont Terri laboratory, which is not located within one of the siting regions but provides access to the host rock selected for the HLW repository, focuses on the understanding of host rock properties and host rock behaviour due to repository-induced effects. The focus of the work at GTS has followed the evolution of the national program, with current emphasis on the behaviour of engineered barrier system components at the engineering scale and mass transport migration models that can be used in fractured sedimentary rocks also. Experiments of the former type are considered complementary to the ones at the Mt. Terri laboratory taking advantage of the geologic boundary conditions offered by GTS.

An outline of the on-going experiments in both URLs, with examples from Nagra-led activities, as well as the expected contributions of these two URLs to Nagra's activities towards the site licence applications are presented.

I. THE TWO URLs

Two operating underground research laboratories are located in Switzerland (Fig. 1) in two different host rocks - the Grimsel Test Site (GTS) and the Mont Terri Project (MT, in Fig. 1, Mt. Terri hereafter). GTS which is owned and operated by Nagra, is situated in crystalline rocks in the Swiss Alps and has been in operation since 1984 (www.grimsel.com); Mt. Terri, which is owned by the Republic and Canton of Jura and operated by the Swiss Geological Survey of the Swiss Federal Office of Topography (swisstopo), is situated in one of the sedimentary formations (Opalinus Clay) of the Jura Mountains and has been in operation since 1996 (www.mont-terri.ch).

Nagra is actively engaged in both URLs with activities derived from the overall Nagra RD&D plan[1]. In addition to the direct contribution to Nagra's national geologic disposal program, both URLs offer a platform for cooperation with international partners, for training and for interaction with interested stakeholders.

In November 2011 the Swiss Federal Government approved Nagra's proposals to focus on sedimentary geological formations as host rocks for the future repositories in Switzerland in six siting regions. This decision concluded the first stage of the site selection in Switzerland and initiated Stage 2, which is on-going and focuses on the selection of at least two sites for each type of geological repository (LILW and SF/HLW/ILW) planned in Switzerland.

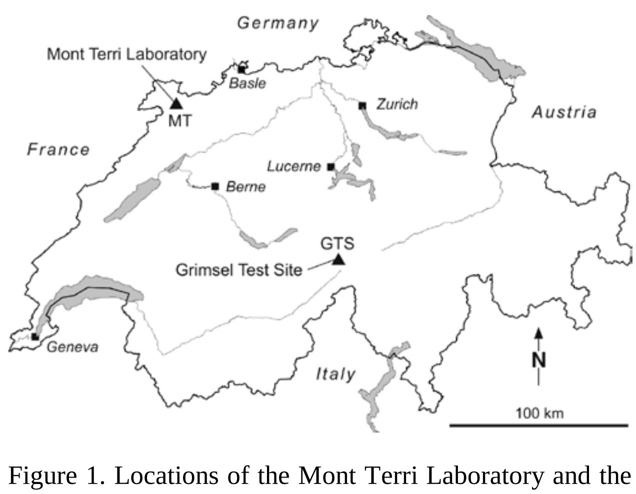

Figure 1. Locations of the Mont Terri Laboratory and the Grimsel Test Site in Switzerland.

As a result of the selection of potential sites for geological disposal in clay-rich host rocks, the work performed by Nagra at the Mt. Terri laboratory focuses on understanding host rock properties and host rock behaviour to repository-induced effects. Thermal, hydraulic, mechanical, chemical (THMC) phenomena and their impact on the host rock properties, repository-generated gas migration, interaction of host-rock with engineered barrier materials and radionuclide transport through the host rock are issues being studied. Large-scale and/or full-scale long-term projects to demonstrate the transient behaviour of the repository components have also been initiated with a planning horizon on the order of decades.

Nagra's current emphasis of its activities at GTS is on the behaviour of engineered barrier system components at the engineering scale and mass transport migration models that can also be used in fractured sedimentary rocks. Experiments of the former type are considered complementary to the ones at the Mt. Terri laboratory taking advantage of the geologic boundary conditions offered by the GTS.

In parallel to their main roles as research facilities, the URLs are important platforms for active interaction with the interested public, contributing to the understanding and acceptance of the scientific and engineering work performed in the area of geological disposal. The projects on-going in these two URLs are presented below and selected projects are highlighted.

II. ACTIVITIES AT THE GRIMSEL TEST SITE

II.A Overview

Nagra's decision to construct its own site-independent rock laboratory in the crystalline rocks of the Aar Massif in the Bernese Oberland dates back to the late 70s. At that time, the feasibility studies for a geological repository for high-level radioactive waste in Switzerland were focused on the crystalline basement and Nagra was very interested in a research rock laboratory in a formation with similar geological conditions.

The first set of tunnels at the GTS was excavated in 1983 and 1984 using a tunnel boring machine and drill and blast techniques. The tunnel system was further expanded in 1995 and 1998 as part of two large-scale demonstration tests. GTS is currently the 2nd longest running URL in the world, slightly younger than the Belgian one in Mol. The branching tunnel system, over 1 kilometre in length (Fig. 2) is located at an elevation of 1,730 m above sea-level, about 450 m beneath the Juchlistock, in the granite and granodiorite of the Aar Massif that was formed some 300 million years ago.

The special geological conditions encountered at the GTS (alteration between tectonically overprinted and fractured areas and homogeneous intact areas) are ideal for implementing a wide range of experimental concepts and for studying a wide variety of topics. A unique characteristic of the GTS among existing rock laboratories worldwide is the existence of a radiation controlled zone (IAEA Level B/C) in one of the investigation tunnels, which allows experiments to be carried out with radioactive tracers in the geosphere under realistic conditions (natural groundwater flow-field). With this set-up, it is possible to check the results of small-scale laboratory experiments in the field and to directly test model calculations of the migration of radioactive substances.

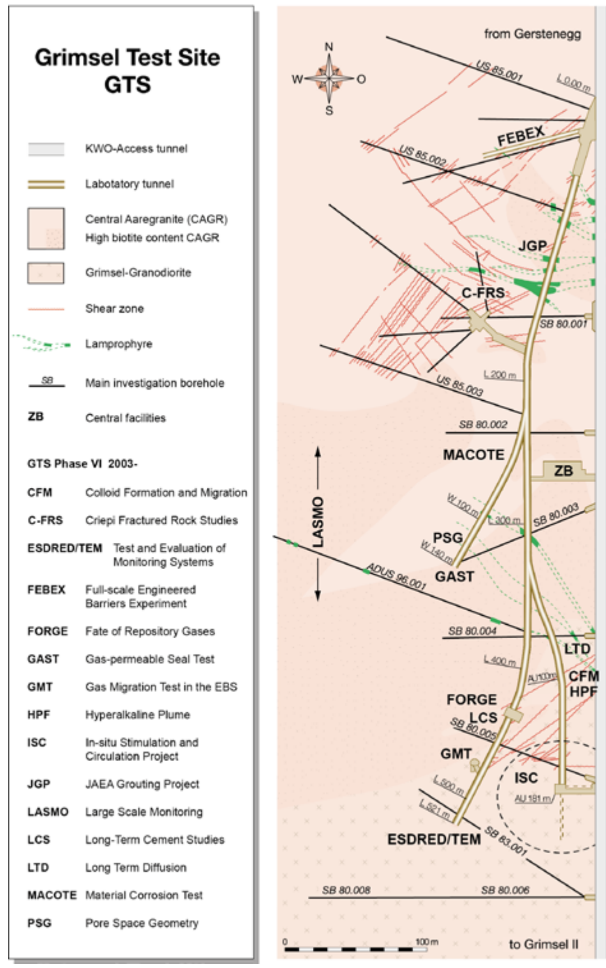

Figure 2: Plan view of the Grimsel Test Site and location of selected Phase VI experiments (Status January 2015).

Phase VI commenced in 2003 with a 10 year planning horizon with objectives focussing on:

- raising confidence and acceptance in key concepts prior to the repository licensing and construction by full-scale demonstration and engineering projects
- applying state-of-the-art science to validate key models over long periods through the performance of longer-term radionuclide retardation projects under repository-relevant boundary conditions
- providing a platform for focused international scientific collaboration in the waste management community and knowledge exchange and a centre for

training future generations of "nuclear-waste" experts (considering the needs of implementers, regulators and research organisations).

Phase VI has been extended to accommodate on-going long-term experiments, with the majority of the experimental plans defined until 2018. This date has been defined, however, only due to budget-cycle reasons and will be extended according to the experimental needs. Phase VI has also expanded in scope to include experiments from other geoscientific disciplines, such as geothermal exploration, as well as education and training activities within geoscience and engineering university programs.

II.B Highlights and Outlook

Table 1 summarises the current GTS Phase VI projects. Selected projects are highlighted below and the interested reader is referred to the GTS web site (www.grimsel.com) for more information and publications on all the projects.

TABLE 1: Projects at GTS – Phase VI (status: January 2015)

Project	**Partner**	**Schedule**
Engineered Barrier Systems (Processes and Long-term behaviour)		
FEBEXe Full-scale engineered barriers experiment extension	CIEMAT, Nagra, POSIVA, SKB, KAERI	(1995) – 2015
FEBEX-DP Dismantling project	CIEMAT, Nagra, POSIVA, SKB, KAERI; ANDRA, BGR, Obayashi, RWM, SURAO, USDOE (LBNL)	2014 – 2016
GAST (Gas Permeable Seal Test)	Nagra, ANDRA, NWMO, KORAD	2010 – *2018*
MACOTE (Material Corrosion Test)	Nagra, NWMO, RWM, SURAO.	2013 – *2018*
BentLab (Bentonite laboratory for testing and characterization of buffer performance mid-scale) – in preparation	Nagra	*2015 -*
Engineering & Operational Aspects of Repository Implementation		
LASMO (Large Scale Monitoring Project)	RWM , SURAO, Nagra	2012 – *2018*
TEM (Test & Evaluation of Monitoring Techniques – initiated as part of MoDeRn, an EC-funded project)	ANDRA, NDA (RWM), Nagra	2006 –
LSP (Low-pH Shotcrete Plug experiment - – initiated as part of ESDRED Module IV, an EC-funded project)	EC (Task Leader ENRESA), Nagra	2006 –
BELLT (Bentonite Large Scale Test)	Nagra	2014-2015
Waste – EBS – Host-rock Interaction		
CFM (Colloid Formation and Migration)	KIT-INE*, JAEA, KAERI, Nagra, POSIVA, RWM	2004 – *2018*
LCS (Long-term Cement Studies)	JAEA, POSIVA, RWM, Nagra	2005 – *2016*
Geological Barrier Processes & Characterisation		
LTD (Long Term Diffusion)	NRI, JAEA, HYRL*, Nagra	2004 – *2018*
Training & general scientific projects		
IAEA - courses	IAEA/NCE*, Nagra	2003 –
Master courses / PhD	University of Bern	2006 –
BBS (Broad-Band Seismometer project)	SED*	2010 –
ISC (In-situ Stimulation and Circulation Test) – in preparation; Part of the project Small-Scale Experiments in Deep Underground Laboratories – Swiss Competence Center on Supply of Electricity/Deep Geothermal Energy)	*ETH*, Nagra*	*2015 -*

* ETH-Z: Federal Institute of Technology, Zurich, Switzerland; HYRL: Hydraulic Research Laboratory, University of Helsinki; IAEA/NCE: IAEA Network of Centers of Excellence in Training and. Demonstration in Underground. Research Facilities; KIT-INE: Karlsruhe Institute of Technology, Institut für Nukleare Entsorgungstechnik, Germany; SED: Swiss Seismological Service;

Currently, more than 20 organisations and research institutes from 12 different countries as well as the European Union are participating in various projects. Particular importance is also attached to the close and fruitful cooperation with universities (e.g. the University of Bern and the Federal Institute of Technology - Zurich, in Switzerland) at both undergraduate and graduate levels.

FEBEX-DP: The FEBEX-DP is an on-going project at GTS focusing on the excavation of the FEBEX experiment. The latter is a full-scale in situ EBS test for the disposal of high-level waste (HLW), performed under natural conditions in which the dummy canisters are placed horizontally in drifts and are surrounded by a clay barrier constructed of highly compacted bentonite blocks. The emplacement tunnel and the EBS system were constructed in 1996 with two heaters simulating the thermal input. Heating started in 1997 and the first heater was dismantled 5 years later, in 2002, The current state of FEBEX is shown in Fig. 3. The thermal load has been maintained at a constant temperature of 100 °C since 1997 (Ref. 2)

Figure 3: The FEBEX in situ test layout for the second operational phase.

The hydration pattern around the canister is relatively symmetric, with no major differences along the x-axis. The re-saturation process is driven by the suction of the bentonite rather than by the availability of water in the rock, especially in the early phase. Whereas the water content in the buffer close to the heater still continues to increase slowly, the hydraulic pore pressures in the buffer and the geosphere have practically stabilized. The total pressure in general continues to increase in most points into the buffer, where pressures of over 6 MPa are registered in some parts.

After 18 years of operation, the experiment will be excavated in 2015 and the focus of the sampling will be on the[3]: i) determination of the distribution of key physical properties, such as density and water content; ii) the characterization of corrosion and microbiological processes on the heater, instruments and coupons resulting from evolving redox conditions and saturation states, including gas analysis, and iii) the characterization of mineralogical interactions at material interfaces (e.g. cement-bentonite or iron-bentonite, rock-bentonite) by macro- and micro-level studies. The focus of the analysis will be the understanding of the thermo-hydro-mechanical (THM) and thermo-hydro-chemical (THC) processes through integration of monitoring and in-situ measurements.

Material Corrosion Test (MaCoTe). Two broad aims of MaCoTe are (i) provide confirmation of the long-term anaerobic corrosion rate of carbon steel, stainless steel and copper in compacted bentonite under repository-relevant environmental conditions and (ii) provide experimental evidence of the inhibiting effect of the bentonite buffer on microbial activity and microbially-influenced corrosion.

Figure 4: Experimental layout: Borehole with modules; cutaway of one module showing the distribution of metal coupons.

The in-situ experiment is made up of a series of specially designed modules (0.3 m long) that are inserted into a 10 m long vertical borehole and sealed with a double packer system. Each module contains 12 specimens embedded in MX-80 bentonite with dry densities of either 1.25 or 1.5 Mg/m^3 (Fig. 4). The first eight modules were inserted into the borehole on 23rd September 2014. Retrieval will be made at increasingly longer intervals; the final two modules will be retrieved after 10 years. Corrosion rates of samples will be determined by weight loss method and the mineral alterations at the interfaces will be analyzed with available analytical methods (e.g. SEM-EDX, XRD, etc.). Microbial populations both in the bentonite and the borehole water will be analyzed using advanced cell counting and DNA mapping techniques.

Large Scale Monitoring (LASMO): The layout of a geological repository will be constrained by existing geological structures, several of which may not be sufficiently characterized from surface exploration only. Characterization from underground with mapping in tunnels or boreholes, although much easier, has to be designed in such a way that the integrity of the host rock formation is not jeopardized by using a dense network of intrusive characterization techniques. As an additional means of characterizing the host rock for the location of the panels with the emplacement tunnels one could take advantage of tunnel excavations in the repository areas to monitor geological, hydraulic, hydrogeochemical and mechanical parameters in the host rock during the excavation activities. The newly generated data and potential time-series developed would enable to better constrain the site descriptive models and reduce model uncertainties. The GTS offers many similarities to future underground constructions within repository programs, in particular (i) design: ramp type of access, large-diameter tunnels and caverns, (ii) excavation methodologies: drill and blast and TBM techniques, (iii) potential host rock formation: crystalline rock, and (iv) location: from surface down to 450 m below surface.

In order to test the capabilities of the existing techniques (measurement, analytics, modeling), a long-term (5 years) monitoring program (LASMO) has started at GTS as a cooperation project. In the early stage the project is taking advantage of the construction work and related lake drainages (Lake Raeterichsboden) of the local hydro power plant (KWO) (Fig. 5), which cause significant hydraulic changes, as well as seismic signals (blasting activities).

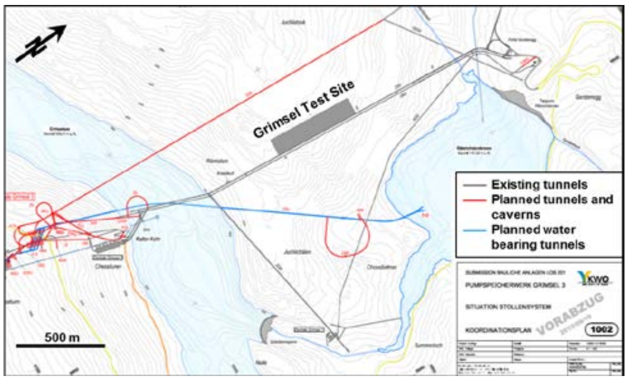

Figure 5: Map of Grimsel area with outline of the existing and planned excavations (courtesy of KWO). Lake Raeterrichsboden is the lake to the right on the figure.

These provide a unique opportunity for developing and testing monitoring strategies and techniques at different phases (baseline, construction, operation) of repository implementation, in a large scale and under realistic boundary conditions. Because some of the new constructions will be located only a few hundreds of meters away from GTS, one will be able to use the existing geological / hydrogeological model of GTS and the adjacent rock formation, predict and continuously update – through the monitoring network - and finally, validate the models once constructions are finished.

The perturbations are currently monitored by a nano-seismic network, continuous hydraulic measurements, strain monitoring system and extensometer network which are accompanied by structural mapping and modelling and an extensive hydrogeochemical sampling program involving dense time-series measurements. Attention will be paid to data-mining and further optimization of data use, e.g.: (i) which type of data has more effect/sensitivity on the disturbances, (ii) which kind of data can be used for imaging, (iii) what would be the optimal spatial and temporal resolution of data (iv) integration of various records and the perturbation signals.

Colloid Formation and Migration (CFM). This large international project is dedicated to studying the generation of colloids from a bentonite-based engineered barrier system (EBS) and to investigating the influence of such colloids on radionuclide migration in a fractured host rock under advective flow conditions. Nagra's specific interest in CFM is on instrumentation and monitoring technology, as well as testing with radionuclides. For the formations currently evaluated as host rocks in Switzerland, colloid migration is not considered a relevant issue. The particular characteristic of CFM is that flow-field conditions will be closer to repository relevant conditions than were preceding experiments at the GTS.

Several EBS designs for deep geological HLW repositories in crystalline rock formations include bentonite as buffer and backfill material[4,5,6]. CFM is designed to study bentonite erosion, colloid formation and colloid-associated radionuclide transport and to examine the colloid formation process under close to repository-like conditions at relatively low hydraulic gradients and flow velocities. A series of in-situ tracer experiments with conservative tracers, bentonite colloids, homologues and radionuclides has been performed in a shear zone at the GTS in a dipole configuration of ca. 6m length.

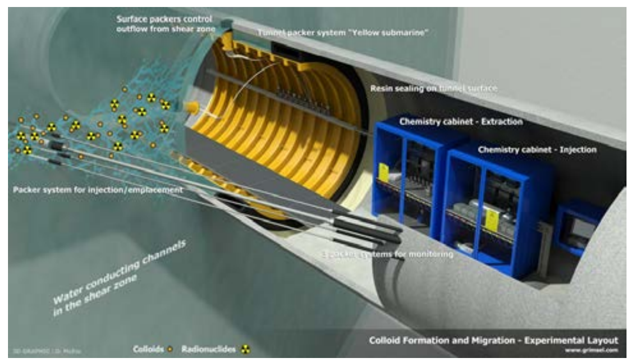

Figure 6: Schematic illustration of the layout of the long-term in-situ test initiated in the framework of CFM in May 2014 (gallery diameter 3.5 m)

The low-gradient flow field has been made possible by the installation of a “Tunnel packer system” in the CFM gallery (see Fig. 6) to seal off high inflow rates from the shear zone and thus achieve flow conditions more relevant for a repository in fractured crystalline rock than in previous shear zone experiments where flow velocities were much higher[6].

With the flow field being well controlled and characterized in ten years of preparatory work, the main component of the field work was initiated in May 2014, the long-term in-situ test. A bentonite source term (Fig. 7) was emplaced in the shear-zone interval of a central borehole whereby the flow field has been controlled with extraction from the surface packer (Fig. 6).

The source consists of bentonite rings and glass vials filled with radionuclides (Table 2) and bentonite slurry. Radionuclide concentrations and bentonite erosion are monitored in the three near-field boreholes (Fig. 6). After about three years the bentonite source term and neighboring shear zone will be overcored for additional postmortem analysis.

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Figure 7: Schematic of CFM Long-term In-situ test packer system (left), showing in grey the four traced pre-compacted bentonite rings with 10% synthetic montmorillonite (Zn labelled) and photograph (right) of the emplacement of the tracer vials (length of test interval with bentonite rings: 40 cm long).

The field program has been supported by many laboratory investigations designed to understand bentonite erosion, colloid formation and radionuclide migration under more controlled conditions than in the field experiments[7].

TABLE 2: Radionuclides used for the long-term injection

Nuclide	Max. activity (Bq) based on license	Nuclide	Max. activity (Bq) based on license
Ca-45	1.00E+06	Cs-137	1.10E+05
Se-75	1.00E+06	U-233	1.00E+03
Tc-99	1.00E+04	Am-241	8.50E+03
Sr-85	1.00E+07	Pu-238	5.00E+03
Na-22	2.00E+06	Pu-242	3.00E+02
		Np-237	1.50E+03

Long-Term Diffusion (LTD). Diffusion from water conducting features into the rock matrix has a particular significance in the context of geological disposal because it provides a mechanism for retarding the migration of weakly to non-sorbing radionuclides in fractured media. This is especially crucial when considering the calculated contribution to dose from radionuclides such as I-129 and C-14. One key target of the ongoing LTD project[8] is to derive diffusion coefficients *in-situ* and to determine and assess any differences in the values derived from laboratory tests on rock samples; the standard approach for deriving diffusion coefficients.

As part of Phase 2 of the LTD project (2013 – 2018), a second experiment (Fig. 8) was set up to study the *in situ* diffusion of HTO, Cl-36, Na-22, Ba-133 (Sr-90 analogue) and Cs-134 as well as stable Se (Se-79 analogue).

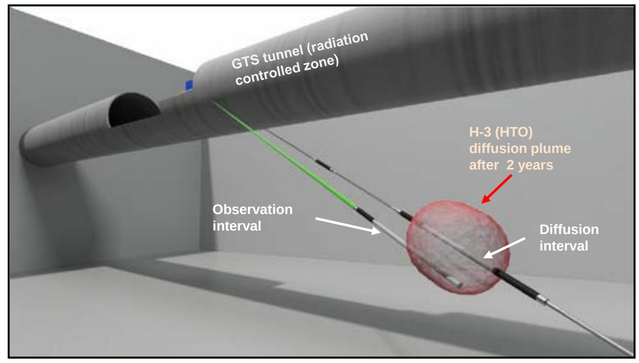

Figure 8: Schematic illustration of the LTD Phase 2 *in situ* test consisting of surface equipment in the GTS radiation controlled zone, injection borehole (17 m) and observation borehole (15 m).

Injection of the radionuclide cocktail was started on 5th March 2014 and will be circulated and monitored for at least three years before being overcored and analyzed. Monitoring of radionuclide concentration decreases with time due to diffusion and sorption is ongoing. The HTO diffusion plume has already reached the observation borehole after about six months from the start of circulation.

III. ACTIVITIES AT MONT TERRI

III.A Overview of the Mt. Terri Project

The Mt. Terri Project is an international research project for the hydrogeological, geochemical, and geotechnical characterisation of a clay formation (Opalinus Clay). Experiments are being performed at the Mt. Terri underground laboratory and their results provide input for assessing the engineering feasibility and long-term safety for radioactive waste disposal in this type of host rock (see also www.mont-terri.ch).

The underground rock laboratory is located in the Opalinus Clay in the Jura Mountains of north-western Switzerland and is owned by the Swiss Canton and Republic of Jura. The Mt. Terri research project was initiated in 1996 with five partners, ANDRA (France), JAEA (at that time JNC, Japan), LHG (Swiss Office for Hydrology and Geology), Nagra, and SCK/CEN (Belgium). To date, the number of partners has increased to 15 and the Mt. Terri Project is managed and operated by swisstopo (the Swiss Federal Office of Topography).

The Mt. Terri underground facilities include part of the reconnaissance gallery (now security gallery) of the National Highway N16 connecting Belfort (France) with the National Highway network of Switzerland, as well as a set of galleries and tunnels excavated as part of the Mt. Terri activities in 1998, 2004, 2008, and 2010 (on-going) (Fig. 9). The reconnaissance gallery, which was constructed prior to the main motorway tunnel, has been excavated using drill and blast methods, whereas sections of the Mt. Terri galleries and drifts have been excavated using other methods, for example road header, hydraulic or pneumatic hammer, horizontal raise boring, large-diameter auger.

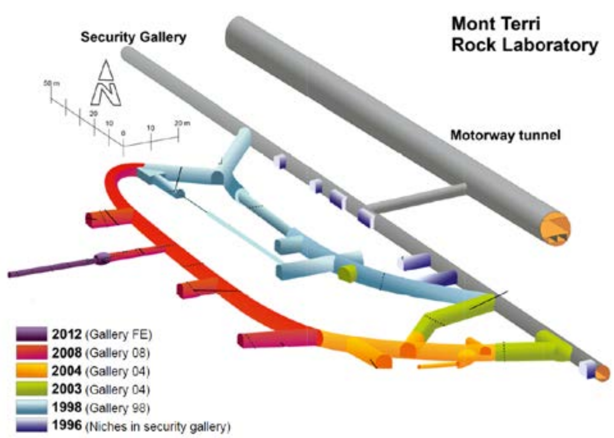

Figure 9: The layout of the Mt. Terri Laboratory (2015)

The activities can be grouped in the following categories:

- understanding processes and mechanisms in undisturbed clays,
- assessing repository-induced perturbations,
- demonstrating the engineering feasibility of construction

From the organisational point of view, the Mt. Terri Project consists of a series of individual experiments and each partner selects experiments and contributes to the scientific programming and financing of these experiments. The project is steered by a programme committee with a delegate from each partner, chaired by the director; the programme is implemented by the project manager, who is supervised by the director. The project results (raw data, evaluations, interpretations, reports) are available to all partners.

III.B Nagra's Activities – Highlights

Nagra was one of the founding members of the Mt. Terri Project. Opalinus Clay was, at that time one, of the sedimentary formations considered for the high-level radioactive waste geological repository and in 2002 Nagra submitted a feasibility project for this rock formation, which was approved by the Federal Government in 2006. Although the region of the Mt. Terri rock laboratory is not considered for a future geological repository due to the tectonic situation and the location of Opalinus Clay at this relatively shallow depth, a lot of information for the understanding of the hydrogeological, geochemical, and geotechnical characteristics of the formation can be obtained on a real scale and with easy horizontal access.

Thus, not only in developing the Opalinus Feasibility Project but also for the next steps in the Swiss geological repository program, the results at Mt. Terri, albeit generic, are an indispensable complementing component to the knowledge from results at the laboratory scale and results from field investigations, e.g. exploration boreholes and seismic investigations.

Nagra's activities are spanning the whole spectrum of experiments: from the techniques and methodologies for the rock characterisation to development of constitutive relationships to large-scale demonstration and assessment of engineering aspects relevant to the future geological repository. A list of the experiments in which Nagra participates and/or leads is shown in Table 3. Selected experiments and results are highlighted below.

HE-E experiment: The HE-E experiment[9] represents a first large-scale test for the understanding of thermo-hydraulic behavior of the Nagra near-field concept. It is a 1:2 scale heating experiment considering natural resaturation of the EBS and a maximum heater surface temperature of 140 °C. It is located in a 50 m long microtunnel of 1.3 m diameter. The experiment was initiated as part of the PEBS project (long-term performance of the engineered barrier system), a 4 year project within the EU 7^{th} Framework Program.

The aims of the HE-E experiment are to investigate the early non-isothermal resaturation period and its impact on the THM behavior by providing the experimental database for: i) the calibration and validation of existing THM models of the early resaturation phase; (2) upscaling the thermal conductivity of the partially saturated buffer from laboratory to field scale (pure bentonite and bentonite-sand mixtures).

The experiment consists of two independently heated sections of 4 meters each (Fig. 10), whereby the heaters are placed in a steel liner supported by MX-80 bentonite blocks (dry density 1,800 kg/m^3, water content 11 %). The two sections are fully symmetric apart from the granular filling material. While section one is filled with a 65/35 granular sand/bentonite mixture, section two is filled with pure MX-80 bentonite pellets. An auger, adapted to the 1.3 m diameter of the tunnel, was developed to emplace the granular EBS material. Emplacement densities, established during off-site tests for the MX-80, were around 1,450 kg/m^3, while for the sand/bentonite mixtures these were estimated to be 1,500 kg/m^3. The construction of the HE-E experiment took place between December 2010 and June 2011. Observations and results[9] from the first 2.5 years of the experiment are highlighted below.

TABLE 3: Mt. Terri field experiments where Nagra actively participates: Phase 20 (6/2014-6/2015)

Abbr.	Title of experiment	Partners	End Phase
CI	Cement-Clay Interaction	A C N O S	37
DB	Deep inclined borehole through the OPA	B G I N T W	22
DB-A	Porewater characterization – benchmarking and investigation of interface to adjacent aquifer	N T W	20
DR-A	Diffusion, retention and perturbations	D N W	20
DR-B	Long term diffusion	N W	23
FE-B	THM part of the full scale emplacement experiment	A B D G N W	35
FE-C/D	Emplacement part of the full scale emplacement experiment FE-D: co-financed by EC (LUCOEX Euratom project)	N	25
FE-E	EDZ-characterization in the vicinity of the FE Gallery	B N T W	20
FE-M	Long-term monitoring of the full scale emplacement experiment	D N	35
GD	Analysis of geochemical data	A E N S	22
HA	Hydrogeological analyses	B N	21
HE-E	In situ heater test in VE microtunnel	B E G N	22
HG-A	Gas path through host rock and seals	A B N W	22
HG-D	Reactive gas transport in Opalinus Clay	A N	22
IC	Iron corrosion of Opalinus Clay	A J N W	22
IC-A	Corrosion of iron in bentonite	A N W	22
LP-A	Long-term monitoring of the measured pore parameters	A B I N T V W	25
LT-A	Properties analysis in lab tests	B G N	20
MA	Microbial activity	A B N W	20
MA-A	Modular platform for microbial studies	N T	21
RA	Rock mechanics analyses	B N	20
SB-A	Borehole sealing experiment	B G N	21
SO-A	Palynology of Opalinus Clay	N T	21
VA	Investigation of spatial variability within Opalinus clay	B N	20
WS-I	Investigation of wet spots	B N	20

Partners-- A:ANDRA; B:BGR; C:CRIEPI; E:ENRESA; G:GRS; H:ENSI (HSK); V:CHEVRON; I:IRSN; J:JAEA; N:Nagra; O:OBAYASHI; S:SCK-CEN; T:swisstopo; W:NWMO

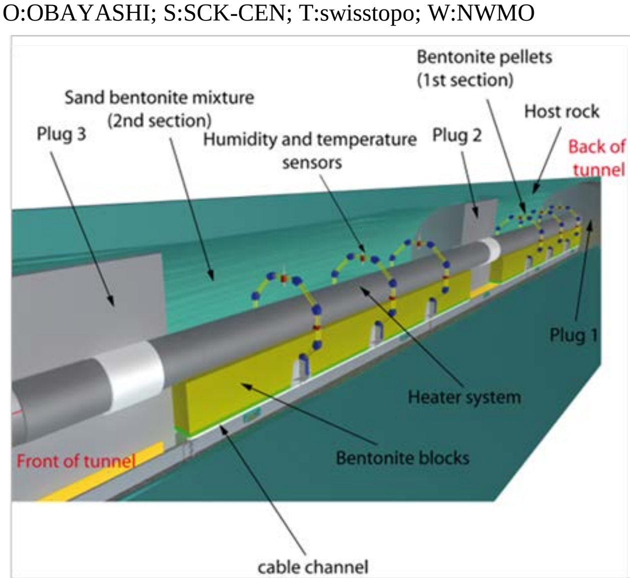

Figure 10: The HE-E experiment layout

The temperature increases observed in the EBS and Opalinus Clay were in line with those predicted by the design calculations. The EBS is characterized by a very strong temperature gradient due to the low thermal conductivity of its very dry state, especially in the inner part of the buffer. A complex development in the humidity profiles takes place which is strongly determined by the different water contents and densities of the materials at installation, the high sensitivity to changing two-phase flow parameters and the impact of vapor diffusion in a changing porous matrix. The vapor is driven out from the heat source, most likely in a radial pattern and part of the increase in relative humidity at the interface between the EBS and the host rock can be attributed to condensation of vapor. The highest temperatures (above 100 °C) prevail in an EBS with very low water content (below 20% relative humidity).

The natural water inflow from the Opalinus Clay occurs slowly through diffusion. The hydraulic pressure front is progressing towards the EBS, but how long this will take and when an equilibrium state will be reached at the constant heater temperature of 140 °C cannot be determined from the current dataset. An important observation is that the measured temperatures and relative humidity in both materials are dominated by the distance of the measurement point to the heater and not by the differences in material properties (recall that conditions of the two at emplacement were somewhat different). This rapid homogenization can also (partly) be explained by vapor movement and has been observed for the first time in the HE-E experiment, as this is the first large-scale, high temperature experiment with different materials.

Full-Scale Emplacement Test (FE). This experiment is intended to provide a demonstration of the disposal concept and an opportunity to further develop and test THM models of the disposal system at full scale[10]. It is based on the Swiss disposal concept for SF/HLW. The construction of the 50 m long experimental tunnel with a diameter of approx. 3 m was completed in September 2012. At the far end of the tunnel the so-called "interjacent sealing section" (ISS) was built using only steel arches for rock support whereas the rest of the tunnel is supported by shotcrete. In the FE tunnel three heaters with dimensions similar to those of waste canisters have been emplaced on top of pedestals built of bentonite blocks (see Fig. 11). The remaining space has been backfilled with granular bentonite. Finally, early in 2015, the experiment will be sealed off towards the FE cavern with a concrete plug holding the buffer in place and reducing air and water flux.

The entire experiment implementation as well as the post-closure THM(C) evolution is monitored using several hundred sensors. The rock in the 'far-field' was instrumented with up to 45 m long bore-holes drilled from the FE cavern; this instrumentation was completed before the FE tunnel was build and therefore allowed a 'mine-by' observation of the later tunnel construction effects.

As backfill material sodium bentonite from Wyoming was used. Compacted blocks (dry density of 1.8 g/cm3, water content of 20 %) were used for filling the ISS as well as the pedestals below the three heaters, and a granulated mixture with highly compacted bentonite granules ("pellets") with an average dry "pellet" density of 2.18 g/cm3 for the buffer. The overall bulk dry emplacement density of the buffer was targeted to at least 1'450 kg/m3 (Swiss concept).

A prototype machine for backfilling the horizontal tunnels was constructed (Fig. 11) and was successfully deployed for the backfill material.

The heating phase started in late 2014. With a target output of 1500 W per heater (according to the Swiss reference case) a temperature of approx. 120-150°C at the heater surface and 60-80°C at the rock surface are expected for the FE experiment at Mont Terri. According to current planning, the heating and monitoring phase of the FE experiment at Mont Terri is envisaged to last at least 10 to 15 years. Co-financing of part of the project is provided by the EU, in the framework of the LUCOEX program

Cement-Interaction Experiment (CI): The aim of the CI experiment is to investigate the spatial extent and the evolution over time of the chemical interactions between cement and the Opalinus Clay/bentonite and associated changes in porosity.

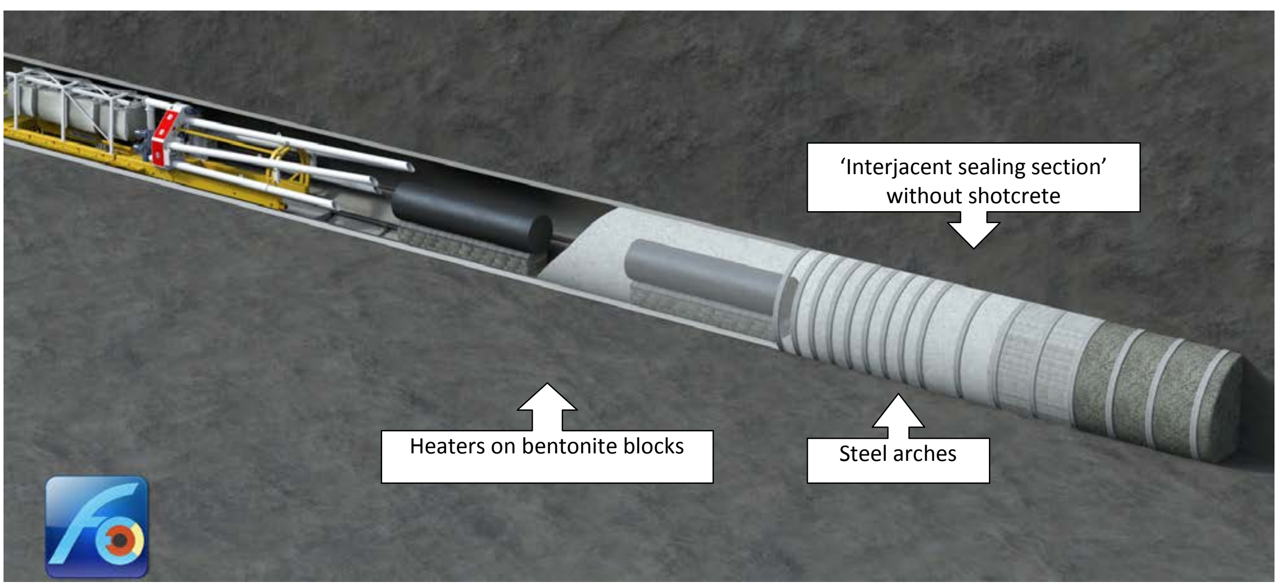

Figure 11: Visualization of the general experimental layout of and backfilling procedure of FE (diameter 3 m), as well as, the developed prototype machine with five auger conveyors used for the backfilling. The longest auger is 8.5m long.

Two boreholes (of 9.1 m deep) were drilled perpendicular to the bedding in the shaly facies of the Opalinus Clay (OPA). Each borehole was filled with multiple 1-1.5 m long sections of 2 different types of low pH concretes (low alkali cement/(LAC) and ESDRED-cement), an ordinary portland cement (OPC) and an in-situ saturated natural Na-bentonite (MX-80) segment (Fig. 12). Sampling of the various cement-OPA interfaces was carried out in 2009 and 2012 by a special over-coring technique, where the core was stabilized in advance by 6 small boreholes (diameter 46 mm) filled resin and glass fiber anchors. A triple-core barrel (131 mm diameter) was used for overcoring to provide intact cement-clay interfaces.

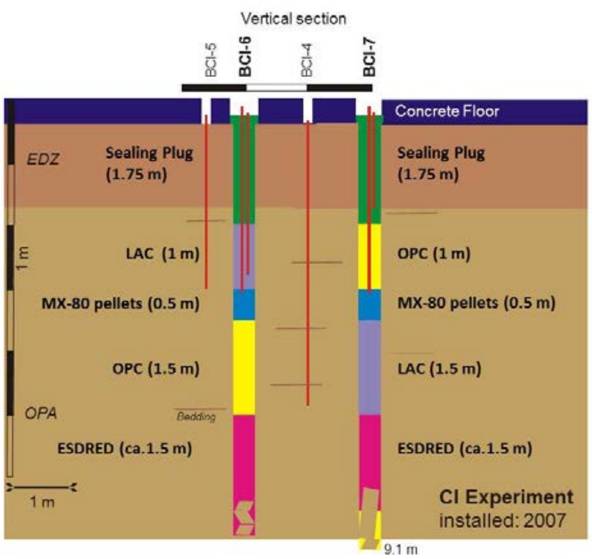

Figure 12: Overview of the Cement-Clay interaction experiment showing two boreholes filled with segments of Bentonite, Low Alkali Cement (LAC), Ordinary Portland Cement (OPC) and ESDRED Low-pH cement.

Highlights from the analysis of samples from the first campaign[11] are summarised below. The analysis focussed on the interface between one of the 3 different cement matrices (OPC, LAC, ESDRED) and the clay, using techniques with spatial resolution of less than 30 μm. These included SEM/EDX, Raman spectroscopy, porosity characterisation using autoradiogarphy (samples impregnated with ^{14}C-MethylMetAcrylate), infrared spectroscopy on bulk powders of concrete and clay samples for the identification of dissolution, precipitation and the identification of the crystalline state of the phases.

The element distribution maps developed show complex zonations in the concrete-clay interface. Up to 6 chemically distinct zones were seen at the concrete side within 2-4 mm from the interface. Depending on the cement recipe, they included zones with sulphur enrichment, zones depleted in Ca but carbonated, or zones with strong Mg enrichment adjacent to the interface. The carbonated zones showed a 7 % lower porosity than the undisturbed OPC in the area furthest from the interface.

On the clay side of the interface, a single zone with increased Ca or Mg content was observed in the first 100 μm next to the interface. The cation occupancy of clay exchanger phases next to the ordinary Portland cement interface was depleted in Mg, but enriched in Na, whereas porosity showed no changes at all.

The analysis of the samples from the second campaign is ongoing. CI is expected to continue for approximately 15 more years.

DB and DB-A. These two experiments aim at understanding groundwater flow and solute transport on a large scale in the natural barrier consisting of clay-rich sedimentary rock sequence. In addition, the DB-A experiment will allow for a benchmarking of various methods used to analyse the chemical and isotopic composition of the porewater as well as dissolved noble gases. For these purposes a 250 m long borehole was recently core-drilled and equipped with a multi-packer-system across the entire Opalinus Clay including its confining units to obtain the undisturbed distribution of water pressure, temperature and natural porewater tracers across this sequence. The challenge in such measurements is to achieve the appropriate degree of spatial resolution in order to unequivocally detect modifications induced by changes in the boundary conditions over the time period of interest.

The inclined borehole, BDB-1, encountered variably composed limestone and calcareous marls on the layers overlying the Opalinus Clay (0 – 106 m along borehole), followed by the intercalation of different facies of the Opalinus Clay (106–238 m) and the underlying argillaceous marls of the Staffelegg Formation (238–248 m, former Liassic).

The design of the drilling allowed, for the first time, at Mont Terri, the collection of samples for porewater chemical, isotopic and noble gas tracers along a borehole profile at a high spatial resolution across the entire sedimentary sequence. A preliminary evaluation of tracer profiles fits the well-established hypothesis of diffusion controlled solute tracer transport in the Opalinus Clay[12], showing stable conditions (very old saline waters) in the Opalinus Clay and comparably young changes in hydrochemical boundary conditions. The first pressure data of the multi-packer-systems indicate overpressures in the center of the Opalinus Clay formation

IV. CONCLUDING REMARKS

Two generic underground research laboratories are operating in Switzerland: the Grimsel Test Site in crystalline rocks (granite/granodiorite) and the Mt. Terri in sedimentary rocks (Opalinus Clay). Nagra is actively engaged in both laboratories, focusing on different types of activities with priorities and duration determined by the overall Nagra RD&D plan. Long-term, large-scale *in situ* experiments with duration until the end of this decade are being conducted.

At Mt. Terri, Nagra supports activities covering a broad spectrum, from development of techniques for characterisation of clay-rich formations to parameter determination, understanding, conceptualisation, parameterisation of their properties, and evaluation of repository-induced effects. The latter include thermal, hydraulic, mechanical, chemical (THMC) phenomena and their impact on the host rock properties, gas production and migration, and interaction of host rock with engineered barrier materials. Large-scale and/or full-scale long-term projects to demonstrate the transient behaviour of repository components have also been initiated with planning horizon on the order of decades.

The focus of Nagra's activities at GTS has evolved over the last 30 years in accordance with the priorities of the RD&D plan and partners wishes. Originally covering a similar spectrum as those at Mt. Terri, current emphasis is placed on the behaviour of EBS components at the engineering scale and mass transport migration models that can be used in fractured sedimentary rocks too. The experiments on engineered barrier systems are, to a large degree, host- rock independent and are considered complementary to the ones at the Mt. Terri laboratory; their performance at GTS is advantageous due to the favourable boundary conditions (practically non-existent EDZ, rocks with high-compressive strength etc).

In addition to the direct contribution to Nagra's national geologic disposal program, both URLs offer a platform for cooperation with international partners, for training, and for interaction with interested stakeholders.

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