International Collaboration Activities in Different Geologic Disposal Environments

Fuel Cycle Research & Development

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Jens Birkholzer
Lawrence Berkeley National Laboratory

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With Contributions from Liange Zheng (LBNL), Paul Reimus and Hari Viswanathan (LANL), and Carlos Jove-Colon (SNL)

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APPENDIX E

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EXECUTIVE SUMMARY

Background and Main Objective

This report describes the current status of international collaboration regarding geologic disposal research in the Used Fuel Disposition (UFD) Campaign. Since 2012, in an effort coordinated by Lawrence Berkeley National Laboratory, UFD has advanced active collaboration with several international geologic disposal programs in Europe and Asia. Such collaboration allows the UFD Campaign to benefit from a deep knowledge base with regards to alternative repository environments developed over decades, and to utilize international investments in research facilities (such as underground research laboratories), saving millions of R&D dollars that have been and are being provided by other countries. To date, UFD's International Disposal R&D Program has established formal collaboration agreements with five international initiatives and several international partners, and national lab scientists associated with UFD have conducted specific collaborative R&D activities that align well with its R&D priorities. Guiding principles for selection of collaboration options and activities are as follows:

- Focus on activities that complement ongoing disposal R&D within UFD (e.g., the science and engineering tools developed in UFD are tested in comparison with international experiments).
- Select collaborative R&D activities based on technical merit, relevance to safety case, and cost/benefit, and strive for balance in terms of host rock focus and repository design.
- Emphasize collaboration that provides access to and/or allows participation in field experiments conducted in operating underground research laboratories not currently available in the U.S. (i.e., clay, crystalline).
- Focus on collaboration opportunities for active R&D participation (i.e., U.S. researchers work closely together with international scientists on specific R&D projects relevant to both sides).

Key Issues Tackled in Current and Planned Portfolio

The current work conducted within international activities centers on the following key research questions:

- **Near-Field Perturbation:** How important is the near-field damage to a host rock (such as clay and salt) due to initial mechanical and thermal perturbation, and how effective is healing and sealing of the damage zone in the long term? How reliable are existing constitutive models for the deformation of elastoplastic and plastic geomaterials as affected by temperature and water-content changes?
- **Engineered Barrier Integrity:** What is the long-term stability and retention capability of backfills and seals? Can bentonite mixtures be developed that allow for gas-pressure release while maintaining sealing properties for water? Can bentonite be eroded when in contact with water from flowing fractures? How relevant are interactions between engineered and natural barrier materials, such as metal-bentonite-cement interactions?
- **Radionuclide Transport:** Can the radionuclide transport in fractured rock be predicted with confidence? What is the potential for enhanced transport with colloids? How can the diffusive transport processes in nanopore materials such as compacted clays and bentonites best be described? What is the effect of high temperature on the swelling and sorption characteristics of clays (i.e., considering the heat load from dual-purpose canisters)?
- **Demonstration of Integrated System Behavior:** Can the behavior of an entire repository system, including all engineered and natural barriers and their interaction, be measured and demonstrated? Are the planned construction/emplacement methods feasible?

International Cooperative Initiatives

Since 2012, UFD has joined five multinational cooperation initiatives as a formal partner, and has established a balanced portfolio of selected R&D projects collaborating with international peers. These projects cover a range of relevant R&D fields like near-field perturbation, engineered barrier integrity, radionuclide (RN) transport, and integrated system behavior.

DECOVALEX Project

The DECOVALEX Project is an international research collaboration and model comparison activity for coupled processes simulations in geologic repository systems (currently 10 project partners). The project develops modeling test cases that involve experimental data sets from international underground research facilities. Typically, these experimental test cases are proposed by one of the project partners, and are then collectively studied and modeled by all DECOVALEX participants. Currently, the project involves test cases from four international underground research laboratories (URLs) in France (Tournemire), Japan (Horonobe), Switzerland (Mont Terri), and the Czech Republic (Bedrichov Tunnel). These URLs, and the activities conducted there, constitute multi-million dollar investments now available to UFD researchers. DOE joined the DECOVALEX Project in January 2012 as a formal partner. Modeling cases with UFD involvement include, for example, an engineered-barrier heater test and the use of environmental tracers for estimating fracture properties. The current DECOVALEX Project phase will end in December 2015; planning of tasks for a new project phase is ongoing.

Mont Terri Project

The Mont Terri Project is an international research partnership for the characterization and performance assessment of a clay/shale formation (currently 15 partners). The partnership essentially provides open access to an existing underground research laboratory (URL) in Switzerland, the Mont Terri URL. Partner organizations can conduct experiments in the URL, can participate in experiments conducted by others, and have access to all project results from past and ongoing efforts. In the current phase, the Mont Terri Project comprises about 40 separate experiments that are relevant to all relevant phases in the lifetime of a repository. The annual budget for the *in situ* work amounts to several million U.S. dollars, complemented by the interpretation, analyses, and modeling work conducted by the partners. DOE joined the Mont Terri Project as a formal partner in July 2012. UFD researchers have engaged in several projects ranging from large-scale heater tests to damage zone and diffusion experiments.

Colloid Formation and Migration (CFM) Project

The CFM Project is an international research project for the investigation of colloid formation, bentonite erosion, colloid migration, and colloid-associated radionuclide transport. This collaborative project (currently nine partners) is one of several experimental R&D projects associated with the Grimsel Test Site (GTS) in the Swiss Alps, a URL situated in sparsely fractured crystalline host rock and one of few facilities underground that permits radionuclide studies. The CFM project conducts radionuclide migration experiments in a fracture shear zone complemented by laboratory and modeling studies. DOE joined the CFM Project in August 2012 but recently decided to cancel its participation. UFD researchers have interpreted field measurements conducted as GTS using semi-analytical and numerical methods, and have supported the field interpretation with laboratory experiments on colloidal transport and sorption.

FEBEX Dismantling Project

The Full-scale Engineered Barriers EXperiment (FEBEX) experiment at GTS consists of an *in situ* full-scale heater test conducted in a crystalline host rock with bentonite backfill (currently 10 partners). 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. The heating phase of the experiment, which ended in Spring 2015 after 18 years of operation, was followed by a new project, the FEBEX Dismantling Project (FEBEX-DP), aimed at dismantling the test site and conducting post-mortem analysis of engineered and natural barrier components. FEBEX-DP, kicked off with a planning phase in June 2014, provides a unique opportunity for better understanding the performance of barrier components that underwent continuous heating and natural resaturation for a significant period of time. DOE joined the FEBEX-DP Project as one of the initial partners. UFD researchers have been participating in the planning and predictive modeling of the experiment, and will soon conduct sample analysis and interpretation of long-term engineered barrier behavior.

SKB (Swedish Nuclear Fuel and Waste Management) Task Forces

The SKB Task Forces are a forum for international collaboration in the area of conceptual and numerical modeling of performance-relevant processes in natural and engineered systems (currently 12 partners). One task force focuses on flow and radionuclide migration processes in naturally fractured crystalline rock (GWFTS Task Force); another task force tackles remaining challenges in predicting the coupled behavior of the engineered barrier system (EBS Task Force). The task force topics center on experimental work conducted at the Äspö Hard Rock Laboratory (HRL) situated in crystalline rock. DOE joined both task forces in January 2014. UFD researchers are actively engaged in the interpretation and modeling of a bentonite-rock interaction experiment currently under way at the Äspö Hard Rock Laboratory (HRL). Planning of additional involvement is underway.

Bilateral Collaborations

UFD has also explored bilateral collaboration opportunities for active collaboration, and has selected additional R&D activities with potential for substantial technical advances. The status of selected opportunities and activities is listed below.

- The Korea Atomic Energy Research Institute (KAERI) Underground Research Tunnel (KURT) is a generic underground research laboratory hosted by a shallow tunnel in a granite host rock, located in a mountainous area near Daejeon, Republic of Korea. In collaboration with the Korean Atomic Energy Institute, UFD researchers are developing improved techniques for *in situ* borehole characterization and are also testing methods for measuring streaming potential (SP) to characterize groundwater flow in a fractured formation. The approach will soon be tested in the field in KURT following an ongoing expansion of the underground facility. This work is being performed under the Joint Fuel Cycle Studies agreement with the Republic of Korea.
- UFD and the German Federal Ministry of Education and Research (BMWi) are collaborating on model benchmarking and data exchange for salt repositories at the Waste Isolation Pilot Plant (WIPP) in New Mexico and at Gorleben in Germany. The U.S.-German collaboration currently focuses on modeling the temperature influence on the deformation behavior of rock salt. This is of particular importance for the design, operation, and evaluation of the long-term safety of underground repositories for disposal of high-level radioactive waste in rock salt.
- A recent Memorandum of Understanding (MoU) between the National Radioactive Waste Management Agency of France (ANDRA) and DOE may be a starting point for collaborative work in clay/shale disposal at the LSMHM Underground Laboratory near Bure, co-located with the French disposal site Cigeo in Meuse/Haute-Marne in the east of France. (LSMHM stands for Laboratoire de recherche Souterrain de Meuse/Haute-Marne, meaning an underground laboratory in the Meuse/Haute-Marne region in France.) Currently, UFD scientists are not engaged in collaborative disposal R&D at Bure.

- Other currently untapped opportunities exist with disposal programs in Japan, Belgium, and Finland. The Horonobe (sedimentary) and Mizunami (crystalline) URLs in Japan are accessible for UFD participation under the JNEAP (Joint U.S.–Japan Nuclear Energy Action Plan) agreement. Belgium and Finland have strong R&D programs in geologic disposal and a long history of work in an underground research laboratory HADES (High Activity Disposal Experimental Site) URL in Belgium, Onkalo URL in Finland), and both countries are open to collaboration with UFD scientists.
- DOE is a member in Nuclear Energy Agency (NEA) collaborative initiatives, such as the NEA Thermochemical Database Project and the NEA Salt Club. Participation in NEA's Clay Club is also being considered. The focus of these collaboration initiatives is less on active collaboration than on the exchange of information and shared approaches.

Status and Outlook

UFD has initiated a balanced portfolio of international R&D activities in disposal science, addressing relevant R&D challenges in fields like near-field perturbation, engineered barrier integrity, RN transport, and integrated system behavior. These now form a considerable portion of UFD disposal research, in particular in the Crystalline and Argillite work packages, and significant advances have been made over the past few years. The joint R&D with international researchers and the access to relevant data/experiments from a variety of URLs and host rocks has helped UFD researchers significantly improve their understanding of the current technical basis for disposal in a range of potential host rock environments. Comparison with experimental data has contributed to testing and validating predictive computational models for evaluation of disposal system performance in a variety of generic disposal system concepts. Comparison of model results with other international modeling groups, using their own simulation tools and conceptual understanding, have enhanced our confidence in the robustness of predictive models used for performance assessment. The possibility of linking model differences to particular choices in conceptual model setup provides guidance into "best" modeling choices and understanding the effect of conceptual model variability. Promising opportunities exist for further expansion of the international program.

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FIGURES

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ACRONYMS/INSTITUTIONS

ANDRA	National Radioactive Waste Management Agency, France
ANL	Argonne National Laboratory, USA
BBM	Barcelona Basic Model
BGR	Federal Institute for Geosciences & Natural Resources, Germany
BMT	Benchmark Test
BMWi	Ministry for Economy and Labor, Germany
BRIE	Bentonite Rock Interaction Experiment, Äspö HRL, Sweden
CAS	Chinese Academy of Sciences, China
CEC	Cation exchange capacity
CFM	Colloid Formation and Migration Project, Grimsel Test Site, Switzerland
CIEMAT	Centro Investigaciones Energéticas Medioambientales y Tecnológicas, Madrid, Spain
CRIEPI	Central Research Institute of Electric Power Industry, Japan
CRR	Colloid and Radionuclide Retardation Project, Grimsel Test Site, Switzerland
CS-A	Well Leakage Simulation and Remediation Experiment, Mont Terri, Switzerland
DECOVALEX	Development of Coupled Models and their Validation Against Experiments
DFN	Discrete Fracture Network
DOE	Department of Energy, USA
DOPAS	Demonstration of Plugs and Seals Experiment, Morsleben, Germany
DR-A	Diffusion, Retention, and Perturbation Experiment, Mont Terri, Switzerland
EBS	Engineered Barrier System
EDL	Electrical Double Layer
EDRAM	International Association for Environmentally Safe Disposal of Radioactive Waste
EDZ	Excavation Damage Zone (or Excavation Disturbed Zone)
ENRESA	National Radioactive Waste Corporation, Spain
ENSI	Swiss Federal Nuclear Safety Inspectorate, Switzerland
FE	Full-scale Emplacement Experiment, Mont Terri, Switzerland
FEBEX	Full-scale High Level Waste Engineered Barriers Experiment, Grimsel Test Site, Switzerland

FEBEX-DP	FEBEX Dismantling Project
FEPs	Features, Events, and Processes
FFM	Fracture-fill material
FORGE	Fate of Repository Gases Experiment, Grimsel Test Site, Switzerland
FS	Faults Slip Hydro-Mechanical Characterization Experiment, Mont Terri, Switzerland
FSC	Forum on Stakeholder Confidence
GAST	Gas-Permeable Seal Test, Grimsel Test Site, Switzerland
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit mbH, Germany
GTS	Grimsel Test Site, Switzerland
GWFTS	Groundwater Flow and Transport Task Force, Sweden
HADES	High Activity Disposal Experimental Site, Mol, Belgium
HG-A	Gas Path through Host Rock and Seals Experiment, Mont Terri, Switzerland
HE-E	In Situ Heater Experiment in Micro-tunnel, Mont Terri, Switzerland
HLW	High-Level Waste
HM	Hydro-mechanical
HMC	Hydro-mechanical-chemical
HPPP	High-Pulse Poroelasticity Protocol
HRL	Hard Rock Laboratory
IAEA	International Atomic Energy Agency
IC	Imperial College of London, UK
IGSC	Integration Group for the Safety Case
IRSN	Institut de Radioprotection et de Sûreté Nucléaire, France
JAEA	Japan Atomic Energy Agency, Japan
JFCS	U.S.–Korea Joint Fuel Cycle Studies
JNEAP	U.S.–Japan Nuclear Energy Action Plan
KAERI	Korea Atomic Energy Research Institute, Republic of Korea
KIT	Karlsruhe Institute of Technology, Karlsruhe, Germany
KTH	Royal Institute of Technology, Stockholm, Sweden
KURT	KAERI Underground Research Tunnel, Republic of Korea

LANL	Los Alamos National Laboratory, USA
LBNL	Lawrence Berkeley National Laboratory, USA
LLNL	Lawrence Livermore National Laboratory, USA
LCS	Long-Term Cement Studies, Grimsel Test Site, Switzerland
LIT	Long-term in-situ test, Grimsel Test Site, Switzerland
LSMHM	Laboratoire de recherche Souterrain de Meuse/Haute-Marne
LTD	Long-Term Diffusion, Grimsel Test Site, Switzerland
LTDE-SD	Long-Term Diffusion Sorption Experiment, Äspö HRL, Sweden
MD	Molecular dynamics
MoU	Memorandum of Understanding
MWCF	Major Water Conducting Feature
NAGRA	National Cooperative for the Disposal of Radioactive Waste, Switzerland
NBS	Natural Barrier System
NE	DOE Office of Nuclear Energy, USA
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission, USA
NWMO	Nuclear Waste Management Organization, Canada
OBAYASHI	Construction, Engineering and Management Company, Japan
ONDRAF/NIRAS	National Agency for Radioactive Waste and Enriched Fissile Material, Belgium
PA	Performance Assessment
PEBS	Long-term Performance of the Engineered Barrier System, European Union Project
POSIVA	Nuclear Waste Management Organization, Finland
PSI	Paul Scherrer Institute, Switzerland
PUNT	U.S.–China Peaceful Uses of Nuclear Technology
RWM	Radioactive Waste Management Limited, UK
R&D	Research and Development
SURAO	Radioactive Waste Repository Authority, Czech Republic
RBSN	Rigid-Body-Spring Network
RELAP	REactive Transport LAPlace Transform

REPRO	Rock Matrix Retention Properties, Onkalo URL, Finland
RH	Relative Humidity
ROK	Republic of Korea
SA	Safety Assessment
SCK/CEN	Belgian Nuclear Research Centre, Belgium
SIERRA	Sandia Integrated Environment for Robust Research Algorithms
SKB	Swedish Nuclear Fuel and Waste Management, Sweden
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories, USA
SNU	Seoul National University, Republic of Korea
SPHM	Single Part Hooke's Model
SSM	Swedish Nuclear Waste Regulator
swisstopo	Federal Office of Topography, Switzerland
TC	Test Case
TDB	Thermochemical Database
TDE	Through Diffusion Experiment
THC	Thermo-hydro-chemical
THM	Thermo-hydro-mechanical
THMC	Thermo-hydro-mechanical-chemical
TPHM	Two-Part Hooke's Model
TSDE	Thermal Simulation for Drift Emplacement Experiment, Asse II Mine, Germany
TUC	Clausthal University of Technology, Germany
UFD	Used Fuel Disposition Campaign, USA
UFZ	Umweltforschungszentrum Leipzig-Halle, Germany
UPC	Polytechnic University of Catalonia, Barcelona, Spain
URL	Underground Research Laboratory
WPDE	Water Phase Diffusion Experiment
WIPP	Waste Isolation Pilot Plant, New Mexico, USA

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1. INTRODUCTION

After decades of focusing geologic disposal R&D on open tunnel emplacement in unsaturated fractured tuff, the United States' interest has shifted to alternative host rocks (e.g., clay, crystalline, salt), hydrogeologic conditions (i.e., saturated, reducing), and repository designs (e.g., bentonite backfill and seals). These alternatives are similar to those that have been investigated by international geologic disposal programs in Europe and Asia. Close collaboration with these programs allows U.S. researchers (1) to benefit from a deep knowledge base with regards to alternative repository solutions developed over decades, and (2) to utilize international investments in research facilities (such as underground research laboratories), saving millions of R&D dollars that have been and are being provided by other countries. In 2012, the U.S. Department of Energy (DOE) embarked on a comprehensive effort to identify international collaboration opportunities in disposal research, to interact with international organizations and advance promising collaborations, and to plan/develop specific R&D activities in cooperation with international partners. To date, DOE has established formal collaboration agreements with five international initiatives and several international partners, and has conducted some specific collaborative R&D activities that align well with its R&D priorities. Several promising opportunities exist for further expansion of the program with relatively modest additional investment.

This report describes the current status of international collaboration regarding geologic disposal research in the Used Fuel Disposition (UFD) Campaign. The focus of the report is on opportunities that provide access to field data (and respective interpretation and modeling), and/or allow participation in ongoing and planned field experiments. The report is an update to earlier reports summarizing UFD's international activities (*Status of UFD Campaign International Activities in Disposal Research, FCRD-UFD-2012-000295, September 2012* [Birkholzer, 2012], and *International Collaboration Activities in Different Geologic Disposal Environments, FCRD-UFD-2014-000065, September 2014* [Birkholzer, 2014]).

2. INTERNATIONAL OPPORTUNITIES AND STRATEGIC CONSIDERATIONS

Recognizing the benefits of international collaboration toward the common goal of safely and efficiently managing the back end of the nuclear fuel cycle, DOE's Office of Nuclear Energy (NE) and its Office of Used Fuel Disposition Research and Development have developed a strategic plan to advance cooperation with international partners (UFD, 2012). International geologic disposal programs are at different maturation states, ranging from essentially "no progress" in some countries to selected sites and pending license applications in others. Table 2-1 summarizes the status of spent nuclear fuel (SNF) and high-level waste (HLW) management programs in several countries. The opportunity exists to collaborate at different levels, ranging from providing expertise to those countries "behind" the U.S. to sharing information and expertise with those countries that have mature programs (*Used Fuel Disposition Campaign International Activities Implementation Plan, FCRD-USED-2011-000016 REV 0, November 2010* [Nutt, 2010]). Working with other countries optimizes limited resources by integrating knowledge developed by researchers across the globe (UFD, 2012).

UFD's strategic plan lays out two interdependent areas of international collaboration (UFD, 2012). The first area is cooperation with the international nuclear community through participation in international organizations, working groups, committees, and expert panels. Such participation typically involves conference and workshop visits, information exchanges, reviews, and training and education. Examples include multinational activities, such as under IAEA (e.g., review activities, conference participation, and education), OECD/NEA (e.g., participation in annual meetings, Integration Group for the Safety Case membership, NEA Thermochemical Database, NEA's Clay Club, NEA's Salt Club), and EDRAM (International Association for Environmentally Safe Disposal of Radioactive Waste). DOE also actively supports bilateral agreements such as PUNT (U.S.–China Peaceful Uses of Nuclear Technology), JNEAP (U.S.–Japan Nuclear Energy Action Plan), and the U.S.-Germany Memorandum of Understanding for Cooperation in the Field of Geologic Disposal of Radioactive Wastes. UFD will continue participation in and/or support of ongoing international collaborations in this first area, will assess their benefits, and will identify the need for expanding or extending their scope. New activities and agreements may be developed with an eye toward the objectives and R&D needs of the United States (UFD, 2012).

The second area of international collaboration laid out in the strategic plan involves active R&D participation of U.S. researchers within international projects or programs (UFD, 2012). By active R&D, it is meant here that U.S. researchers work closely together with international scientists on specific R&D projects relevant to both sides. With respect to geologic disposal of radioactive waste, such active collaboration provides direct access to information, data, and expertise on various disposal options and geologic environments that have been collected internationally over the past decades. Many international programs have been operating underground research laboratories (URLs) in clay/shale, granite, and salt environments, in which relevant field experiments have been and are being conducted. Depending on the type of collaboration, U.S. researchers can participate in planning, conducting, and interpreting experiments in these URLs, and thereby get early access to field studies without having *in situ* underground research facilities in the United States.

Table 2-1. Summary of SNF and HLW Management Programs in Other Countries

Country	Material to be Disposed	Centralized Storage	Geologic Environments	URL	Site-Selection	Anticipated Start of Repository Operations
Finland	SNF		Granite, Gneiss, Grandiorite, Migmatite	ONKALO (Granite)	Site at Olkiluoto Selected	2020
Sweden	SNF	CLAB - Oskarshamn	Granite	Aspo (Granite)	Site at Osthammar Selected	2023
France	HLW and ILW		Argillite and Granite	Bure (Argillite)	Site near Bure Selected	2025
Belgium	HLW		Clay/Shale	Mol (clay)	Not Initiated	~2040
China	HLW		Granite		Preliminary Investigations Underway - Beishan in Gobi Desert	~2050
Switzerland	HLW	Wulenlingen (ZWILAG)	Clay and Granite	Mont Terri (Clay) Grimsel (Clay)	Initiated	No sooner than 2040
Japan	HLW		Granite and Sedimentary	Mizunami (Granite) Hornonobe (Sedimentary)	Initiated	No Decision Made
Canada	SNF		Granite and Sedimentary	Pinawa (Granite) - being decommissioned	Initiated	No Decision Made
United Kingdom	HLW and ILW		Undecided		Initiated	No Decision Made
Germany	HLW, SNF, heat generating ILW	Gorleben and Ahaus	Salt	Gorleben (Salt)	On Hold	No Decision Made
Republic of Korea	SNF	Envisioned	Granite	Korea Underground Research Tunnel (Granite, Shallow)	Not Initiated	No Decision Made
Spain	No Decision Made	Siting Process Initiated	Granite, Clay, Salt		Not Initiated	No Decision Made

Source: Nuclear Waste Technical Review Board, 2009. Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel

UFD considers this second area, active international R&D, to be very beneficial to the program, helping to efficiently achieve the program's key disposal research goals, such as short- and medium-term research objectives as described in *Update of the Used Fuel Disposition Campaign Implementation Plan (FCRD-UFD-2014-000047, September 2014* [Bragg-Sitton et al., 2014]). For example, the Campaign Implementation Plan calls for 5-year objectives of achieving a "comprehensive understanding of the current technical basis for disposal of used nuclear fuel and high-level nuclear waste in a range of potential disposal environments to identify long-term R&D needs" and developing "advanced, predictive computational models, with experimental validation, for evaluation of disposal system performance in a variety of generic disposal system concepts and environments." These research goals and objectives were formulated under the assumption of specific target dates for geologic repository development set out in the 2013 *DOE Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* (http://energy.gov/downloads/strategy-management-and-disposal-used-nuclear-fuel-and-high-level-radioactive-waste). With the caveat that full execution of the DOE strategy requires enactment of revised legislative authority dates, the target dates identified are, respectively, Year 2026 to have a repository sited, Year 2042 to have it characterized, designed, and licensed, and finally, Year 2048 for a repository constructed and operations commenced.

In 2012, UFD decided that advancing and utilizing such active international collaboration in disposal research should be a campaign priority. Coordinated by LBNL, a focused effort was made to collect information on international opportunities that complement ongoing disposal R&D within the UFD, help identify those activities that provide the greatest potential for substantive technical advances, interact with international organizations and programs to help advance specific collaborations, and initiate specific R&D activities in cooperation with international partners. Active collaboration can be achieved under different working models. One option stems from informal peer-to-peer interaction with international R&D organizations. Many U.S. scientists involved in UFD research activities have close relationships with their international counterparts, resulting from workshops and symposia meetings, or from active R&D collaboration outside of UFD. Continued UFD support for participation of U.S. researchers in relevant international workshops, meetings, conferences and symposia will help to foster discussion and expand such relationships.

Other working models for active international collaboration require that DOE becomes a formal member in multinational initiatives. Dr. Jens Birkholzer from LBNL, UFD's coordinator for international collaboration in disposal research, identified and examined several such multinational opportunities and made recommendations to DOE/UFD leadership as to which initiatives would be most beneficial. Since 2012, DOE has joined five international cooperation initiatives as a formal partner, the DECOVALEX Project, the Mont Terri Project, the Colloid Formation and Migration Project, the FEBEX Dismantling Project, and the SKB Task Forces. All of these provide access to field data from URLs and/or allow participation in ongoing and planned URL field experiments. Section 3 of this report gives a comprehensive overview of these initiatives and describes the various opportunities arising from DOE's membership. Outside of the above initiatives, UFD scientists can also collaborate with individual international disposal programs, which may or may not require formal bilateral agreements. Section 4 such presents international disposal programs that are open to bilateral collaboration with U.S. researchers.

The benefit of international collaboration needs to be evaluated, and periodically reevaluated, in the context of the open R&D issues that can be addressed through collaborative scientific activities. Open R&D issues with respect to NBS behavior are summarized in UFD reports (e.g., *Natural System Evaluation and Tool Development – FY10 Progress Report, August 2010* [Wang, 2010]); specific R&D issues related to clay/shale host rock are discussed, for example, in Tsang et al. (2011). EBS-related R&D items have also been considered in previous progress reports (e.g., Jove-Colon et al., 2010). All R&D

gaps identified in these reports have been evaluated in consideration of their importance to the safety case in a recently conducted roadmap exercise (*Used Fuel Disposition Campaign Disposal Research and Development Roadmap, FCRD-USED-2011-000065 Rev 0, March 2011; Tables 7 and 8;* [Nutt, 2011]). The ranking of features, events, and processes (FEPs) in this roadmap report founded the basis for identifying the most relevant and promising international opportunities. Section 5 describes the planning exercise conducted by UFD in FY11 and FY12, which led to the initial selection of a set of R&D activities that align with current goals, priorities, and funded plans of UFD. In FY15, UFD reassessed its international research portfolio, as research priorities and boundary conditions changed and as new opportunities for collaboration developed. Results from this reassessment are also described in Section 5.

The current status of R&D activities conducted in FY14 and FY15 is described in the remainder of the report. Section 6 is dedicated to R&D work with primary focus on participation in, and analysis of, URL experiments. Example R&D results are presented, albeit without providing exhaustive explanations. Ongoing international collaboration activities unrelated to URLs are briefly mentioned in Section 7.

3. MULTINATIONAL COOPERATIVE INITIATIVES

This section gives a comprehensive overview of the five international cooperation initiatives that DOE has joined as a formal partner. These are the DECOVALEX Project, the Mont Terri Project, the Colloid Formation and Migration Project (CFM), the FEBEX Dismantling Project, and the SKB Task Forces. (Note that just recently, in July 2015, a decision was made by DOE to not renew its partnership in the Colloid Formation and Migration Project, due to cost/benefit considerations). Table 3-1 lists the international waste disposal organizations currently participating in those five initiatives, sorted by country. The table demonstrates the high level of cooperation between nuclear nations. As mentioned before, the focus of DOE's international collaboration strategy is on initiatives that foster active research with other international disposal programs, provide access to field data (and respective interpretation/modeling), and/or may allow participation in ongoing and planned field experiments in URLs (Sections 3.1 to 3.4). Section 3.5 at the end briefly touches on other international collaboration initiatives organized by the Nuclear Energy Agency (NEA) where the focus is less on active collaboration and more on the exchange of information and shared approaches.

3.1 DECOVALEX Project

3.1.1 Introduction to the DECOVALEX Project

The DECOVALEX Project is a multinational research collaboration for advancing the understanding and mathematical modeling of coupled thermo-hydro-mechanical (THM) and thermo-hydro-chemical (THC) processes in geologic and engineered systems associated with geologic disposal of radioactive waste. DECOVALEX is an acronym for "Development of Coupled Models and their Validation against Experiments." Starting in 1992, the project has made important progress and played a key role in the development and validation of advanced numerical models. Through this project, in-depth knowledge has been gained of the complex THM and THC behavior of different host rock formations and buffer/backfill materials, and significant advances have been made in numerical simulation methods for their quantitative analysis. The knowledge accumulated from this project, in the form of a large number of research reports and international journal and conference papers in the open literature, has been applied effectively in the implementation and review of national radioactive-waste-management programs in the participating countries. The project has been conducted by research teams from a large number of radioactive-waste-management organizations and regulatory authorities, from countries such as Canada, China, Finland, France, Japan, Germany, Spain, Sweden, UK, Republic of Korea, Czech Republic, and the USA. A good overview of the project is provided on the DECOVALEX Project web site (www.decovalex.org) and also given in Tsang et al. (2009).

The DECOVALEX Project has been conducted in separate 3-4 year project phases. Each phase features a small number (typically three to six) of modeling tasks of importance to radioactive waste disposal. Modeling tasks can either be Test Cases (TC) or Benchmark Tests (BMT). TCs are laboratory and field experiments that have been conducted by one of the project partners and are then collectively studied and modeled by DECOVALEX participants. BMTs involve less complex modeling problems, often targeted at comparing specific solution methods or developing new constitutive relationships. Numerical modeling of TCs and BMTs, followed by comparative assessment of model results between international modeling teams, can assist both to interpret the test results and to test the models used. While code verification and benchmarking efforts have been undertaken elsewhere to test simulation codes, the model comparison conducted within the DECOVALEX framework is different, because (a) the modeling tasks are often actual laboratory and field experiments, and (b) DECOVALEX engages model comparison in a broad and comprehensive sense, including the modelers' choice of interpretation of experimental data, boundary conditions, rock and fluid properties, etc., in addition to their choice of simulators. Over the years, a number of large-scale, multiyear field experiments have been studied within the project (e.g., the Kamaishi THM Experiment in Japan, the FEBEX heater test at Grimsel Test Site in Switzerland, and the Yucca Mountain Drift-Scale Heater Test). Thus, the project provides access to valuable technical data and expertise obtained by DECOVALEX partner organizations; this is particularly useful in disposal programs that are starting their research on certain disposal or repository environments and have no URLs. DECOVALEX has a modeling focus, but with a tight connection to experimental data.

To participate in a given DECOVALEX phase, interested parties—such as waste management organizations or regulatory authorities—need to formally join the project and pay an annual fee that covers the cost of administrative and technical matters. In addition to this fee, participating (funding) organizations provide funding to their own research teams to work on some or all of the problems defined in the project phase. Representatives from the funding organizations form a Steering Committee that collectively directs all project activities.

DOE had been a DECOVALEX funding organization for several past project phases, but decided to drop out in 2007 with the increasing focus on the license application for Yucca Mountain. When the radioactive waste disposal program shifted to other disposal options and geologic environments, a renewed DOE engagement with DECOVALEX was suggested in 2011 (Birkholzer, 2011) as a logical step for advancing collaborative research with international scientists. In 2011, DOE evaluated the benefits of joining the upcoming DECOVALEX phase for the years 2012 through 2015, referred to as DECOVALEX-2015. UFD leadership realized that a renewed DECOVALEX participation would provide UFD researchers access to relevant field data from international programs and would allow them to work collaboratively with international scientists on analyzing and modeling these data. More specifically, the modeling test cases and experimental data sets proposed for DECOVALEX-2015 were highly relevant to UFD's R&D objectives. A decision was made in early 2012 that DOE would formally join the DECOVALEX-2015 project as a funding organization. In April 2012, the kick-off workshop for DECOVALEX-2015 was hosted by DOE and held at Lawrence Berkeley National Laboratory in Berkeley, California. UFD researchers are now involved in two of the three main modeling tasks in DECOVALEX-2015, as described below. Planning of a new DECOVALEX phase with new modeling tasks (referred to as DECOVALEX-2019) is currently under way; relevant potential tasks for this next DECOVALEX phase are briefly described in Section 3.1.3.

Table 3-1. Participation of International Programs in Cooperative Initiatives Related to URLs: Status September 2015

Nuclear Nation	Organizations	DECOVALEX	Mont Terri	CFM	FEBEX-DP	SKB Task Forces
Belgium	SCK/CEN		x			
Canada	NWMO		x			x
China	CAS	x				
Czech Republic	SURAO	x			x	x
France	ANDRA		x		x	
	IRSN	x	x			
Finland	POSIVA			x	x	x
Germany	BGR	x	x		x	x
	GRS		x			
	BMWi/KIT		x	x		x
Great Britain	RWM	x		x	x	x
Japan	JAEA	x	x	x		x
	CRIEPI		x	x		x
	Obayashi		x		x	
Republic of Korea	KAERI	x		x	x	x
Spain	ENRESA		x		x	
	CIEMAT				x	
Sweden	SKB			x	x	x
Switzerland	NAGRA		x	x	x	x
	ENSI	x	x			
	swisstopo		x			
United States	DOE	x	x	(x)	x	x
	NRC	x				
	Chevron		x			

3.1.2 Modeling Tasks for DECOVALEX-2015

Three main modeling tasks were defined for DECOVALEX-2015, all of which involve using data from experiments conducted in URLs (Table 3-2):

- ***Task A:***
  SEALEX Experiment: A long-term test of the hydraulic (sealing) performance of a swelling bentonite core (5 m long) in a mini tunnel (60 cm diameter) at the Tournemire URL in France
- ***Task B:***
  B1) HE-E Heater Test: Studies of bentonite/rock interaction to evaluate sealing and clay barrier performance, in a micro-tunnel at the Mont Terri URL
  B2) EBS Experiment: Studies of the THMC behavior of the EBS under heating conditions in both the early resaturation and post-closure stages of the repository, in a vertical emplacement hole at the Horonobe URL
- ***Task C:***
  C1) THMC Modeling of Rock Fractures: Modeling of laboratory experiments on THMC impacts on fracture flow
  C2) Bedrichov Tunnel Experiment: Interpretation of inflow patterns and tracer transport behavior in fractured granite

Of these modeling tasks, Tasks A, B1, and B2 are mostly relevant to the Argillite work package of UFD; both target the behavior of clay-based backfill and sealing materials in interaction with clay host rock, at ambient (Task A) and heated conditions (Task B1 and B2). Tasks C1 and C2, the THMC Modeling Study and the Bedrichov Tunnel Experiment, are mostly relevant to the Crystalline work package of UFD. Details on Tasks A, B1, B2, C1, and C2 are given below.

The current funding organizations for DECOVALEX-2015 are:

BGR/UFZ	Federal Inst. for Geosciences & Natural Resources (BGR) and Umweltforschungszentrum Leipzig-Halle (UFZ)	Germany
CAS	Chinese Academy of Sciences	China
DOE	Department of Energy	United States
ENSI	Swiss Federal Nuclear Safety Inspectorate	Switzerland
IRSN	Inst. for Radiological Protection & Nuclear Safety	France
JAEA	Japan Atomic Energy Agency	Japan
KAERI	Korean Atomic Energy Research Institute:	Korea
NRC	Nuclear Regulatory Commission	United States
RWM	Radioactive Waste Management Limited	Great Britain
SURAO	Radioactive Waste Repository Authority	Czech Republic

These organizations are participating in the three modeling tasks as follows:

- Task A: IRSN, RWM, NRC, SURAO
- Task B: BGR/UFZ, CAS, DOE, ENSI, JAEA, KAERI, NRC
- Task C: CAS, DOE, RWM, NRC, SURAO

Since each modeling task is being investigated by four or more modeling groups, in-depth collaboration and model comparison between several international research teams is ensured.

Table 3-2. Modeling Test Cases for DECOVALEX-2015 (from Jing and Hudson, 2011)

	Task A	**Task B**		**Task C**	
Task No.		**Task B1**	**Task B2**	**Task C1**	**Task C2**
Task Title	**SEALEX Experiment**	**HE-E Heater Test**	**EBS Experiment**	**THMC Fracture**	**Bedrichov Tunnel**
Proponent	IRSN	NAGRA	JAEA	RWM	SURAO
Main topic	EBS & EBS-rock interaction	EBS & EBS-rock interaction	EBS & EBS-rock interaction	NBS, Fundamental study on flow & transport	NBS, Flow & transport in fractured crystalline rocks
Relevance to repository development	Excavation, sealing & post-closure	Sealing & post-closure	Excavation, sealing & post-closure	Site characterization through to safety assessment	Site characterization and safety assessment
Processes	HMC	THM	THMC	THMC	HMC
Test time	2011–2015+	2011–2015 and beyond	2014–2015+	Data obtained, published data & literature support	Basic characterization completed, tracer tests planned
Host rock	Clay	Clay	Sedimentary rock	Granite and other hard rocks	Granite
Test site	Tournemire, France	Mont Terri, Switzerland	Horonobe, Japan	Laboratory tests	Czech Republic
Relevance to other rock types	Argillaceous but applies to all types of host rocks using EBS	Argillaceous but applies to all types of host rocks using EBS	Sedimentary but applies to all types of host rocks using EBS	Applies to all types of host rocks	Specific to crystalline but principles can be applied to other rocks
BMT or TC	TC	TC	TC	BMT	BMT/TC
Impact on PA/SA	Important for EBS, PA & total system SA	Important for EBS PA & total system SA	Important for EBS PA & total system SA	Important for scientific basis of radioactive waste disposal	Important for site characterization and total system SA
Group leader	IRSN	NAGRA	JAEA	NDA	SURAO

3.1.2.1 Task A: SEALEX Experiment at the Tournemire URL, France

The SEALEX experiment aims at investigating the long-term HM behavior and hydraulic performance of swelling clay-based seals (Figure 3-1). A suite of experiments is conducted in several 60 cm diameter mini-tunnels (5 m long) (Figures 3-2 and 3-3), which are exposed to nominal conditions, different technological choices for seal mixtures (e.g., bentonite-sand mixtures) and emplacement, and altered situations (e.g., forced resaturation or not, loss of mechanical confinement or not) (Figure 3-4). Forced resaturation can lead to heterogeneous saturation and porosity/permeability fields within the bentonite-sand core, and hence the possibility of clay-core erosion due to flow channeling. The experiments test these hydraulic parameters and their spatial distribution via state-of-the-art measurement technology (e.g., wireless sensors installed within the core to limit preferential flow along cables). Hydraulic tests (pulse tests and constant load tests) are conducted to determine the overall hydraulic properties (permeability, leaks) of the seals, for different representative conditions.

The SEALEX experimental site is located in the Tournemire URL in the south of France. The URL is characterized by a subhorizontal indurated argillaceous claystone layer 250 m thick. A railway tunnel, constructed in 1881 through the argillaceous formation, is 2 km long, 6 m high, and 4.7 m wide, and was excavated using a pneumatic tool. In 1996 and 2003, additional research tunnels were excavated off the main railway tunnel. Thus, this facility allows study of near-field rock behavior in indurated clay with different time periods of exposure to the atmosphere, namely 130, 15, and 8 years, respectively (Rejeb and Cabrera, 2006) (Figure 3-5).

The main objective of the SEALEX *in situ* tests is to evaluate the long-term hydraulic performance of swelling seal cores. Relevant scientific issues considered are:

- Investigation of hydraulic and mechanical processes such as evolution of excavation damage zone (EDZ), hydraulic performance of seals, and processes at bentonite-rock interfaces
- Investigation of the hydraulic performance of the seal-rock interface, including forced saturation effects, seal core swelling, sealing performance of the bentonite-rock interfaces
- Investigation of the generation of gas

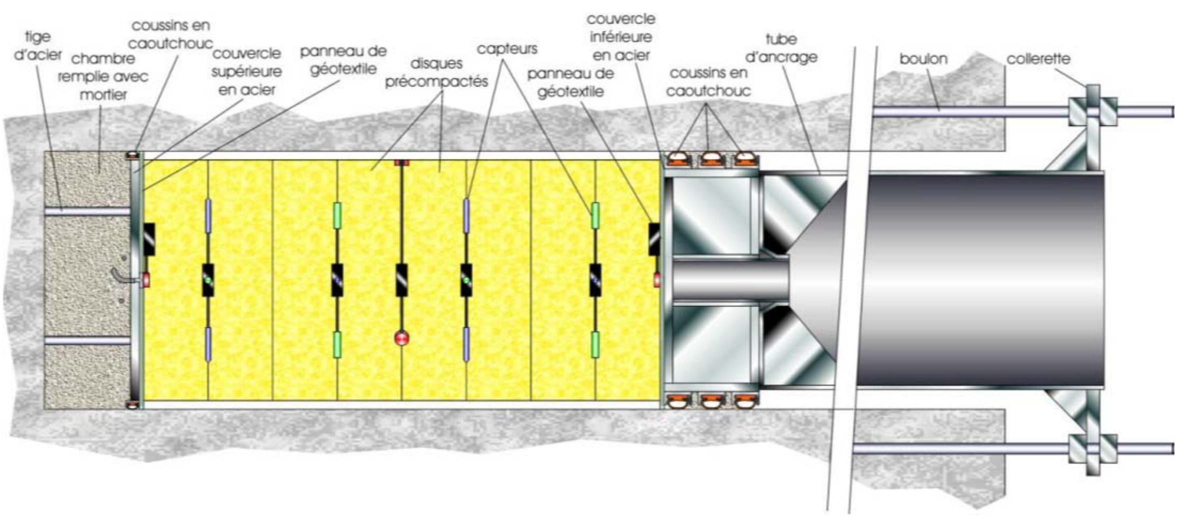

Figure 3-1. SEALEX Experiment at the Tournemire URL: Schematic setup of mini-tunnel with seal core and instrumentation (from Barnichon and Millard, 2012)

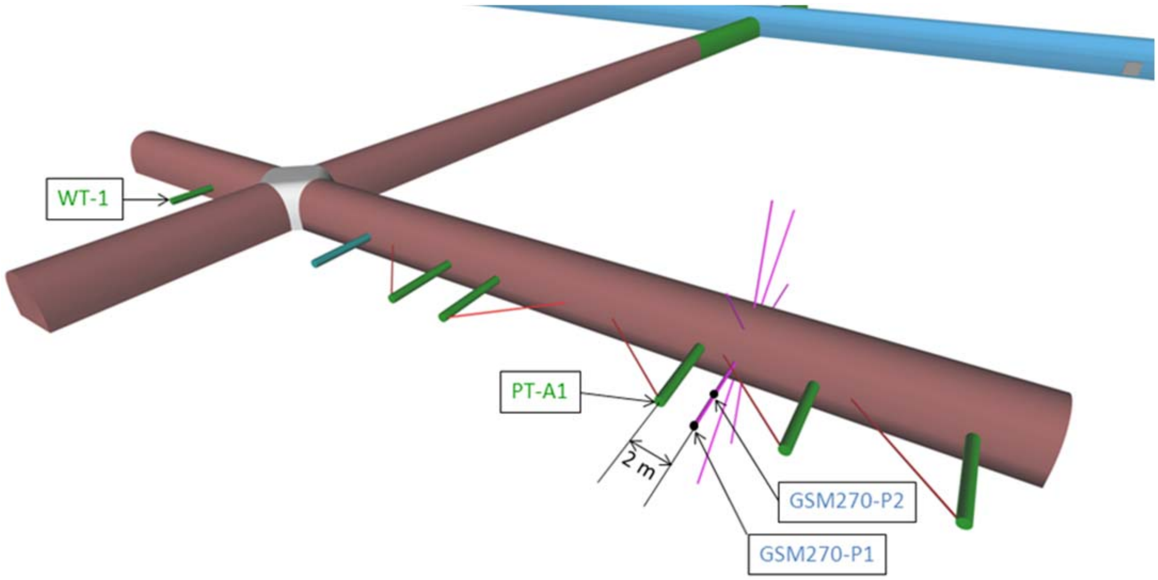

Figure 3-2. SEALEX Experiment at the Tournemire URL: Layout of mini-tunnels, access tunnels, and main gallery (from Millard and Barnichon, 2014)

Figure 3-3. SEALEX Experiment at the Tournemire URL: View of mini-tunnel from gallery after seal emplacement (from Barnichon, 2011)

	Reference Tests	Performance Tests	Intra-core geometry Core conditioning Composition (MX80/sand)	Core view	Altered conditions	Emplacement date
Base case	RT-1		Monolithic disks Precompacted (70/30)		No	12/2010
		PT-N1				06/2011
Variations / Base case	-	PT-A1	Monolithic disks Precompacted (70/30)		Confinement loss	06/2012
	-	PT-N2	Disks + internal joints (4/4) Precompacted (70/30)		No	12/2011
	RT-2		Pellets/powder In situ compacted (100/0)		No	12/2012
		PT-N3				06/2013
	-	PT-N4	Monolithic disks Precompacted (20/80)		No	12/2013

Figure 3-4. SEALEX Experiment at the Tournemire URL: Planned experiments and schedule (from Barnichon, 2011)

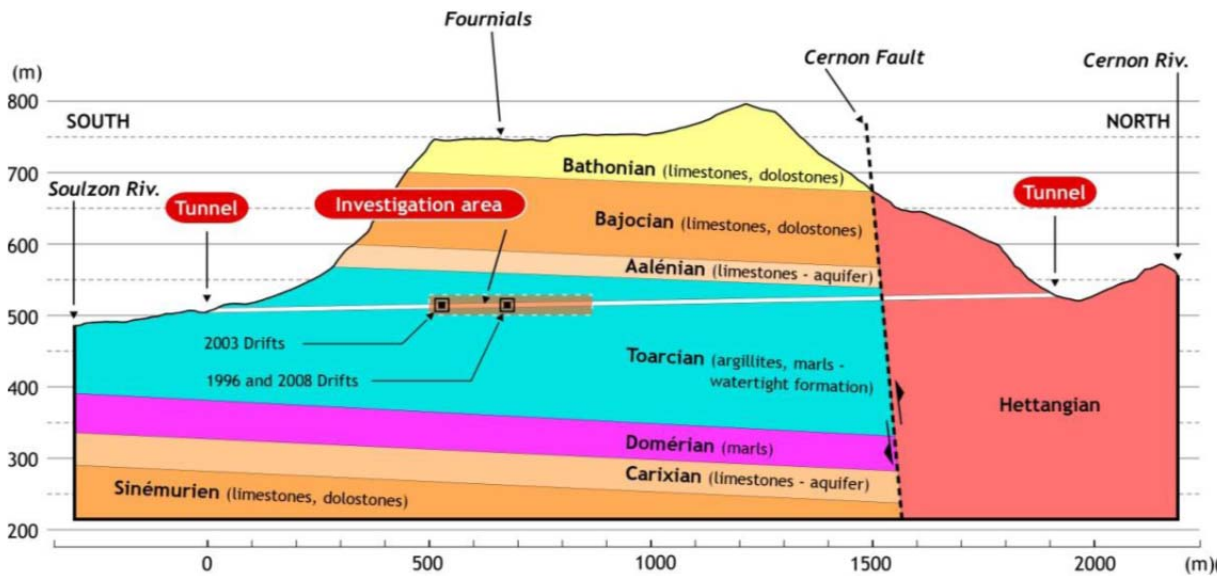

Figure 3-5. Geologic cross section of the Tournemire URL (from Barnichon, 2011)

The SEALEX test program is divided into reference tests and performance tests. The reference tests are performed mainly for quantifying the coupled hydro-mechanical fields inside the seal cores, characterized by stress, swelling pressure, pore pressure, and relative humidity, measured by high quality intracore wireless instrumentation. The performance tests consider mainly hydraulic tests (pulse tests and constant pressure tests) to determine the overall permeability fields and leaking of the seal cores, under alternative testing and core representation conditions. A progressive parametric testing approach has been designed to perform the reference and performance tests with alternative bentonite core characteristics, instrument designs, and installation conditions of the cores. For Task A of the DECOVALEX-2015 project, the participating research teams perform numerical simulations of the saturation phase of the SEALEX experiments and investigate the coupled hydro-mechanical behavior of the seal/rock interfaces and intracore (rock) regions.

The modeling plan for Task A starts with simpler models for the investigation of seal hydration behavior from laboratory experiments, followed by modeling of a 1/10 scale generic mock-up reproduction of the SEALEX experiment without rock-mass interaction, followed by an *in situ* experiment testing the behavior of the rock-mass surrounding the test site, and finally the most complex modeling step targeted at fully understanding the HM behavior of a selected *in situ* performance test. To this end, four successive modeling steps are being conducted:

- Step 0: Modeling of bentonite-sand mixture hydro-mechanical behavior and parameter identification from various laboratory tests
- Step 1: Hydro-mechanical modeling of a 1/10 scale mock-up of the SEALEX experiment
- Step 2: Modeling of hydraulic behavior of the rock surrounding an experiment
- Step 3: Hydro-mechanical modeling of an *in situ* performance test

UFD researchers are currently not involved in Task A.

3.1.2.2 Task B1: HE-E Heater Test at Mont Terri URL, Switzerland

The HE-E Heater Test at the Mont Terri URL focuses on the THM behavior of bentonite barriers in the early nonisothermal resaturation stage and the THM interaction with Opalinus Clay (see Section 3.2 for more information on the Mont Terri URL). Comparison between model results and *in situ* measurements allow for model validation. The main scientific issues considered are the thermal evolution, buffer resaturation (including *in situ* determination of the thermal conductivity of bentonite and its dependency on saturation), pore-water pressure in the near field, the evolution of swelling pressures in the buffer, and water exchange between the EBS and the surrounding clay rock.

Because the HE-E Heater Test is conducted in a micro-tunnel at 1:2 scale (Figures 3-6 and 3-7), it is considered a process and model validation, not a demonstration experiment. The heater test is conducted to assess the performance of two types of bentonite buffer materials, one consisting of bentonite pellets, the other made of a bentonite-sand mixture. A dense instrumentation network that had already been in place in the host rock surrounding the micro-tunnel (from a previous experiment testing the impact of ventilation on the clay host rock) was amended (up to 40 piezometers in total); various sensors were also placed into the buffer material (Figure 3-8). Heating started in the summer of 2011 and has been continuously operating since. The heater-buffer interface is heated to a maximum of 140°C; the temperature at the buffer-rock interface is about 60–70°C (Figure 3-9).

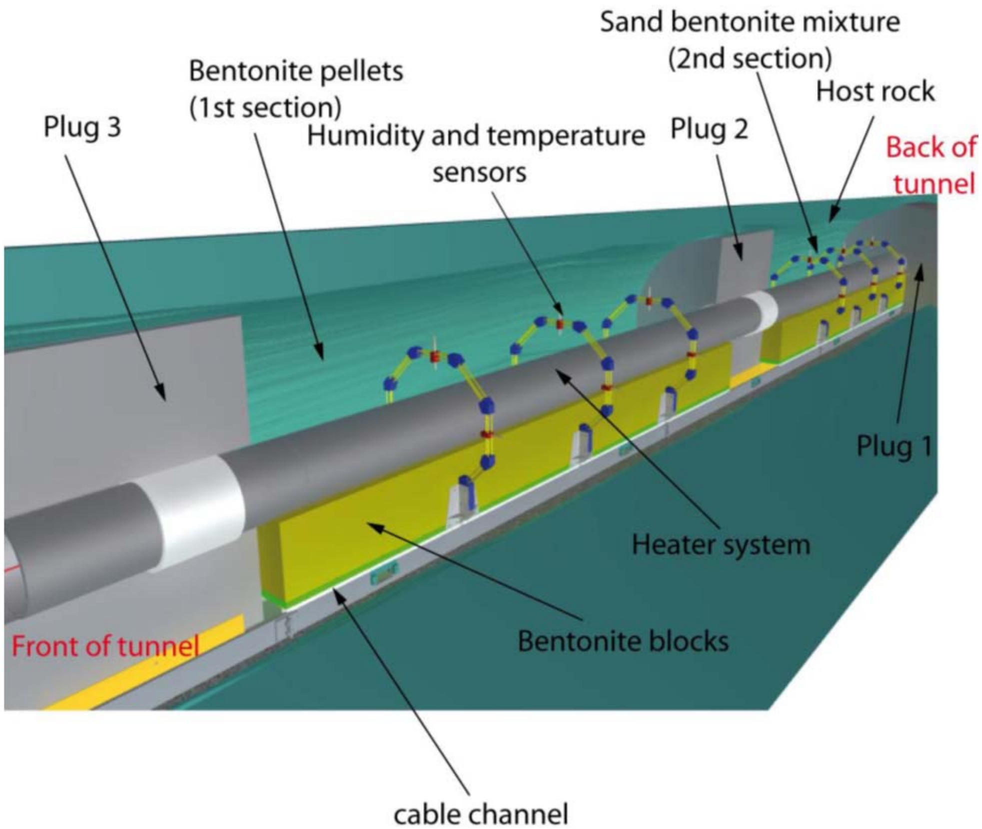

Figure 3-6. Schematic setup of HE-E Heater Test at Mont Terri URL (from Garitte et al., 2011)

Figure 3-7. HE-E Heater Test at Mont Terri URL: Photo of micro-tunnel before buffer emplacement (from Gaus et al., 2012)

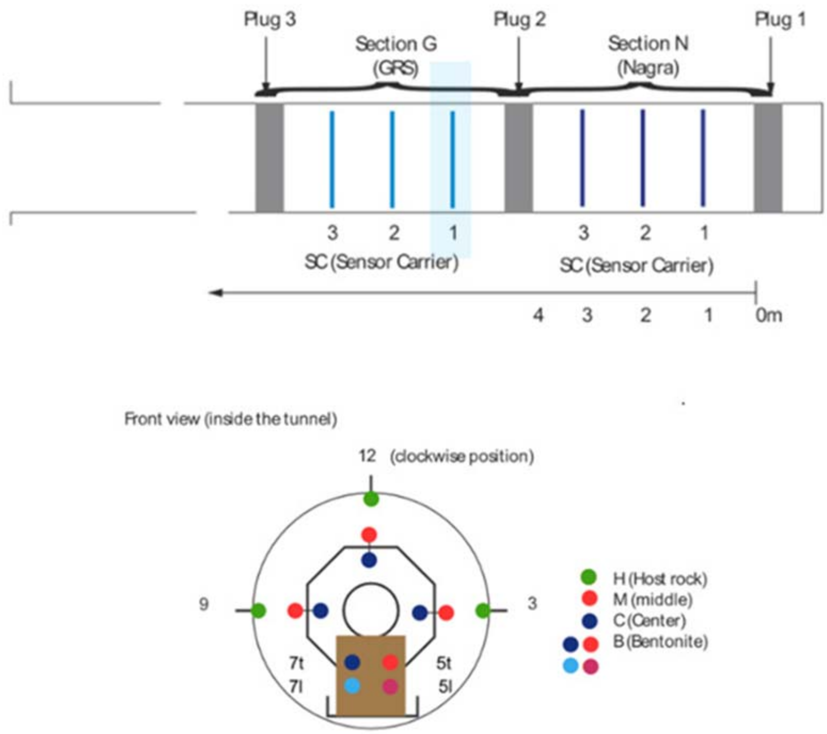

Figure 3-8. HE-E Heater Test at Mont Terri URL: Typical sensor placement (from Gaus et al., 2014)

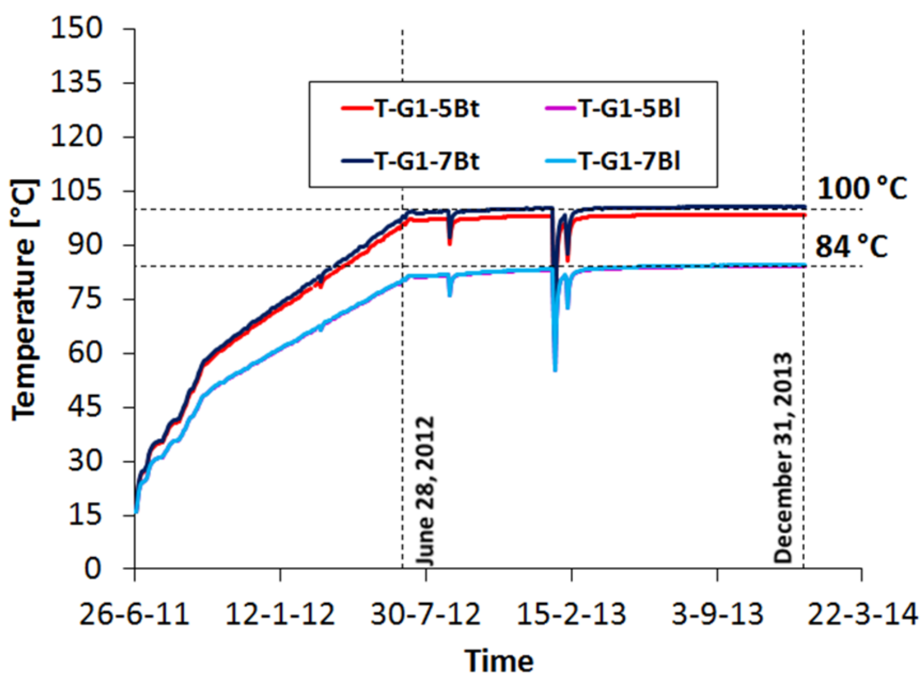

Figure 3-9. HE-E Heater Test at Mont Terri URL: Measured temperature inside compacted bentonite blocks near heater surface (from Gaus et al., 2014)

The organizers of Task B1 designed a modeling plan with increasingly complex modeling steps as listed below. Instead of starting directly with the HE-E experiment, modeling teams initially focused on two preparatory modeling steps that looked separately at the THM response in clay host rock and bentonite respectively. Once this was achieved, modeling teams were asked to move to the HE-E experiment to test the THM behavior of bentonite barriers *and* the THM interaction with Opalinus Clay. The modeling plan for Task B1 includes the following steps:

- Step 1a: Opalinus Clay study including HE-D experiment, literature study, process understanding, and parameter determination.
- Step 1b: Buffer material study including column cells, literature study, process understanding, and parameter determination.
- Step 2: HE-E predictive modeling using as-built characteristics and true power load.
- Step 3: 3D HE-E interpretative modeling when monitoring data were made available.

UFD researchers from LBNL are participating as DOE's modeling team in this task (see Section 6.1.1.1).

3.1.2.3 Task B2: EBS Experiment at Horonobe URL, Japan

The EBS Experiment at Horonobe URL investigates the THMC behavior of the EBS under heating conditions in both the early resaturation and post-closure stage of the repository and its interaction with the host rock. The scientific issues include thermal evolution, buffer (bentonite) resaturation processes, backfill effects, pore-water pressure evolution in the near-field, swelling pressure evolution of the bentonite, water input from rock to EBS (involving characterization of rock saturation surrounding the EBS), and possible chemical issues, with model development and validation, and confidence building as one of the major objectives. The schedule of the experimental work in Task B2, with a heater start in January 2015, made it possible to adopt a blind prediction and validation approach, conducting a first set of simulations before obtaining data from the EBS experiment.

The EBS Experiment is carried out at a depth of 350 m in sedimentary rock in the Horonobe URL (Figure 3-10). Figure 3-11 shows the experimental layout with a vertical heater emplacement installed in a test pit at the bottom of an experimental drift. The experimental drift has been backfilled after the installation of the heater and bentonite buffer into the test pit. Backfill and buffer materials are based on the Japanese Kunigel V1 bentonite. Over one hundred sensors have been placed in the buffer, backfill, and surrounding rock mass to monitor the coupled THMC processes, including temperature, pH, lithostatic and pore pressure, water content, resistivity, displacement, and strain (Figure 3-12). The exact sensor layout was decided upon based on model predictions by the DECOVALEX teams.

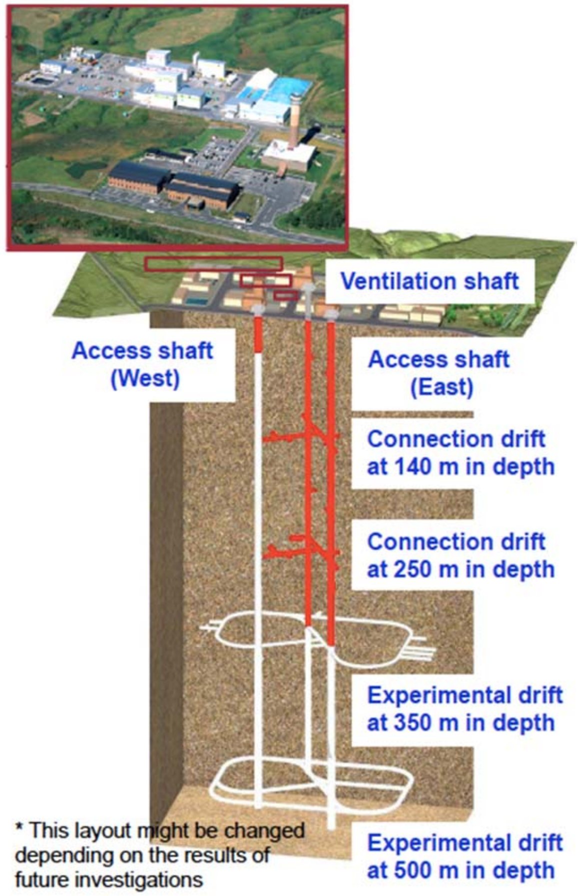

Figure 3-10. Design of Horonobe URL (from Sugita and Nakama, 2012)

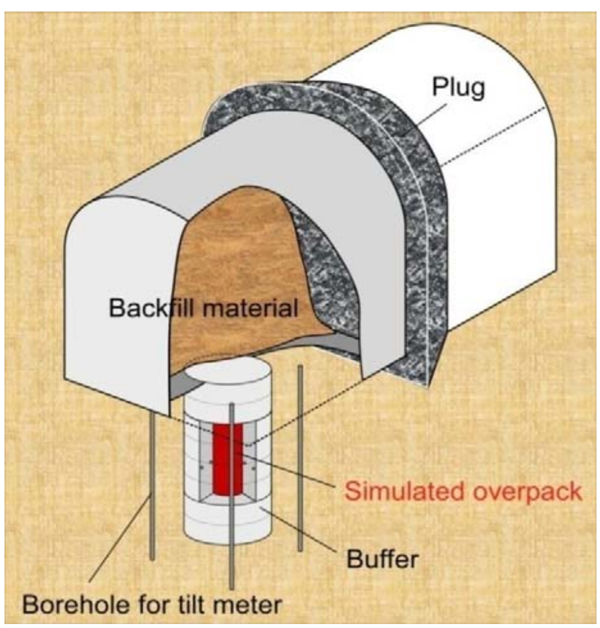

Figure 3-11. Design of EBS Experiment at Horonobe URL (from Sugita and Nakama, 2012)

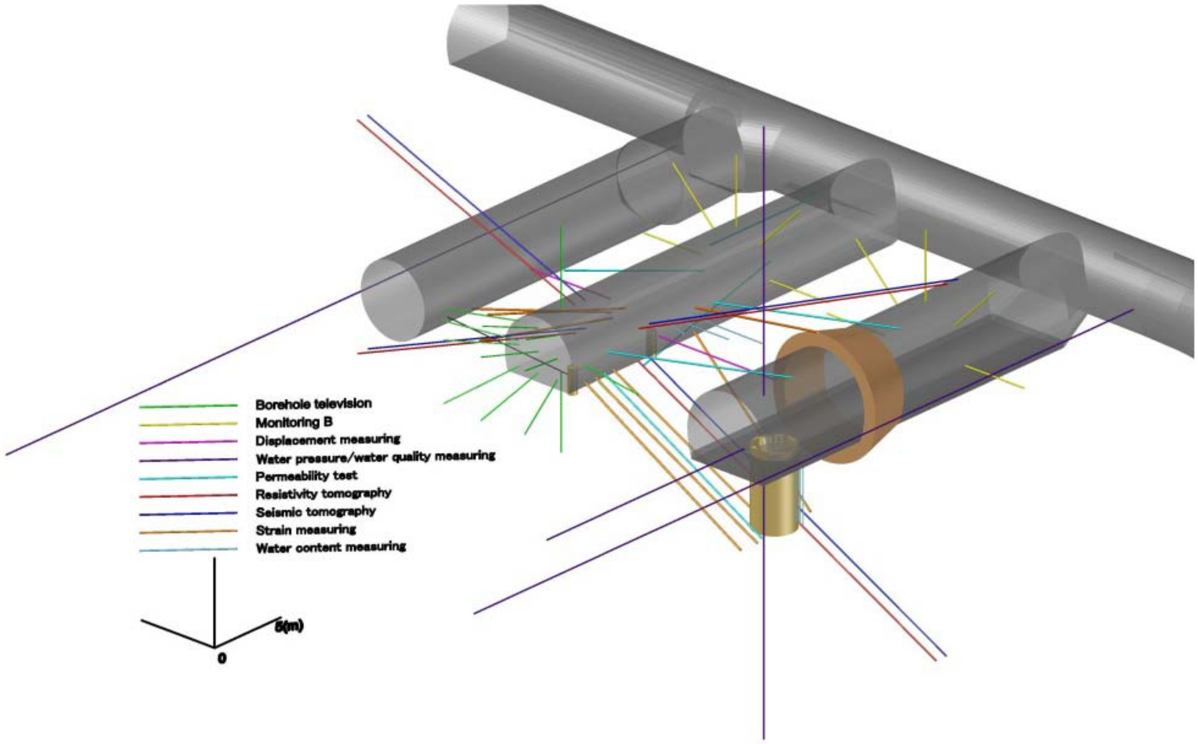

Figure 3-12. EBS Experiment: design of monitoring boreholes for sensor installation (from DECOVALEX web site, www.decovalex.org)

The modeling steps related to Task B2, the Horonobe EBS experiment, are defined as follows:

- Step 1: 1D benchmark test designed for validation of the numerical models
- Step 2: Prediction analysis and proposal of the sensor layout
- Step 3: Calibration analysis once experimental data become available

The 1D benchmark test (Step 1) was designed to take into account the host rock properties and boundary conditions given by the JAEA. This modeling exercise was conducted so that modeling teams could familiarize themselves with the problem and to obtain the data for the development and validation of computer codes and models before going into the more complex full-scale case. In Step 2, modeling teams were asked to construct a model of the real experiment and to conduct a first set of predictive THM simulations. As mentioned, these results were used to guide the installation of sensors, which began in the spring of 2014. Recently, after several months of heating, JAEA provided an initial set of monitoring data to the research teams. The research teams are currently calibrating their models against the first months of field data, and in the future may carry out coupled numerical analysis for long-term predictions (100–1,000 years) using the data from the EBS experiment. UFD researchers from LBNL are participating as DOE's modeling team in this task (see Section 6.1.1.2).

3.1.2.4 Task C1: THMC Processes in Single Fractures

Many of the proposed sites for nuclear waste repositories are naturally fractured, and the macroscopic permeability is controlled by the transmissivity of the individual fractures. These may be altered by the dissolution and precipitation of minerals, a process strongly influenced by temperature, and by the stresses acting within the asperities the fractures. This process constitutes a truly thermo-hydro-mechanical-chemical (THMC) coupled system.

Task C1 uses data from single-fracture-flow laboratory experiments to model such THMC processes, in particular looking at the linkage of thermal stresses mediating chemical effects, and conversely of chemical potentials mediating mechanical behavior (e.g., pressure solution), and how any of these processes affect flow behavior. This task requires fully coupled THMC model capabilities, which only recently have become available and still require thorough validation. Early laboratory experiments available to target such THMC behavior have been conducted on single rock fractures in novaculite (a form of microcrystalline or cryptocrystalline quartz) (Figure 3-13) (Polak et al., 2003; Yasuhara et al., 2004; Yasuhara et al., 2006). These experiments involved reactive flow-through compression and shear tests conducted on single natural-fracture specimens under different temperature, stress, and chemical conditions. The experiments were constrained by concurrent monitoring of stress/strain, influent and effluent flows/chemical reactants, and by intermittent nondestructive imaging by x-ray computer tomography. More recently, similar experiments have been conducted on granite (Yasuhara et al., 2011). The data sets from these experiments can be used for validation of THMC models with direct chemical-mechanical coupling between chemical reaction and strain.

Task C1 aims at modeling, in a fully coupled manner, the THMC processes in rock fractures based on the two sets of experiments described by Yasuhara et al. (2006) and Yasuhara et al. (2011), which exhibit coupled THMC responses in single artificial fractures in novaculite (quartzite) and granite, respectively. The ultimate objective is to investigate, develop, and test robust process models for the representation of coupled THMC processes in fractured rock, by using the experimental data and the results of the modeling work above. The modeling plan developed for Task C1 includes seven distinct steps. The focus was initially on the novaculite experiment where the simpler geochemistry and more comprehensive fracture topography data make for a more natural starting point (Figure 3-14). Teams then moved on to conduct more complex geochemical experiments in granite.

- Step 0: Novaculite: Basic benchmarking and initial models of the early part of the experiment.
- Step 1: Novaculite: More complete models covering only the isothermal part of the experiment
- Step 2: Novaculite: Complete models for the whole experiment
- Step 3: Granite: Basic benchmarking and initial models of the early part of the experiment
- Step 4: Granite: Models covering only the isothermal part of the experiment
- Step 5: Granite: Non-isothermal models
- Step 6: Application (Optional). Blind long-term comparison of the granite models using a synthetic mock-up of a fracture close to a heat generating waste disposal canister.

UFD researchers from Sandia National Laboratories are participating as DOE's modeling team in this task (see Section 6.1.5).

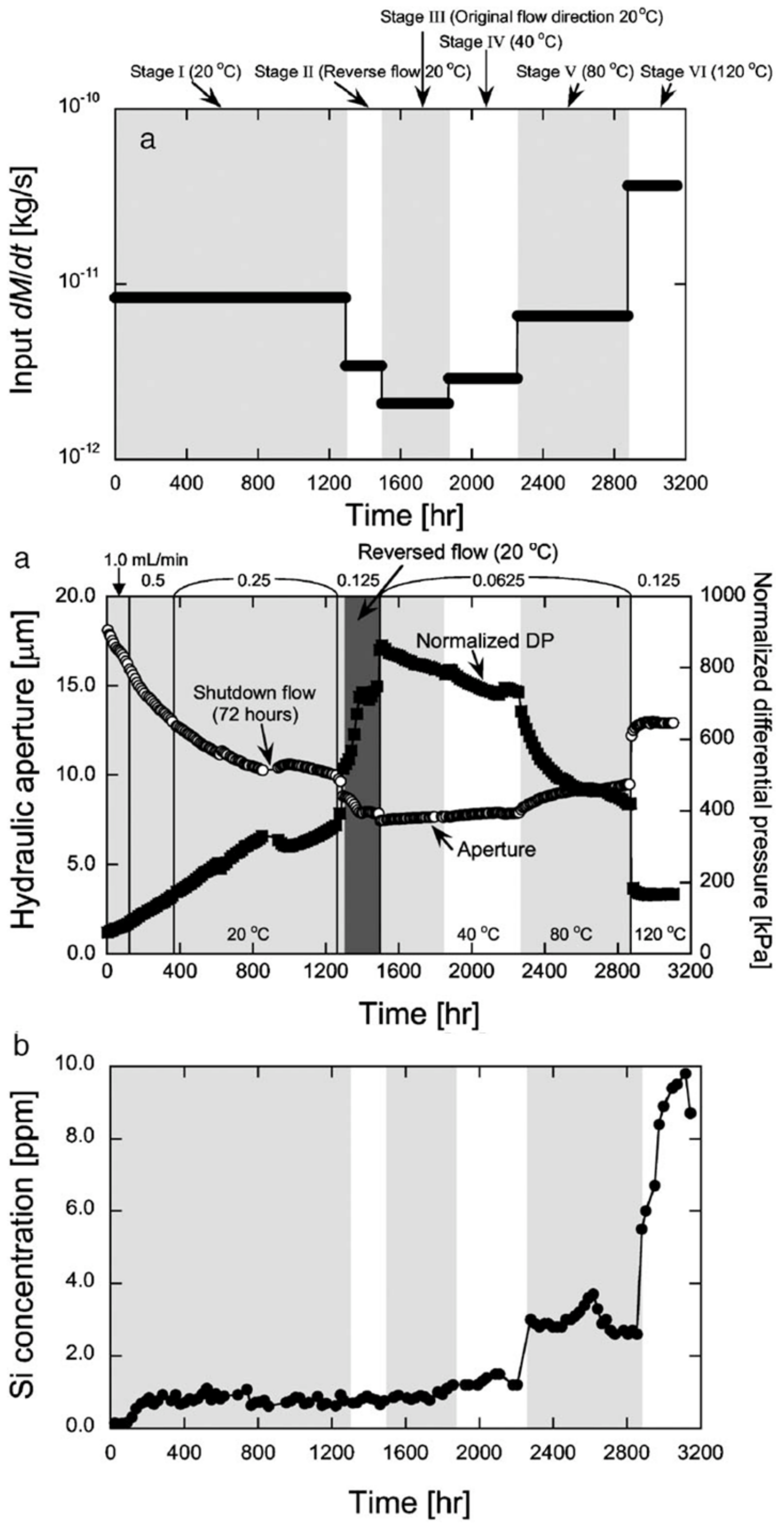

Figure 3-13. THMC behavior effects in a single fracture exposed to different external temperatures and varying stress conditions (from Yasuhara et al., 2006)

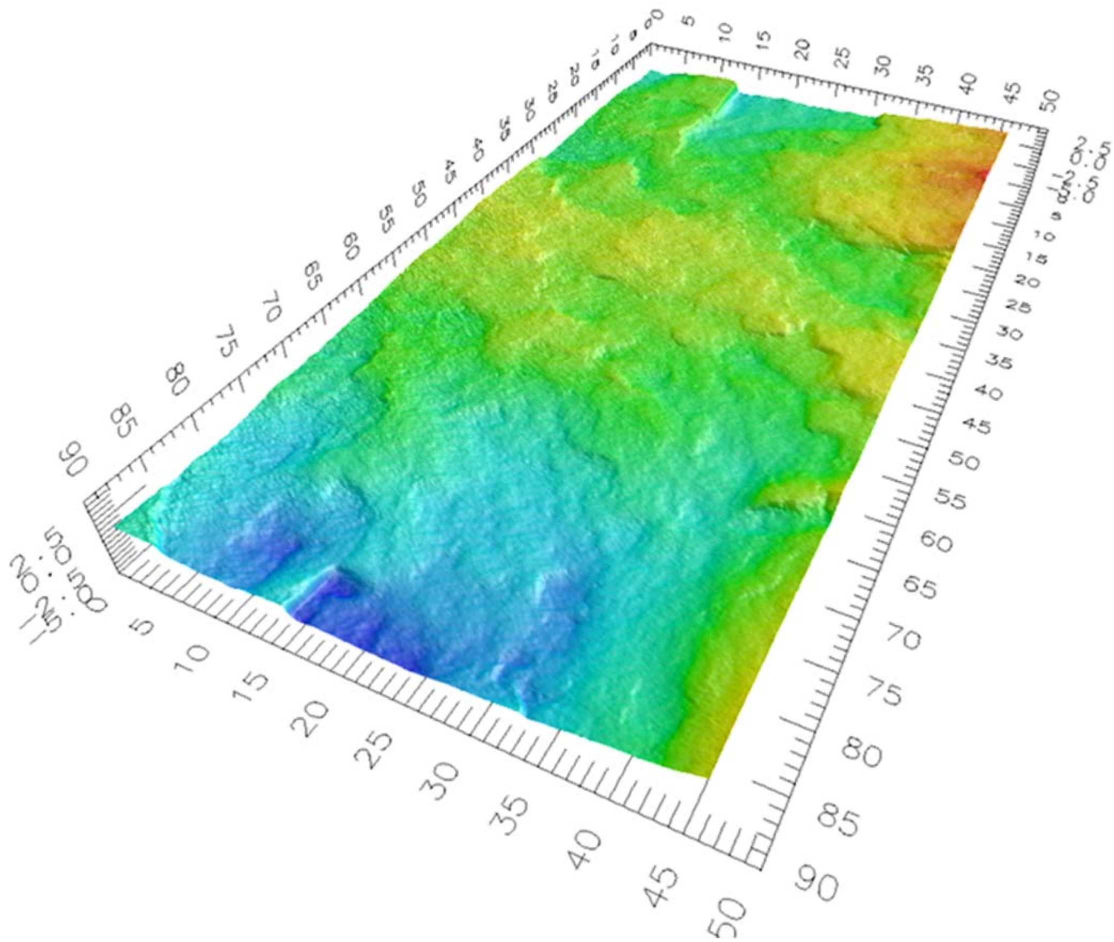

Figure 3-14. Fracture surface topography for the novaculite experiment (dimensions in mm) (from DECOVALEX web site, www.decovalex.org)

3.1.2.5 Task C2: Bedrichov Tunnel Experiment, Czech Republic

The Bedrichov tunnel is an existing tunnel, 2,600 m in length, located in the Northern Czech Republic. The tunnel hosts a water pipe, but was recently made available for geologic studies. SURAO (the Radioactive Waste Management Authority of the Czech Republic) and associated university researchers use the tunnel as a preliminary underground laboratory to study the suitability of the Bohemian granitic massif as a host rock for a radioactive waste repository (Figures 3-15 and 3-16). The site was already selected as a test case for flow models in the previous DECOVALEX phase, and since then, data collection and interpretation have progressed gradually.

The new modeling test case for DECOVALEX–2015 aims at better understanding and predicting flow patterns and tracer transport behavior within the fractured rock, between the ground surface (about 120 m above the tunnel axis) and the tunnel, including the zone around the tunnel where mechanical damage has occurred. The main issue is inhomogeneity of water inflow along the tunnel axis, i.e., the heterogeneous distribution of water inflow as a result of conduits of different size and scale (faults, fractures), and relation of water quantity and flow velocity (or residence time). Measured data include tunnel-water inflow patterns and rates, precipitation and infiltration at the ground surface), water temperature, and water chemistry, the latter including chemical composition of major elements, pH, and several natural isotopes as tracers. Discrete representations of the fracture network surrounding the tunnel have been obtained based on fracture mapping in the tunnel and electrical resistivity profiles (Figure 3-17). A comprehensive database has been established, containing data on site geology, fracture mapping (inside the tunnel), resistivity profiles, water inflow, water chemistry, and fracture displacements. The dataset also includes stable isotopes of water, tritium, tritiogenic ^{3}He and noble gases, and dissolved chlorofluorocarbons measured in fracture discharge.

The goal of Task C2 is to model groundwater flow and transport of environmental tracers in the fractured system surrounding the Bedrichov Tunnel, and utilize these data to constrain fracture-network parameters. The following modeling steps have been laid out by the task organizers:

- Step 1: Steady-state modeling of flow with average inflow (calibration of hydraulic conductivity and comparison of models between the teams)
- Step 2: Lumped-parameter model interpretation of natural tracers and coarse estimation of residence time
- Step 3: Transient hydraulic model interpretation to understand response of inflow to changing infiltration, for more precise calibration of conductivity, and to evaluate interaction between the shallow and the deep zones
- Step 4: Tracer transport in 3D for calibration of hydraulic parameters and porosity/apertures, with hypothetical pulse tracer (optionally) and actual natural tracer measurements
- Optional Step: 1D models of reaction of infiltrated water with rock minerals, fitting the tunnel inflow ion composition
- Step 5: Evaluation of residence time and other parameter determining uncertainty – comparing models with new data measured during the project

UFD researchers from Sandia National Laboratories are participating as DOE's modeling team in this task (see Section 6.2.1).

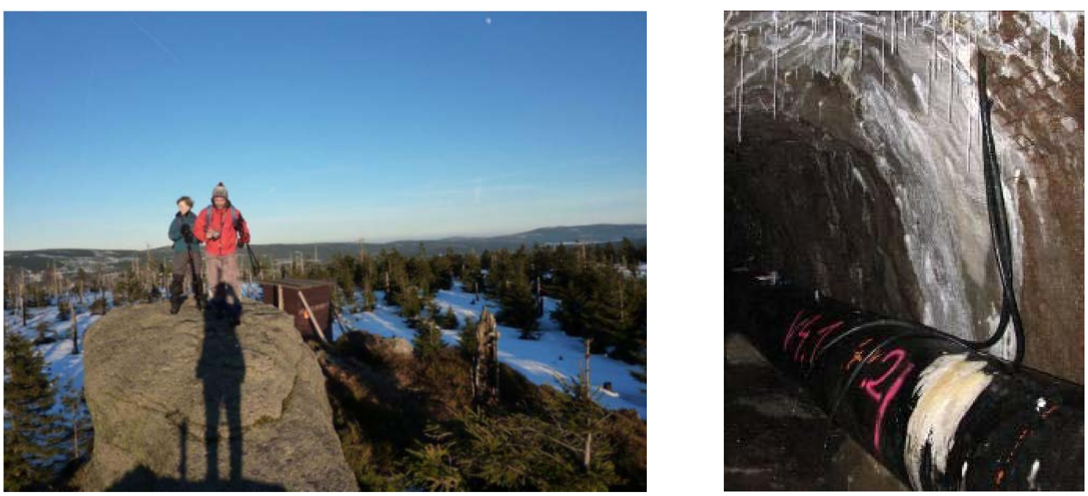

Figure 3-15. Bohemian granitic massif in Czech Republic and water inflow evidence in the Bedrichov Tunnel (from Hokr and Slovak, 2011)

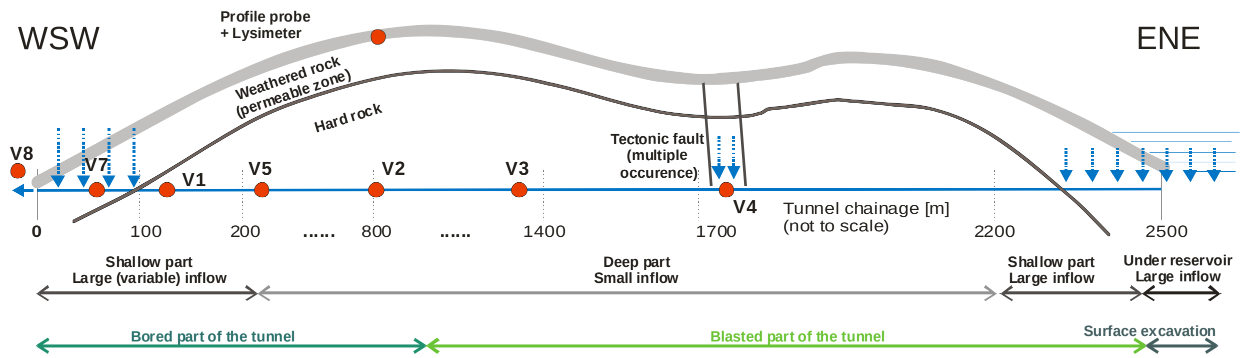

Figure 3-16. Profile of the tunnel with basic hydrogeological features and some measurement points (from DECOVALEX web site, www.decovalex.org**)**

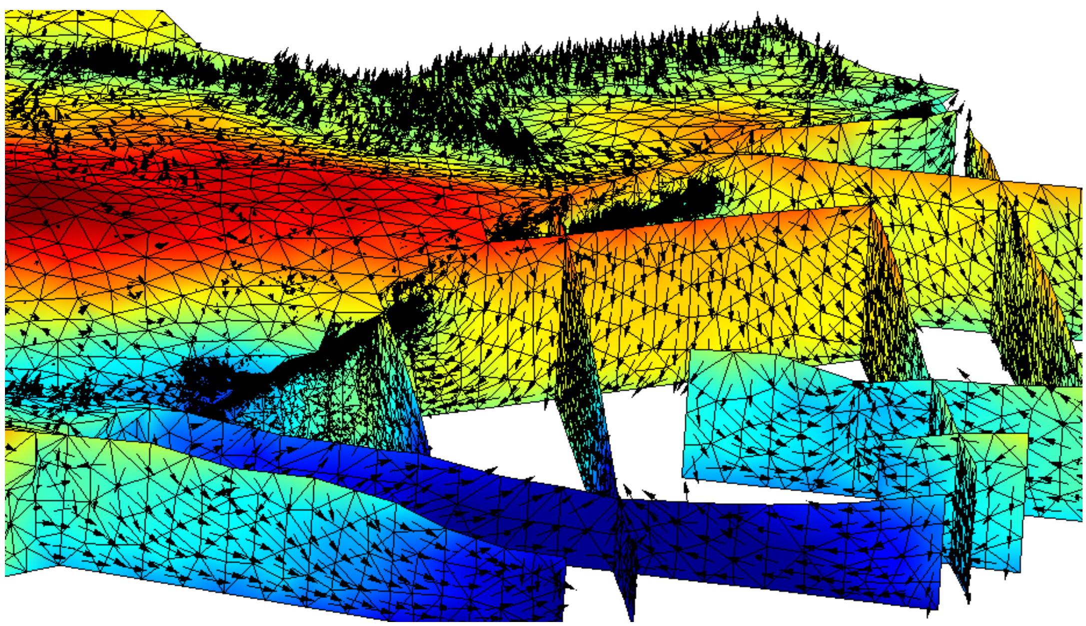

Figure 3-17. Example of numerical model of flow at the site, with combined 3D and 2D domains (from Hokr et al., 2014)

3.1.3 Proposed Modeling Tasks for DECOVALEX-2019

As mentioned before, a new DECOVALEX Project phase is planned starting in April 2016 until December 2019, referred to as DECOVALEX-2019. Current and potential new funding organizations have been developing and presenting task proposals for this new phase, as summarized below. The current list of possible tasks include seven proposals, of which three to five will be selected for inclusion in DECOVALEX-2019, based on the level of interest from funding organizations. The final task selection will be done in October 2015 at the last DECOVALEX-2015 workshop held near the Horonobe URL in Japan.

The seven modeling tasks currently proposed for DECOVALEX-2019 are listed below, most of which involve data from experiments conducted in URLs:

- ENGINEER: Modeling Advective Gas Flow in Low Permeability Sealing Materials (proposed by RWM, Great Britain)
- INBEB: HM and THM Interactions in Bentonite Barriers (proposed by ENRESA, Spain)
- GREET: Modeling of Coupled Behavior During Groundwater Recovery around a Gallery in Crystalline Rock (proposed by JAEA, Japan)
- Modeling the Induced Slip of a Fault in Argillaceous Rock (proposed by ENSI, Switzerland)
- Upscaling of Heater Test Modeling Results from Half-scale to Full-scale: from the HE-E Heater Test to the FE Heater Test (proposed by NAGRA, Switzerland)
- Fluid Inclusion and Movement in the Tight Rock (proposed by BGR, Germany)
- Reliability, Feasibility, and Significance of Measurements of Conductivity and Transmissivity of the Rock Mass for the Understanding of the Evolution of a Repository of Spent Nuclear Fuel (proposed by SSM, Sweden)

Based on preliminary level of interest by Funding Organizations, the first five proposed tasks in above list are most likely to be selected for DECOVALEX-2019. More information on these five tasks is provided in the following Sections 3.1.3.1 through 3.1.3.5.

3.1.3.1 ENGINEER - Modeling Advective Gas Flow in Low Permeability Sealing Materials

This task addresses the fate of repository gases that are generated over long time periods from corrosion of metallic materials under anoxic conditions and related formation of hydrogen. Radioactive decay of the waste and the radiolysis of water are additional source terms for gas production. If the gas production rate exceeds the rate of diffusion of gas molecules in the pores of the bentonite backfill or clay host rock, a discrete gas phase will form. Gas would continue to accumulate until its pressure becomes sufficiently large for it to enter the engineered barrier or host rock, possibly creating advective pathways in the bentonite (Figure 3-18). Accumulation and migration will impact near-field hydrogeological processes, potentially coupling to other issues from contaminant transport to fracture/fault reactivation. Understanding and modeling the flow of gas through the seals (which act as chokes in the system) is paramount. There is now a general consensus that in the case of plastic clay-rich clays and in particular bentonite, classic concepts of porous medium two-phase flow are inappropriate and continuum approaches to modeling gas flow may be questionable depending on the scale of the processes and resolution of the numerical model. The “memory” of dilatant pathways within clay may also impair barrier performance, in particular, acting as preferential flow paths for the movement of radionuclides. There is now a consensus that development of new and novel numerical representations, including discrete fracture representations, is required for the quantitative treatment of gas migration in clay-based repository systems, which would be the goal of this DECOVALEX task.

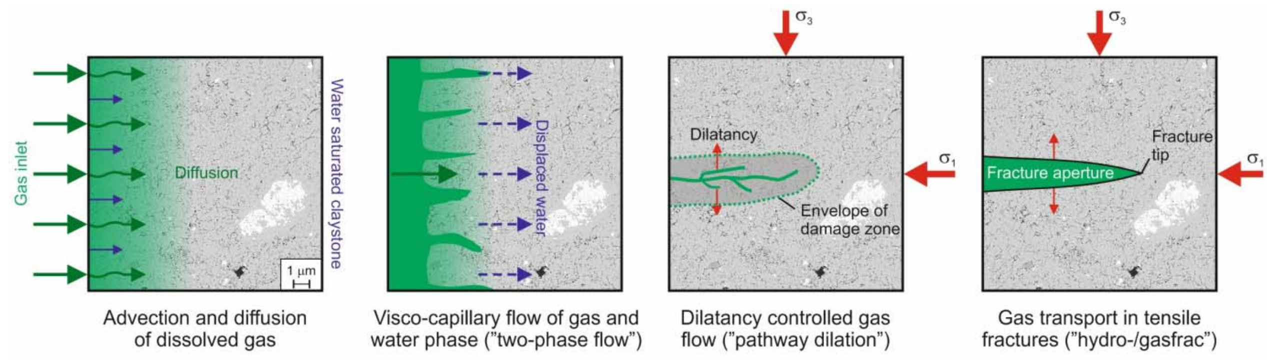

Figure 3-18. Processes for movement of gas in low-permeability bentonite (from Harrington et al., 2015)

The proposed modeling task will focus on LASGIT, a large-scale gas migration experiment at Äspö HRL in Sweden, and will also utilize a series of well-instrumented small-scale laboratory experiments that were conducted by the British Geological Survey (BGS). LASGIT, which has been in operation for several years, was specifically designed to address specific issues relating to gas migration and its long-term effect on the hydro-mechanical performance of the buffer clay, the question of heterogeneity and tortuosity of flow paths and the possible generation of new flow paths, and the complex coupling between gas, stress, and pore-water pressure at different scales (Figure 3-19). The main organization conducting the experiment is SKB (Sweden), together with BGS.

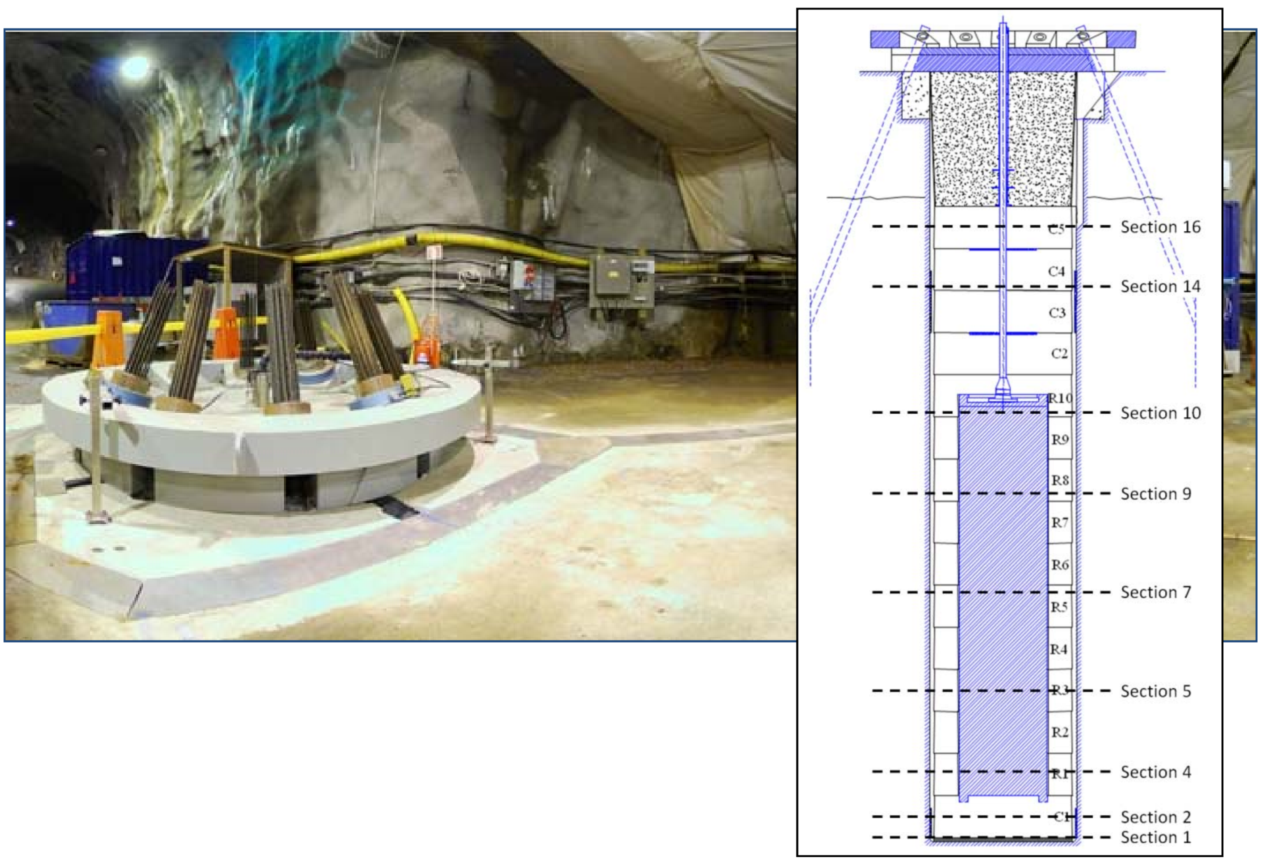

Figure 3-19. LASGIT Experiment at Äspö HRL (from Harrington et al., 2015)

Before modeling the large-scale LASGIT experiment, task participants would be asked to test new model representations in comparison to laboratory experiments that were conducted under varying conditions and dimensionalities, ranging from 1D gas flow under isotropically stressed samples to spherical gas flow from a central injection point under constant volume conditions (Figure 3-20). In addition to gas flux measurements, the laboratory testing allowed simultaneous measurements of stress and porewater pressure for better understanding of hydromechanical couplings. Application to LASGIT data would be a final full-scale verification test for new model concepts.

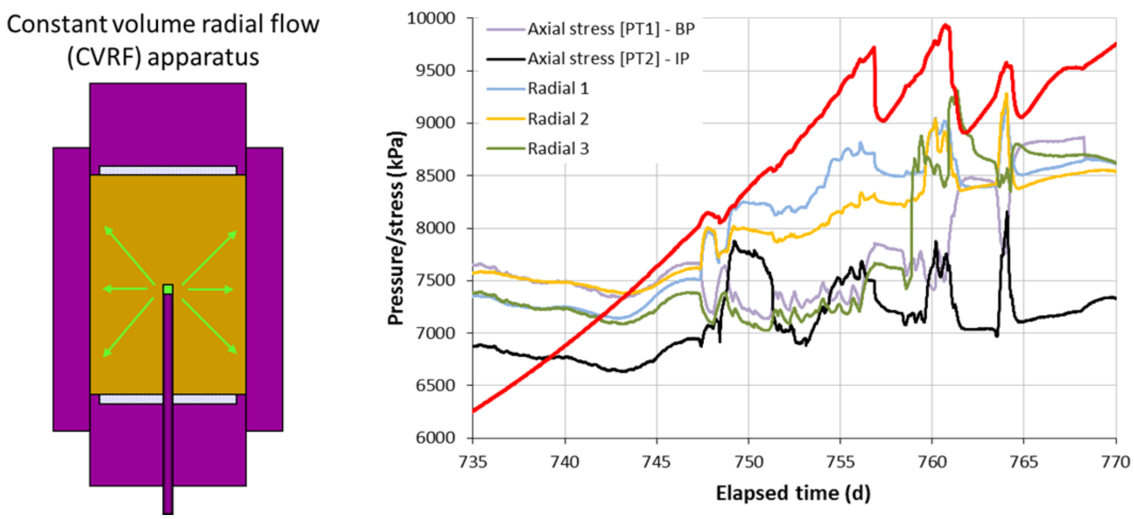

Figure 3-20. Typical design and measurements from constant volume flow test conducted at BGS (from Harrington et al., 2015)

The proposed task would be of high relevance to UFD. The overall objective is to understand the processes and mechanisms governing the advective movement of gas in compact bentonite and natural clay-based materials and its impact on performance assessment. While LASGIT is a test conducted in a crystalline environment, the model simulations are relevant to different host rock types: The knowledge gained through understanding the processes and mechanisms governing gas flow is of direct relevance to many repository concepts that use compacted bentonite in deposition holes, boreholes or gallery seals.

3.1.3.2 INBEB: HM and THM Interactions in Bentonite Barriers

The objective of the INBEB task is the interpretation and modeling of the performance of an initially inhomogeneous bentonite barrier using two full-scale long-term experiments, namely the isothermal Engineered Barrier experiment (EB) which ran for over ten years at the Mont Terri URL and the non-isothermal FEBEX experiment which ran for over 18 years at the Grimsel Test Site. The evolution from an installed unsaturated engineered system to a fully functioning barrier will be assessed with HM and THM models in comparison to experimental data. This will require an increased understanding of material behavior and properties, an enhanced understanding of the fundamental processes that lead to barrier homogenization, and improved capabilities for numerical modeling.

In both full-scale experiments, the bentonite component and surrounding host rocks were instrumented at high spatial resolution. In addition, both tests (EB and FEBEX) have been dismantled after 10 years and 18 years of operation respectively; therefore there is the unique opportunity to observe the final state of the bentonite barrier after saturation and homogenization. Also, complementary small-scale laboratory tests on the same bentonite material will be made available to DECOVALEX modeling teams.

Note that more information on the non-isothermal FEBEX experiment is provided in Section 3.3.2. Here we briefly provide specifics on the isothermal EB (or Engineered Barrier) experiment. The test was conducted at the Mont Terri URL to demonstrate an advanced concept for the construction of a clay-based buffer for emplacement in horizontal drifts. The concept was based on the combined use of a lower bed made of compacted bentonite blocks and an upper backfill made with a granular bentonite material (GBM) that can be blown in from some distance (see Figures 3-21, 3-22, and 3-23). After emplacement of mockup canister and bentonite backfill in 2001, the experiment started with artificial water supply to enable faster hydration of the bentonite and to achieve full saturation at the end of the experiment. Sensors were emplaced to measure canister displacements, relative humidity in the buffer, pore pressures in the rock and total stress in the interfaces between canister/buffer and rock/buffer. Observations from the monitoring system are available for the full duration of the test up to practically full saturation, after about 10 years of hydration. Dismantling of the hydrated bentonite, which started in October 2012 and concluded in January 2013, provides a large amount of high quality data concerning the final state of the buffer (especially water content, density and degree of saturation, hydraulic conductivity). In addition, there is information on EDZ behavior before and after dismantling.

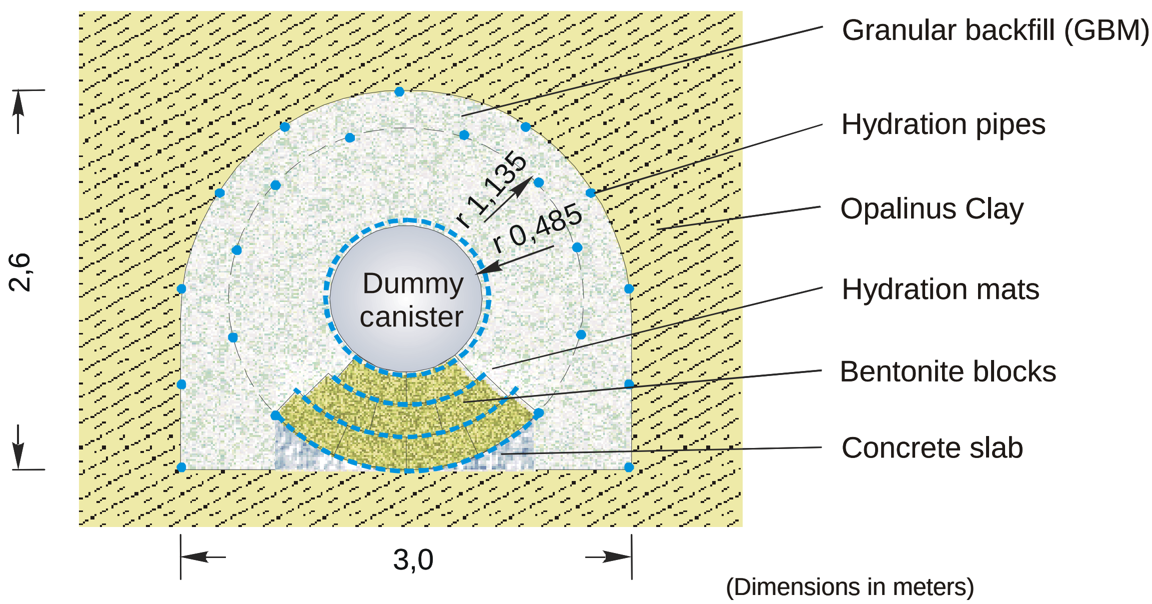

Figure 3-21. EB experiment design (from Mayor and Gens, 2015)

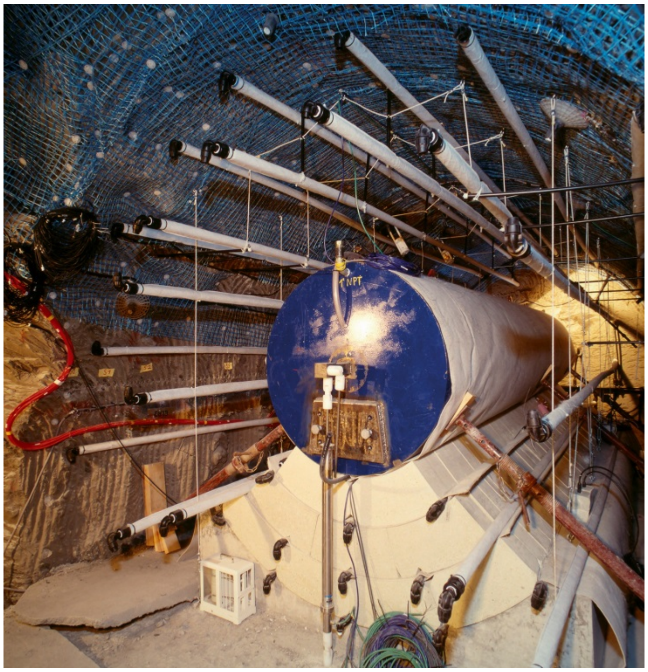

Figure 3-22. Photo showing the assembly of the EB experiment with mockup canister sitting on bentonite blocks and hydration pipes (from Mayor and Gens, 2015)

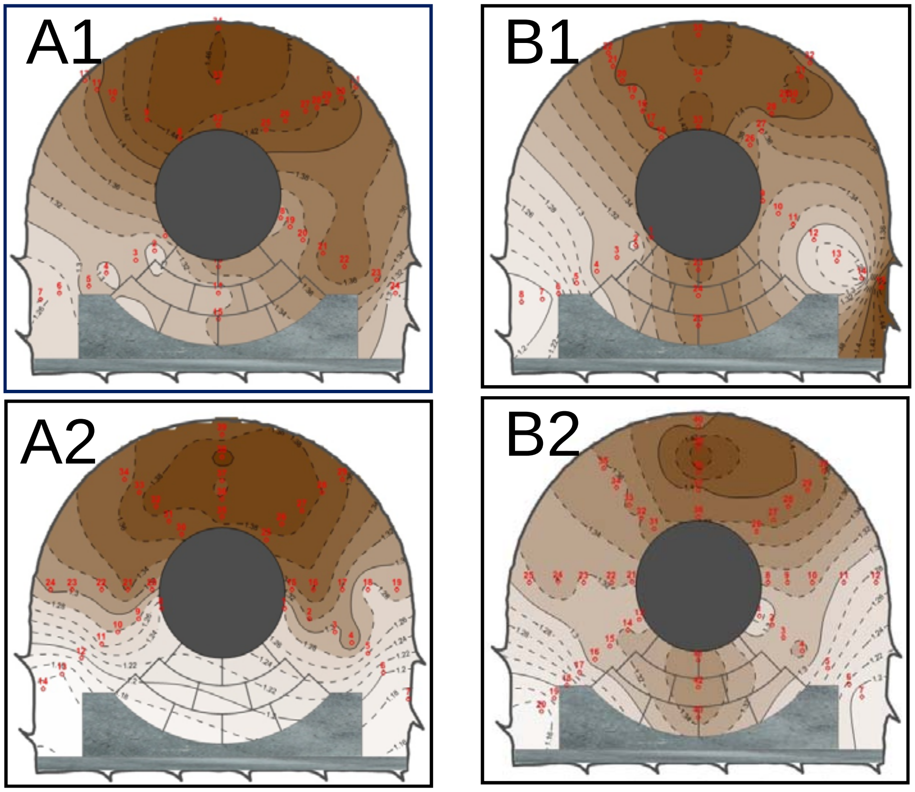

Figure 3-23. Example results from dismantling project: distribution of bentonite density in four different cross sections (from Mayor and Gens, 2015)

3.1.3.3 GREET: Groundwater Recovery around a Gallery in Crystalline Rock

GREET is a full-scale experiment being conducted in the Japanese Mizunami URL (crystalline rock). The objective of the test is to evaluate the processes and implications of natural resaturation of the repository near-field environment after construction and before repository closure. To test these processes, GREET is essentially a drift closure and water-filling experiment, measuring, for example, the mechanisms of groundwater recovery, alkalization of groundwater, microbial redox change, and hydraulic conductivity reduction in fractures by filling with cementing materials. The goals are as follows: (1) to understand the water recovery processes and mechanisms of the geological environment during facility closure, (2) to verify coupled hydrological-mechanical-chemical and -biological simulation methods for modeling these processes, and (3) to develop monitoring techniques for the facility closure phase and appropriate closure methods taking recovery processes into account. Figures 3-24, 3-25, and 3-26 show, respectively, the test design with an inclined tunnel leading to a sealed-off drift section, an example of the hydrogeologic data available for the near-field fractured rock mass, and an illustration of the test sequence with filling and drainage cycles.

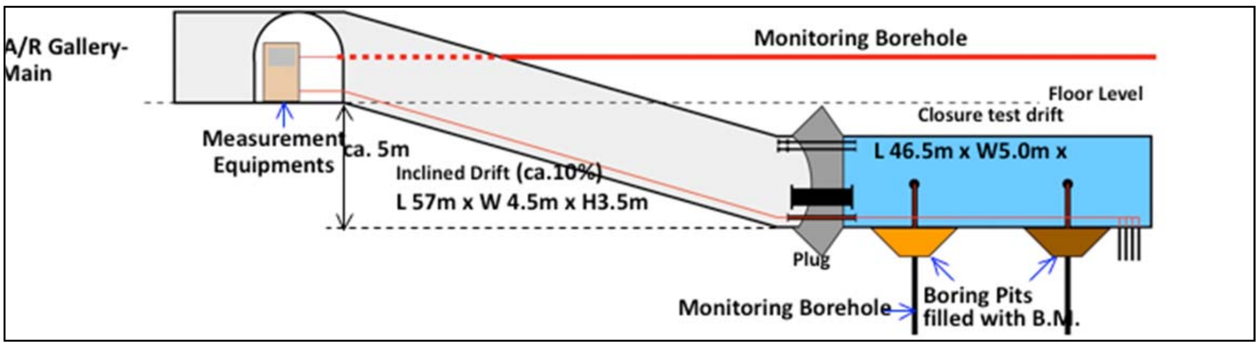

Figure 3-24. Schematic showing GREET tunnel design in a cross-section (from Sugita, 2015)

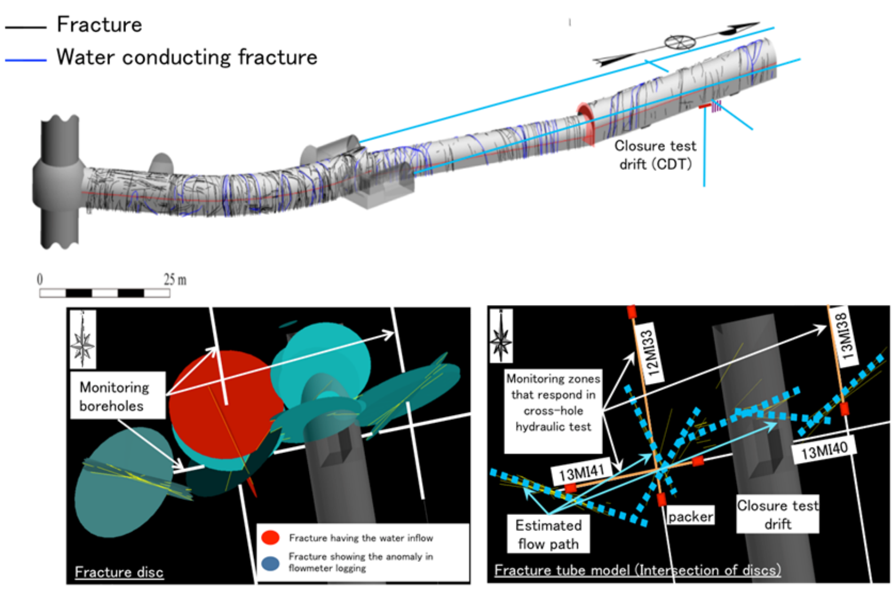

Figure 3-25. Flowing and non-flowing fracture in test tunnel section (from Sugita, 2015)

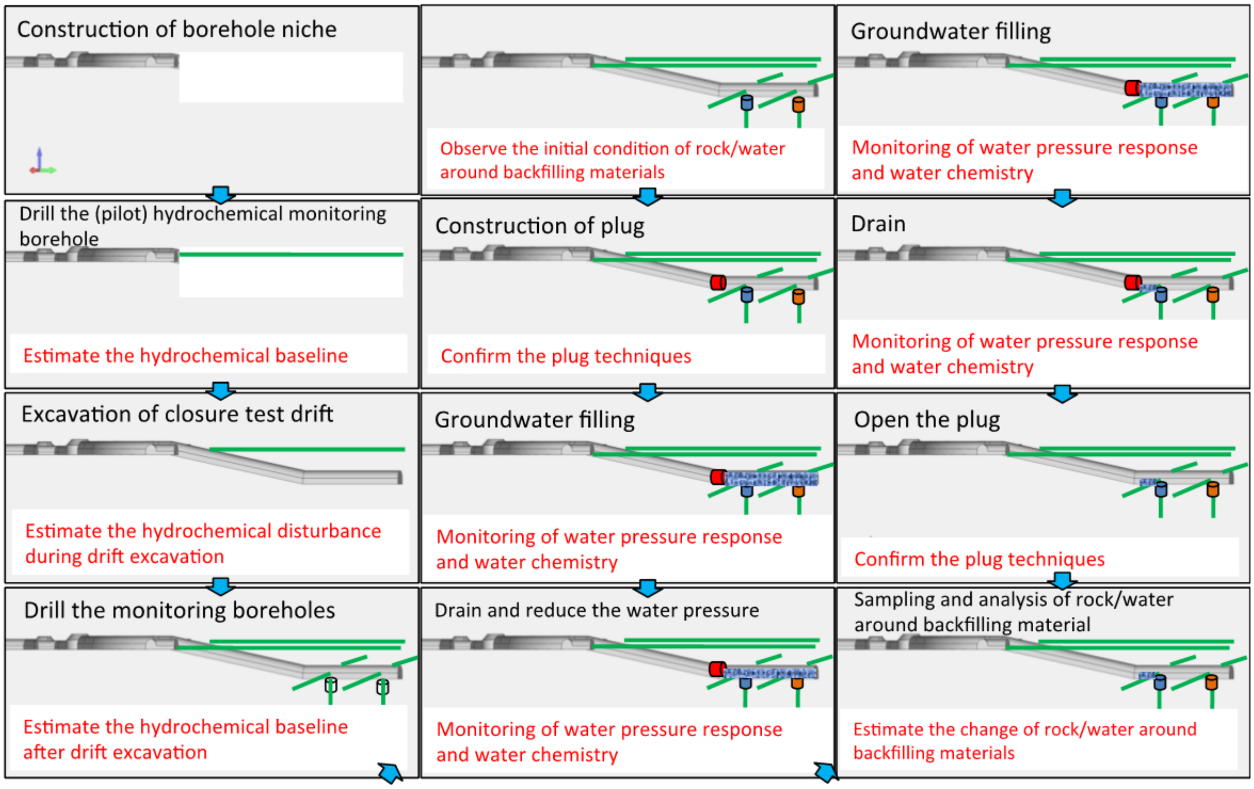

Figure 3-26. Proposed experimental sequence for GREET experiment (from Sugita, 2015)

3.1.3.4 Modeling the Induced Slip of a Fault in Argillaceous Rock

This modeling task evaluates the conditions for slip activation and stability of faults in clay formations and in particular addresses the complex coupling between fault slip, pore pressure, permeability creation, and fluid migration. This subject is of great importance to many subsurface applications where injection of fluids leads to pore pressure increase and reduction of effective normal stresses on faults, which in turn can cause fault reactivation. Regarding radioactive waste emplacement, increases in pore pressure could be caused by release of heat from the high-level waste or by the generation of gas due to steel corrosion. The possibility of an increased permeability caused by fault slip and generation of potential pathways in the host rock or in an upper sealing formation could be a major risk for the long-term safety of a repository.

The central element of the proposed task is a novel experimental setup that allows controlled fault slip testing in realistic underground settings at field scale. As shown in Figure 3-27, a borehole intersecting a fault is equipped with a borehole probe (High-Pulse Poroelasticity Protocol probe or HPPP probe) consisting of a straddle packer system that can be stepwise pressurized via fluid injection. High-resolution devices measure at unprecedented resolution both axial and radial micro-scale deformations at the borehole wall while monitoring downhole fluid pressure and flow rate as the fault is slipping. The testing approach has so far been applied in two tunnel-based underground research facilities in France, in the Laboratoire Souterrain à Bas Bruit (http://lsbb.oca.eu) which is a French national facility situated in porous-fractured carbonates in South of France, in the Tournemire URL (www.irsn.fr) which is an IRSN (France) facility located in a shaley claystone, and recently in the Mont Terri URL in an argillaceous claystone in Switzerland (Section 3.2.5).

The modeling task would be organized in a stepwise approach. Task 1 would include preparatory tasks like the simulation of lab experiments on slip properties, the modeling of fluid flow with permeability changes based on stress-dependent permeability relationship and modeling of Mohr-Coulomb reactivation criteria with plastic effects. Task 2 would focus on the recent fault slip experiment at Mont Terri. The modeling of pulse tests and leak-off tests are to be used to identify the initial properties. The fault slip activation experiment would then be used to model pressure induced movements and the stress dependent permeability evolution. Task 3 would allow the application of the model developed and calibrated for Mont Terri to comparable tests at other sites like the Tournemire URL.

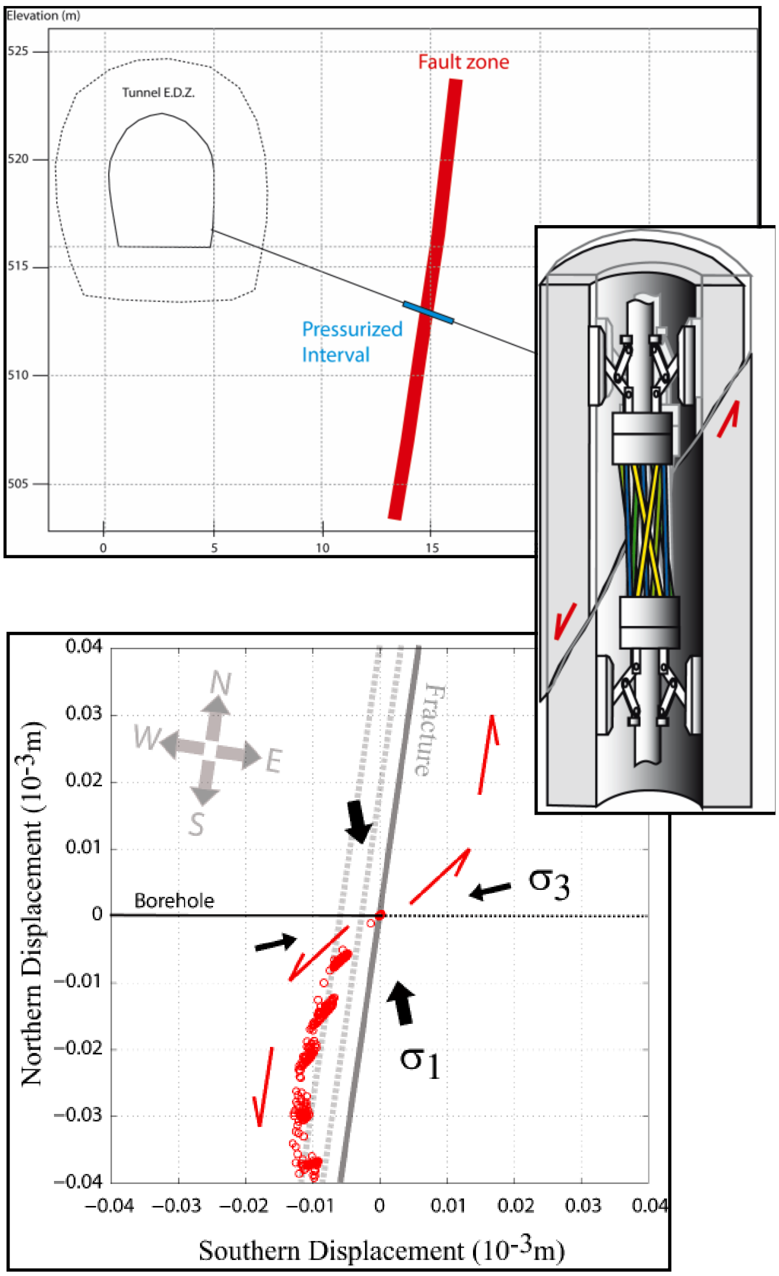

Figure 3-27. Basic design of fault slip experiment and measured deformation along and normal to fault plane (from Graupner, 2015)

3.1.3.5 Upscaling of Heater Test Modeling Results from Half-scale to Full-scale

This potential modeling task would attempt to understand the complexities involved in upscaling the THM behavior in argillaceous rocks. The basis for this exercise is a modeling comparison of two ongoing heater experiments at Mont Terri, the half-scale HE-E experiment (see Section 3.1.2.2) as well as the full-scale FE Heater Test, which is further described in Section 3.2.2 below. In continuation of the current DECOVALEX Task B1, the proposed task would examine the long-term evolution of the HE Heater Test until its planned end date of 2017. Task participants would then develop predictive models for the FE Heater Test, and would later conduct interpretative modeling analysis when measurements become available. There is furthermore a possibility of bringing into this task another heater experiment representative of the French repository design, a full-size reproduction of a typical high-level waste cell envisioned in the French program. The so-called Alveole HA Experiment Meuse/Haute-Marne URL at Bure started its main heating phase in April 2013, and has been at a maximum temperature of about 90 ^{o}C since then (Figure 3-28). Planning for this task proposal is still ongoing.

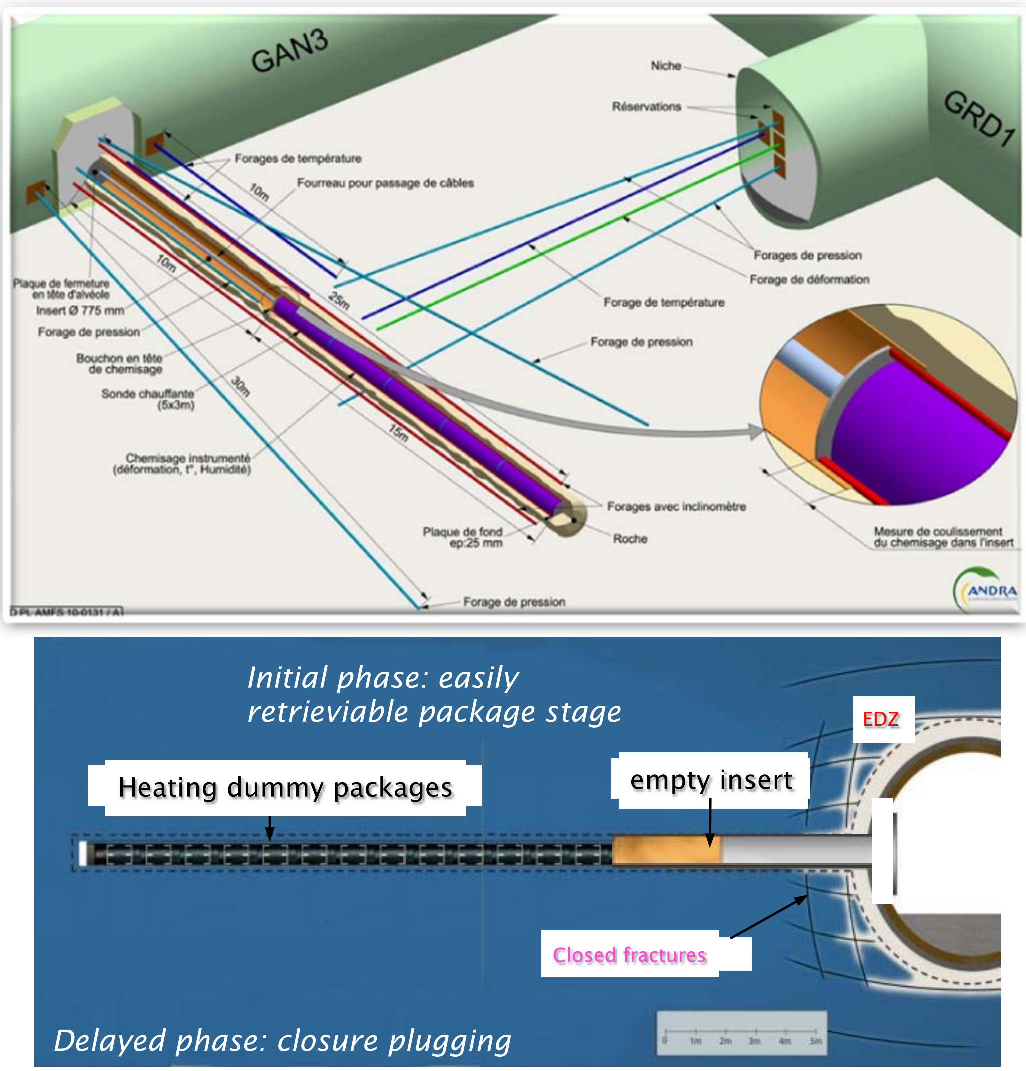

Figure 3-28. Basic design of Alveole HA Test conducted at Bure (from Armand, 2015)

3.1.4 DECOVALEX Summary

Benefits of Participation:

- Access to **four to six** sets of experimental data from **different** URLs and **different** host rock environments
- Opportunities for **modeling and analysis of existing data** in collaboration with other modeling groups (typically less direct interaction with the project teams that run or interpret the experiments)
- Opportunity to suggest **modeling test cases** of interest to DOE.

Status of Participation:

DOE has formally joined the DECOVALEX project for the current phase, DECOVALEX-2015. A small annual membership fee is paid that covers the cost of administrative and technical matters. DECOVALEX–2015 started in spring 2012 with a kick-off workshop held in Berkeley, and will run for four years until the end of 2015. Researchers affiliated with UFD are currently participating in two DECOVALEX tasks, namely Tasks B and C (see Sections 6.1.1 and 6.2.1).

Outlook:

UFD scientists will finalize Task B and Task C participation in December 2015, when the ongoing DECOVALEX phase officially ends. DECOVALEX leadership has started planning for a new DECOVALEX phase referred to as DECOVALEX-2019. Preliminary ideas for new modeling tasks have been developed, as discussed in Section 3.1.3, many of which with high relevance for UFD. Dr. Jens Birkholzer of LBNL will be the new chairman of the DECOVALEX project with the start of the new phase.

Contact Information:

DOE Contact:
Mark Tynan, DOE-NE

UFD Contact:
Jens Birkholzer, LBNL

DECOVALEX Contact:
John Hudson, Chairman of DECOVALEX-2015, Imperial College, Great Britain
Jens Birkholzer, Vice Chairman of DECOVALEX-2015, and Incoming Chairman for DECOVALEX-2019, LBNL, USA
Lanru Jing, DECOVALEX Secretariat, KTH, Sweden

3.2 Mont Terri Project

3.2.1 Introduction to the Mont Terri Project

The Mont Terri Project is an international research project for the hydrogeological, geochemical, and geotechnical characterization of a clay/shale formation suitable for geologic disposal of radioactive waste (Zuidema, 2007; Bossart and Thury, 2007). The project, which was officially initiated in 1996, has been conducted in a clay-rock underground rock laboratory, which lies north of the town of St-Ursanne in northwestern Switzerland and is located at a depth of ~300 m below the surface in argillaceous claystone (Opalinus Clay). The rock laboratory is located in and beside the security gallery (initially the reconnaissance gallery) of the Mont Terri motorway tunnel, which was opened to traffic at the end of 1998. The rock laboratory consists mainly of eight small niches along the security gallery, excavated in 1996, Gallery 98 with 5 lateral niches, excavated in 1997/98, a gallery for the EZ-A experiment, excavated in 2003, Gallery 04 with 4 lateral niches, excavated in 2004, and lastly, Gallery 08 with side galleries for the Mine-by Test and FE Heater Test, excavated in 2008 (Figure 3-29).

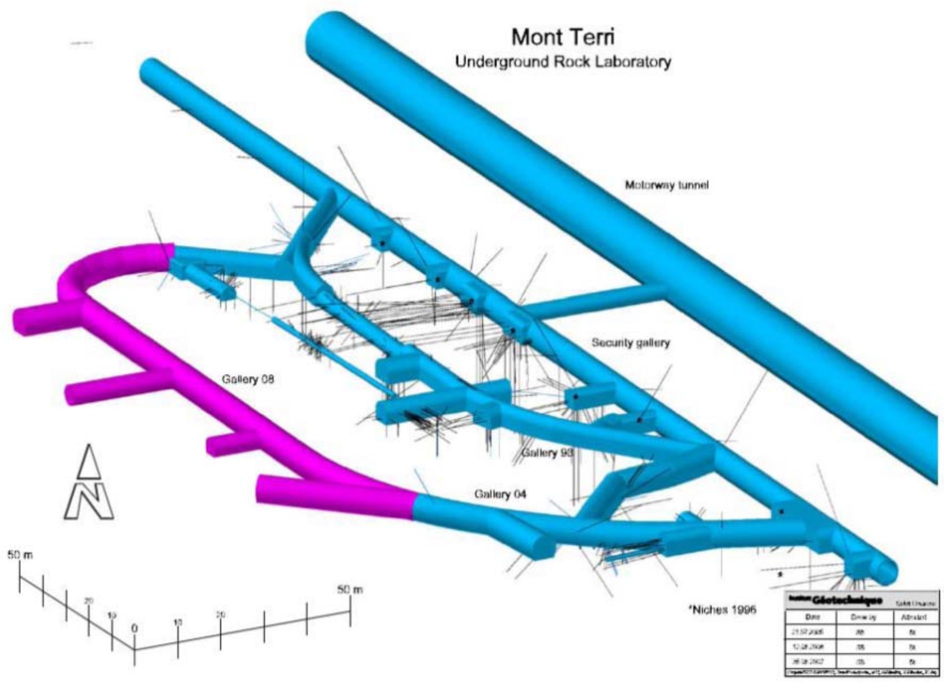

Figure 3-29. 3D schematic of the Mont Terri URL with side galleries and drifts. Pink area shows access gallery drilled for Mine-by Test and FE Heater Test (from Bossart, 2012)

The Mont Terri Project essentially operates as a collaborative program providing open access to an existing URL. The research program consists of a series of individual experiments and is divided into annual project phases, running from July 1 in one year to June 30 the next year. The Swiss Federal Office of Topography, swisstopo, helps with the operation and maintenance of the rock laboratory, and provides the operational management and experimental support. The research-partner organizations fund the experiments and their evaluations. Partner organizations can select and conduct experiments and participate in experiments conducted by others, and they have access to all project results from past and ongoing efforts, which are available in reports and publications and a project-owned web-based database. Planning, steering, and financing is the responsibility of all partners participating in the experiment.

(Larger field experiments are therefore often conducted by more than one organization.) Over the years, the organizations involved in the Mont Terri Project have provided substantial financial investments. Additional support has been contributed by the European Community and by the Swiss Federal Office for Science and Education. It is not surprising, therefore, that the Mont Terri Project has been very successful, and a wide range of experimental studies on clay/shale behavior (including backfill/buffer behavior) have been and are being conducted.

DOE leadership started to realize in 2011 that membership in the Mont Terri Project could be highly beneficial to UFD's R&D mission, and decided in early 2012 to formally apply for membership. On January 27, 2012, a letter was sent to the Mont Terri Project Director confirming DOE's intent to become a partner. Shortly thereafter, all existing Mont Terri Project partners unanimously accepted DOE as a new partner organization, and DOE's partnership started officially with Phase 18 of the project, which ran from July 1, 2012 through June 30, 2013. DOE is now one of 15 Mont Terri Project partners from eight countries, namely from Switzerland (swisstopo, ENSI, NAGRA), Belgium (SCK/CEN), France (ANDRA, IRSN), Germany (BGR, GRS), Japan (OBAYASHI, JAEA, CRIEPI), Spain (ENRESA), Canada (NWMO), and the U.S. (Chevron, DOE). DOE participation in the project provides unlimited access to an operating underground rock laboratory in a claystone environment, with several past and ongoing experiments that are highly relevant to UFD's R&D objectives. Membership has provided UFD researchers with relevant field data and project results from all past Mont Terri phases. More importantly, UFD researchers have started working collaboratively with international scientists on selected ongoing and future experimental studies, which include all design, characterization, modeling, and interpretation aspects related to field experiments. DOE also has an opportunity to propose and eventually conduct its own experiments at the Mont Terri URL, which could be an option for project future phases. This type of international collaboration goes beyond the mostly modeling focus of DECOVALEX, and may be the most fruitful approach to active international R&D.

Figures 3-30 and 3-31 show an overview of experiments currently conducted at the Mont Terri URL. The timeline in Figure 3-30 places these experiments in the context of relevance to different phases in the lifetime of a repository: (1) Experiments related to initial conditions and repository construction, (2) Experiments related to buffer emplacement and monitoring, (3) Experiments related to the transient post-closure phase of a repository, (4) Experiments related to the equilibrated post-closure phase of a repository, and (5) Experiments related to radionuclide transport. In terms of the experimental objective, one may distinguish three categories: (a) Experiments to provide a better understanding of performance-relevant processes during the lifetime of a generic clay repository (e.g., EDZ, thermal effects, gas generation and transport, RN transport), (b) Experiments to better characterize the site-specific conditions at Mont Terri (e.g., host rock properties, *in situ* stresses, *in situ* geochemistry), and (c) Experiments testing and improving characterization and monitoring technologies.

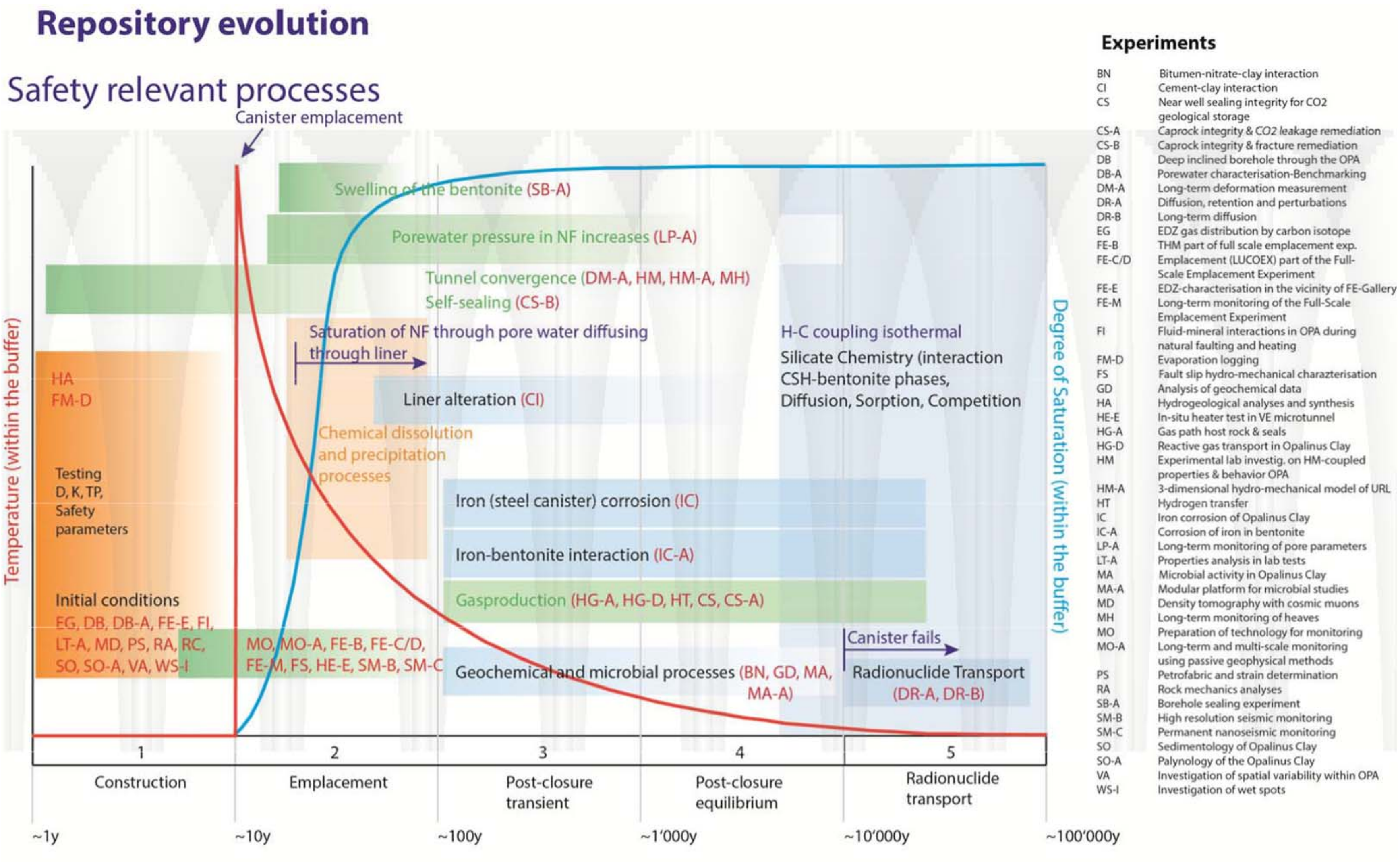

Figure 3-30. List of main Mont Terri URL experiments conducted during Phase 20 (July 2014 through June 2015), displayed with respect to relevancy during different repository stages (from Bossart, 2015)

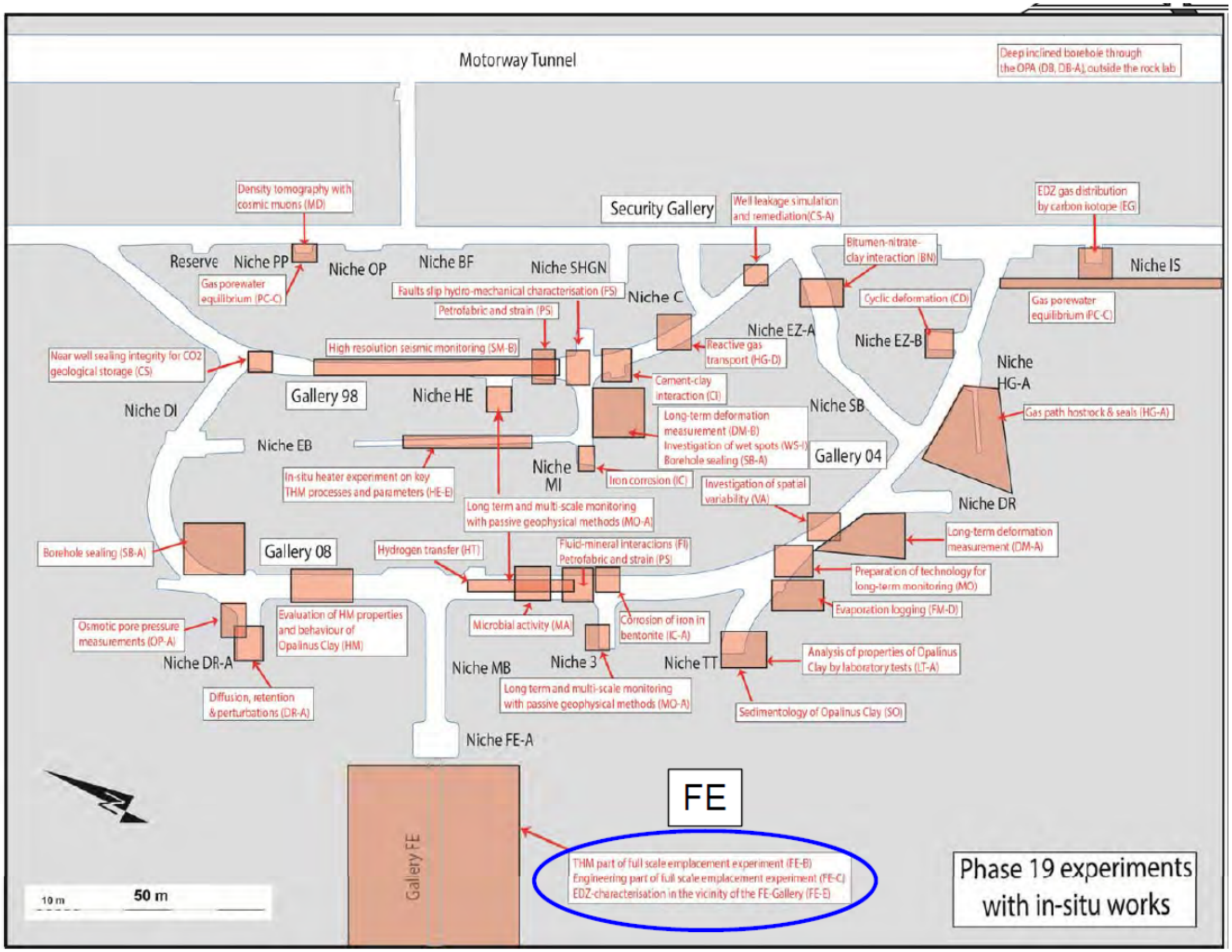

Figure 3-31. Plan view of the Mont Terri URL with 42 experiments conducted during Phase 19 (July 2013 through June 2014). Gallery FE indicates the area of the FE Heater test, which is currently the largest subsurface heater experiment worldwide (Bossart, 2014b)

Many experiments shown in Figure 3-30 (Status January 2015, Phase 20) are long-running tests that have carried on into the ongoing Phase 20 of the Mont Terri Project, and that will continue into future project phases. While a few additional experiments have recently been initiated at Mont Terri that are relevant to other subsurface applications such as geologic carbon sequestration (i.e., CS-A Experiment: Well-leakage simulation & remediation experiment), the majority of activities continue to be related to geologic disposal of radioactive waste. Since 2012, DOE has engaged in several such experiments: the FE Heater Test, the Mine-by Test, the HG-A Experiment, and the DR-A Diffusion, Retention, and Perturbation Experiment. Some detail on these experiments is given in sub-sections below, and summaries of UFD research activities related to these experiments are provided in Section 6. In addition, there is the HE-E Heater Test at Mont Terri, used as Task B1 of the current DECOVALEX-2015 phase and previously introduced in Section 3.1.4. Almost all experiments include substantial laboratory and modeling tasks, in addition to the actual field components of the project.

It is worth describing how the collaborative Mont Terri project operates and how the process of planning and initiating new experiments works. Once a year, at the Technical Meeting held in late winter, partner organizations may propose in brief presentations any new work that they would like to undertake in the upcoming Mont Terri project phase(s) (as mentioned before, project phases always run from July 1 of one year through June 30th of the following year). The proposing partners will present the technical scope and merit of the proposed work and will give a rough estimate of the cost. Then, they will invite other partner organizations to consider joining the new task. In some cases, that could mean a direct financial contribution to the cost of the experiment; in other cases, they may invite partners to conduct monitoring or modeling analysis complementing their proposal. They will then write a short project description prior to the next Mont Terri Steering Committee Meeting (which is typically held a few months after the Technical Meeting) where ongoing and new experiments are selected. The experimental program for the next project phase is then finalized, including the financial contributions of each partner, in a second Steering Committee Meeting held just before the start of the new phase. This process is repeated every year.

For DOE, there is thus a clear path forward at Mont Terri, if, in the future, UFD had an interest in proposing its own experiments. Partners can be found if the proposed work aligns well with the interest of other Mont Terri organizations. It is important to note in this context that the existing infrastructure at Mont Terri makes developing and conducting experiments very easy, even if the proposing partner is located far away from the URL. Swisstopo can handle a lot of the organizational details, if needed, and there is a long list of experienced contractors that are available to conduct the actual experimental work. Furthermore, swisstopo and its partners have started to engage in a planning exercise regarding potential extension of the underground research laboratory in the 2018-2020 timeframe, to provide additional working space for future large-scale experiments relating geologic disposal, but also to CO_2 sequestration and geothermal applications. As shown in Figure 3.32, a feasible extension of the URL could be achieved via a tunnel loop excavated in a south-westward direction. However, several variants are being discussed and no decision has been made yet.

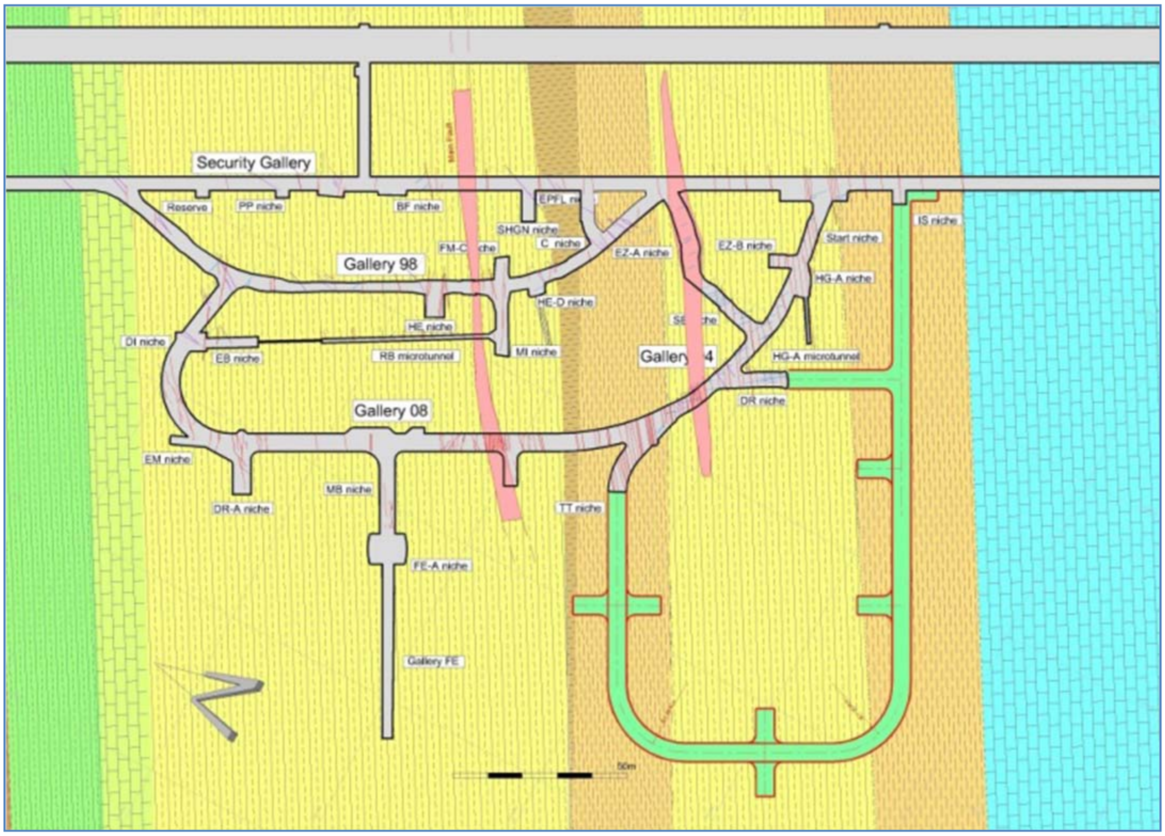

Figure 3-32. Plan view of the Mont Terri URL with potential extension in mostly south-westward direction (from Bossart, 2015)

3.2.2 FE Heater Test

The Full-Scale Emplacement Experiment (FE Heater Test) is one of the largest and longest-duration subsurface heater tests ever conducted. This heater experiment has been designed by NAGRA as an ultimate test for the performance of geologic disposal in Opalinus Clay, with focus on both EBS components and host-rock behavior. Mont Terri partners collaborating with NAGRA in this experiment are ANDRA, BGR, GRS, NWMO, and, as of July 2012, also DOE (see Section 5.2.1). As shown in Figures 3-33 through 3-35, the FE Heater Test is conducted in a side niche and gallery at Mont Terri, excavated along the claystone bedding plane for this purpose, with 50 m length and about 2.8 m diameter. Heating from emplaced waste is simulated by three heat-producing canisters of 1500 W maximum power. A sophisticated monitoring program was planned and implemented, including dense pre-instrumentation of the site for *in situ* characterization, dense instrumentation of bentonite buffer and host rock, and extensive geophysical monitoring. A THM modeling program is conducted in parallel with the testing and monitoring activities.

After years of preparation and construction, all the heaters, the bentonite buffer, and instrumentation have been now been installed, the tunnel has been plugged, and the final heater started operating on February 15, 2015 (Figure 3-36). During the preparation phase, predictive THM models of the anticipated FE Heater Test behavior had been developed by some project partners (among them UFD scientists from LBNL, see Section 6.1.1.3), for the support of design and for instrumentation planning, as well as for later comparison of “blind predictions” with measured THM effects. In the final design, a staged heating approach was employed in which the three heaters were turned on in stages. This ensured that the models for predicting the maximum temperature in the buffer were validated against early temperature data before running all three heaters at the same time.

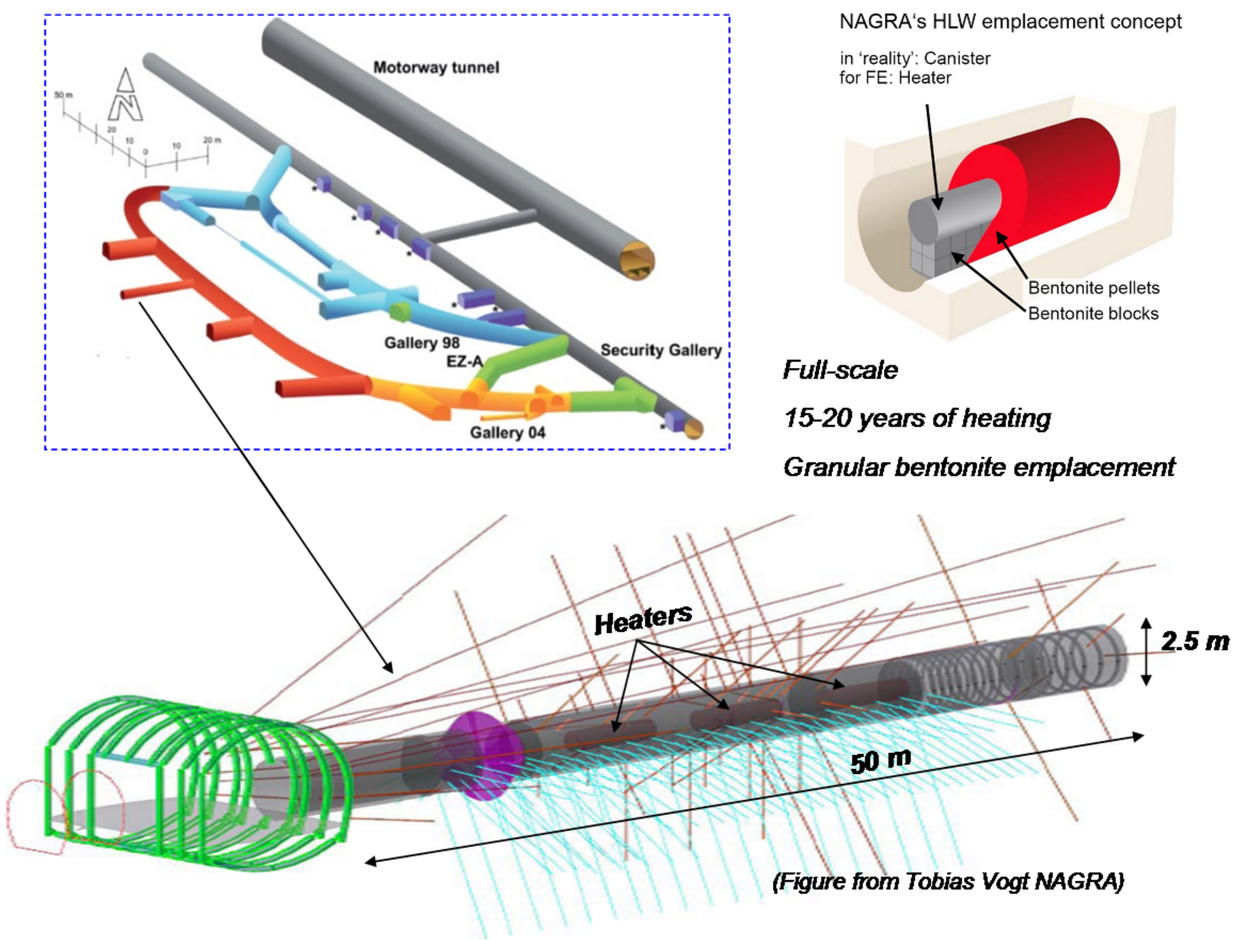

Figure 3-33. FE Heater Test at Mont Terri URL: experiment setup and borehole layout (from Zheng et al., 2015)

The experiment will provide data useful for the validation of THM coupling effects regarding the processes in the host rock, while correctly accounting for (and examining) the expected conditions in the emplacement tunnel (temperature, saturation, and swelling pressure). Due to the 1:1 scale of the experiment, it will be possible to achieve realistic temperature, saturation, and stress gradients. It will also be possible to test backfilling technology with granular bentonite, as well as lining technology with shotcrete, anchors, and steel ribs. Processes examined in the test cover many aspects of repository evolution, such as EDZ creation and desaturation of the EDZ during tunnel excavation and operation (including ventilation for about one year), reconsolidation of the EDZ, resaturation, thermal stresses, and thermal pore-pressure increase after backfilling and heating (heating and monitoring period > 10 years).

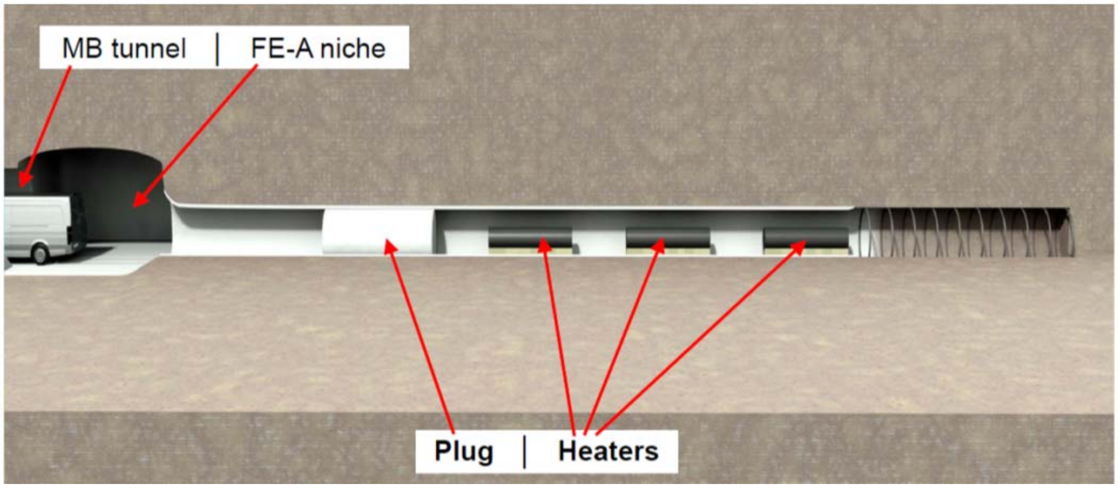

Figure 3-34. FE Heater Test at Mont Terri URL: Side view of experiment setup and heater layout (from Garitte, 2010)

Figure 3-35. View from the FE gallery into the heater tunnel during final installation (from Bossart, 2014a)

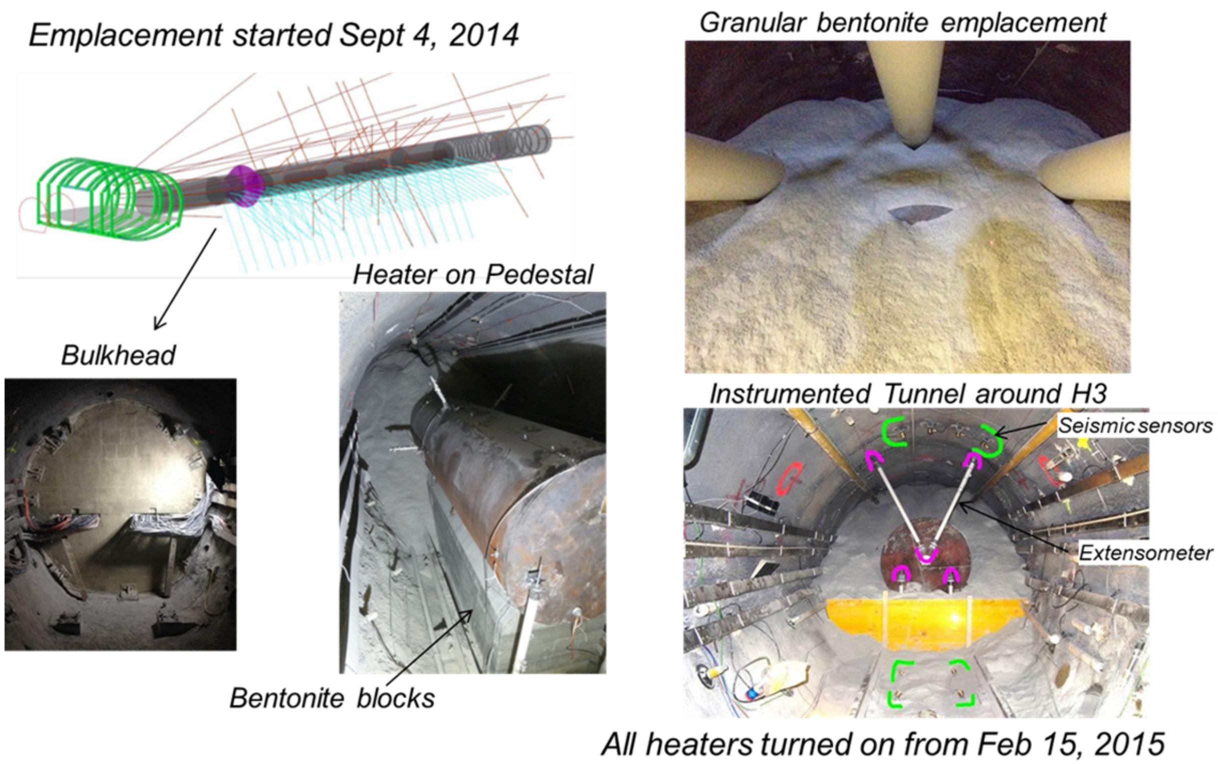

Figure 3-36. Images from the construction and installation of heaters, bentonite buffer and plugs (from NAGRA daily reports by Herwig Müller, NAGRA)

3.2.3 HG-A Experiment

The HG-A Experiment focuses on investigations of gas paths through the near-field host rock and specifically along seal sections. The objectives are to assess the potential for gas escape from a sealed disposal tunnel, to investigate the role of the EDZ as an important gas path, to understand the importance of sealing processes along the EDZ, and to determine the rock permeability along the tunnel, through measurements and predictions of fluid and gas flow. Partner organizations currently involved in the HG-A experiment are ANDRA, BGR, NAGRA, and NWMO. UFD scientists from Lawrence Berkeley National Laboratory have been using EDZ characteristics from the HG-A Experiment to test a new THM simulator for coupled fluid flow and discrete geomechanics including fracture propagation (see Section 6.1.3).

The HG-A experiment is conducted in a horizontal micro-tunnel that represents a sealed disposal tunnel section at a scale of 1:2.5 (Figures 3-37 and 3-38). Initial characterization of the stress conditions and EDZ extent in the near-field of the open micro-tunnel indicated localized damage and exfoliations along the wall, clearly affected by the anisotropic strength characteristics of the rock. The tunnel was then backfilled, sealed, and artificially resaturated. Starting in 2006, several long-term hydraulic and gas-injection tests have been performed to determine "macro-permeability" before, during, and after the gas-injection phase. Gas injection was conducted by pressurization of the deep micro-tunnel section with nitrogen gas and monitoring of pressure build-up in the sealed disposal tunnel section. Hydraulic testing of the sealed tunnel subsequent to the gas-injection phase was conducted to determine possible alteration of the barrier function of the Opalinus Clay. Results obtained so far confirm that the EDZ serves as a preferential flow path along a seal section, and that it carries the gas efficiently, but in a localized manner, at moderate gas pressures. Further experiments are planned for current and future project phases, for example a new gas-injection test with increased injection rate followed by a seal test.

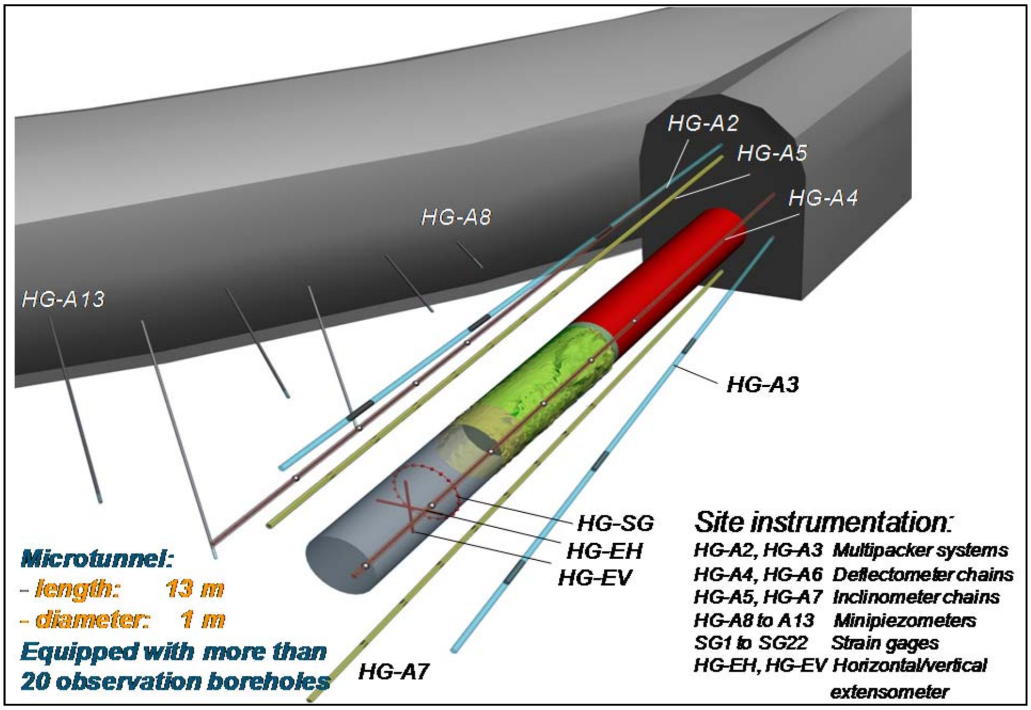

Figure 3-37. Schematic setup of HG-A Experiment at Mont Terri URL (from Marschall et al., 2012)

Figure 3-38. HG-A Experiment at Mont Terri URL: Installation of packer system (from Marschall et al., 2012)

3.2.4 DR-A Diffusion, Retention and Perturbation Experiment

The DR-A Experiment was conducted at Mont Terri to characterize the diffusive transport behavior in a low-permeability Opalinus Clay host rock, which is the dominant mode for radionuclide transport. As shown in Figure 3-39 for an earlier diffusion test with similar setup, the experimental design consisted of a single borehole drilled in the Opalinus Clay, which contained a constant ionic strength cocktail of anions, cations, and nonreactive tracers such as tritium (HTO). Measurements of water-chemistry changes in the borehole then allowed for an evaluation of several processes affecting effective diffusion behavior, such as anion exclusion and sorption of cations. One novel aspect of the DR-A Experiment was that the solutions were perturbed to be in disequilibrium with the host rock: mineral reactions were therefore induced in the rock, and tracer response to different solution chemistries and altered clay mineralogies could be examined. Perturbations of the pore-water chemistry in the DR-A Experiment were introduced by a stepwise change in the ionic strength of the circulating solution. A higher ionic strength is likely to affect sorption, but can also affect the transport of weakly sorbing anions that are partly excluded from the electrical double layer (EDL). Ionic strength furthermore has a direct effect on the volume of "EDL porosity" through its control on the thickness of the diffuse layer. In the first stage of the experiment through Day 189, the borehole cocktail was a 0.384 M ionic strength solution dominated by sodium. At Day 189, a higher ionic strength solution (1.135 M) was circulated in the borehole without diluting the tracers (HTO, iodine, and bromine) in the cocktail. The higher ionic strength was made up of both Na^+ (0.50M) and K^+ (0.56M) and Cl^- (1.13M) and was allowed to diffuse out of the borehole through Day 412. The aim behind inducing disturbances is to test the predictive capabilities of reactive transport models currently being used by disposal programs. Partner organizations involved in the DR-A experiment were NAGRA and NWMO, and at later stages also DOE (see Section 6.2.2).

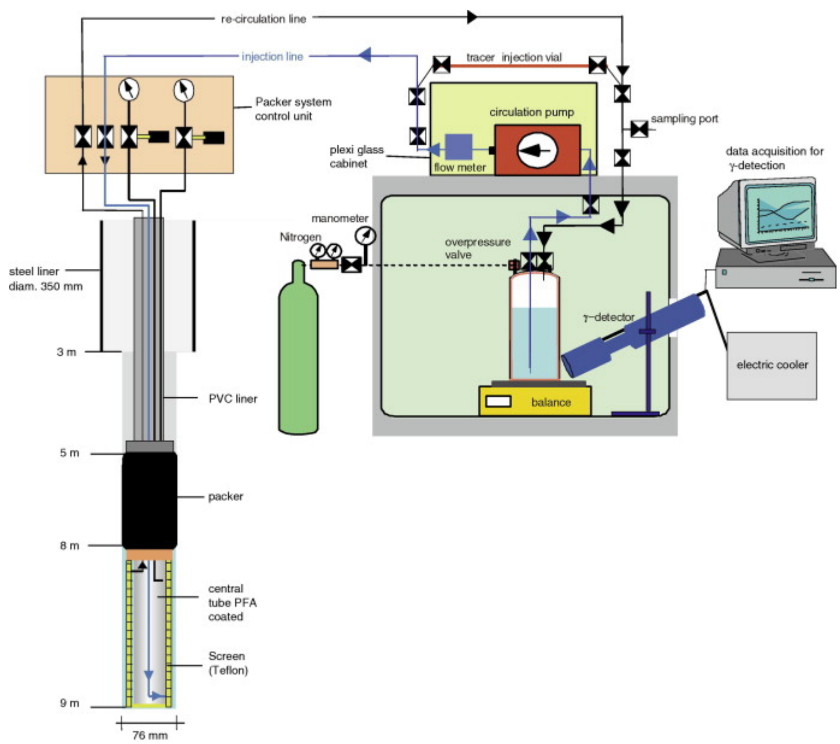

Figure 3-39. Schematic of the Diffusion Experiment at Mont Terri URL, showing main features of the down-hole and surface equipment (from Wersin et al., 2004; 2008)

3.2.5 FS Fault Slip Experiment

One of the more recent experiments at the Mont Terri URL is the Fault Slip (or FS) Test, which aims at understanding (i) the conditions for slip activation and stability of clay faults, and (ii) the evolution of the coupling between fault slip, pore pressure and fluids migration. Results obtained by the experiment are crucial in defining mechanisms of natural and induced earthquakes, their precursors and risk assessment, but also the loss of integrity of natural low permeability barriers. Recent studies suggest that slow slip on faults may be a dominant deformation mechanism of shales during hydraulic stimulation or other large subsurface injection activities (Zoback et al., 2012). The same mechanism may be of importance in many other contexts where a stress perturbation is high enough to reactivate the faults, for example drilling a network of underground galleries for radioactive waste emplacement could activate slip on pre-existing faults and eventually enhance the formation permeability. Of similar concern to radioactive waste emplacement may be fault slip caused by pore pressure increase from the release of heat from the high-level waste or from the generation of gas due to steel corrosion. Hence, the possibility of an increased permeability caused by fault slip and generation of potential pathways in the host rock or in an upper sealing formation could be a major risk for the long-term safety of a repository.

The conditions for slip activation on clay faults are generally poorly understood, the clay content being suspected to constrain the slip stability and the type of seismicity that can be triggered. Field observations indicate that active faults can be hydraulically conductive even in low permeability clay dominated formations. Laboratory experiments on clay-rich samples generally conclude that for a given mean effective stress, shearing tends to reduce permeability (Zhang and Cox, 2000). However, significant increases (a factor of 10-100) have been measured on silt/clay mixes sheared or failed under highly over consolidated conditions (Bolton et al., 1999), and similar increases have been observed in intermediate-scale experiments in two tunnel-based underground research facilities in France.

The key idea of the FS experiment is to conduct localized pressurizations in a packed-off section of a borehole drilled through the Mont Terri main fault zone (Figures 3-30 and 3-31). Water is injected between inflatable packers at increasing flow rates in order to progressively decrease the effective stress until fault destabilization occurs, while monitoring injection flow rate, pore pressure, fault slip and normal displacement evolution from the stable to the unstable fault states. Monitoring is performed with a new device called the High-Pulse Poroelasticity Protocol (HPPP) probe (Guglielmi et al., 2013a and b), which is capable of measuring slip velocities and slip deformation at unprecedented spatial resolution. The HPPP probe allows simultaneous high-frequency monitoring of full 3D-deformations of the borehole wall, fluid pressures, and injection flow rates within a 1.5 m long injection chamber set between two inflatable packers (Figure 3-40). Accuracy of measurements is of 10^{-6} in deformations, 10^{-3} Pa in pressure, and 0.1 L/min in flow rate. Figure 3-41 shows that if the probe is set across a fault, it can continuously capture the fault movements through an anchoring system that is controlled from the surface. The probe, which uses fiber-optic sensors (fiber Bragg gratings) with reflection of light at specific wavelengths, requires no down-hole electrical supply. Thus, the operation is simple and passive, with response times << 0.5 10^{-3} s. Probe sensors are immune to electromagnetic interference and can withstand harsh environments. The probe is calibrated in the laboratory prior to borehole installation. With the current probe, hydromechanical tests can be conducted up to 70 MPa differential pressures and 60°C temperatures. The probe (diameter of the HPPP probe is 0.1 m) can be lowered to depths of about 300 m or more from gallery (underground drift) walls or in characterization wells.

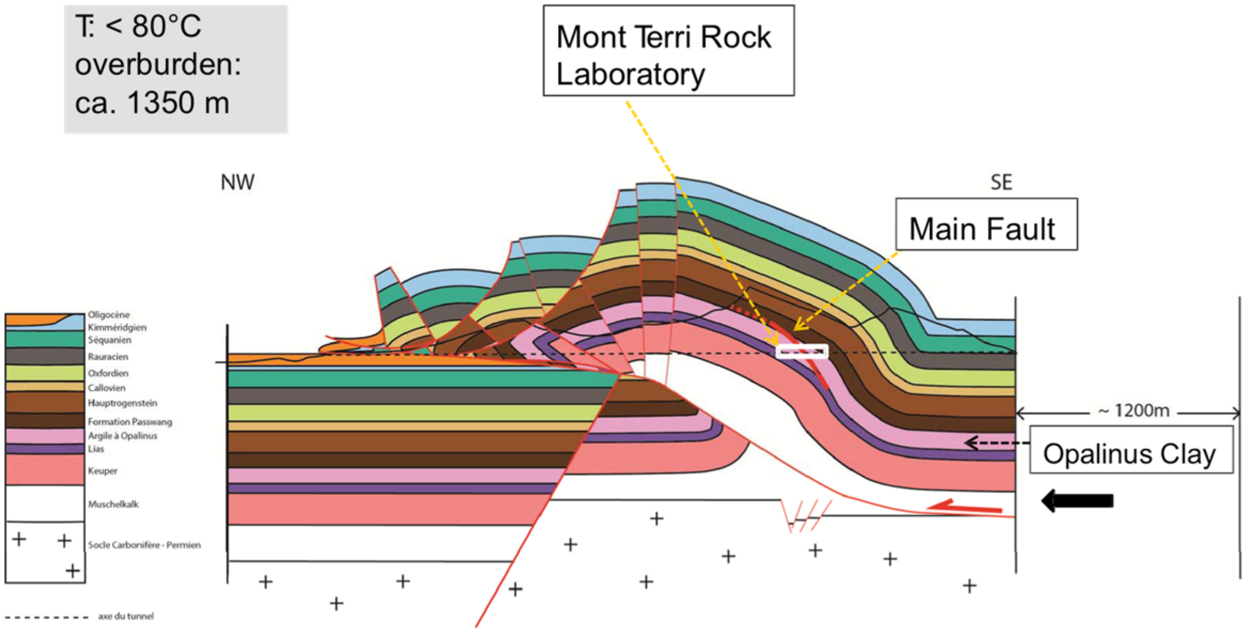

Figure 3-40. Geologic setting showing Mont Terri URL and location of main fault (from Guglielmi et al., 2015)

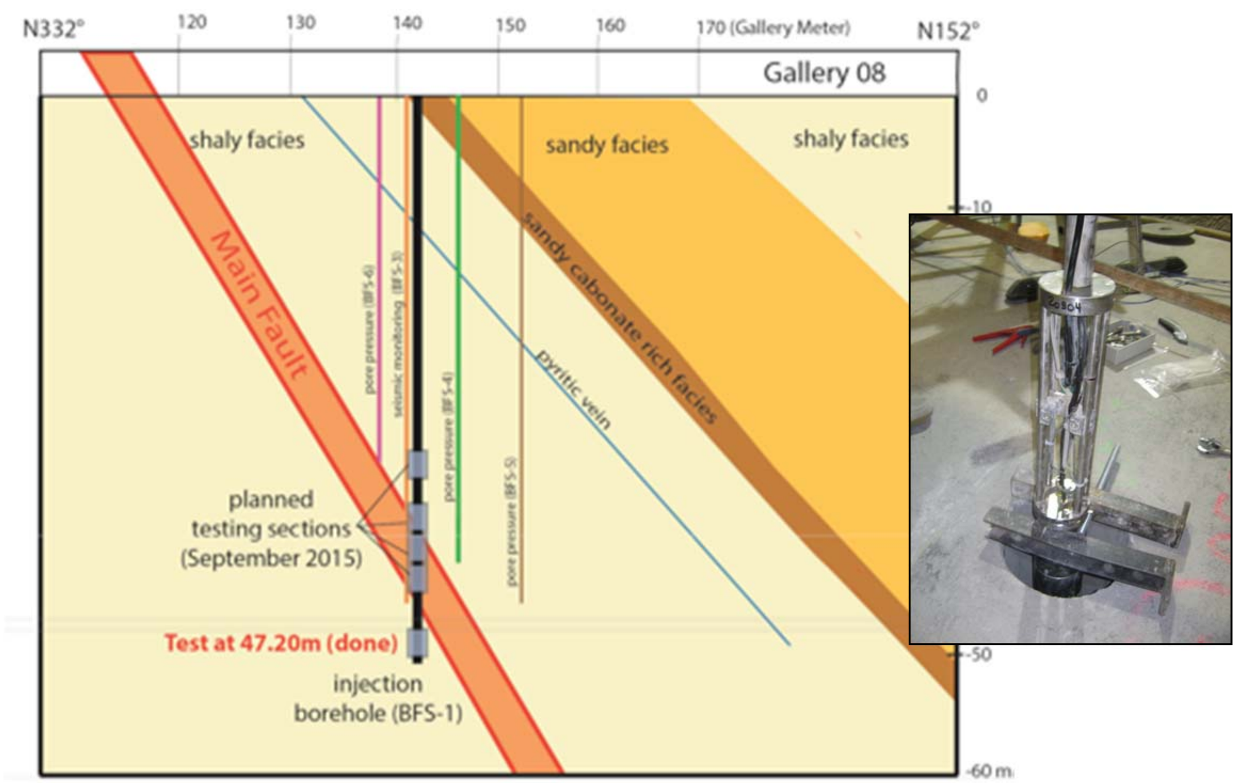

Figure 3-41. General design of fault slip monitoring system for testing of Mont Terri main fault, showing the layout of test borehole and HPPP probe packer system. Image on the right shows HPPP probe before moving deeper into the borehole (from Guglielmi et al., 2015)

The HPPP testing approach has so far been applied in two tunnel-based underground research facilities in France, in the Laboratoire Souterrain à Bas Bruit (http://lsbb.oca.eu) which is a French national facility situated in porous-fractured carbonates in South of France, and in the Tournemire URL (www.irsn.fr) which is an IRSN (France) facility located in a shaley claystone, and recently in the Mont Terri URL in an argillaceous claystone in Switzerland. At Mont Terri, two experimental test sequences using the HPPP probe in the main fault zone are conducted in 2015, one in May and one in September. Prior to active testing, the detailed three-dimensional geology of the main fault was characterized and the regional state of stress was determined. The aim of the analysis was to estimate how the fault zone structural heterogeneity controls the fault slip activation and what may be the effects on pore pressures. Indeed, these faults display a high structural heterogeneity characterized by solitary slickensides, mm-thin gouges associated with scaly clay having contrasted hydraulic and mechanical properties that can generate complex shear stresses concentrations and hydromechanical couplings (Figures 3-42 and 3-43). Note that results from these tests may be utilized in a proposed task for the new DECOVALEX phase starting in 2016 (see Section 3.1.3.4).

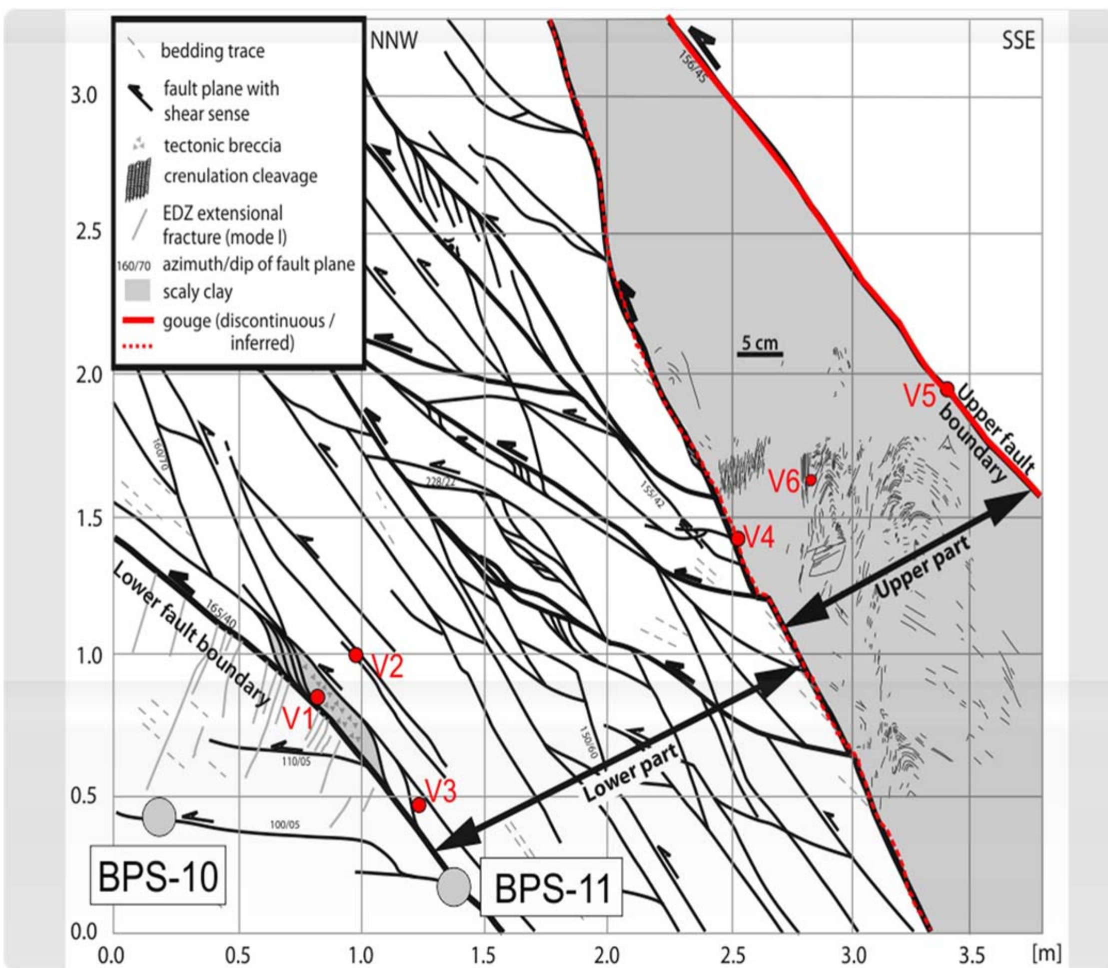

Figure 3-42. Detailed fault geometry at Mont Terri (from Guglielmi et al., 2015)

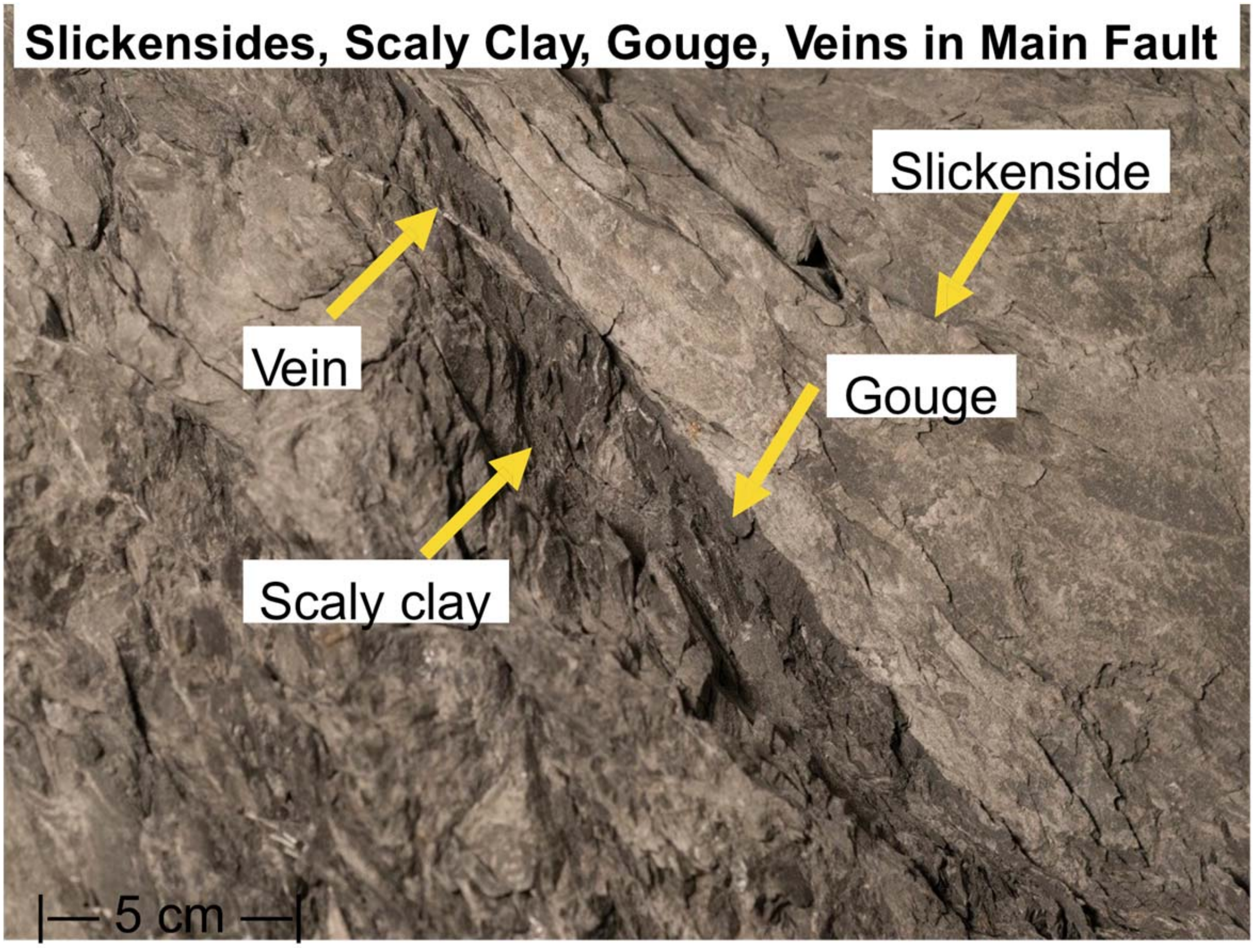

Figure 3-43. Close-up image of main fault with structural features (from Guglielmi et al., 2015)

3.2.6 Mont Terri Summary

Benefits of Participation:

- Access to experimental data from **one URL in clay/shale host rock**, with **many past, ongoing and future experiments** addressing various FEPs
- Opportunity to **participate directly in international research groups that conduct, analyze, and model** experiments (more direct involvement than DECOVALEX)
- Opportunity for participating in and steering ongoing or planned experiments as well as **conducting own experiments**

Status of Participation:

Effective July 1, 2012, DOE formally joined the Mont Terri Project as a partner organization. A substantial part of DOE's partnership fee is provided as an in-kind contribution provided by DOE researchers (i.e., by having UFD researchers conduct work related to ongoing Mont Terri experiments). Specifically, the in-kind contribution of DOE is participation of LBNL researchers in the design and prediction modeling of the FE Heater Test. In addition to the FE Heater Test, UFD researchers have participated, or are participating, in the Mine-by Test, the HE-E Heater Test, the HG-A Experiment, and the DR-A Diffusion Experiment (Section 6).

Outlook:

Ongoing participation of UFD researchers in the Mont Terri Project has been very beneficial. UFD researchers will continue to stay involved in relevant experiments, in particular in the long-term FE Heater Test, and they will keep abreast of new opportunities in the URL as they evolve. Eventually, DOE/UFD may propose its own experiments to be conducted at the site (e.g., a heater test to evaluate strongly elevated temperature in EBS and host rock for understanding direct disposal options for dual-purpose canisters).

Contact Information:

DOE Contact:
Prasad Nair, DOE-NE (R&D)

UFD Contact:
Jens Birkholzer, LBNL

Mont Terri Project Contact:
Paul Bossart, Director, swisstopo, Switzerland
Christophe Nussbaum, Project Manager, swisstopo, Switzerland

3.3 Grimsel Test Site Projects

The Grimsel Test Site (GTS) is a URL situated in sparsely fractured crystalline host rock in the Swiss Alps. The URL was established in 1984 as a center for underground R&D supporting a wide range of research projects on the geologic disposal of radioactive waste (Figure 3-44). GTS provides an environment, analogous to that of a repository site, thus allowing the development and testing of equipment, methodology, and models under fully realistic conditions. GTS is a research facility and not a potential repository site, though investigations may utilize a wide range of radioactive tracers. NAGRA, as the site operator, has organized most experimental activities in the URL as multinational collaborative projects, which typically include several partners from Europe, Asia, and North America. Participation in these collaborative projects requires formal project agreement between NAGRA and its partners. As discussed below, DOE has been a project partner in two international projects at GTS, the Colloid Formation and Migration Project and the FEBEX Dismantling Project, further described in Sections 3.3.1 and 3.3.2, respectively. However, DOE's direct participation with the Colloid Formation and Migration Project has recently ended.

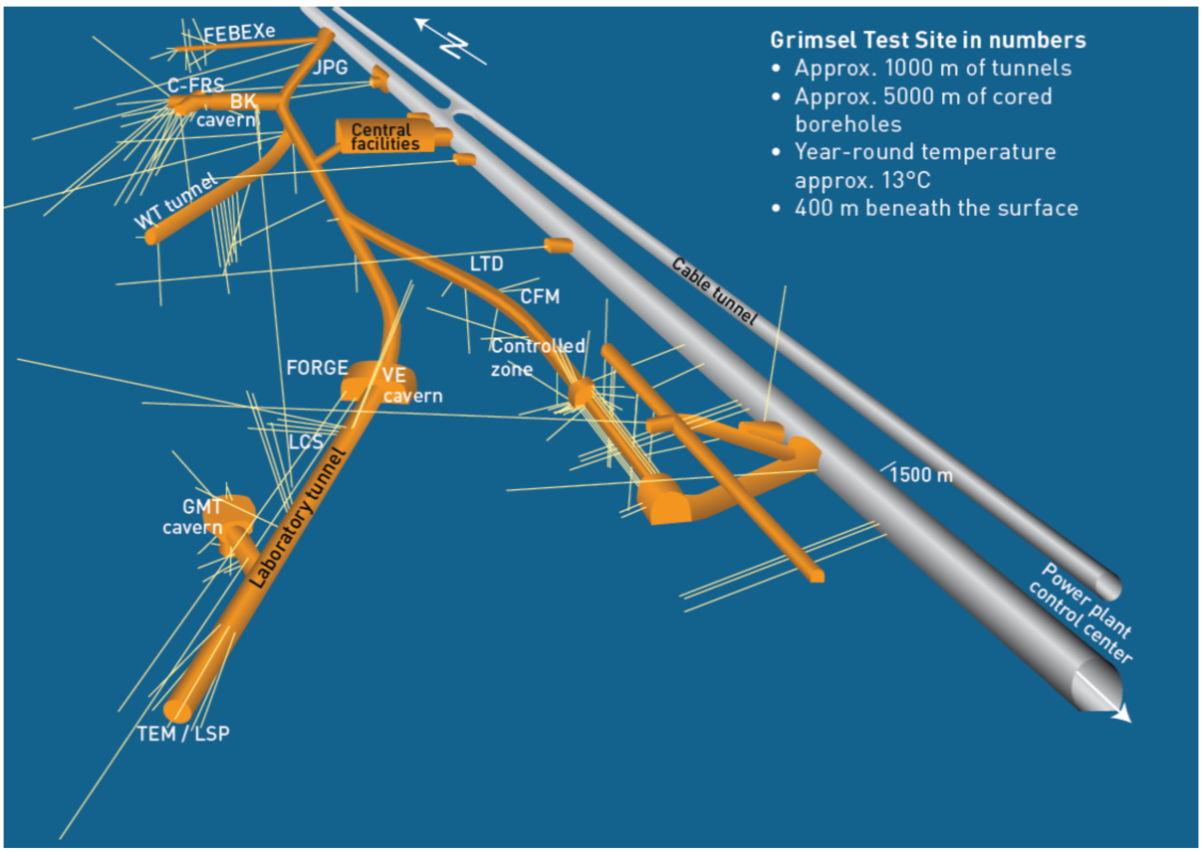

Figure 3-44. 3D view of layout of the Grimsel Test Site in Switzerland (from NAGRA, 2010)

3.3.1 Colloid Formation and Migration Project

3.3.1.1 Introduction to the CFM Project

The Colloid Formation and Migration (CFM) Project is an international research project for the investigation of colloid formation/bentonite erosion, colloid migration, and colloid-associated radionuclide transport, relevant to both NBS and EBS areas of UFD. Colloid-related R&D at GTS comprises *in situ* migration experiments conducted between boreholes in a fracture shear zone; these are complemented by laboratory and modeling studies. The main R&D objectives are as follows:

- To examine colloid generation rates and mechanisms at the EBS–host rock boundary under *in situ* conditions
- To study the long-term geochemical behavior (mobility, mineralization, colloid formation, etc.) of radionuclides at the EBS–host rock interface
- To evaluate the long-distance migration behavior of radionuclides and colloids in water-conducting features in a repository-relevant flow system (i.e., with a very low flow rate/water flux)
- To examine reversibility of radionuclide uptake onto colloids
- To gain experience in long-term monitoring of radionuclide/colloid propagation near a repository.

The CFM project was preceded by the Colloid and Radionuclide Retardation (CRR) project, conducted at the Grimsel Test Site from 1997 to 2003. Twenty-seven field tracer tests were conducted during the CRR, including seven that involved short-lived radionuclides, one involving a suite of long-lived radionuclides with isotopes of U, Np, Am, and Pu, and one involving a suite of radionuclides (including Cs, Sr, Tc, U, Np, Am, and Pu isotopes) injected with bentonite colloids. Colloid-facilitated radionuclide transport was quantified by comparing the breakthrough curves of the radionuclides in the latter two tests (with and without the colloids). Similar tests with and without colloids were also conducted using nonradioactive homologues of actinides (e.g., stable isotopes of Th, Hf, and Tb). All of the CRR tests were conducted as weak-dipole tests between boreholes completed in a fracture shear zone, with the tests involving radionuclides being conducted between boreholes separated by 2.2 m. Tracer residence times in all tests were no more than a few hours.

The CFM project was initiated soon after the Grimsel Test Site transitioned to Phase VI testing in 2004. While similar in many respects to the CRR project, the CFM project aimed to improve or expand upon CRR in two key areas: (1) increase tracer residence times in the fracture shear zone to allow interrogation of processes that may not be observed over the very short time scales of the CRR tests (e.g., colloid filtration, radionuclide desorption from colloids), and (2) directly evaluate the performance of bentonite backfill with respect to swelling, erosion, and colloid generation, by emplacing a bentonite plug into a borehole completed in the fracture shear zone. To accomplish these objectives, a “tunnel packer” system was installed to seal off the entire access tunnel (Figures 3-45 and 3-46) where it was intersected by the shear zone. With this packer system, the flow rate from the shear zone into the tunnel could be throttled back from a natural rate of ~700 mL/min to any desired value, and the water from the shear zone could be collected in a controlled manner. Boreholes penetrating the shear zone could then be used as injection boreholes for tracer tests or for emplacement of the bentonite plug, with the tunnel packer effectively serving as an extraction location.

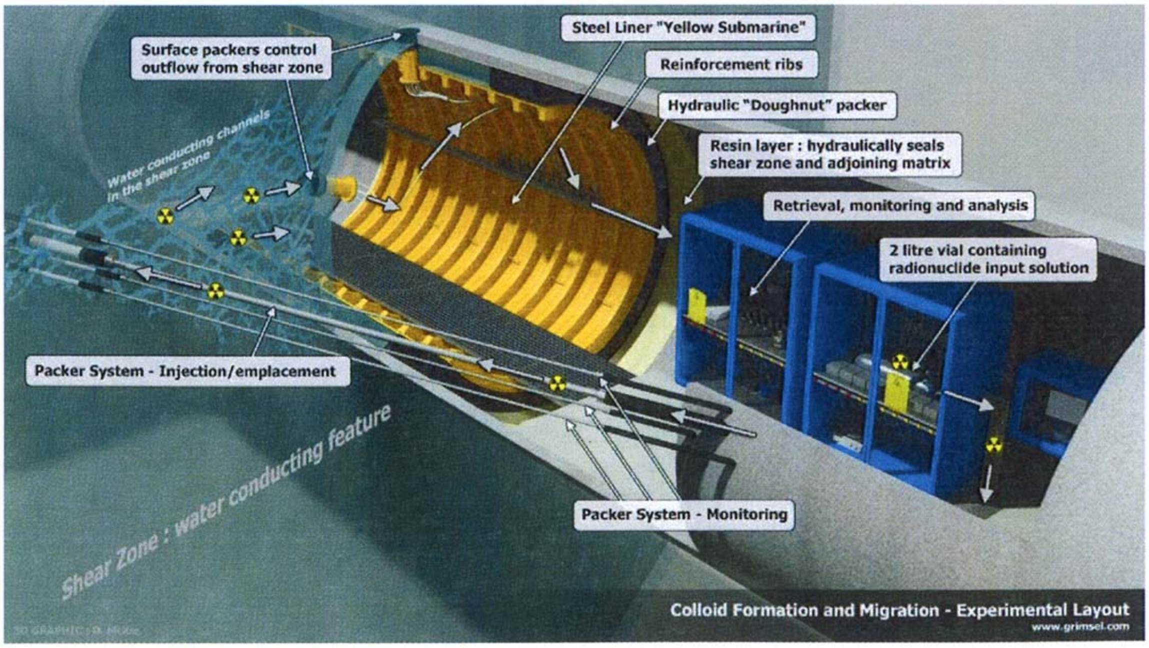

Figure 3-45. Schematic illustration of the CFM field test bed at Grimsel Test Site (from Reimus, 2012)

Figure 3-46. CFM field test bed at Grimsel Test Site: Tunnel packer system used to isolate the shear zone (from http://www.grimsel.com/gts-phase-vi/cfm-section/cfm-site-preparation). Small disks with tubing issuing from them (inside yellow packer) are "surface packers" that seal the tunnel wall and collect water from inflow points. Tunnel diameter is 3.5 meters.

Seven conservative (nonsorbing) tracer tests were conducted in late 2006 through 2007 at various shear zone flow rates using different boreholes as injection holes to test the tunnel packer system and to evaluate tracer residence times that could be achieved. Tracer transport pathways in these tests and in all the CRR tests are depicted in Figure 3-47, which shows the locations of several boreholes relative to the main tunnel within the shear zone. Borehole CFM 06.002, drilled in 2006 for the CFM project, was established as the primary injection borehole to be used in subsequent tracer testing involving colloids, homologues, and radionuclides. Tests were conducted with injections of tracer solutions into borehole CFM 06.002 while extracting water from the Pinkel surface packer located at the tunnel wall ~6.2 m from the injection interval. In 2008, a tracer test was conducted in which a bentonite colloid solution with homologues presorbed onto the colloids was injected into CFM 06.002 (referred to as Test 08-01, where the first number indicates the year and the second number indicates the sequential test for that year). This test was followed immediately with a conservative tracer test in the same configuration. Based on lessons learned from these tests, a series of five more tests was conducted in 2009 and 2010. Three of these included only conservative tracers, and two included bentonite colloids and homologues in addition to conservative tracers (Test 10-01 and 10-03). More recently, the CFM Project conducted a new test (12-02), described in Section 3.3.1.2 below, involving the injection of a radionuclide-colloid cocktail including the actinides Pu(IV) and Am(III) into injection interval CFM 06.002. This experiment evaluated the transport of bentonite colloids with radionuclides from the source to the extraction point at the tunnel wall.

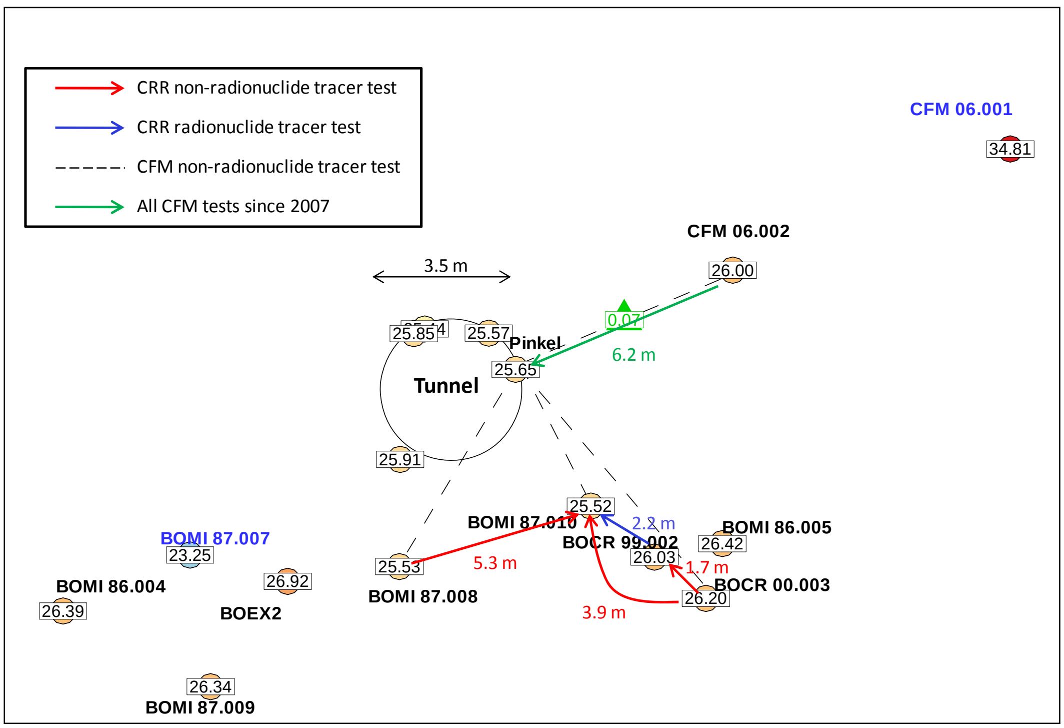

Figure 3-47. CFM field test bed at Grimsel Test Site: Borehole layout and test locations for all tracer tests 2001-2012 (from Reimus, 2012)

The CFM project entered a new phase of testing in May 2014 with the emplacement of a radionuclide-doped bentonite plug into the same injection interval CFM 06.002 intersecting the flowing shear zone at the GTS. This experiment is being called the Long-term In-situ Test, or LIT. In 2011, three smaller diameter boreholes, CFM 11.001, 11.002, and 11.003, were drilled through the shear zone in roughly a triangular pattern around CFM 06.002 to serve as near-field monitoring boreholes during the LIT. A plan view of the borehole configuration around 06.002 is shown in Fig. 3-48. In addition to providing near-field access for monitoring and sampling during the LIT, these boreholes will be used for injection of epoxy to provide stability for post-experiment overcoring of 06.002 through the shear zone over a diameter that encompasses the three smaller boreholes (shown as dashed lines in Fig. 3-48). This overcoring will allow a careful post-mortem of the LIT to determine the disposition of both bentonite and radionuclides in the shear zone at the end of the experiment. More detail on the LIT experiment is given in Section 3.3.1.3 below.

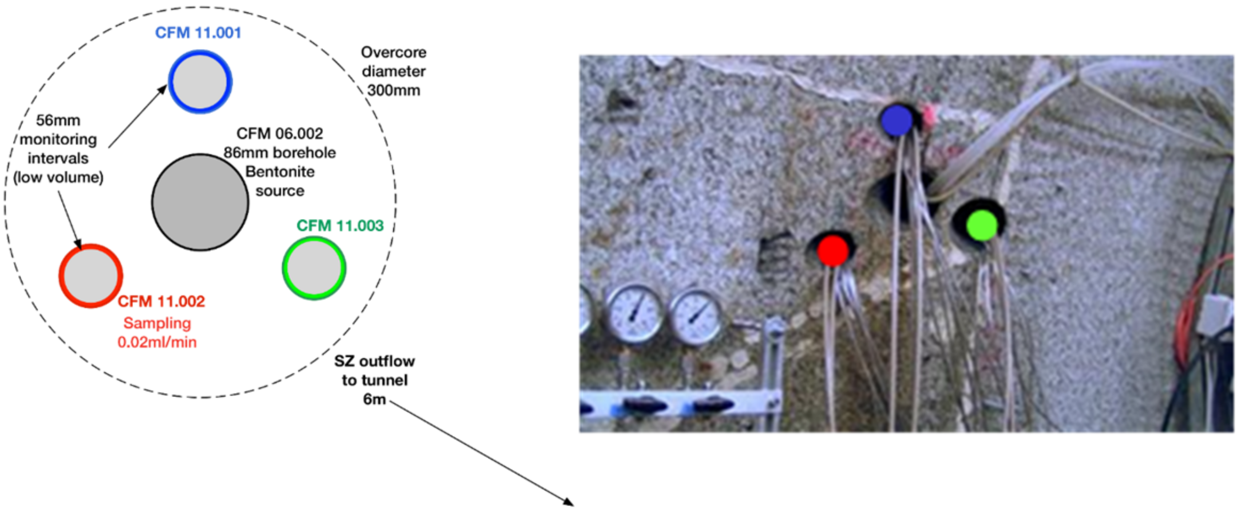

Figure 3-48. Plan view of the borehole configuration for the LIT (left) and photo showing the boreholes at the access tunnel wall (right)

In addition to the field activities conducted at the Grimsel Test Site, the CFM project includes many complementary activities aimed at helping achieve the R&D objectives listed at the beginning of this section. These activities include:

- Bentonite swelling and erosion experiments in various laboratory configurations, including artificial fractures, to better understand the processes of swelling and erosion that will occur in the bentonite-plug field experiment
- Laboratory sorption and desorption experiments of radionuclides and homologues onto both bentonite colloids and Grimsel fracture fill material
- Sorption/desorption experiments involving the competitive sorption and desorption of radionuclides/homologues in the presence of both colloids and fracture-fill material
- Colloid-facilitated radionuclide transport experiments in both crushed rock columns and in fractures in the laboratory.
- Laboratory experiments to improve detection and quantification methods for colloid analyses in field experiments, including possibly labeling the bentonite with a marker element
- Development of a bentonite swelling/erosion model
- Interpretive modeling of the laboratory experiments and the field tracer tests

Realizing the benefit of becoming a formal partner, DOE in early 2012 formally applied for partnership in the CFM Project and was accepted as a new partner in August 2012. Other current CFM project partners are from Germany (BGR, BMWi/KIT), Japan (JAEA, CRIEPI), Great Britain (NDA), Sweden (SKB), Republic of Korea (KAERI), Finland (POSIVA), and Switzerland (NAGRA). Partnership gave DOE and affiliated National Laboratories exclusive access to all experimental data generated by CFM. More importantly, it allowed for UFD researchers to work collaboratively with international scientists in ongoing experimental and modeling studies, and it involves them in the planning of new experimental studies to be conducted in the future. Like the Mont Terri Project, this type of international collaboration goes beyond the mostly modeling focus of DECOVALEX. In contrast to both the DECOVALEX project and the Mont Terri project, which comprise a range of experiments covering a wide spectrum of relevant R&D issues, the CFM has a relatively narrow focus, i.e., colloid-facilitated radionuclide migration. In part because of this narrow focus and the comparably high membership fee relative to other international initiatives, DOE recently decided to not renew its participation in the CFM Project beyond 2015. However, UFD researchers from LANL and LLNL have actively collaborated with their international partners in FY15 and before. LANL performed interpretative analysis of CFM field measurements (Section 6.2.3), and both LANL and LLNL conducted complementary laboratory investigations of colloid-facilitated transport (Section 6.2.4 and 6.2.5).

3.3.1.2 Colloid-Facilitated Radionuclide Tracer Test

In February 2012, a colloid-facilitated radionuclide tracer test referred to as Test 12-02 (second test in 2012) was conducted in a fracture shear zone at Grimsel. The colloids were derived from FEBEX bentonite, which is mined in Spain and is being considered as a potential waste-package backfill material for a Spanish nuclear waste repository. The radionuclides were pre-sorbed onto the colloids to varying degrees, dictated by their sorption to the colloids (probably ~100% sorbed for Pu and Am, ~50% sorbed for U and Np, somewhere in between for fission products Cs and Sr). The tracer cocktail was injected into injection interval CFM 06.002i2 at a target flow rate of ~0.35 mL/min, while water was being continuously extracted at a rate of 25 mL/min from the Pinkel surface packer at the tunnel wall ~6.1 m from the injection interval. The test was initiated by introducing the tracer cocktail into a flow loop that circulated through the injection interval at a relatively high rate to keep the interval well mixed while maintaining a near-constant net injection flow rate into the shear zone. The volume of the vessel containing the tracer cocktail was 2.25 L, and the volume of the injection flow loop was 1.0 L, so the entire injection circuit volume was 3.25 L after the tracer vessel was plumbed into the system. This arrangement resulted in an exponentially decaying source term in the shear zone as the tracers were slowly bled out of the injection circuit. Two previous colloid-facilitated transport tests were conducted in this configuration, but they involved nonradioactive homologues, not radionuclides. Figure 3-49 shows measurements from the tracer test, depicting the normalized concentrations of tracers (concentrations divided by injection volume) in the water extracted from the Pinkel surface packer as a function of time.

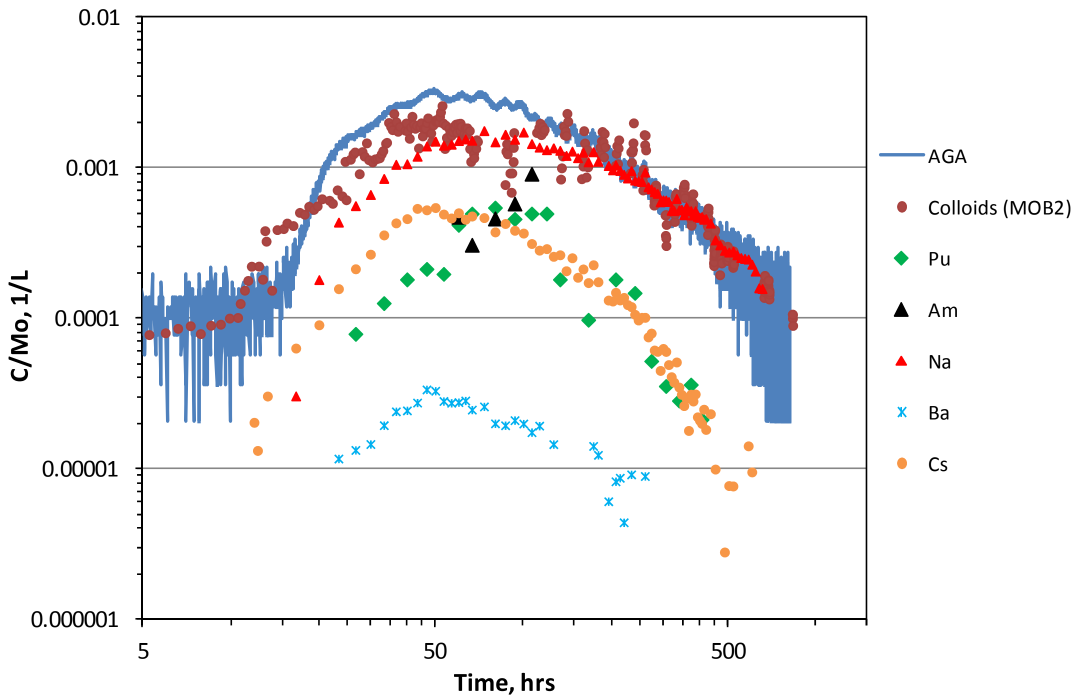

Figure 3-49. Colloid-Facilitated Radionuclide Tracer Test at Grimsel Test Site: Normalized breakthrough curves of all tracers in CFM Tracer Test 12-02 (from Reimus, 2012)

3.3.1.3 LIT - Radionuclide-Doped Bentonite Plug Transport Experiment

This section describes the ongoing LIT experiment at CFM which involves a bentonite plug (FEBEX backfill material) doped with a suite of radionuclides that in May 2014 was emplaced into the CFM 06.002 injection interval used in previous tracer tests. As mentioned above, new small boreholes were drilled and instrumented around CFM 06.002 for sampling at very low rates to provide an early indication of swelling and radionuclide release. Here we describe the LIT design/configuration as well as the emplacement and monitoring activities that have been conducted to date (from May 2014 through about June 2015). This summary is intended to document the current status of the LIT so that future involvement in the CFM project can be considered from an informed point of view. Much of this information comes from a current draft NAGRA report on the status of the LIT after one year that is not currently citable but was provided by NAGRA as a courtesy to a project partner.

The emplacement of the radionuclide-doped bentonite plug for the LIT was a significant challenge. There were several design considerations and test constraints, including the following:

- the need to confine the emplaced bentonite between straddle packers in the borehole at the depth of the shear zone and to fill as much of the empty space between the packers as possible with bentonite,
- the need for minimally reactive materials in the straddle packer assembly so that the radionuclides would not interact with these materials in the borehole,
- the need to dope the bentonite with radionuclides in a way that would allow the straddle packer assembly to be inserted into the emplacement hole without smearing contamination onto the borehole walls.

The resulting emplacement system is shown in Figures 3-50 and 3-51. Its features included:

- A set of 16 bentonite rings compressed to a target dry density of 1.65 g/cm^3 and designed to fit snugly over a straddle packer mandrel made of nonreactive PEEK® material (shown in previous studies to be one of the most nonreactive materials to the radionuclides) (Figure 3-50),
- 16 small glass vials filled with radionuclide-doped bentonite that were inserted into holes drilled into the central 4 of bentonite rings (the glass provided containment of the radionuclides during insertion of the system into the borehole, with the expectation that the vials would break open when the bentonite wetted and exerted swelling pressure on them) (Figure 3-51),
- pressure transducers in both the upper and the lower packer assemblies to measure both total axial pressure exerted on the packers (redundant transducers in each packer) and pore pressure in the bentonite (measured with a transducer behind a fine-mesh screen that prevented the bentonite from exerting pressure directly on the transducer).

The bentonite in the four central rings into which holes were drilled consisted of 90% regular FEBEX bentonite (used in all previous CFM experiments; obtained from a mine in Spain) and 10% synthetic bentonite labeled with Zn, and the bentonite inserted into the vials was a Ni-labeled synthetic bentonite. The Zn and Ni were to be subsequently used to distinguish colloids from the bentonite source term from natural colloids in groundwater samples. The radionuclides and a dye tracer (Amino-G Acid, or AGA) were added to a solution that was used to create a concentrated bentonite slurry that was packed into each of the vials (leaving a small amount of void space in the vials). The bentonite rings had to be broken to fit them around the mandrel of the packer system, but they were pieced back together with negligible loss of bentonite and held together with plastic tape until just before they were inserted into the borehole, after which the borehole walls prevented them from falling away from the mandrel.

The bentonite packer system emplacement was accomplished without incident on May 12, 2014, with a last-minute adjustment that involved removing all the vial caps before placing the vials open-end-first into the holes drilled into the bentonite rings. This adjustment ensured that the radionuclides would have a release pathway out of the vials even if the swelling pressure was not sufficient to cause them to break (laboratory tests had shown that breakage did not always occur when the bentonite swelled). The vials were also pre-scored to facilitate their breakage.

In parallel with the emplacement, low-flow sampling of one of the three near-field monitoring boreholes was established in the shear zone. This sampling was conducted at a steady rate of 0.02 ml/min in the monitoring borehole (CFM 11.002) that was shown in previous tracer tests to be the best connected of the three small boreholes to the emplacement hole. The other two monitoring boreholes were shut in and are simply being used for pressure monitoring, although they also have sampling systems that can be activated later if desired. Each of the monitoring boreholes is equipped with a PEEK ‘dummy’ that occupies the majority of the dead space between the packers, leaving only a ~1-mm annular space to reduce dead volume for sampling.

Prior to and after the bentonite emplacement, a steady outflow rate of 25 ml/min was maintained in the Pinkel surface packer installed in the mega-packer system at the access tunnel wall approximately 6 m from the bentonite emplacement. This flow rate had been shown in previous tracer tests to be sufficient to induce a shear zone flow that captured most of the water passing through the shear zone near the emplacement borehole, thus maximizing the probability that radionuclides and colloids released from the bentonite source term would be collected at the tunnel wall. Samples collected in both the near-field monitoring borehole sampling system and at the Pinkel surface packer were analyzed onsite for fluorescence to detect the appearance of the dye tracer included in the radionuclide cocktail and turbidity to detect the appearance of bentonite colloids. Additionally, parameters such as pH, Eh/ORP and specific conductance can be routinely monitored on site. The radionuclide concentrations and additional colloid parameters (e.g., more quantitative determinations of concentrations as well as size distributions) are being measured in analyses conducted at offsite laboratories. Additionally, a laser-induced breakdown system has been used intermittently onsite to obtain colloid concentration and size distribution data.

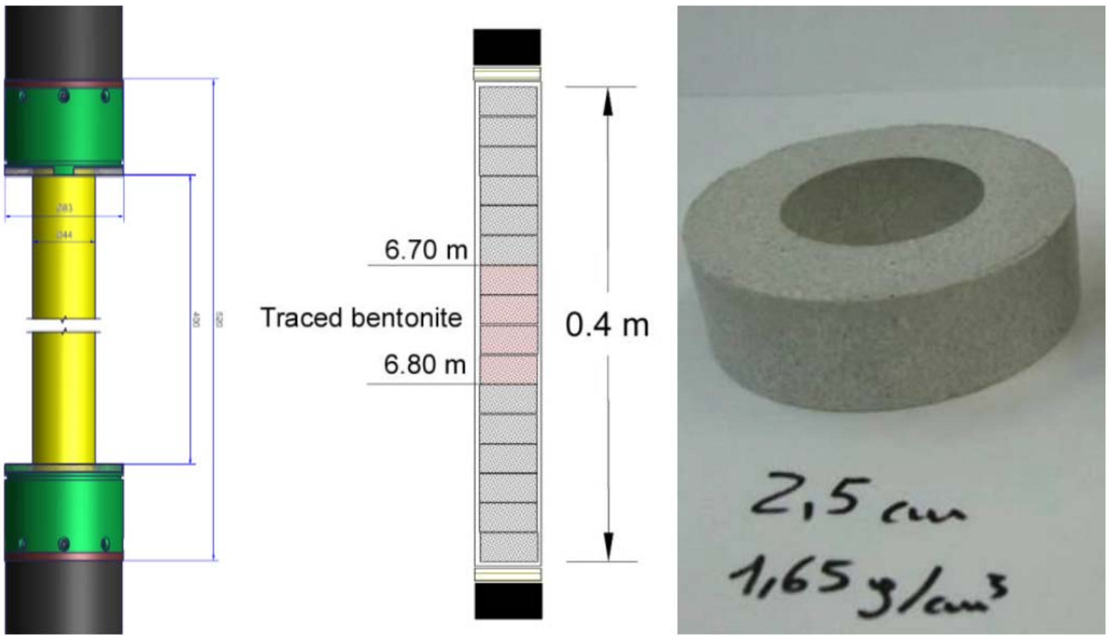

Figure 3-50. LIT packer system with PEEK mandrel shown in yellow (left), configuration of 16 bentonite rings between packers (middle), and photo of compacted bentonite ring (right). The four central bentonite rings were traced with a synthetic Zn-labeled montmorillonite (10% of mass) and had 4 holes drilled in each of them for insertion of glass vials containing radionuclide-doped bentonite.

Figure 3-51. Schematic showing the LIT packer string and a photo of one of the radionuclide-doped bentonite vials after insertion into a hole in one of the four central bentonite rings

Preliminary test results since May 2014 show that the bentonite rings emplaced between the packers in CFM 06.002i2 wetted and swelled rapidly. Figure 3-52 shows the early pressure history measured by the transducers in both CFM 06.002 and in one of the nearby monitoring boreholes that was not being actively sampled, CFM 11.003. The pressures exerted on the transducers exposed to the swelling bentonite rose very rapidly to different pressures in the top and bottom packers, although both pressures were significantly elevated above the shear zone porewater pressure (indicated by the CFM 11.003 pressure). The pore pressures measured behind the mesh screens that prevented bentonite contact with the transducers rose somewhat less rapidly to the ambient water pressure in the shear zone, indicating relatively quick saturation within the interval and pressure equilibration with the shear zone. These results suggest rapid swelling of the bentonite near the shear zone inflow point(s) and rapid transmittal of the swelling pressure to the ends of the packed-off interval, followed by later arrival of the water itself at the ends of the interval, resulting in a delayed rise in pore pressure. The different total pressures exerted at the different ends of interval indicate some apparent heterogeneity in the swelling of the bentonite.

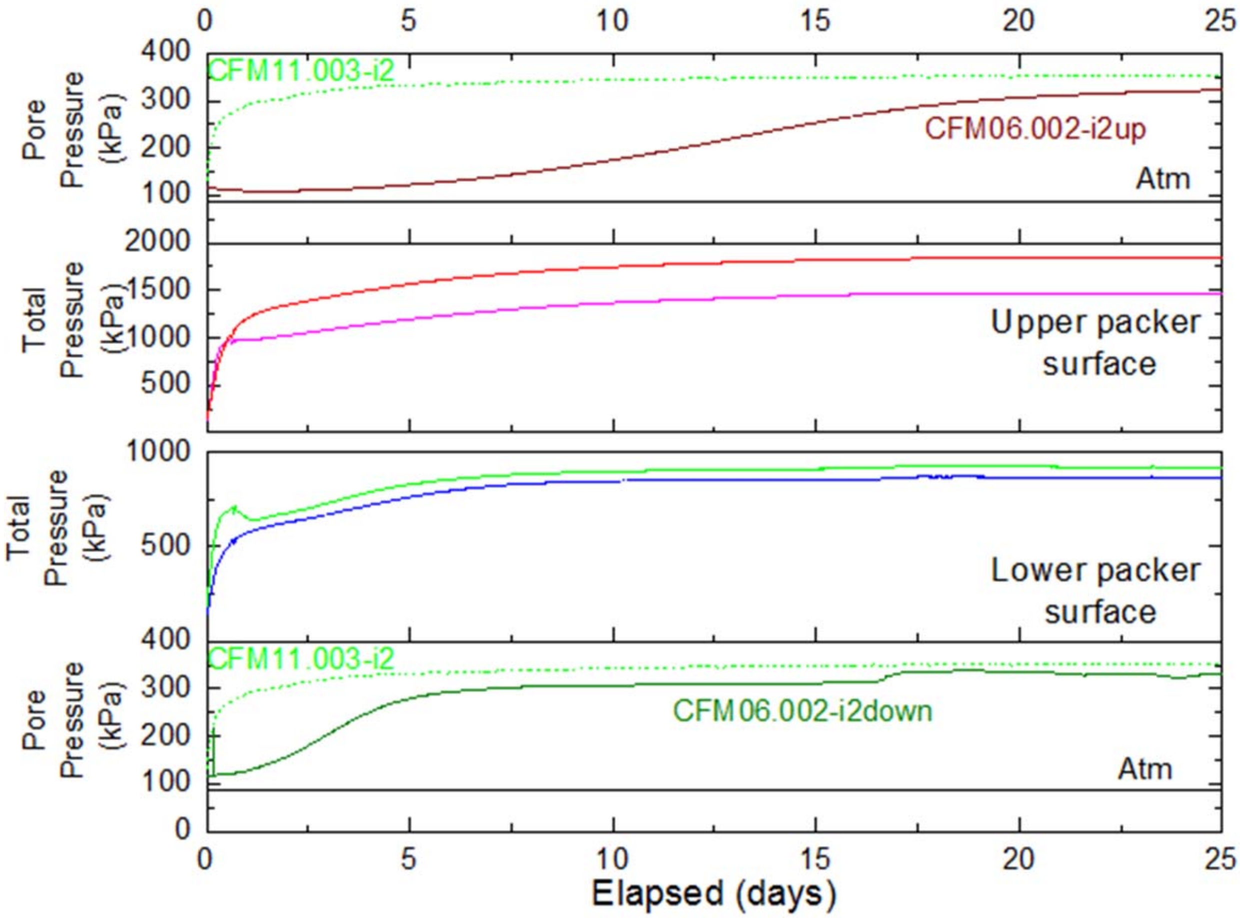

Figure 3-52. Pressures recorded during the first 25 days after bentonite emplacement. Note there are two redundant total pressure transducers in the upper and lower packer surfaces and one pore pressure transducer in each packer surface. CFM 11.003 is one of the near-field monitoring boreholes.

Figure 3-53 shows the onsite chemistry monitoring data in the near-field monitoring borehole (red), and also the specific conductance, Eh and pH in the water extracted from the surface packer at the tunnel wall (black) during the first year after bentonite emplacement. The data appear somewhat choppy with occasional discontinuities (particularly SC, Eh and pH) because of power interruptions and periodic calibrations of the monitoring instrumentation. The specific conductance quickly rose from ambient values, suggesting some dissolution of accessory minerals in the bentonite (which is not pure montmorillonite), but it then leveled off and decreased throughout the remainder of the one-year period. pH initially drifted downward in the near-field monitoring borehole but then reversed, mirroring the specific conductance trend. Eh showed an initial decrease in the near-field borehole, consistent with the consumption and flushing of the oxygen/air that was introduced to the system during the emplacement, but it never reached the low values recorded at the tunnel wall.

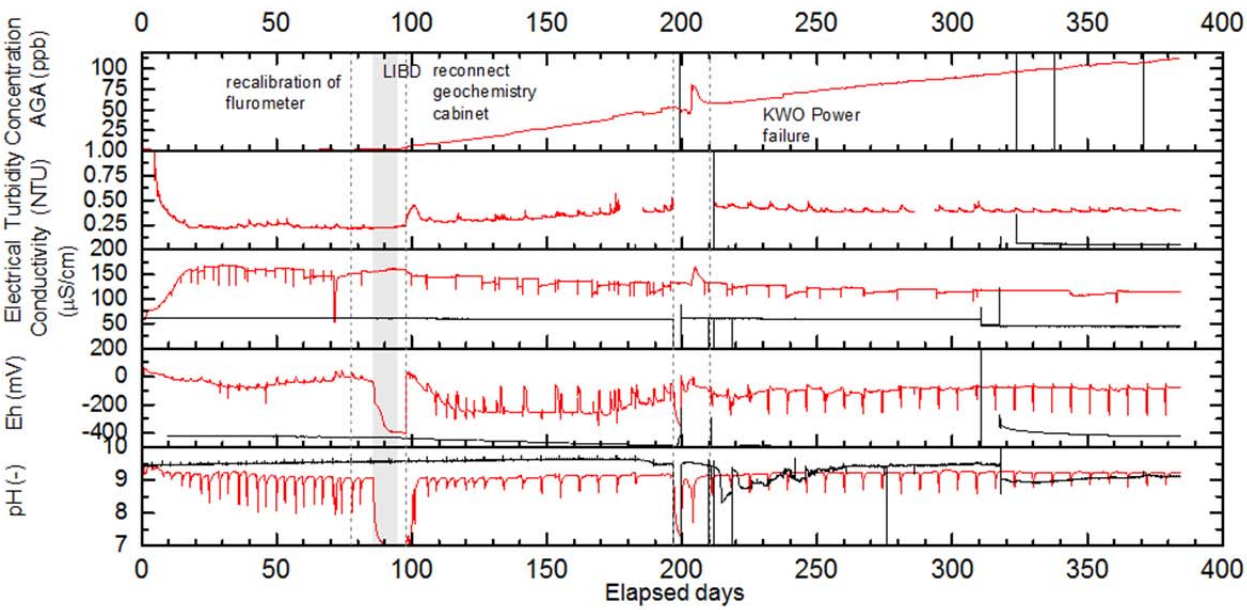

Figure 3-53. Onsite chemistry monitoring data during the first year of after bentonite emplacement. Red lines correspond to the CFM 11.002 near-field monitoring borehole and black lines correspond to the Pinkel surface packer at the access tunnel wall (EC, Eh and pH).

The fluorescence (AGA concentration) and turbidity data of Figure 3-53 indicate the arrival of both conservative dye tracer and colloids (turbidity) in CFM 11.002 after about 100 days. The AGA fluorescence results suggest that at least one of the vials started contributing dye tracer to the shear zone flow system at this time, and the turbidity results suggest that some of the emplaced bentonite began eroding to form mobile colloids at this time. It should be noted that an acoustic monitoring system was deployed within the packer system to monitor for glass vial breakage, but the system failed to detect any definitive breakage signals. Of course, given that the vials were inserted uncapped, breakage would not strictly be necessary to release the dye tracer into the bentonite.

Figure 3-54 shows the apparent breakthrough of Amino-G Acid at the Pinkel surface packer at the tunnel wall. The signal is somewhat noisy because the concentrations are barely above detection limits. Also shown in Figure 3-54 is a scaled-down version of the tracer response in the near-field monitoring borehole, and it is apparent that the breakthrough at the tunnel wall was essentially coincident with the breakthrough in CFM 11.002. This result is not surprising, as the mean shear zone residence times in all previous tracer tests conducted between the CFM 06.002 emplacement hole and the tunnel wall were on the order of a day, so over the time scale of the LIT, the breakthroughs at the two location would be expected to be essentially coincident. Radionuclide and colloid concentrations in samples are in the process of being analyzed at the time this chapter was written, and there are no results to report yet (other than the onsite turbidity measurements for colloids in CFM 11.002).

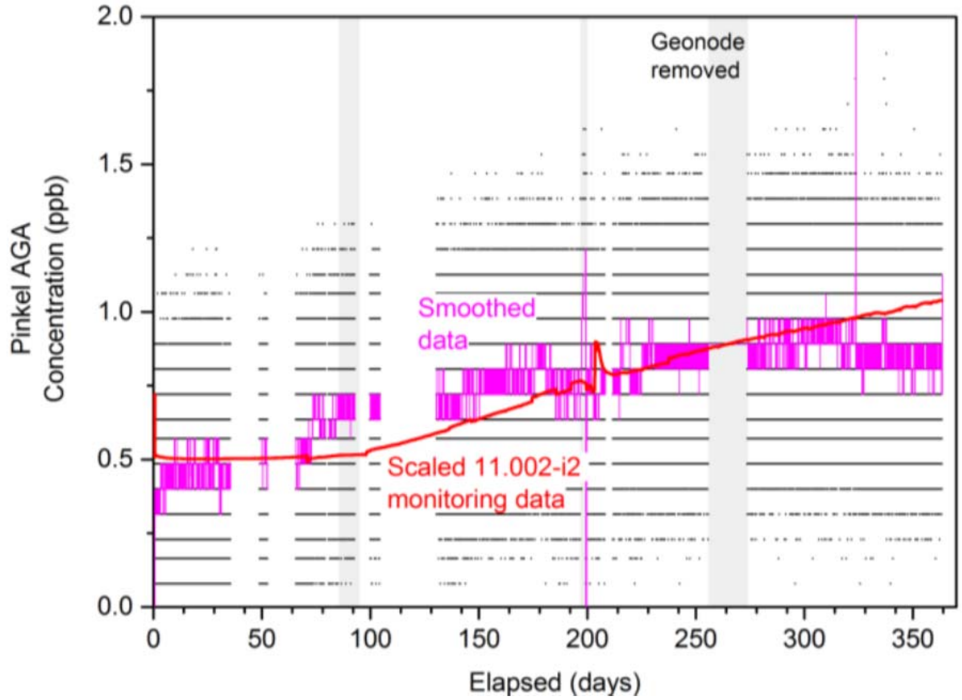

Figure 3-54. Amino-G acid signal at the Pinkel surface packer (magenta) and a scaled down plot of the Amino-G acid signal in the near-field monitoring borehole (red)

Overall, the LIT is progressing very well with successful monitoring of swelling of the emplaced bentonite water saturation of the emplacement interval during the early portions of the test. Although the swelling pressures are quite different at the two ends of the emplacement interval, the pressures are consistent with expected dry densities in the interval (within 10% of theoretical/calculated) assuming the emplaced bentonite swelled to fill the available space in the interval. Chemistry monitoring in a near-field monitoring borehole indicates some early chemical transients likely associated with accessory mineral dissolution in the emplaced bentonite, followed by the appearance of the conservative dye tracer and (less prominently) colloids about 100 days after bentonite emplacement. The conservative dye tracer has also been detected at very low levels in the water drawn from the surface packer at the tunnel wall (starting at about 100 days after emplacement and roughly mirroring the breakthrough in the near-field borehole).

The LIT will progress for at least another year, at which time the project partners will decide whether to continue the test in its current configuration for an additional period of time or to stop the test and proceed with the planned overcoring of the emplacement borehole and near-field monitoring boreholes to determine the disposition of the swelled bentonite and radionuclides in the shear zone. The information obtained from both the shut-in/monitoring phase of the test (i.e., the current phase) and the overcoring phase of the test should be useful for the development and validation of models for swelling and erosion of clays, and for models of radionuclide release and transport from a bentonite buffer/backfill.

3.3.1.4 Colloid Formation and Migration Summary

Benefits of Participation:

- Access to experimental data from a **suite of past, ongoing, and future experiments** on colloid-facilitated migration at Grimsel, more narrow focus than other initiatives (Note that CFM membership does not provide access to other experiments at Grimsel)
- Opportunity to **participate directly in international research groups that conduct, analyze, and model** migration experiments (more direct involvement than DECOVALEX)
- Opportunity for participating in and steering ongoing or planned experiments as well as **conducting own experiments**

Status of Participation:

DOE formally joined the CFM Project in August 2012. UFD researchers have been involved in the interpretation and analysis of several colloid-facilitated tracer tests (Section 6.2.3) and have recently conducted batch and column transport experiments to refine a colloid-facilitated transport model and to provide insight into potential colloid-facilitated transport of Cs isotopes in a crystalline rock repository (Sections 6.2.4 and 6.2.5).

Outlook:

The interpretation of the colloid-facilitated tracer tests by UFD researchers has led to important findings with regards to relevance and predictability of colloid migration and colloid-associated RN transport. The ongoing LIT is providing valuable insights on additional aspects of colloid transport related to bentonite erosion, an important subject for UFD. However, UFD recently decided against continued participation in the CFM project, in part due to resource constraints but also because the scientific focus of the CFM Project is narrower than other initiatives discussed in this section.

Contact Information:

DOE Contact:
Prasad Nair, DOE-NE

UFD Contact:
Jens Birkholzer (LBNL)
Paul Reimus (LANL)

CFM Contact:
Ingo Blechschmidt, Head of Grimsel Test Site, NAGRA, Switzerland

3.3.2 FEBEX Dismantling Project

3.3.2.1 Introduction to FEBEX Dismantling Project

The FEBEX heater test is a full-scale Engineered Barrier System (EBS) test that has been operating under natural resaturation conditions for almost two decades (Figures 3-55). The overall objective was to evaluate the long-term performance of the EBS and, to a lesser degree, the near-field crystalline rock, with emphasis on the thermal evolution and resaturation of bentonite backfill surrounding a heated waste package. With heating started in 1997, the FEBEX experiment is the longest running full-scale heater experiment in the world, providing a unique data set for the transient behavior of a heated repository. A fixed temperature of 100°C has been maintained at the heater/bentonite contact during this time, while the bentonite buffer has been slowly hydrating with the water naturally coming from the rock. A total of 632 sensors of diverse types were installed in the clay barrier, the rock mass, the heaters, and the service zone to measure the following variables: temperature, humidity, total pressure, displacement, and pore pressure.

Partial dismantling of the *in situ* test was carried out during 2002, after five years of heating. The first one of the two heaters was removed and the materials recovered (bentonite, metals, instruments, etc.) have been analyzed to investigate the different types of processes undergone, while the second heater continued (Figures 3-56 and 3-57). The samples recovered from this first heater experiment provided valuable information on the long-term condition of heated EBS materials (Lanyon et al., 2013). In FY15, about 12 years after the first partial dismantling, NAGRA launched the FEBEX Dismantling Project (FEBEX-DP), which removed the second heater and recovered relevant EBS and host rock materials. This provides a unique opportunity for analyzing samples from an engineered barrier and its components that underwent continuous heating and natural resaturation for 18 years. DOE has joined the FEBEX-DP Project as one of the initial partners, together with NAGRA, SKB, POSIVA, ENRESA, CIEMAT, KAERI, OBAYASHI, ANDRA, and possibly RWM and SURAO. In FY15, UFD researchers from LANL, LBNL, and SNL participated in the test design and sampling plan development and conducted preliminary model predictions (Section 6.1.2).

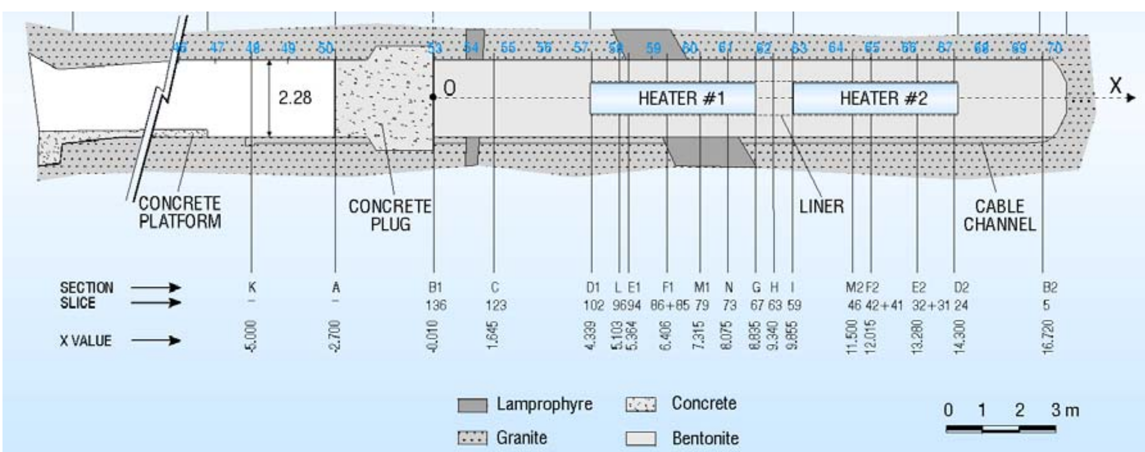

Figure 3-55. Schematic cross section of the FEBEX Test at Grimsel Test Site (from NAGRA, 2014)

Figure 3-56. Bentonite blocks during installation of the experiment in 1996 (left) and after the first dismantling in 2002 (right). In 2002, all initial emplacement gaps between blocks were closed (from NAGRA, 2014).

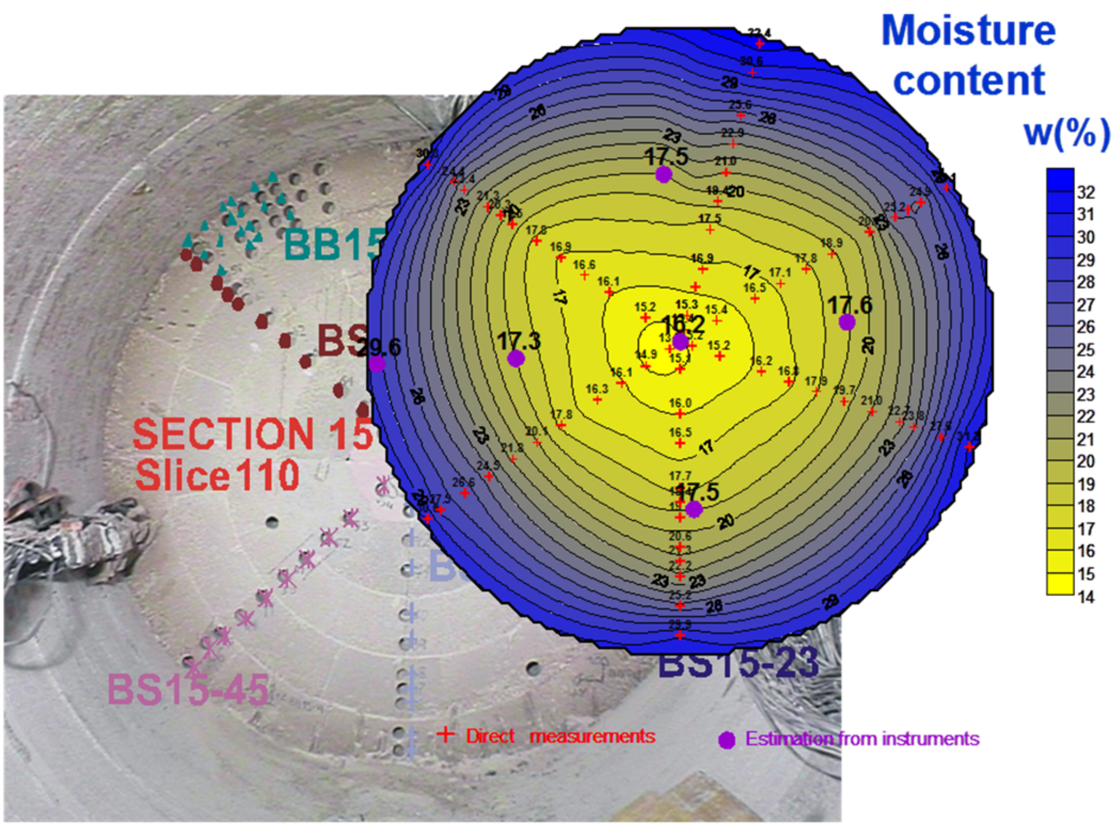

Figure 3-57. Moisture content and sampling locations derived from 2002 dismantling campaign. Moisture distribution in the bentonite shows an axial symmetry independent of the geologic variability in the adjacent host rock (from NAGRA, 2014).

3.3.2.2 FEBEX-DP Objectives

The FEBEX-DP project is conducted to provide data and to improve understanding of the long-term THMC performance of the EBS components and their interactions with the host rock. This will increase confidence in the models required for predicting the long-term evolution of the engineered barriers and how these are affected by their natural environment. The FEBEX-DP Project thus focuses on the following primary goals (Gaus and Kober, 2014; NAGRA, 2014) (Figure 3-58):

- Characterization of the key physical properties (density, water content) of the bentonite and their distribution
- Characterization of corrosion processes on instruments and coupons under evolving redox conditions and saturation states
- Characterization of mineralogical interactions at material interfaces and potential impacts on porosity
- Integration of monitoring results and modeling

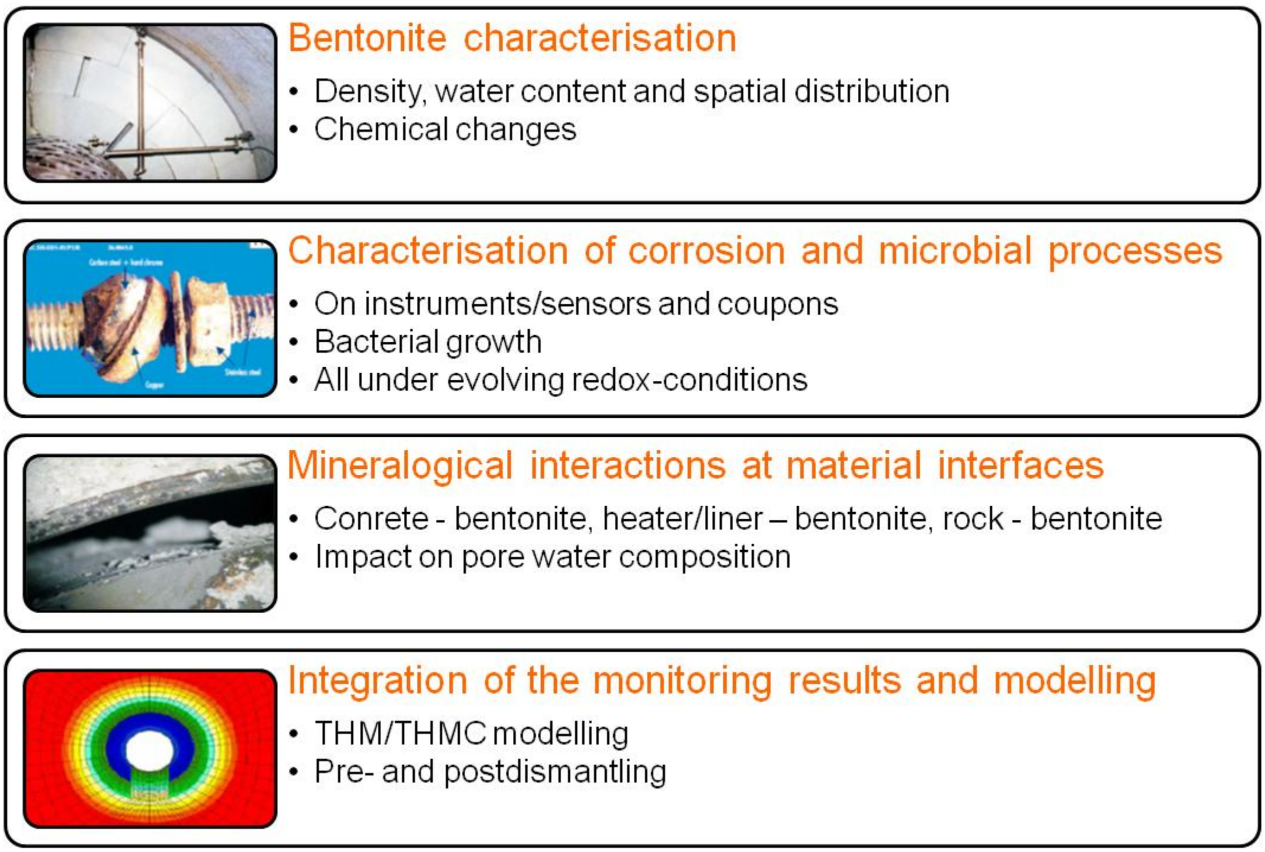

Figure 3-58. Primary goals of FEBEX-DP Project (from NAGRA, 2014)

These primary goals are realized by pursuing the following secondary objectives regarding the main elements of the experiment:

- Buffer and interfaces:
  - Obtain 3D insight into the water content and density distributions of the bentonite through extensive sampling.
  - Obtain insight into THM parameters and their evolution in time through comparison with the values of the first dismantling
  - Characterize pore water changes, modifications in the absorbed cations in the clays and potentially mineralogical alteration.
  - Microbiological characterization
  - Characterize interfaces with the liner, the heater, the embedded corrosion coupons and instrumentation and identify potential chemical interactions affecting the bentonite
- Instrumentation and metal coupons:
  - Recalibrate and correct the monitoring results if required, analyze their mechanical performance
  - Analyze corrosion products
- Plug and interfaces
  - Investigate the performance of the shotcrete at macro and micro level as well as the potential chemical changes occurring along the interfaces
- Granite host rock (service area and heated zone)
  - Investigate the rock properties of both zones, in particular the performance of the granite and the interfaces granite/bentonite.
- Heater and liner
  - Analyze potential corrosion, changes of position of the heater and deformations of the liner

3.3.2.3 FEBEX-DP Activities and Timeline

The FEBEX-DP project officially started with a kick-off meeting held June 10, 2014, in Thun, Switzerland. The project will continue until the end of 2016, when a final synthesis report is expected on the project findings. The FEBEX-DP project includes the following activities (Gaus and Kober, 2014):

<u>Pre-dismantling modeling:</u>

Pre-test modeling was conducted by a few international modeling groups to evaluate the predictive capability of THM and THC models regarding the long-term behavior of the EBS components. The THM models were developed by the Technical University of Catalonia to analyze the potential impact of switching off the heaters on the stress, pore pressure and relative water content in the EBS and granite. Preliminary THC models have been developed by LBNL to provide a scope of the geochemical changes after the dismantling of Heater 2 (see Section 6.1.2).

<u>Field work related to the dismantling:</u>

A final dismantling plan was developed in January 2015. Figure 3-59 shows the configuration of the dismantling sections during the dismantling of Heater 2. In February 2015, drilling was conducted through the concrete plug and parts of the bentonite to get access to the heater test area, and in about two weeks of dismantling, the dismantling crew retrieved several overcores with intact shotcrete/bentonite interface (Figure 3-60). Then the concrete plug was demolished staring from April 8, 2015 until April 16, 2015. On April 24, 2015, the heater was switched off, after 6630 days of operation. The sampling on the first bentonite section (Section 36) started on May 11, 2015. Sampling of all other sections was finished on August 6, 2015. Figure 3-61 shows an example of several core samples drilled out of one dismantling section, in this case section 62. The samples are currently being distributed to partners of FEBEX-DP for THMC and biological characterization and further experimental study.

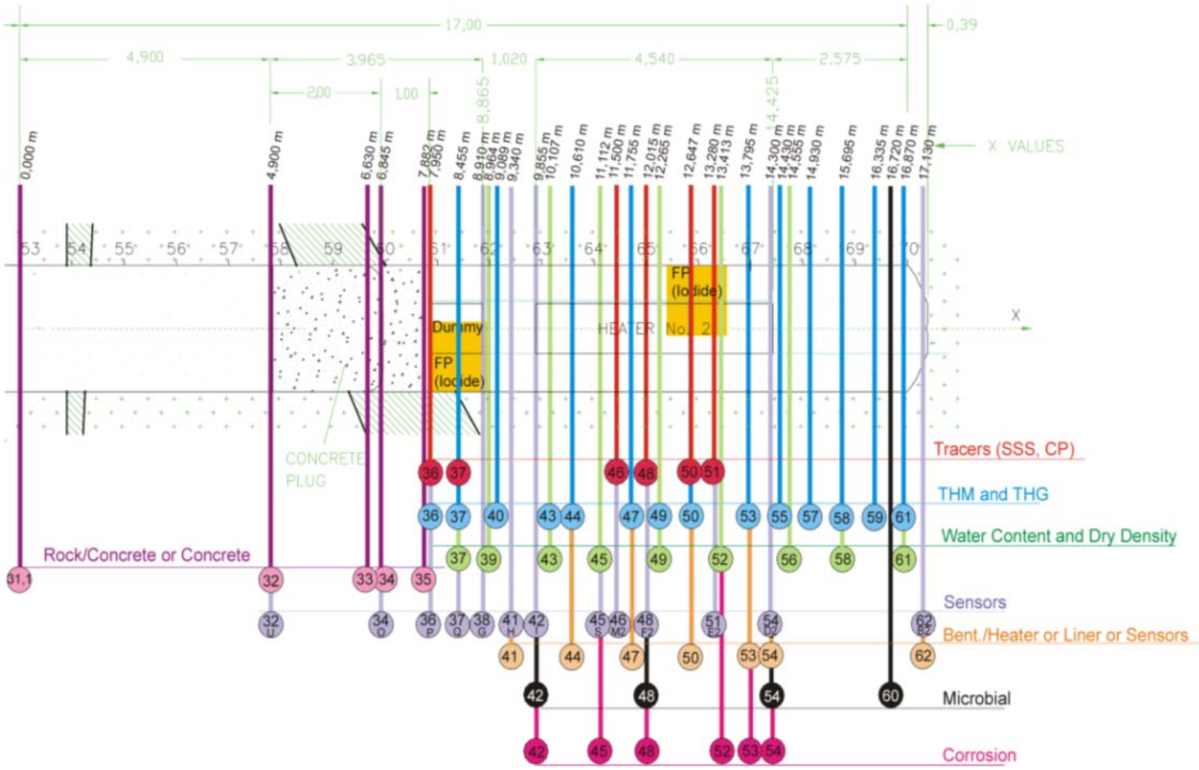

Figure 3-59. Sampling cross-sections (numbers in circles are cross-section numbers) for FEBEX-DP Project (from NAGRA, 2014)

Figure 3-60. An overcore that preserves the interface between shotcrete and bentonite

Figure 3-61. The front of dismantling section 62 with the core samples taken for microbiological studies, the blue bar prevents the partially detached bentonite from collapsing.

Data synthesis and post-dismantling modeling:

Starting in early FY16, results from laboratory analysis of various types of samples will be tested and compared against the predicted behavior of the EBS components, using coupled THM and THC models. UFD researchers have participated in the pre-dismantling modeling (see Section 6.1.2.1). Post-dismantling modeling, analytical work on samples and further laboratory experiments on FEBEX bentonite will be conducted by UFD in FY16 (see Section 6.1.2.2).

3.3.2.4 FEBEX-DP Summary

Benefits of Participation:

- Access to experimental samples and laboratory investigations from a **long-term heater experiment** with focus on engineered barrier components, more narrow focus than other initiatives (Note that FEBEX-DP membership does not provide access to other experiments at Grimsel)
- Opportunity to **participate directly in international research groups that analyze samples and conduct modeling work** on coupled THM and THC behavior (more direct involvement than DECOVALEX)
- Opportunity for **designing sampling plans** as well as **conducting own laboratory experiments**

Status of Participation:

DOE joined the FEBEX-DP Project as one of the initial partners. UFD researchers have participated in the test design and sampling plan development, and will continue working on the post-dismantling modeling and experimental studies (Section 6.1.2). In FY15, the dismantling operation of the FEBEX test bed was successfully finalized and has provided valuable core samples for further analysis, testing and modeling.

Outlook:

In FY15, LBNL researchers finished a preliminary THC model (Zheng et al., 2015) for pre-dismantling analyses. DOE/UFD is expected to receive samples at the beginning of FY16. Until the end of project in calendar year 2016, DOE/UFD researcher will develop coupled THMC model for post-dismantling interpretation and will conduct further laboratory experiments with FEBEX bentonite samples to study the pore structure of bentonite and chemical alteration under high temperatures.

Contact Information:

DOE Contact:
Prasad Nair, DOE-NE

UFD Contact:
Jens Birkholzer (LBNL)
Carlos Jove-Colon (SNL)
Liange Zheng (LBNL)

CFM Contact:
Irina Gaus and Florian Kober, NAGRA, Switzerland

3.3.3 Other Experiments at Grimsel Test Site, Switzerland

3.3.3.1 Ongoing Experiments

Besides the CFM and the FEBEX-DP Project, other collaboratively conducted experiment at the Grimsel Test Site (GTS) may also be of interest to DOE/UFD. Worth considering is perhaps the Gas-Permeable Seal Test (GAST) (Focus: EBS), which looks at bentonite-sand mixtures for increased gas transport capacity (to mitigate pressure buildup from gas generation) within the backfilled underground structures, without compromising the radionuclide retention capacity of the engineered barrier system (Figure 3-62). Other options include the Long-Term Cement Studies (LCS) project (Focus: EBS), which has the overall aim to increase understanding of the cement-leachate interaction effects in the repository near field and geosphere, the (2) the Long-Term Diffusion (LTD) project (Focus: NBS), which has the overall aim to provide quantitative information on matrix diffusion of radionuclides in fractured rock under *in situ* conditions over long time scales, and (3) the experiments on gas production and migration conducted within the European Union project FORGE (Fate of Repository Gases). The possibility of participation, and the conditions of being involved in these latter three projects, requires further clarification.

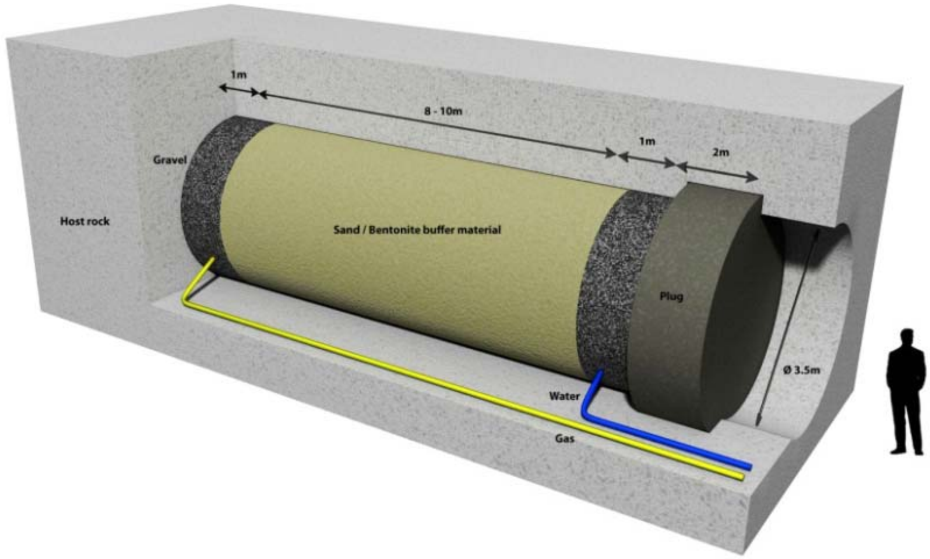

Figure 3-62. GAST Experiment at Grimsel Test Site: Schematic picture of repository seal design with 8–10 m long sand/bentonite plug in between two gravel packs and a concrete plug for reinforcement (from http://www.grimsel.com/gts-phase-vi/gast/gast-introduction)

3.3.3.2 High-Temperature Heater Test

On a final note, several international disposal programs have recently initiated investigating if clay-based barriers can withstand temperatures higher than the 100 °C threshold for bentonite performance usually assumed in advanced repository designs. For example, the UFD campaign is investigating the feasibility of direct geological disposal of large spent nuclear fuel canisters currently in dry storage (Hardin et al., 2014), which would benefit from much higher emplacement temperatures. The performance of bentonite barriers in the <100 °C temperature range is underpinned by a broad knowledge base built on laboratory and large-scale in-situ experiments. Bentonite parameter characterization above 100°C is sparser (especially for pelletized materials), although up to about 150 °C no significant changes in safety-relevant properties are indicated. At temperatures above 150 °C, it is possible that a potentially detrimental temperature-driven physico-chemical response of materials (cementation, illitization) may occur, the characteristics of which are highly dependent on, and coupled with, the complex moisture transport processes induced by strong thermal gradients. The impact of such complex processes on the performance of a repository cannot be realistically reproduced and properly (non-conservatively) assessed at the smaller laboratory scale. Such an assessment needs to be conducted by large in-situ experiments in underground research laboratories (URLs), where the most relevant features of future emplacement conditions can be adequately reproduced.

Potential options for a targeted high-temperature experiment (150 °C to 200 °C) in a fractured rock environment are currently being considered (Vomvoris et al., 2015). NAGRA has recently suggested that one possibility would be to use the well-characterized FEBEX drift at the Grimsel Test Site once the FEBEX-DP dismantling is finalized (Figure 3-63). Design characteristics for such an experiment still need to be developed, for example type of bentonite, target temperature, duration and additional processes to be investigated. The benefit of such a large-scale test, accompanied by a systematic laboratory program and modeling effort, is that the temperature effects can be evaluated under realistic conditions of strong thermal, hydraulic and density gradients, which cannot be reproduced in the laboratory. This will lead to improved mechanistic models for the prediction of temperature-induced processes, including chemical alteration and mechanical changes, which can then be used for performance assessment (PA) analysis of high-temperature scenarios. The key question is whether higher repository temperatures would trigger mechanisms that compromise the various barrier functions assigned to the engineered components and host rock. If the barrier function is (partially) compromised, PA analysis can evaluate whether reduced performance of a sub-barrier (or parts thereof) would still give adequate performance. Discussions are ongoing within the international community regarding the feasibility and specifications of a "hot" FEBEX test.

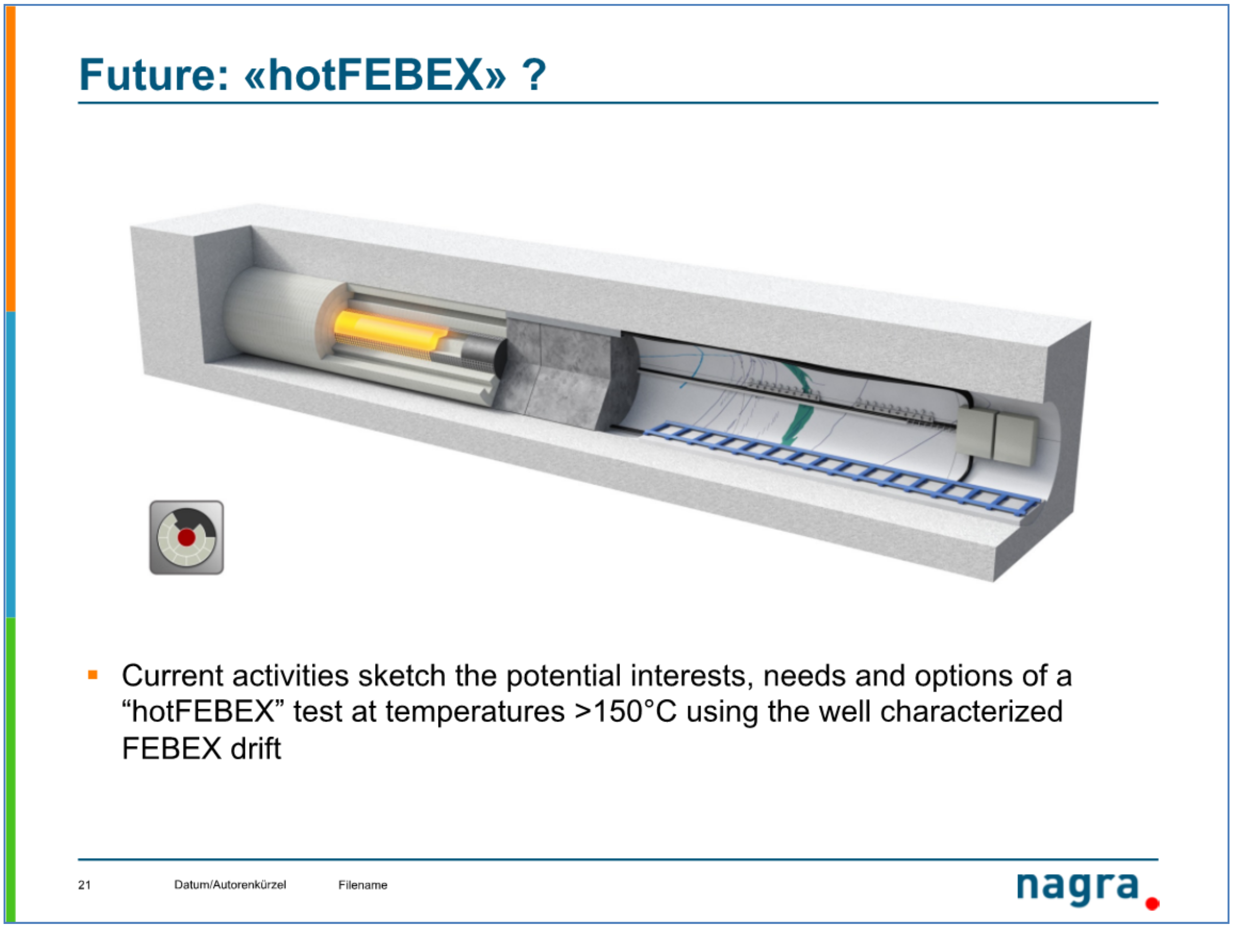

Figure 3-63. Conceptual design of a potential high-temperature heater test to be conducted at Grimsel Test Site, in the well-characterized FEBEX drift (Vomvoris et al., 2015)

3.4 SKB Task Forces

3.4.1 Introduction to SKB Task Forces

SKB, the Swedish Nuclear Fuel and Waste Management Company, has been organizing task forces as a forum for international organizations to interact in the area of conceptual and numerical modeling of performance-relevant processes in natural and engineered systems. There are two task forces: the Groundwater Flow and Transport (GWFTS) Task Force initiated in 1992, and the Engineered Barrier Systems (EBS) Task Force initiated in 2004. The GWFTS Task Force is led by Björn Gylling of SKB. The EBS Task Force has two parts, one for THM processes (led by Antonio Gens from UPC in Spain), the other for THC processes (led by Urs Maeder of University of Bern). Different modeling tasks are being addressed collaboratively, often involving experiments carried out at SKB's Äspö Hard Rock Laboratory (HRL) situated in crystalline rock near Oskarshamn in Sweden. The Äspö HRL consists of a main tunnel that descends in two spiral turns to a depth of 460 m, where various tests have been and are being performed in several side galleries and niches (Figure 3-64).

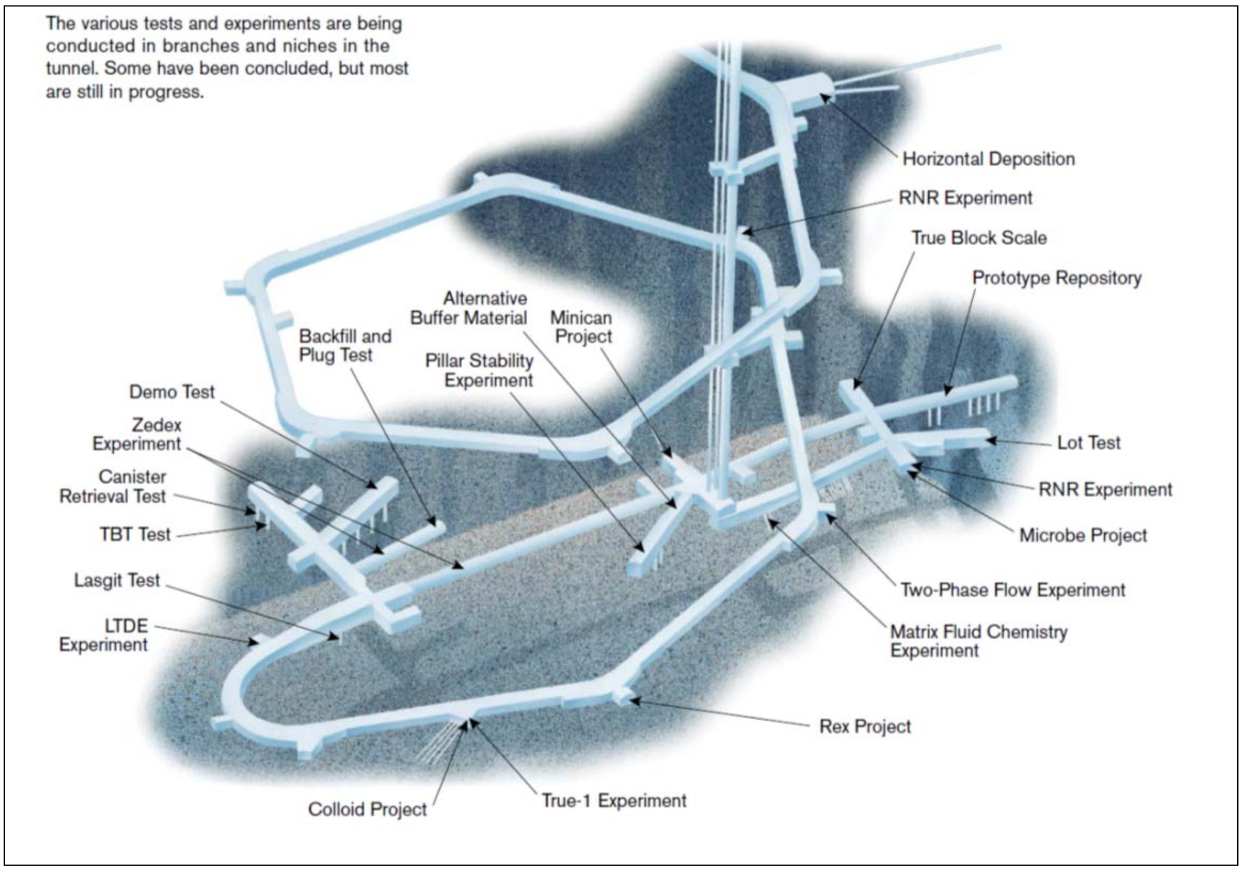

Figure 3-64. Layout of Äspö HRL and location of main experiments (from Birkholzer, 2012)

Like the other collaborative initiatives introduced earlier in this report, participation in SKB in the Task Forces requires a formal membership agreement. Each participating organization is represented by a delegate; the modeling work is performed by modeling groups associated with these organizations (not unlike the DECOVALEX framework). The task forces meet regularly about once to twice a year. Task force members interact closely with the principal investigators responsible for carrying out experiments at Äspö HRL. Much emphasis is put on building of confidence in the approaches and methods in use for modeling of groundwater flow and migration, as well as coupled THM and THC process, in order to demonstrate their use for performance and safety assessments.

In the past years, DOE/UFD's liaison for international collaboration frequently interacted with SKB representatives to evaluate the condition and benefits of joining one or both task forces. UFD representatives participated in the GWFTS Task Force meeting in April 24-25, 2012, in Oskarshamn in Sweden and also participated in a joint meeting of the GWFTS and EBS Task Forces held in Lund, Sweden, November 27-29, 2012. DOE eventually joined both task forces in January 2014 and hosted a joint task force meeting in Berkeley in December 2014. Other participating organizations in the GWFTS and/or EBS Task Forces are SKB, POSIVA, KAERI, CRIEPI, JAEA, NAGRA, BMWi/KIT, RWM, NWMO, and SURAO.

In the past, UFD researchers have been actively engaged in the GWFTS task force and have conducted simulation work supporting the interpretation of the BRIE experiment (see Section 6.1.4). Currently, DOE/UFD is going through a planning and selection process regarding future work with SKB as both task forces are in a transition stage with several long-running modeling tasks winding down and new task proposals being developed and discussed.

3.4.2 GWFTS Task Force

The main objective of the GWFTS Task Force is to develop and apply appropriate methods for investigating flow and transport in fractured crystalline rock, in particular to obtain better understanding of the retention of radionuclides transport in crystalline rock, and to improve the credibility of simulation models. The task force also provides a platform for interaction in the area of conceptual and numerical modeling of groundwater flow and solute transport in fractured rock.

The main modeling task currently conducted in the GWFTS task force is Task 8: Modeling of the Bentonite Rock Interaction Experiment (BRIE) at Äspö HRL. The BRIE experiment is a joint task shared between the GWFTS and the EBS Task Forces. The main objective of the BRIE experiment is to enhance the understanding of the hydraulic interaction between the fractured crystalline rock at Äspö HRL and the unsaturated bentonite used as backfill. The experiment is subdivided into two parts: the first part involving the selection and characterization of a test site and two central boreholes, the second part handling the installation, monitoring, and later overcoring of the bentonite-rock interface. Modeling groups seek (a) to gain a better understanding of water exchange at the bentonite-rock interface, and (b) to obtain better predictions of bentonite wetting in a fractured rock mass. Task 8 has been ongoing for several years now and is expected to wind down in 2016 or 2017. A new task is currently under consideration in the GWFTS Task Force, which would involve modeling of diffusion/sorption experiments such as the Long Term Diffusion Experiment at Äspö HRL or the REPRO (Rock Matrix Retention Properties) Experiment at Onkalo URL in Finland. More details on Tasks 8 and 9 are given below.

3.4.2.1 Task 8: Bentonite Rock Interaction Experiment (BRIE)

The main objective of the ongoing BRIE experiment is to enhance the understanding of the hydraulic interaction between the fractured crystalline rock at Äspö HRL and the initially unsaturated bentonite used as backfill (SKB, 2011b). The setup is aligned with the Swedish concept of emplacing canisters into vertical deposition holes that are subsequently backfilled (Figures 3-65 and 3-66). The experiment is subdivided into two main parts: the first part describing the selection and characterization of a test site and two central boreholes, the second part handling the installation and extraction of the bentonite buffer. Initial characterization resulted in a deterministic description of the fracture network at a small scale (10 m). This includes all identified fractures and the water-bearing part of the fractures. BRIE has its focus on the common boundary between the bentonite clay and the water-bearing fractures in the near-field host rock, and as mentioned above, is a modeling task jointly undertaken by the Task Force on Groundwater Flow and Transport and the Task Force on Engineered Barrier Systems. UFD researchers from Los Alamos National Laboratories have been participating in the modeling analysis of the BRIE experiment (see Section 6.1.4).

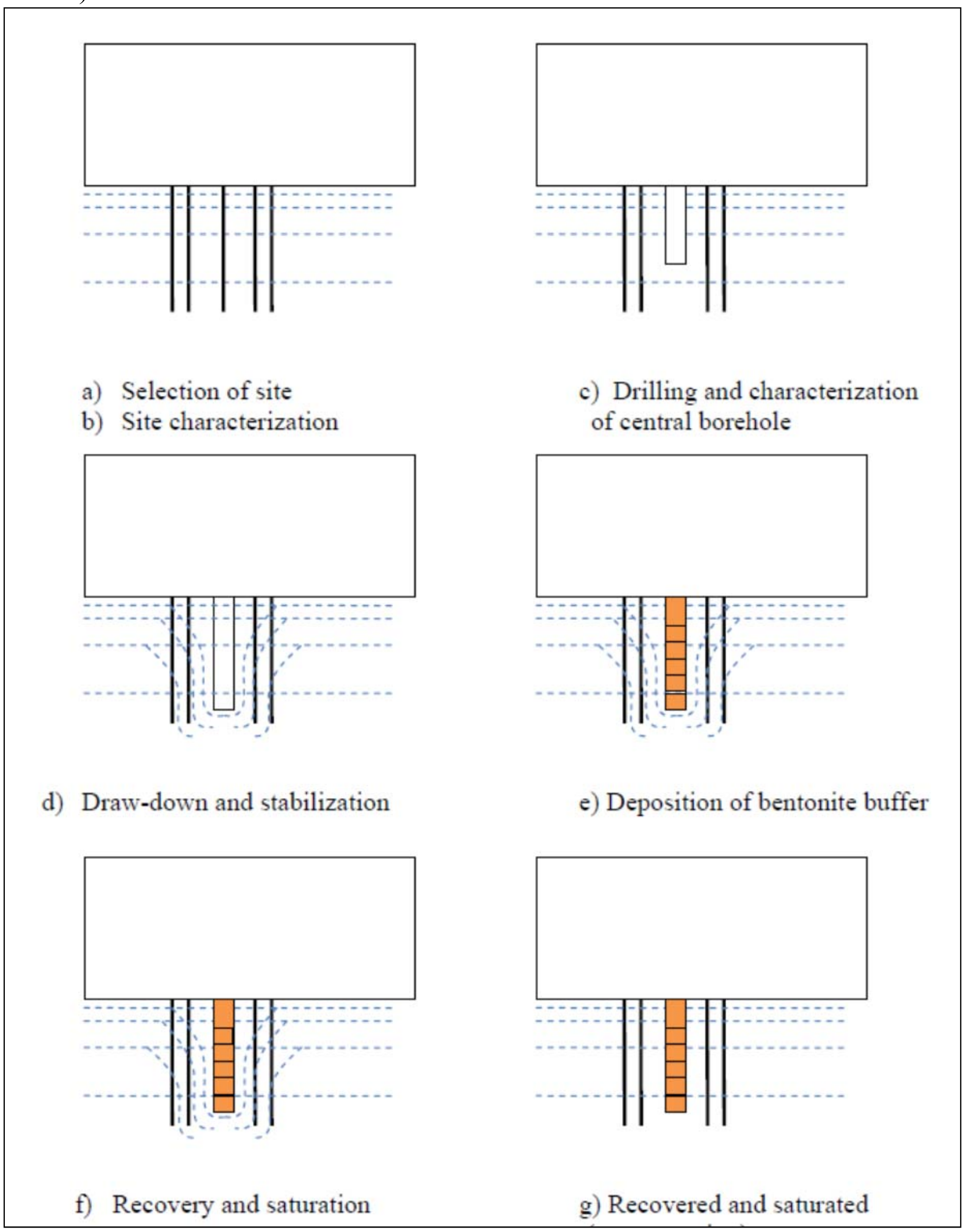

Figure 3-65. Schematic presentation of the stages of the BRIE Experiment at Äspö HRL (from Bockgård et al., 2012)

Figure 3-66. BRIE Experiment at Äspö HRL: The test niche and five boreholes (distance 1.5 m) used for initial characterization and selection of BRIE site (from SKB, 2011b)

3.4.2.2 Task 9: Modeling Two Diffusion and Sorption Experiments in Crystalline Rock

This proposed task focuses on the modeling of coupled matrix diffusion and sorption in heterogeneous crystalline rock matrix at depth. This is done in the context of inverse and predictive modeling of tracer concentrations measured in two *in-situ* experiments performed within LTDE-SD at the Äspö HRL in Sweden as well as within the REPRO project at Onkalo URL in Finland (see Section 4.6), focusing on sorption and diffusion. The ultimate aim is to develop models that in a more realistic way represent retardation in the natural rock matrix at depth. Researchers from DOE/UFD are likely to participate in Task 9 starting FY16.

LTDE-SD, the Long-Term Diffusion Sorption Experiment was completed in 2010. The experiment was designed to examine diffusion and sorption processes in both matrix rock and a typical conductive fracture identified in a pilot borehole. A telescoped large-diameter borehole was drilled subparallel to the pilot borehole, in such a way that it intercepts the identified fracture some 10 m from the tunnel wall, and with an approximate separation of 0.3 m between the circumferences of the two boreholes (Figure 3-67). A cocktail of nonsorbing and sorbing tracers was circulated between the boreholes in packed-off sections for a period of 6 ½ months, after which the borehole was overcored and the extracted rock analyzed for tracer penetration and fixation. The specific objectives of LTDE-SD were to:

- Obtain data on sorption properties and processes of individual radionuclides, and their effect on natural fracture surfaces and internal surfaces in the rock matrix.
- Investigate the magnitude and extent of diffusion into matrix rock from a natural fracture *in situ* under natural rock stress conditions and hydraulic pressure and groundwater chemical conditions.
- Compare laboratory-derived diffusion constants and sorption coefficients for the investigated rock fracture system with the sorption behavior observed *in situ* under natural conditions, and to evaluate whether laboratory-scale sorption results are representative also for larger scales.