International Collaboration Activities in Different Geologic Disposal Environments

Fuel Cycle Research & Development

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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 UFD 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 started 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 granites 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 demonstrated? Is the planned construction/emplacement method feasible?

International Cooperative Initiatives

As of September 2014, 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, 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. The current project phase involves test cases from four international 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. Current modeling cases with UFD involvement include an engineered-barrier heater test and the use of environmental tracers for estimating fracture properties.

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 are currently 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 (currently 9 partners). This collaborative project 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. UFD researchers help interpret colloid-transport-data measurements with semi-analytical and numerical methods.

FEBEX Dismantling Project

The 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 will end in Spring 2015, followed by a new project aimed at dismantling the test site. The FEBEX Dismantling Project (FEBEX-DP), which was kicked off with a planning phase in June 2014, provides a unique opportunity for removing and sampling an engineered barrier and its components that underwent continuous heating and natural resaturation for 18 years. DOE joined the FEBEX-DP Project as one of the initial partners. UFD researchers currently participate in the test design and sampling plan development.

SKB Task Forces

SKB's 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).

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 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 WIPP and Gorleben. 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 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. Ongoing experiments at Bure are mainly aiming at developing industrial solutions for construction and operation. Currently, UFD scientists are not engaged 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 URL in Belgium, Onkalo URL in Finland), and both countries are open to collaboration with UFD scientists.
- DOE is a member in OECD/NEA collaborative initiatives, such as the NEA Thermochemical Database Project and the NEA Salt Club. Participation in NEA's Clay Club is 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 selected activities have made significant advances over the past two years. The joint R&D with international researchers and the access to relevant data/experiments from a variety of URLs and host rocks helped UFD researchers to significantly improve their understanding of the current technical basis for disposal in a range of potential host rock environments. Comparison with experimental data contributed to testing and validating predictive computational models for evaluation of disposal system performance in a variety of generic disposal system concepts. Promising opportunities exist for further expansion of the international program.

In the near future, UFD will re-assess its international research portfolio, as research priorities and boundary conditions change and as new opportunities for collaboration develop. UFD will also evaluate whether its international collaboration focus should move from a mostly participatory role in ongoing *in situ* experiments conducted by other nations, to a more active role in developing its own experimental program in international URLs. Some collaborative initiatives like the Mont Terri Project provide their partner organizations with the opportunity of conducting their own experimental work and inviting other partners to join. This option would allow the U.S. disposal program to perform *in situ* field work in representative host rocks (clay, crystalline), even though there are currently no operating underground research laboratories in the U.S.

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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	Bundesministerium für Wirtschaft und Arbeit, Germany
BRIE	Bentonite Rock Interaction Experiment, Äspö HRL, Sweden
CAS	Chinese Academy of Sciences, China
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
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
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
LTD	Long-Term Diffusion, Grimsel Test Site, Switzerland
LTDE-SD	Long-Term Diffusion Sorption Experiment, Äspö HRL, Sweden
MoU	Memorandum of Understanding
MWCF	Major Water Conducting Feature
NAGRA	National Cooperative for the Disposal of Radioactive Waste, Switzerland
NBS	Natural Barrier System
NDA	Nuclear Decommissioning Authority, UK
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
OECD	Organization for Economic Co-operation and Development
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
R&D	Research and Development
RAWRA	Radioactive Waste Repository Authority, Czech Republic (also referred to as SURAO)
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

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
swisstopo	Federal Office of Topography, Switzerland
TC	Test Case
TDB	Thermochemical Database
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
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 now 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 started 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/modeling), and/or allow participation in ongoing and planned field experiments. The report is an update to an earlier 2012 summary of UFD's international activities (*Status of UFD Campaign International Activities in Disposal Research, FCRD-UFD-2012-000295, September 2012* [Birkholzer, 2012]).

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 Energy), 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 *Used Fuel Disposition Campaign Campaign Implementation Plan (FCRD-UFD-2014-000047, March 2014* [Bragg-Sitton et al., 2014]). For example, the Campaign Implementation Plan calls for 5 yr 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 has been 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. During the past few years, UFD's liaison for international collaboration in disposal research has identified and examined several such multinational opportunities and has made recommendations to DOE/UFD leadership as to which initiatives would be most beneficial. As mentioned above, DOE has acted on these recommendations and has now 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. Plans for a revisit of this selection in another round of brainstorming exercises are also discussed. The current status of ongoing R&D activities is described in Sections 6 and 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, the FEBEX Dismantling Project, and the SKB Task Forces. 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 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 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 to 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 U.S. R&D 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.

Table 3-1. Participation of International Programs in Cooperative Initiatives Related to URLs: Status September 2014

Nuclear Nation	Organizations	DECOVALEX	Mont Terri	CFM	FEBEX-DP	SKB Task Forces
Belgium	SCK/CEN		x			
Canada	NWMO		x			x
Czech Republic	RAWRA	x			TBD	x
China	CAS	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	NDA	x		x	TBD	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 Overview of Modeling Tasks for DECOVALEX-2015

Three main modeling tasks were defined for DECOVALEX-2015, all of which involve 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 stage 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 EBS 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 NBS work package of UFD. Details on Tasks A, B1, B2, C1, and C2 are given in Sections 3.1.3 through 3.1.7 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
NDA	Nuclear Decommissioning Authority	Great Britain
NRC	Nuclear Regulatory Commission	United States
RAWRA	Radioactive Waste Repository Authority	Czech Republic

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

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

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	NDA	RAWRA
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	RAWRA

3.1.3 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 influence of relevant parameters with respect to 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

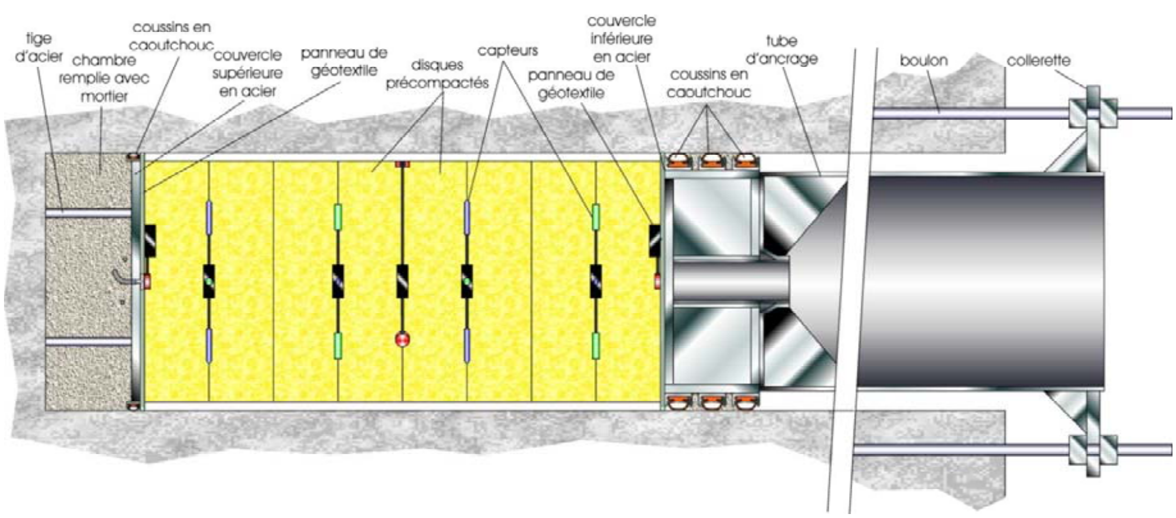

Figure 3-1. SEALEX Experiment at the Tournemire URL: Schematic setup of mini-tunnel with seal core and instrumentation (from Barnichon and Millard, 2012)

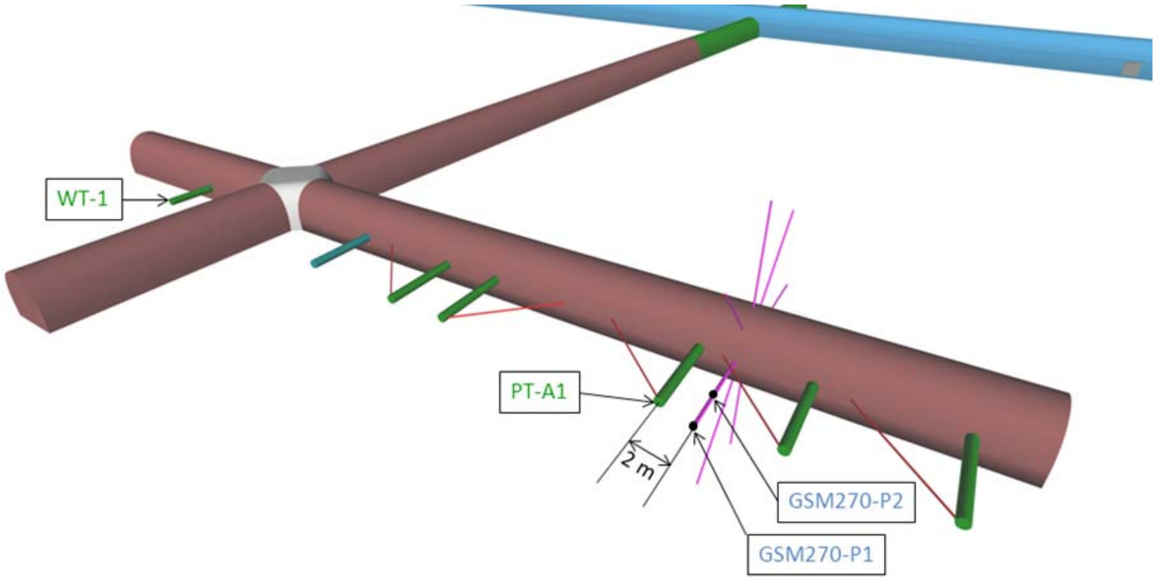

Figure 3-2. SEALEX Experiment at the Tournemire URL: Layout of mini-tunnels, access tunnels, and main gallery (from Millard and Barnichon, 2014)

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	PT-N1	Monolithic disks Precompacted (70/30)		No	12/2010 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	PT-N3	Pellets/powder In situ compacted (100/0)		No	12/2012 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)

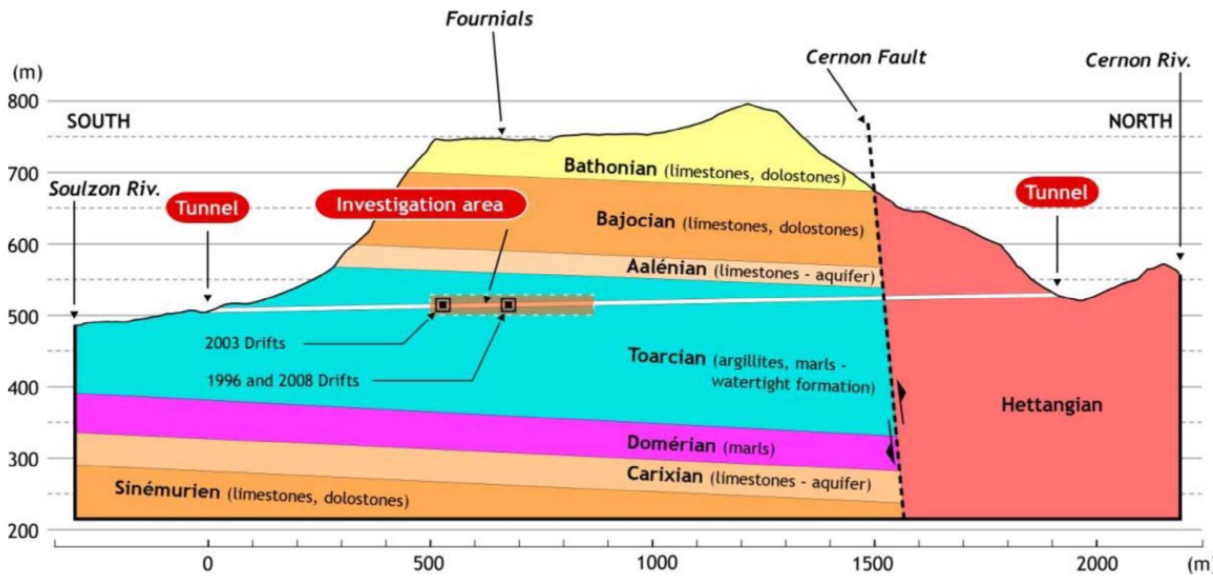

Figure 3-5. Geologic cross section of the Tournemire URL (from Barnichon, 2011)

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, 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 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 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.

3.1.4 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 4 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 involves 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).

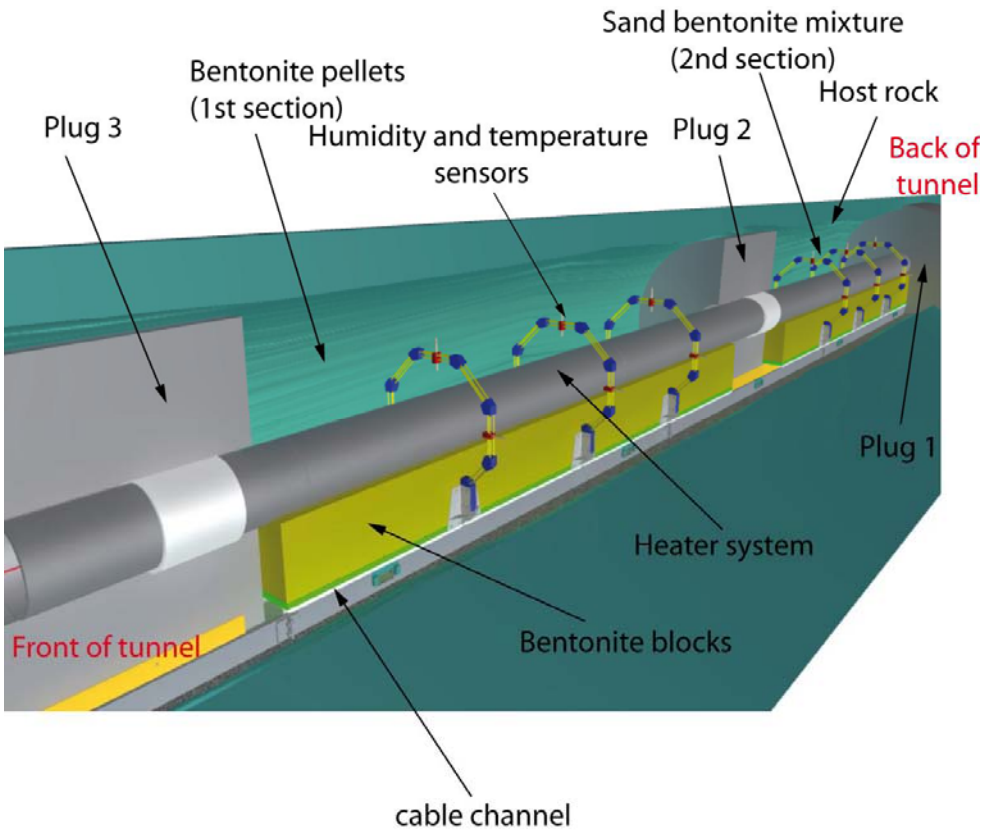

Figure 3-6. Schematic setup of HE-E Heater Test at Mont Terri URL (from Garitte et al., 2011)

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

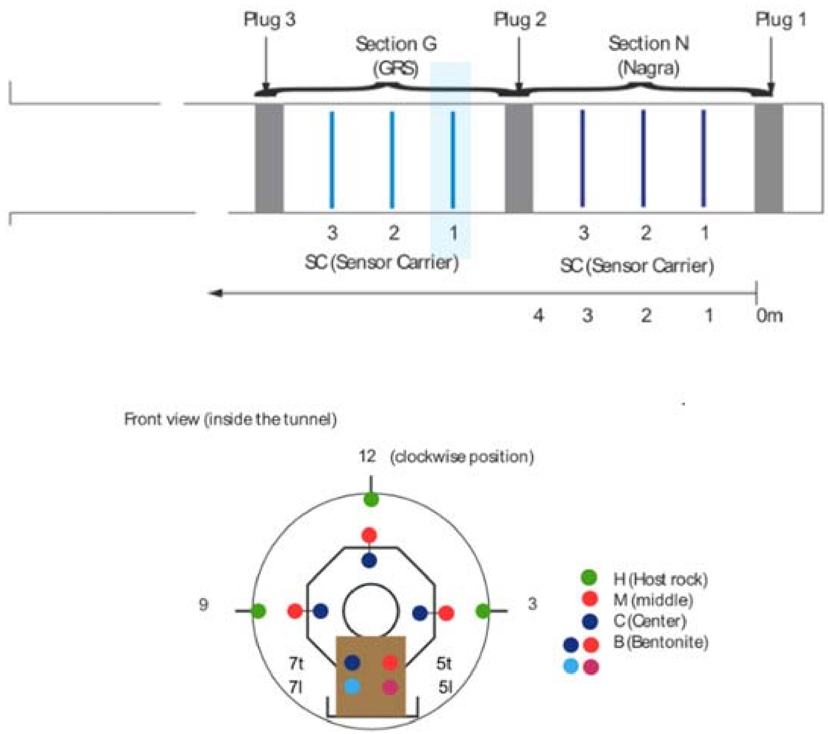

Figure 3-8. HE-E Heater Test at Mont Terri URL: Typical sensor placement (from Gaus et al., 2014)

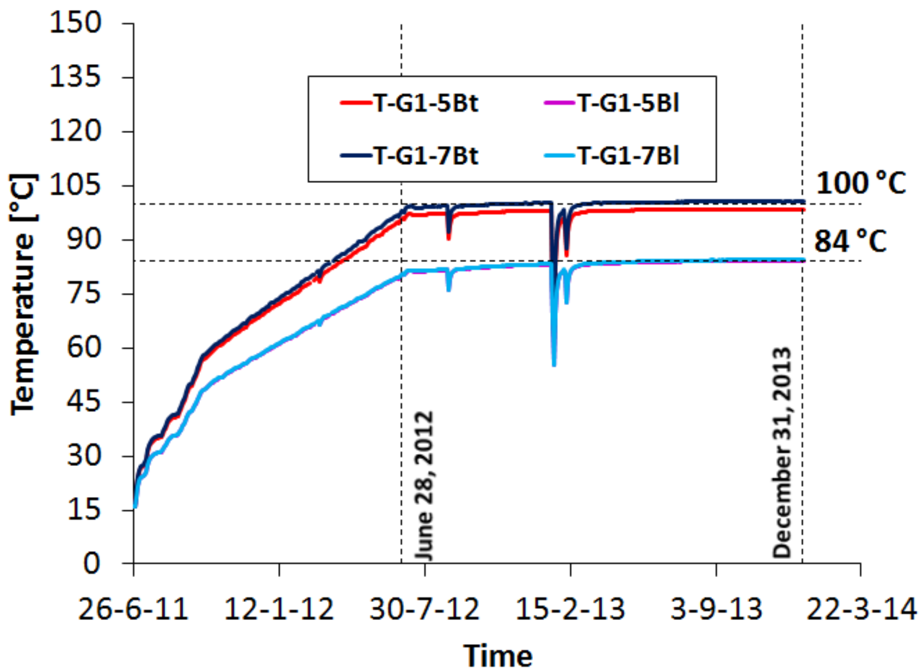

Figure 3-9. HE-E Heater Test at Mont Terri URL: Measured temperature inside compacted bentonite blocks near heater surface (from Gaus et al., 2014)

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, which tests the THM behavior of bentonite barriers *and* the THM interaction with Opalinus Clay:

- 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 data are made available.

Step 1a started in 2012 with the modeling of an earlier heater test conducted at the Mont Terri URL. This heater test, referred to as the HE-D experiment, involved 1 year of heating of Opalinus Clay without bentonite buffer. Step 1b, which is a study of bentonite buffer material properties through modeling of long-term laboratory experiments, has just been completed by all modeling teams. Steps 2 and 3 are currently under way. UFD researchers from Lawrence Berkeley National Laboratory are participating as DOE's modeling team in this task (see Section 6.1.1.1).

3.1.5 Task B2: EBS Experiment at Horonobe URL, Japan

The EBS Experiment at Horonobe URL will investigate 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. Comparison between model results and *in situ* measurements will allow for model validation when experimental data become available towards the end of the ongoing DECOVALEX-2015 project. 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, with a planned heating start in November 2014, makes it possible for modeling teams associated with Task B to start with the HE-E Heater Test (Task B1) before focusing on the EBS Experiment (Task B2). Also, a blind prediction and validation approach can be adopted—so that the predicted THMC behavior of the EBS system can be compared in real time with measured data, thereby providing support and suggestions for improved design and execution of data acquisition and analysis.

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 are being 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.

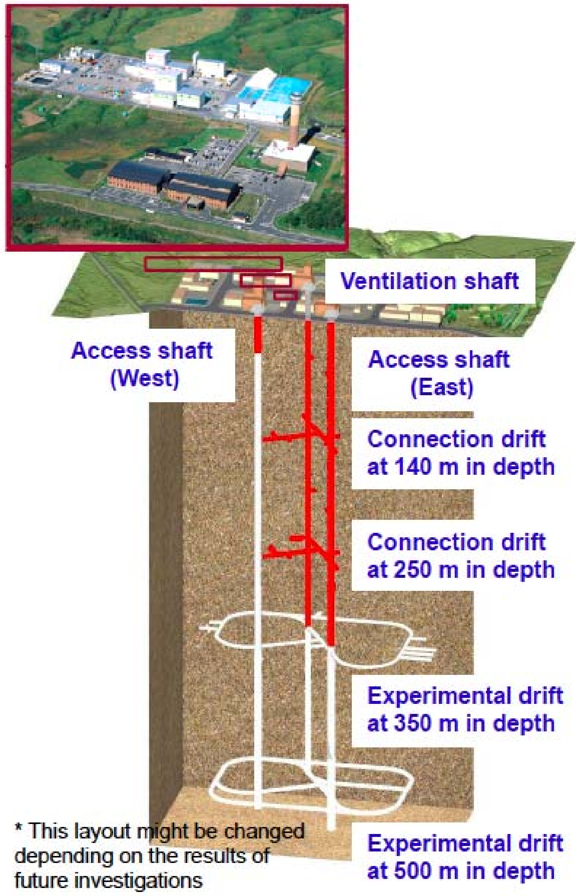

Figure 3-10. Design of Horonobe URL (from Sugita and Nakama, 2012)

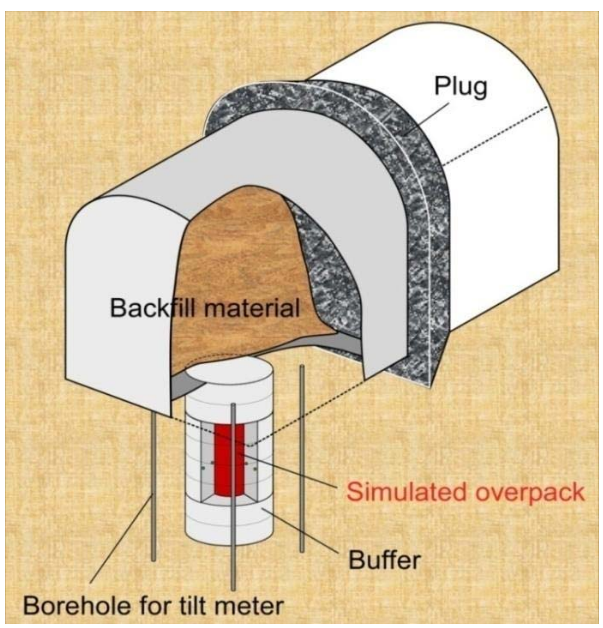

Figure 3-11. Planned design of EBS Experiment at Horonobe URL (from Sugita and Nakama, 2012)

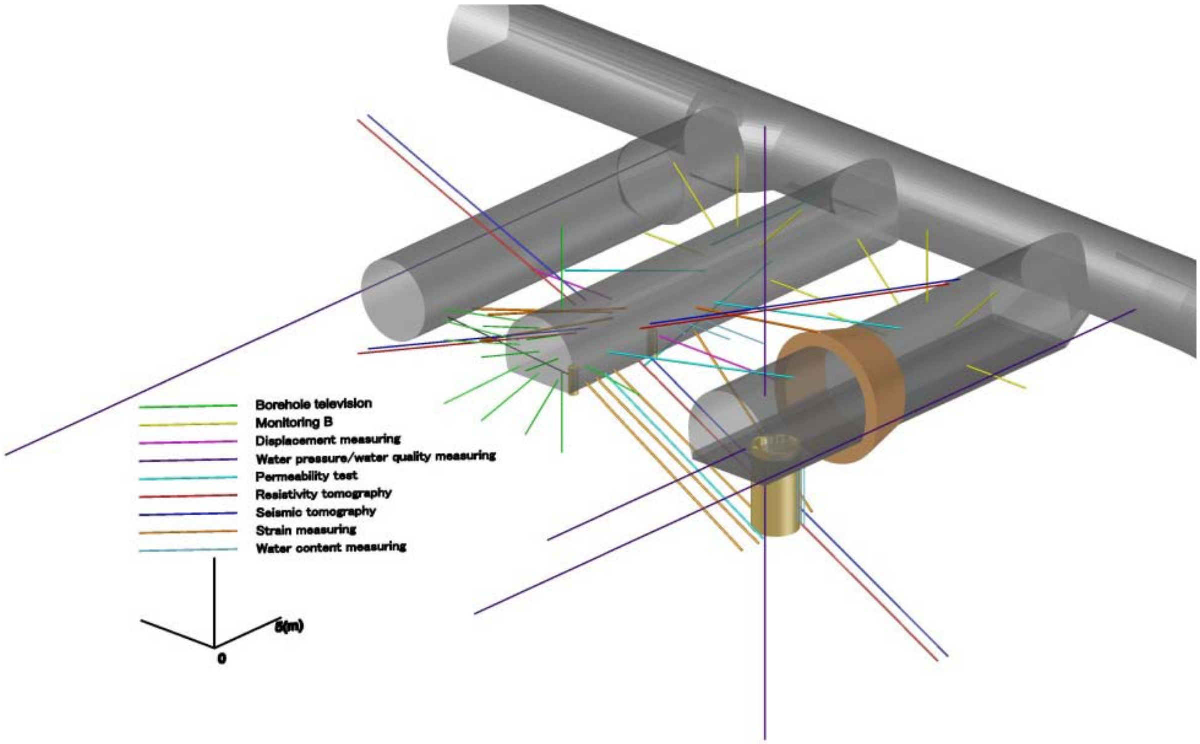

Figure 3-12. EBS Experiment: design of monitoring boreholes for sensor installation (from DECOVALEX web site, www.decovalex.org)

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

- Step 1: 1D benchmark test with comparison of 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 defined with exact properties and boundary conditions given by the JAEA. This modeling exercise was conducted for the teams to familiarize themselves with the problem and for precise comparison of computer codes before going into the more complex full-scale case. In Step 2, modeling teams were asked to construct a model of the real experimental design and 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. In April 2015, after six months of heating, JAEA will provide an initial set monitoring data to the research teams. The research teams will calibrate their models against the first 6 months of field data and then carry out coupled numerical analysis for long-term predictions (100–1,000 years) using the test conditions of the EBS experiment. UFD researchers from Lawrence Berkeley National Laboratory are participating as DOE's modeling team in this task (see Section 6.1.1.2).

3.1.6 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 transmissivities 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 at which the fracture faces are in contact. 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 affects 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 is 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 move to the geochemically more complex granite experiments.

- 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 are not currently involved in Task C1.

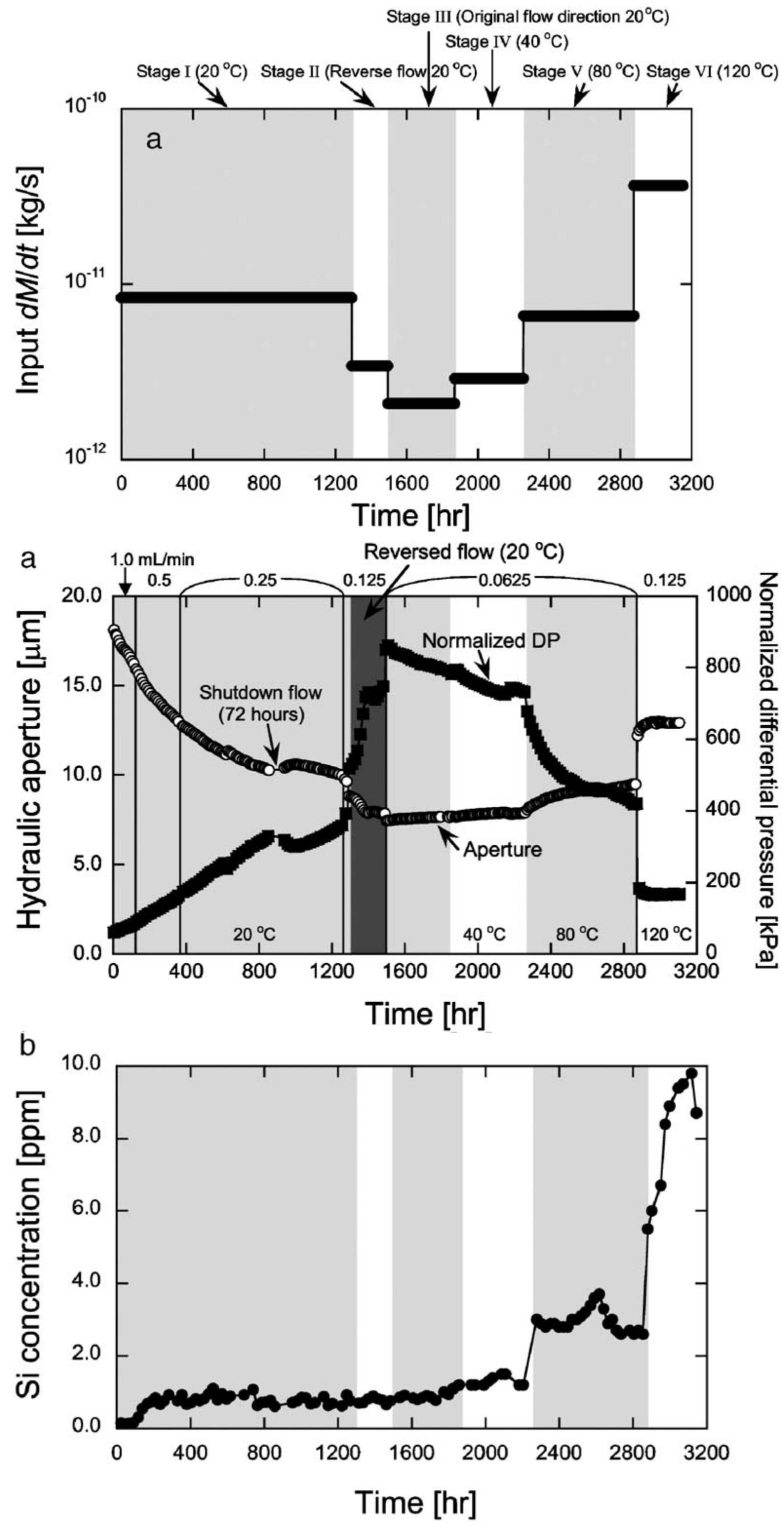

Figure 3-13. THMC behavior effects in a single fracture exposed to different external temperatures and varying stress conditions (from Yasuhara et al., 2006)

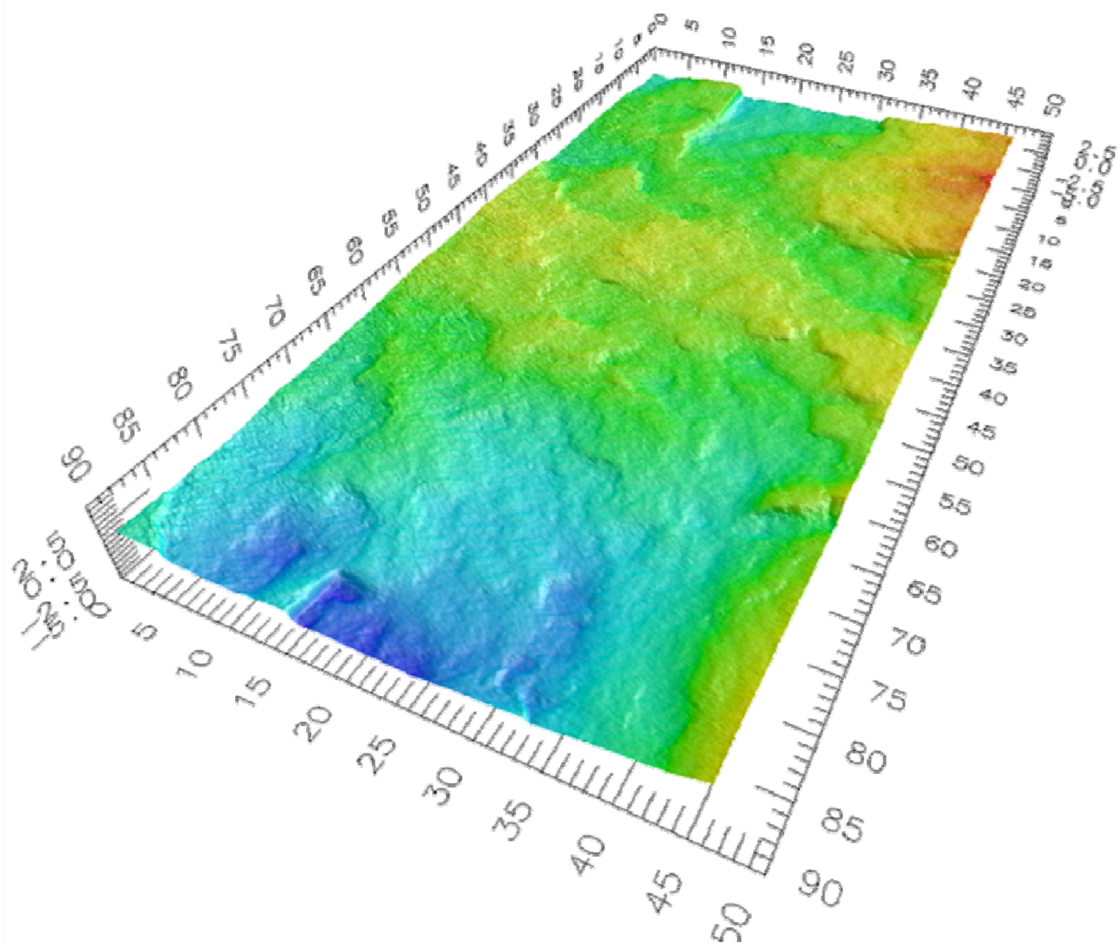

Figure 3-14. Fracture surface topography for the novaculite experiment (dimensions in mm) (from DECOVALEX web site, www.decovalex.org)

3.1.7 Task C2: Bedrichov Tunnel Experiment, Czech Republic

The Bedrichov tunnel is an existing tunnel of 2,600 m length located in the Northern Czech Republic. The tunnel hosts a water pipe, but was recently made available for geologic studies. RAWRA (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 built 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 other 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 check 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 fictitious 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).

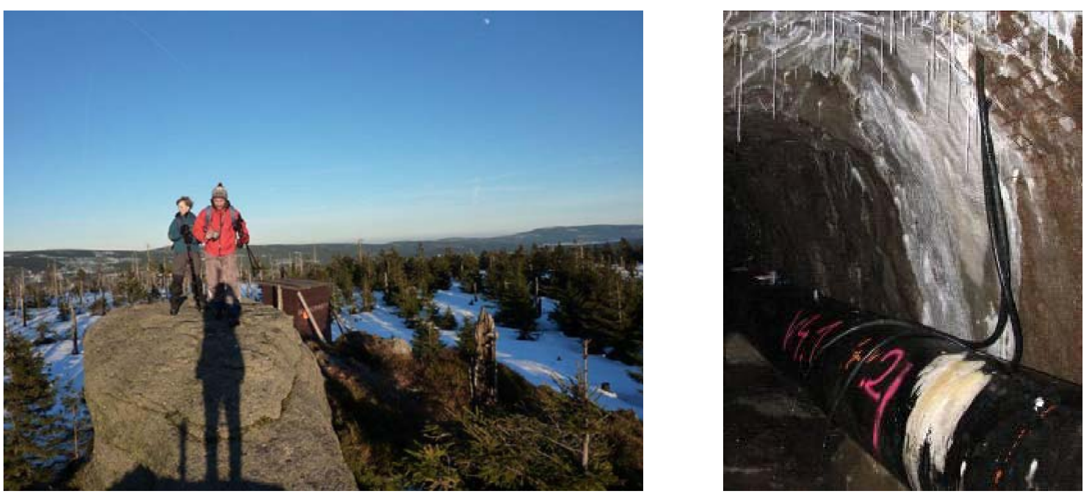

Figure 3-15. Bohemian granitic massif in Czech Republic and water inflow evidence in the Bedrichov Tunnel (from Hokr and Slovak, 2011)

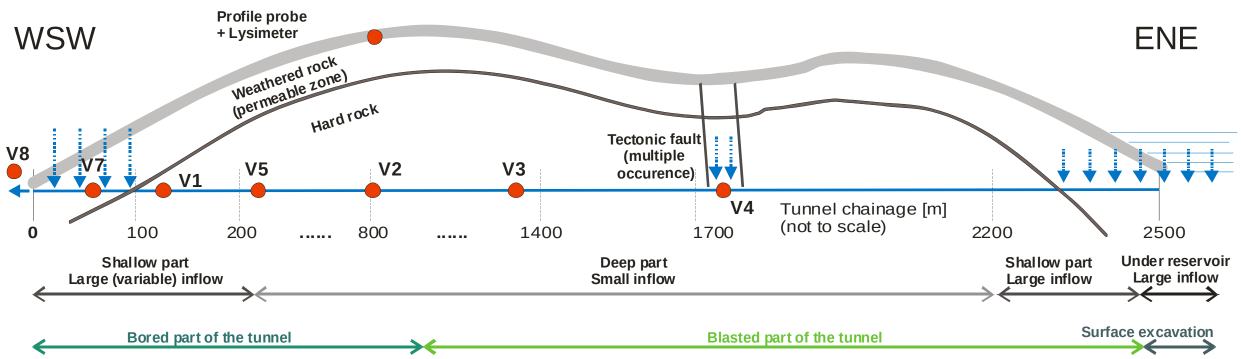

Figure 3-16. Profile of the tunnel with basic hydrogeological features and some measurement points (from DECOVALEX web site, www.decovalex.org)

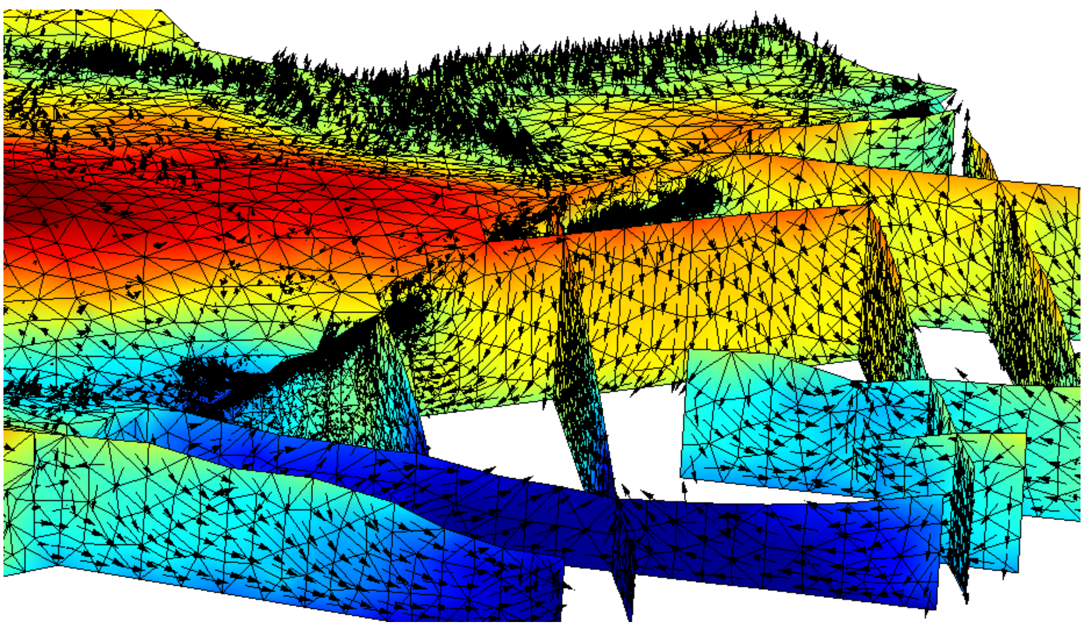

Figure 3-17. Example of numerical model of flow at the site, with combined 3D and 2D domains (from Hokr et al., 2014)

3.1.8 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 end of 2015. Researchers affiliated with UFD are 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. Dr. Jens Birkholzer of LBNL will be the new chairman of the DECOVALEX project with the start of the new phase.

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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, utilizes an 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, the Gallery 98 and 5 lateral niches, excavated in 1997/98, a gallery for the EZ-A experiment, excavated in 2003, the Gallery 04 and 4 lateral niches, excavated in 2004, and lastly, the Gallery 08 and side galleries for the Mine-by Test and FE Heater Test, excavated in 2008 (Figure 3-18).

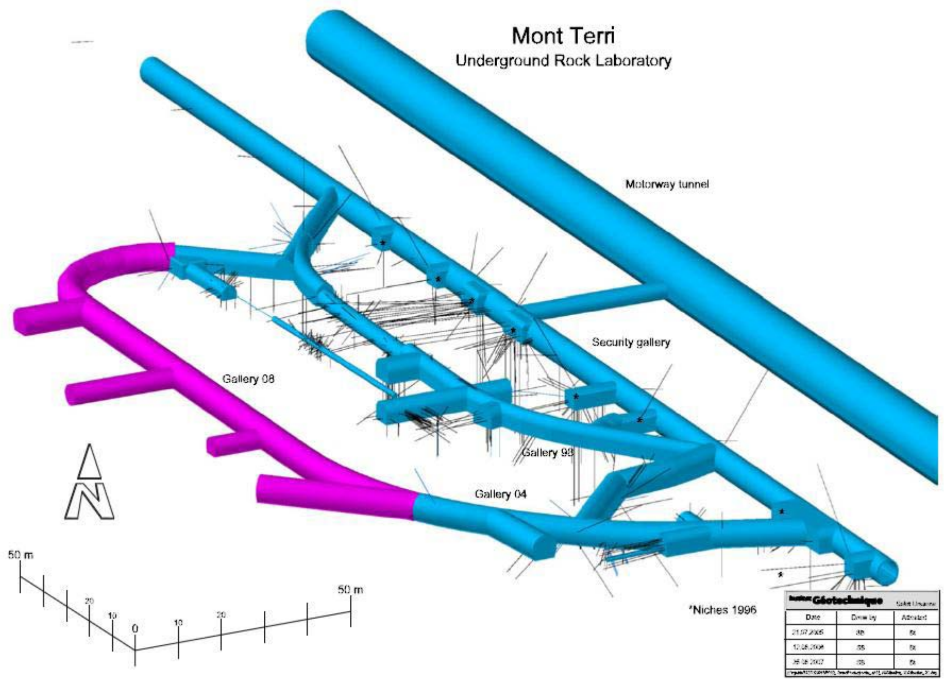

Figure 3-18. 3D schematic of the Mont Terri URL with side galleries and drifts. Pink area shows acess gallery drilled for Mine-by Test and FE Heater Test. (from Bossart, 2012)

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 Teri 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 3-19 and 3-20 show an overview of experiments currently conducted at the Mont Terri URL. The timeline in Figure 3-16 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 post-closure of repository: pore-pressure evolution, self-sealing, and long-term deformations, (4) Experiments related to chemical dissolution, precipitation, and microbial processes, (5) Experiments related to liner alteration, iron corrosion, iron-bentonite interaction, and gas production, and (6) Experiments related to radionuclide transport. In terms of the experimental objective, one may distinguish between 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.

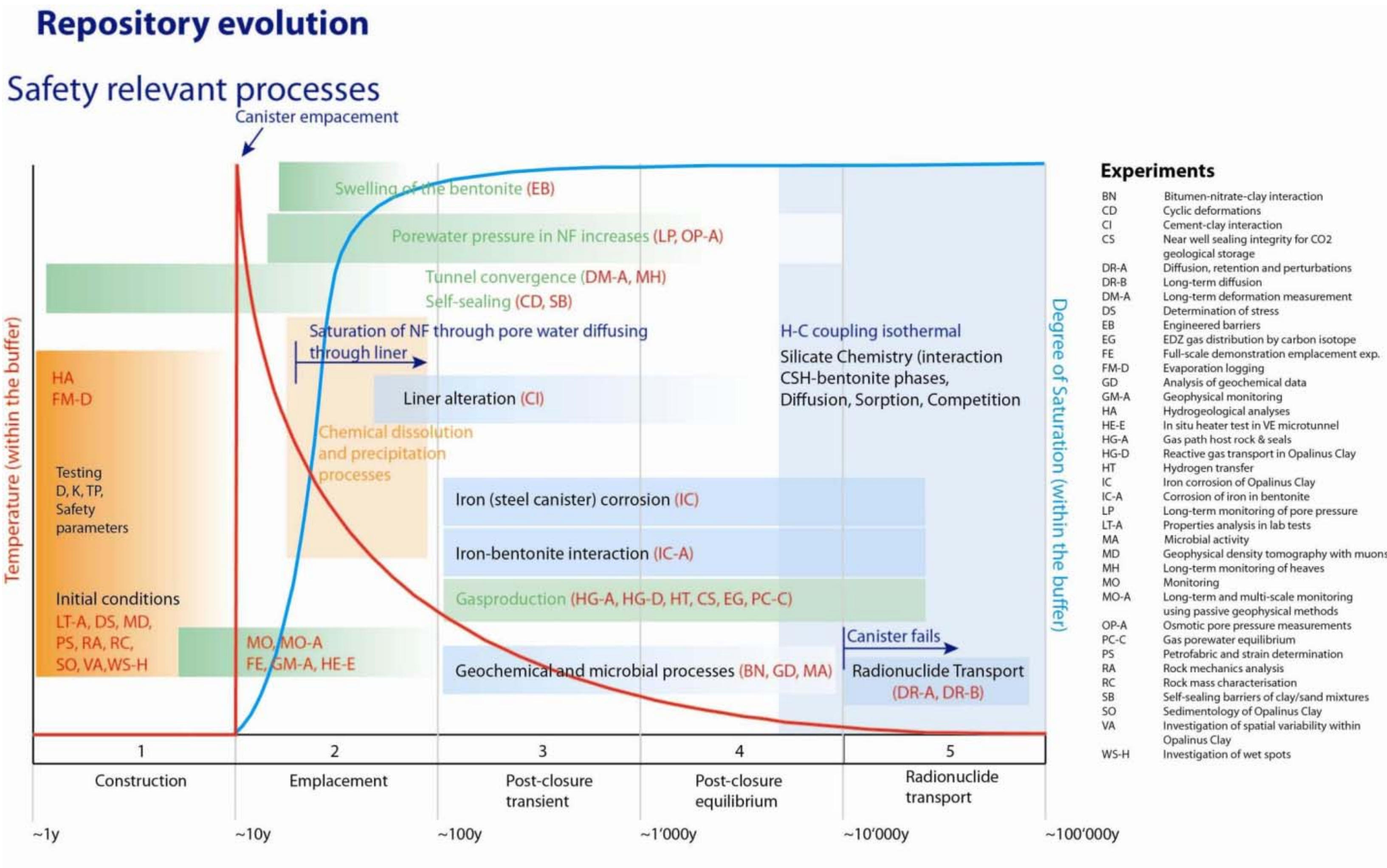

Figure 3-19. List of main Mont Terri URL experiments conducted during Phase 17 (July 2011 through June 2012), displayed with respect to relevancy during different repository stages (from Bossart, 2012)

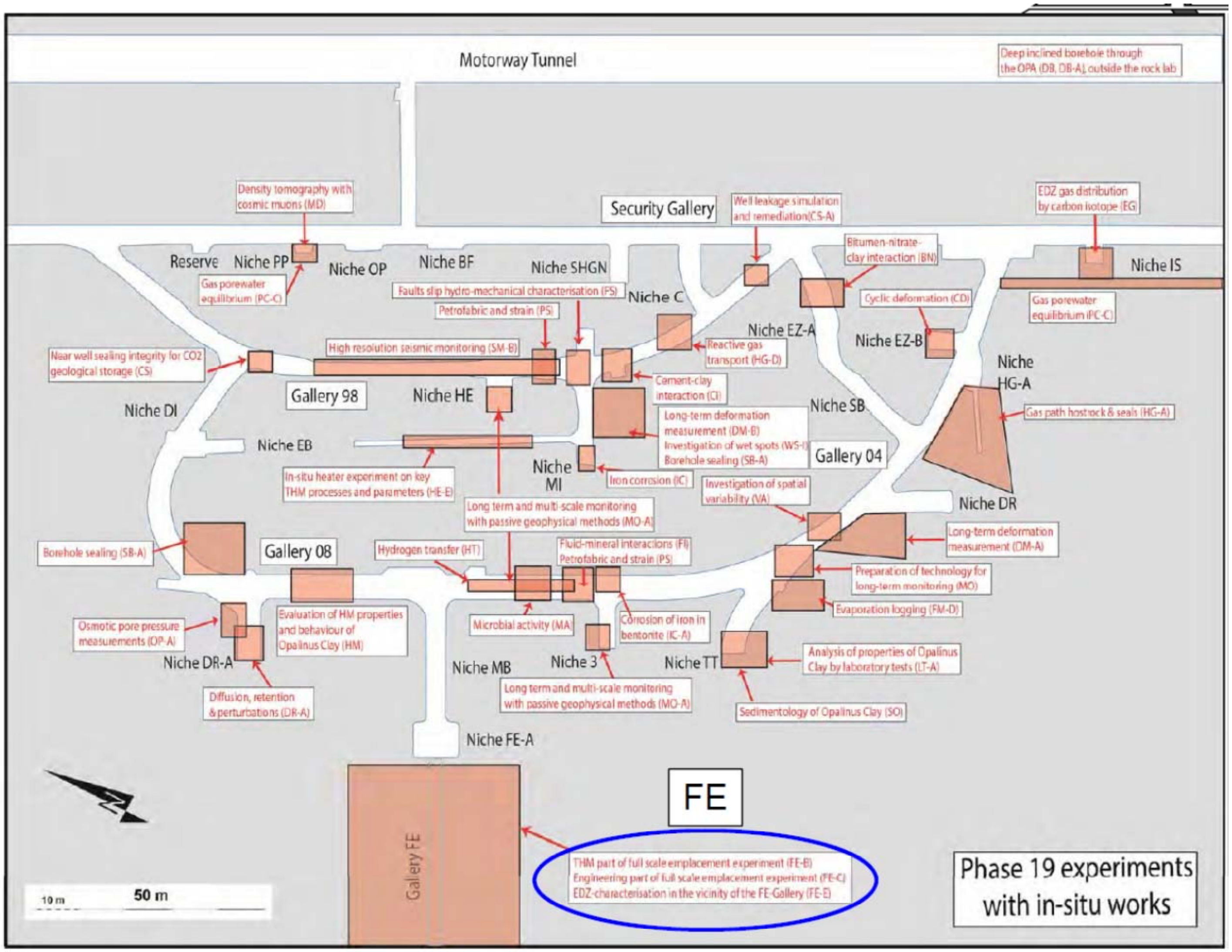

Figure 3-20. Plan view of the Mont Terri URL with 42 experiments conducted during Phase 19 (July 2013 through June 2014). Gallery FE indicates the area of the FE Heater test, which is currently the largest subsurface heater experiment worldwide. (Bossart, 2014b)

Many experiments shown in Figure 3-19 (Status June 2012, Phase 17) 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. A few additional experiments have since been proposed and initiated, among them two experiments relevant to other subsurface applications such as geologic carbon sequestration (i.e., FS Experiment: Fault slip hydro-mechanical characterization, and CS-A Experiment: Well-leakage simulation & remediation experiment). The majority of activities, however, 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, in 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 repeats itself 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, 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 3.21, a feasible extension of the URL could be achieved via a 1 km tunnel excavated in a south-westward direction.

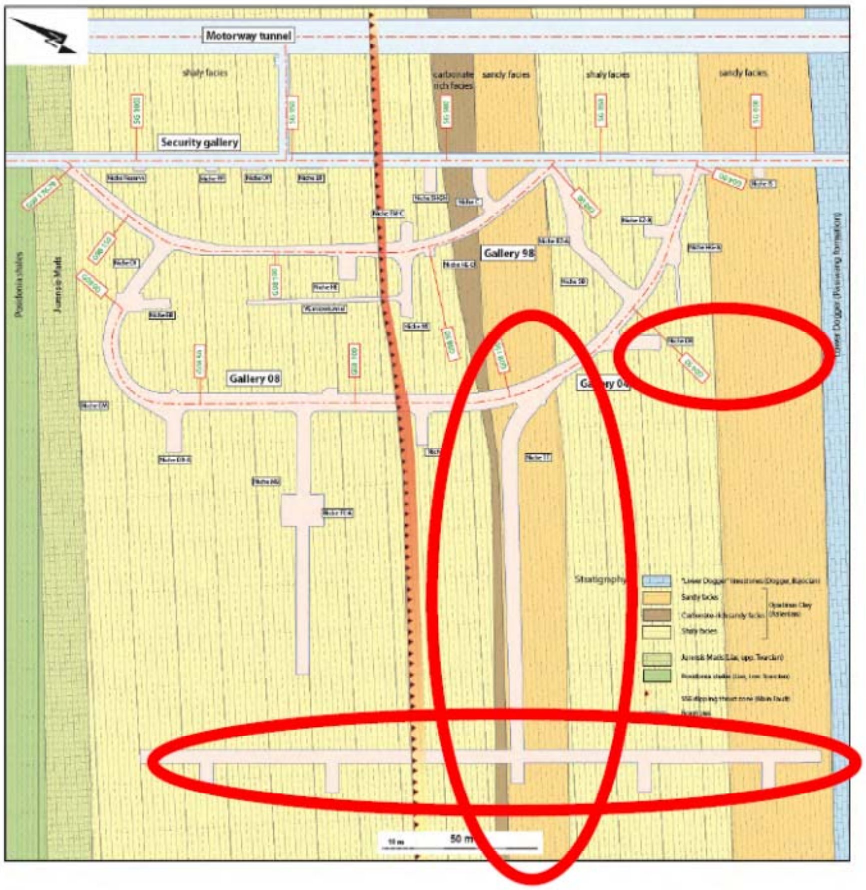

Figure 3-21. Plan view of the Mont Terri URL with potential extension in mostly south-westward direction (from Bossart, 2014b)

3.2.2 FE Heater Test

The Full-Scale Emplacement Experiment (FE Heater Test) will be one of the largest and longest-duration subsurface heater tests ever conducted. This heater experiment is planned 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 3-22 through 3-24, the FE Heater Test will be conducted in a side alcove 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 will be simulated by three heat-producing canisters of 1500 W maximum power. A sophisticated monitoring program is planned, 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.

The FE experiment is currently in the final stages of construction, emplacement, and instrumentation. It is expected that the bentonite backfill and instrumentation will be emplaced in the second half of 2014 and that the heaters can be turned on in early 2015 after installation of a bulkhead as a plug. Over the last two years, predictive THM models of the anticipated FE test behavior have been developed by some project partners (among them UFD scientists from Lawrence Berkeley National Laboratory, 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.

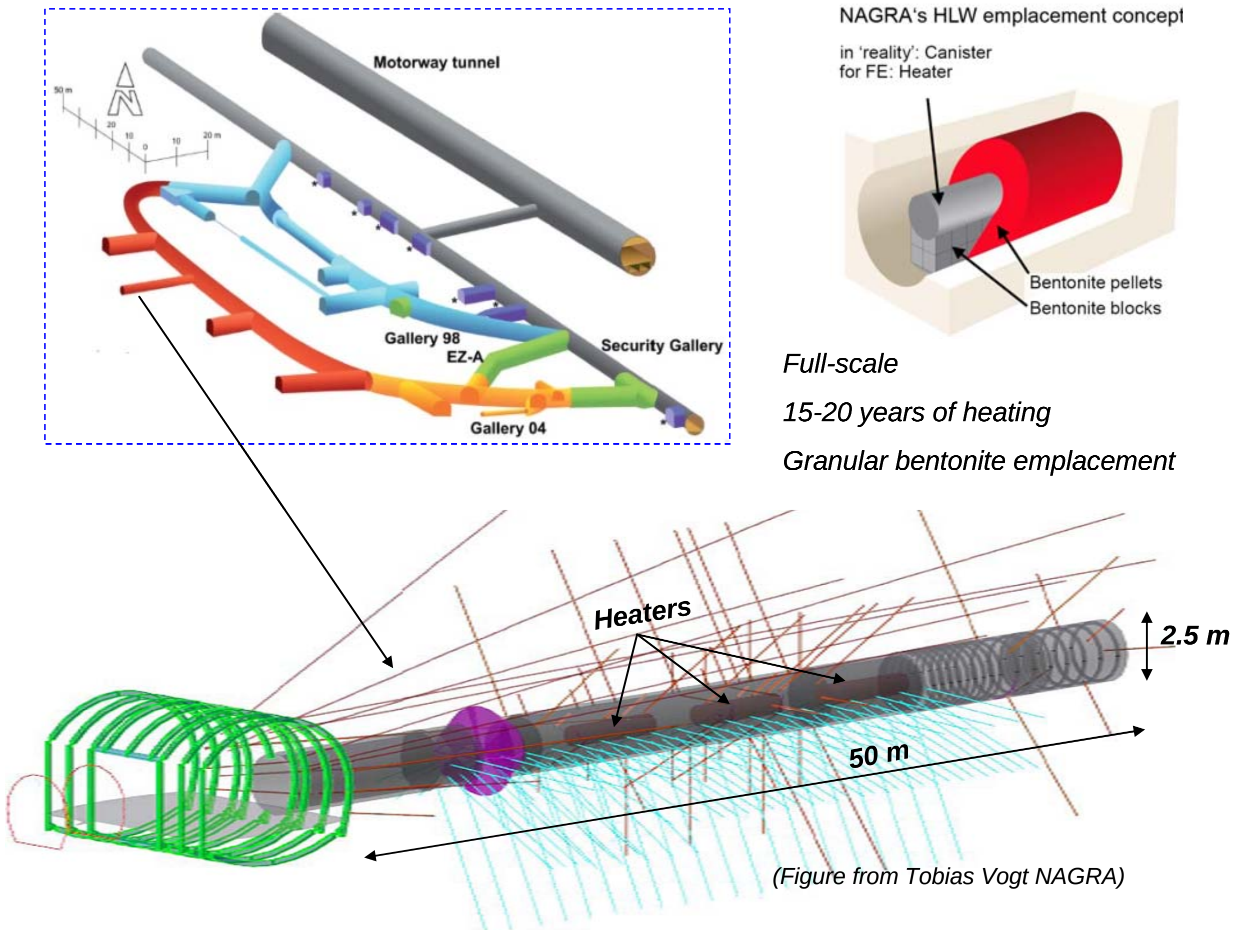

Figure 3-22. FE Heater Test at Mont Terri URL: experiment setup and borehole layout (from Zheng et al., 2014)

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 rips. 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).

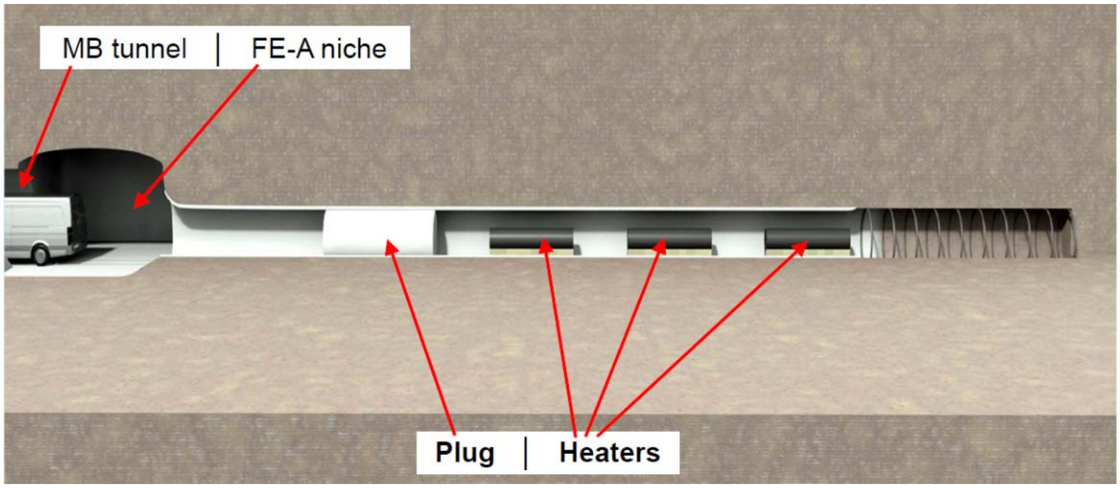

Figure 3-23. FE Heater Test at Mont Terri URL: Side view of experiment setup and heater layout (from Garitte, 2010)

Figure 3-24. View from the FE gallery into the heater tunnel during final installation (from Bossart, 2014a)

3.2.3 Mine-by Test

The Mine-By Test at the Mont Terri URL, shown in Figure 3-25, involved tunneling through a pre-instrumented region of Opalinus Clay. The test, conducted at full emplacement tunnel scale, was completed in 2012, and several years of data on EDZ behavior were made available to Mont Terri Project participants for modeling and interpretation. The test allows evaluating the excavation-generated pressure, stress, displacement, and rock-damage response in the argillaceous clay host rock near a mined tunnel, and also provides measurements of related changes in the near-field hydrologic properties. Data available for analysis include stress and convergence measurements, pore-pressure results, and hydrotest results before and after mining. UFD researchers from Lawrence Berkeley National Laboratory used new conceptual models for THM processes to evaluate and interpret the test results (see Section 6.1.3). Some of the most interesting observations are related to the fact that pore pressure and deformation signals can be observed several meters before the advancing tunnel face, a response that could not be easily explained with existing constitutive relationships (Figure 3-26). New fractures created in the EDZ show interaction with bedding planes and crosscutting joints. Mine-by leads to a significant increase in hydraulic conductivity by up to four orders of magnitude. Note that the Mine-by Test niche functions as the access gallery to the tunnel sections hosting the above-mentioned FE Heater Test.

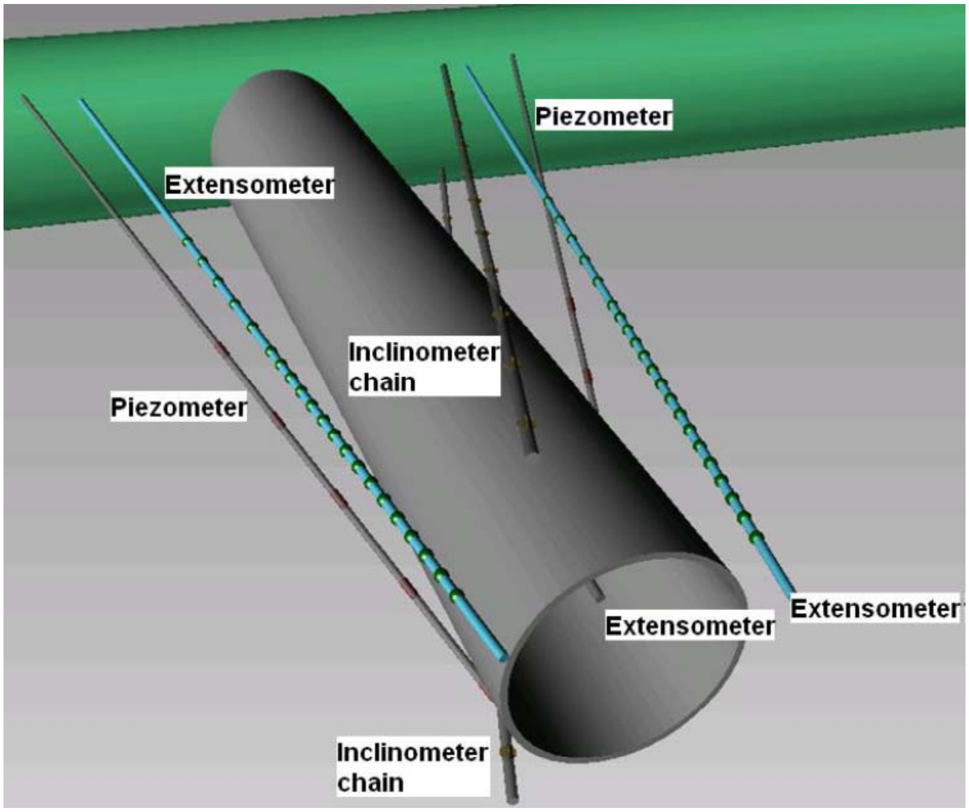

Figure 3-25. Schematic setup of Mine-by Test at Mont Terri showing location of selected boreholes for piezometer, extensometer, and inclinometer data (from Vietor et al., 2011)

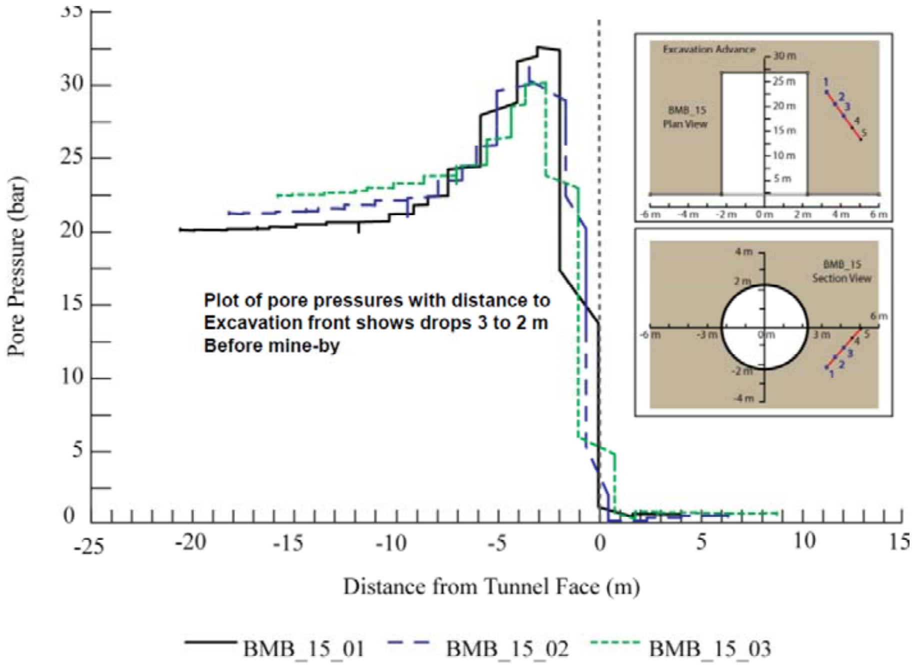

Figure 3-26. Mine-by Test at Mont Terri URL: Measurements of pore pressure relative to distance from advancing excavation front. Pore-pressure signals can be observed several meters before the advancing tunnel face. (from Vietor et al., 2011)

3.2.4 HG-A Experiment

The HG-A Experiment focuses on 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 6.1.4).

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 3-27 and 3-28). 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.

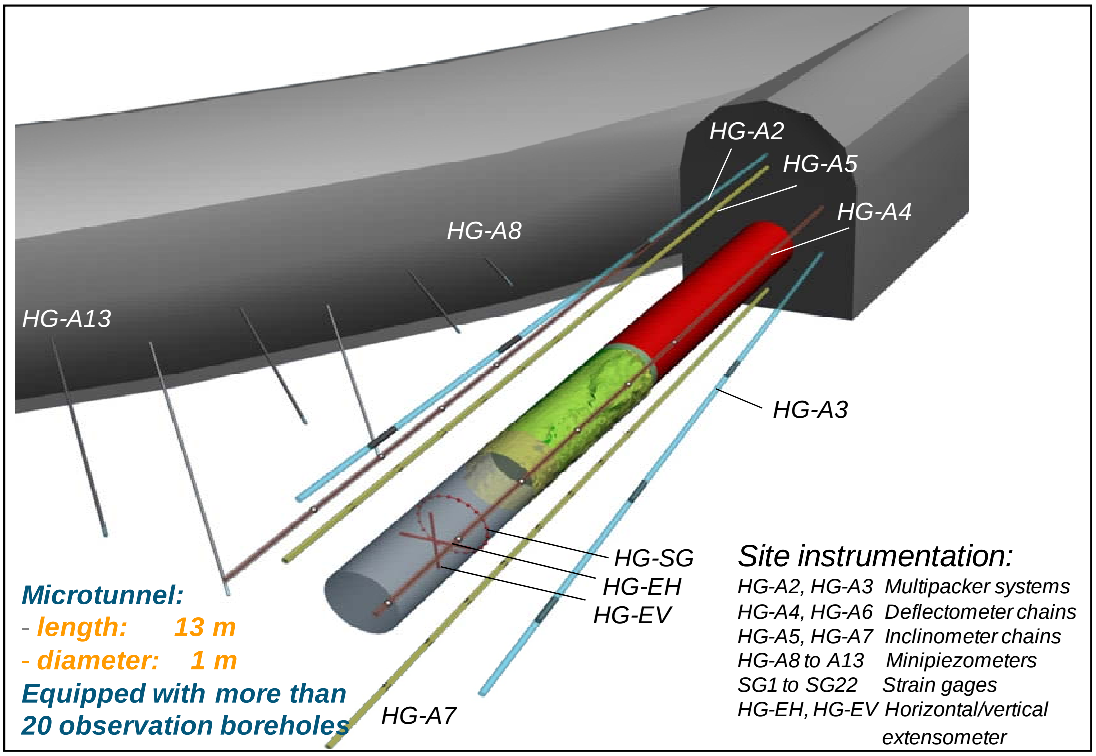

Figure 3-27. Schematic setup of HG-A Experiment at Mont Terri URL (from Marschall et al., 2012)

Figure 3-28. HG-A Experiment at Mont Terri URL: Installation of packer system (from Marschall et al., 2012)

3.2.5 DR-A Diffusion, Retention and Perturbation Experiment

The DR-A Experiment was recently conducted at Mont Terri to characterize the diffusive transport behavior at the site, which in a low-permeability host rock as Opalinus Clay is the dominant mode for radionuclide transport. As shown in Figure 3-29 for an earlier diffusion test with similar setup, the experimental design consisted of a single borehole drilled in the Opalinus Clay that contained a constant ionic strength cocktail of anions, cations, and nonreactive tracers like 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 width 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 (1.135M) 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 6.2.3).

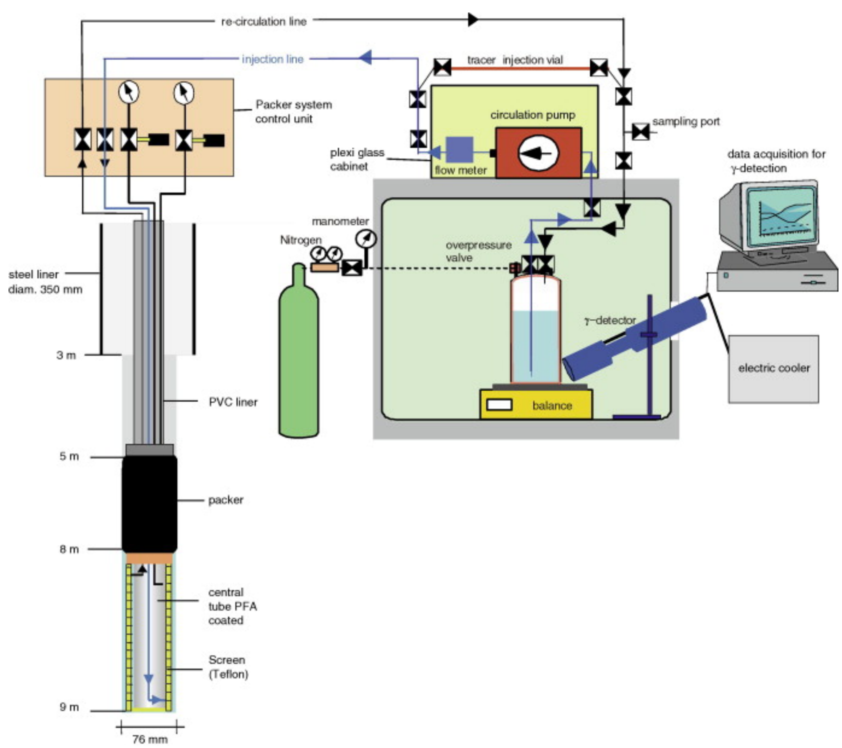

Figure 3-29. Schematic of the Diffusion Experiment at Mont Terri URL, showing main features of the down-hole and surface equipment (from Wersin et al., 2004; 2008)

3.2.6 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).

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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 3-30). 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 is currently 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.

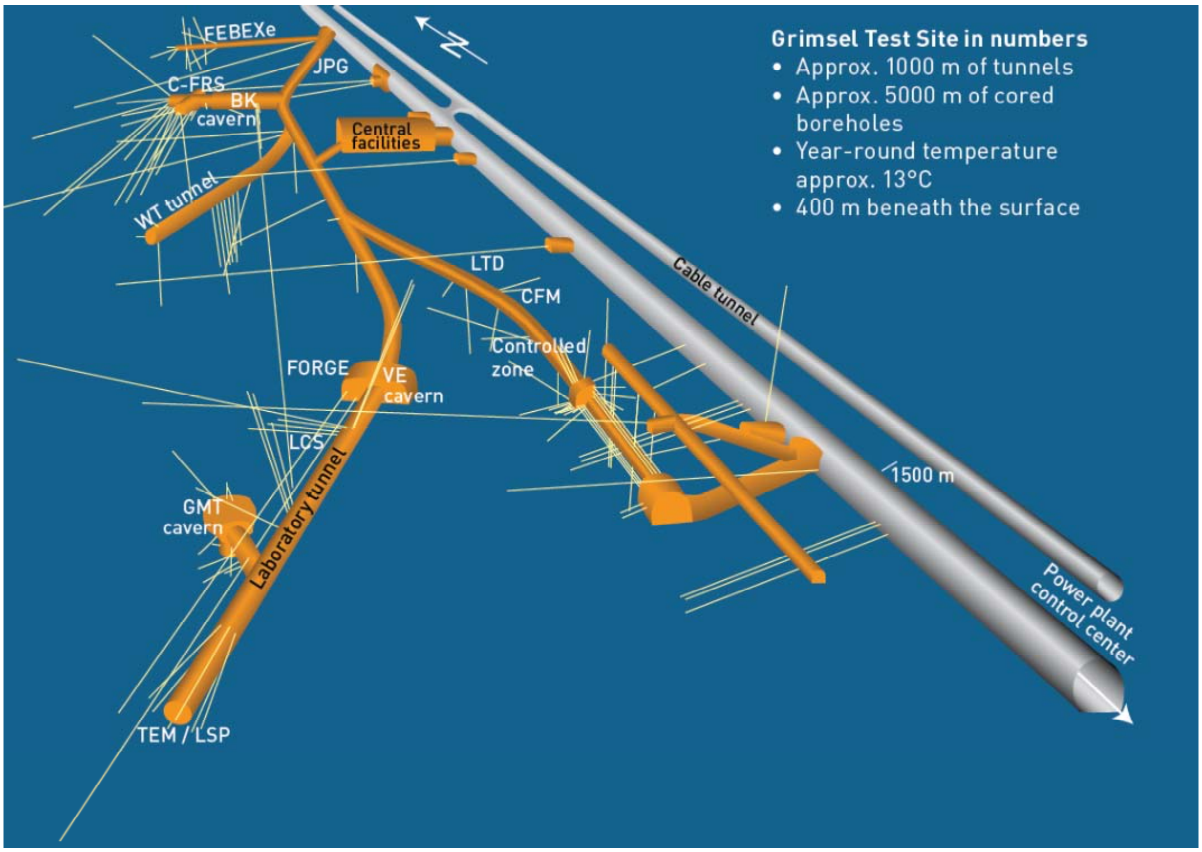

Figure 3-30. 3D view of layout of the Grimsel Test Site in Switzerland (from NAGRA, 2010)

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 3-31 and 3-32) 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.

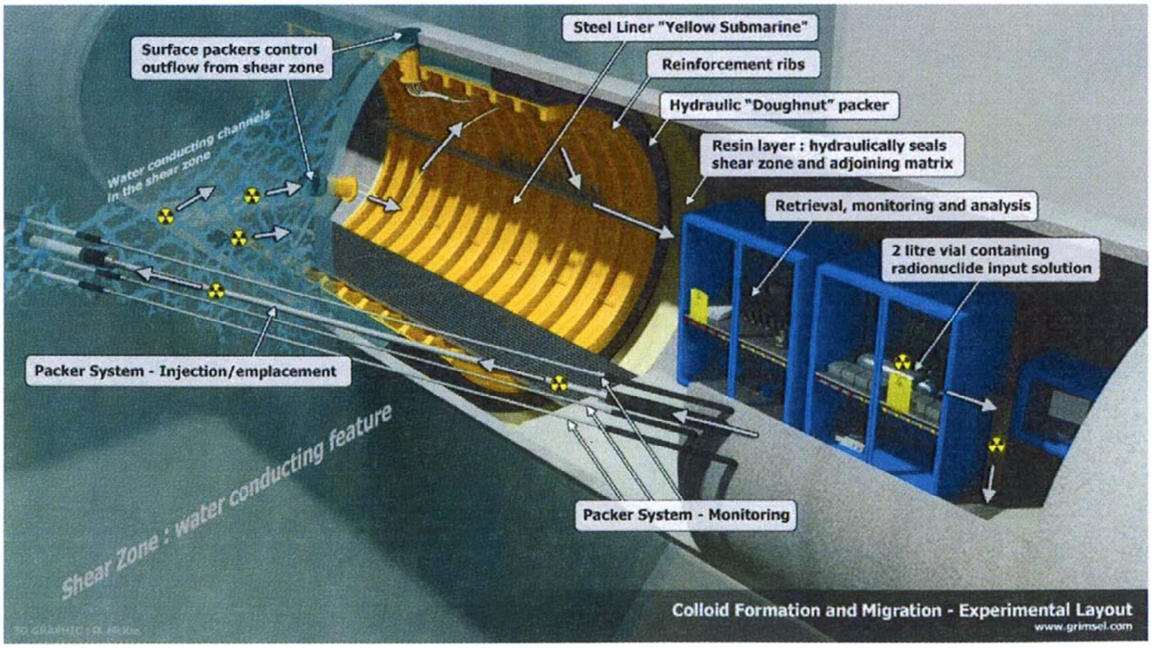

Figure 3-31. Schematic illustration of the CFM field test bed at Grimsel Test Site (from Reimus, 2012)

Figure 3-32. 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 3-33, 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) 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. Another experiment, ongoing since May 2014, involves the emplacement of a radionuclide-doped bentonite plug into the same injection interval to evaluate the swelling and erosion of the bentonite and subsequent transport. These two latter migration experiments, which constitute the culmination of the CFM project during Phase VI testing at Grimsel, are very relevant to UFD's R&D objectives and are further described in Sections 3.3.2 and 3.3.3 below.

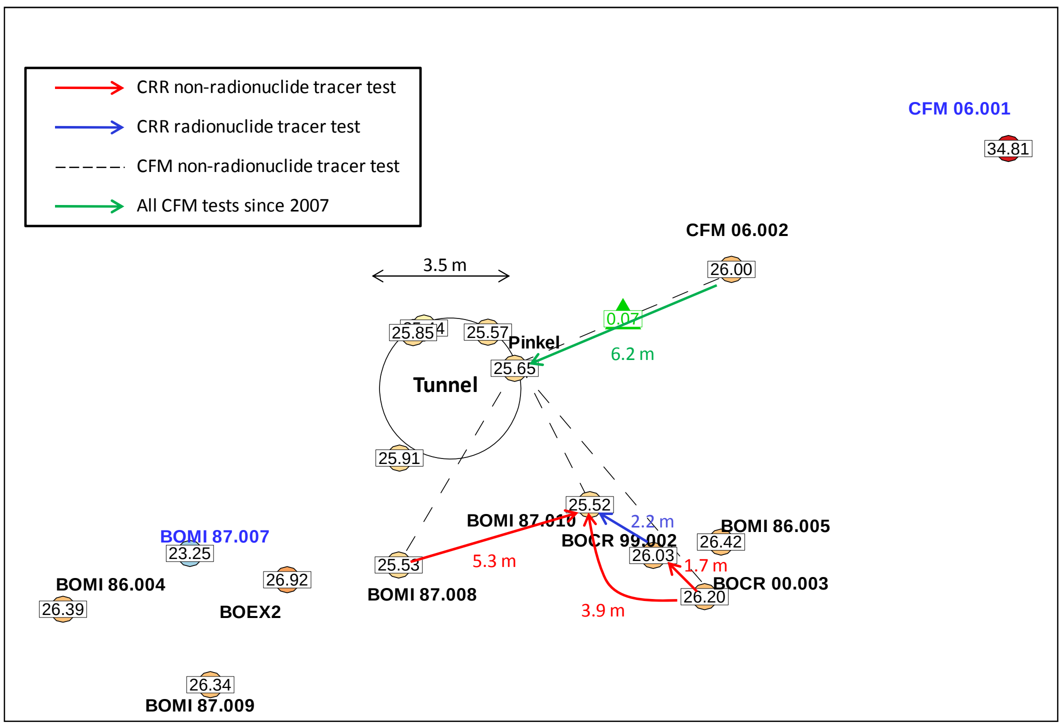

Figure 3-33. CFM field test bed at Grimsel Test Site: Borehole layout and test locations for all tracer tests (2001-present). (from Reimus, 2012)

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
- Ternary 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 decided in early 2012 to formally apply 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. As described in Section 6.2.4, UFD researchers from Los Alamos National Laboratories have collaborated with their international partners on interpreting colloid-transport-data measurements with semi-analytical and numerical methods.

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 (Figure 3-31). 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 3-34 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.

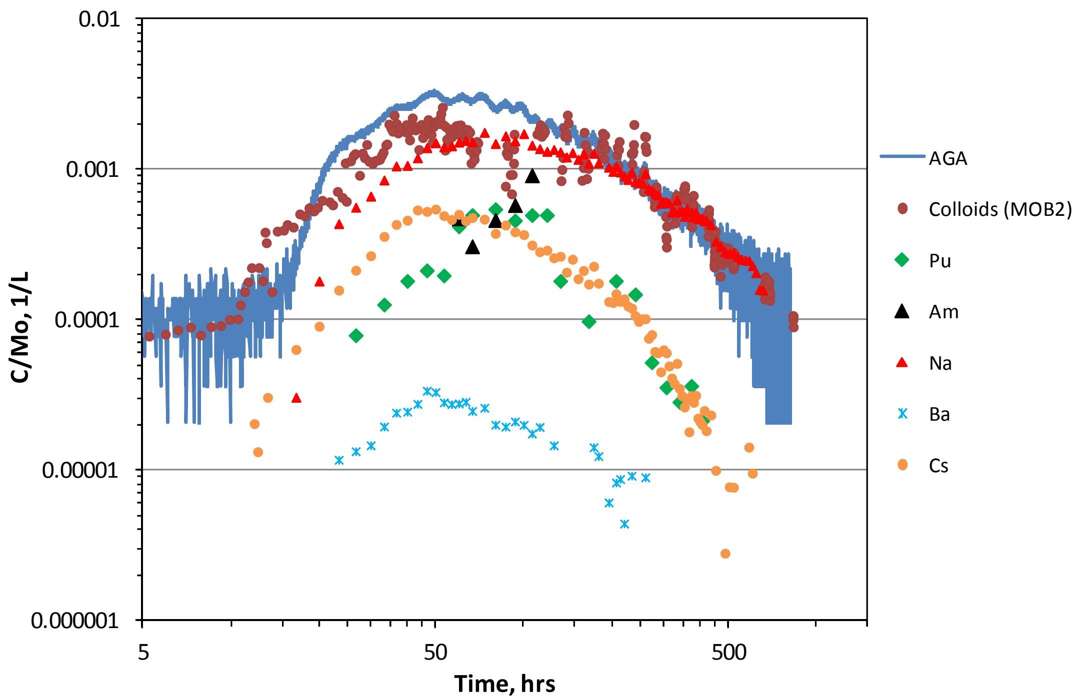

Figure 3-34. Colloid-Facilitated Radionuclide Tracer Test at Grimsel Test Site: Normalized breakthrough curves of all tracers in CFM Tracer Test 12-02 (from Reimus, 2012)

3.3.1.3 Radionuclide-Doped Bentonite Plug Transport Experiment

An ongoing experiment at CFM 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. The bentonite plug is allowed to remain in place for at least two years to enable long-term monitoring of both colloidal and radionuclide arrival. Many of the same radionuclides are used as in the test described above, but different isotopes allow the observations from the two tests to be distinguished. The bentonite is expected to swell into the fracture zone and erode under the influence of the flow field, while flow samples are collected at the tunnel wall. New small boreholes have been instrumented for sampling at very low rates to provide an early indication of swelling and radionuclide release. At the conclusion of the test, these boreholes will be filled with a resin to stabilize the rock mass, and a large-diameter overcoring of the entire injection interval will be conducted. While the primary purpose of this procedure is to recover the majority of the radionuclide inventory remaining at the source location at the conclusion of the test, it will also enable detailed post-mortem characterizations of bentonite swelling into the fracture shear zone and determination of radionuclide dispositions in the emplacement borehole and shear zone at the end of the test.

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 are involved in the interpretation and analysis of several colloid-facilitated tracer tests and also plan to participate in the ongoing Radionuclide-Doped Bentonite Plug Transport Experiment (Section 6.2.4).

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 Radionuclide-Doped Bentonite Plug Transport Experiment will test additional aspects of colloid transport related to bentonite erosion, an important subject for UFD.

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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 3-35). 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 3-36 and 3-37). The samples recovered from this first heater experiment provided valuable information on the long-term condition of heated EBS materials (Lanyon et al., 2013). Now, 12 years after the first partial dismantling, NAGRA has launched the FEBEX Dismantling Project (FEBEX-DP), which plans to remove the second heater and recover relevant EBS materials in the summer of 2015. The FEBEX-DP project, officially kicked off in June 2014, provides a unique opportunity for removing, sampling, and analyzing 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 NDA and RAWRA/SURAO. UFD researchers from LANL, LBNL, and SNL currently participate in the test design and sampling plan development.

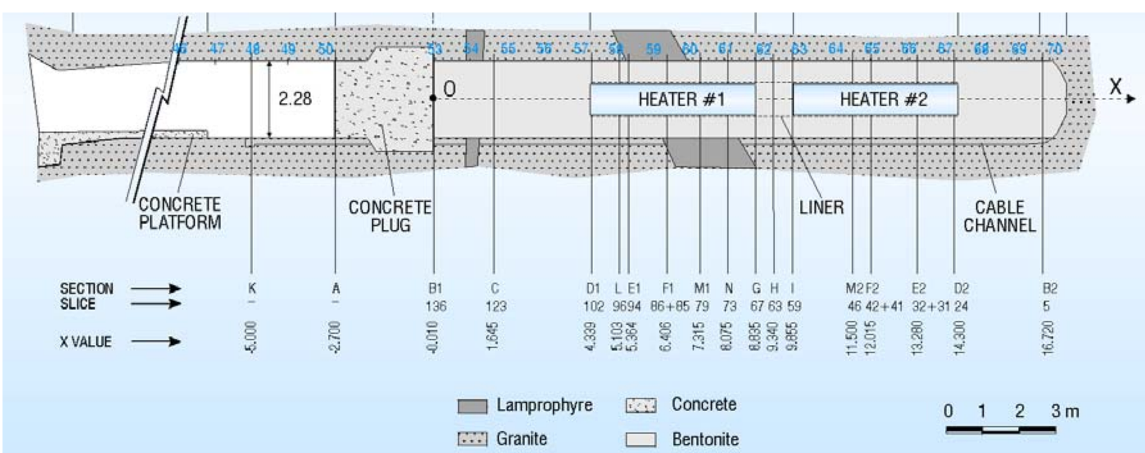

Figure 3-35. Schematic cross section of the FEBEX Test at Grimsel Test Site (from NAGRA, 2014)

Figure 3-36. 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)

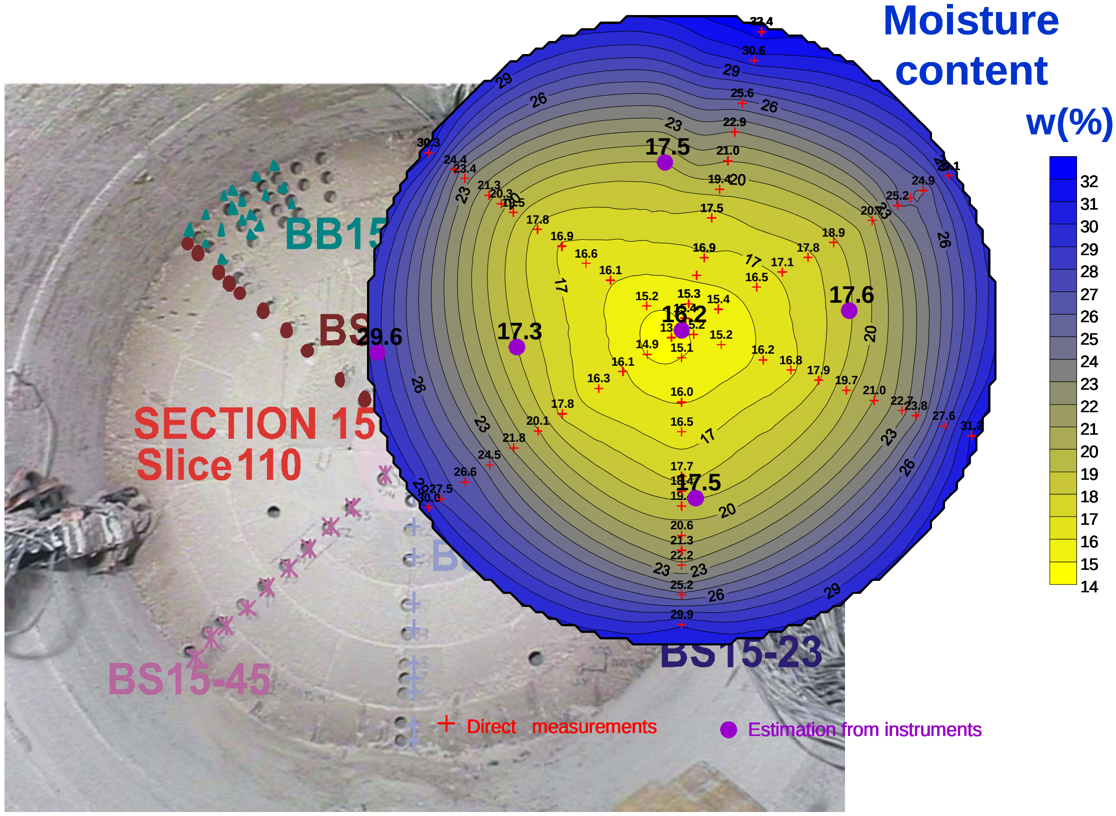

Figure 3-37. Moisture content and sample locations derived from 2002 dismantling campaign. Moisture distribution shows an axial symmetry independent of the geologic variability in the adjacent host rock. (from NAGRA, 2014)

3.3.2.2 FEBEX-DP Objectives

The FEBEX-DP project will provide unique data and 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 will thus focus on the following primary objectives (Gaus and Kober, 2014; NAGRA, 2014) (Figure 3-38):

- 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

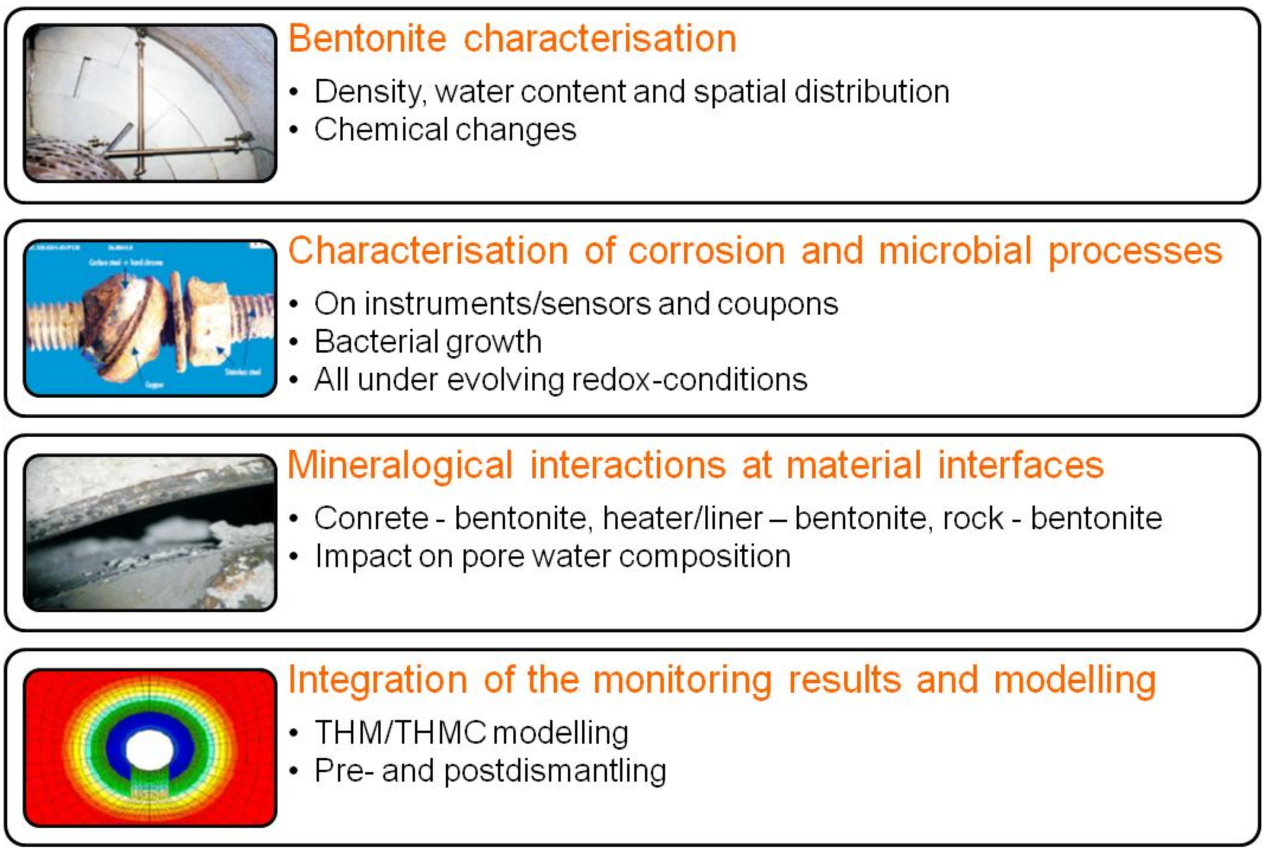

Figure 3-38. Primary objectives of FEBEX-DP Project (from NAGRA, 2014)

These primary objectives will be realized by pursuing the following secondary objectives regarding the main elements of the experiment:

- Buffer and interfaces:
  - Obtain 3D insight in the water content and density distributions of the bentonite through extensive sampling.
  - Obtain insight in 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 implementation of the FEBEX-DP project foresees the following activities (Gaus and Kober, 2014):

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

Pre-test modeling will be 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 models will also be used to analyze the potential impact of switching off the heaters on the pressure and relative water content in the EBS. An assessment of the potential geochemical perturbations (dissolution, precipitation due to changing temperatures and water content) of the buffer will be used as input for optimizing the sampling plan.

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

The first dismantling step is to drill through the plug to obtain interface samples, one month after turning of the heaters (Spring 2015). In order to obtain intact and undisturbed samples from the shotcrete/bentonite interface, novel sampling techniques (based on core stabilization and overcoring) will be used. These have been tested successfully at GTS and Mont Terri. The actual dismantling operation will then be carried out in summer 2015, according to the following sequence:

- Removal of instrumentation and auxiliary systems, protection of acquisition cabinets
- Completion of steel tracks up to plug
- Shotcrete plug demolition (and sampling if required) thereby trying to avoid damage to cables and instruments. Fulfillment of the associated quality control documentation during the sampling (samples/instrumentation removal included)
- Removal of “dummy canister”
- Removal and sampling of bentonite and liner up to the front of the heater 2, and shipping of samples. Fulfillment of the associated quality control documentation during the sampling.
- Analysis and extraction of heater 2
- Removal and sampling of the remaining bentonite and liner, and shipping of samples. Fulfillment of the associated quality control documentation during the sampling.
- Removal of monitoring and control system

Laboratory program and analysis of the samples

A detailed sampling and analysis plan is currently in development at NAGRA with input from all FEBEX-DP partners. Partner organizations have the option of sending their own sampling teams and/or can request samples extracted by the project leads. The following components are considered in the sampling program: service area and heated zone, plug and plug interfaces, bentonite blocks, coupons and instrumentation, heater, liner, and host rock. As shown in Figures 3-39 and 3-40, samples will be strategically selected in cross-sectional segments along the heater axis, as well as radially distributed within each segments. The field sampling campaign will be finalized by October 2015. Laboratory work on the samples is planned starting in the fall of 2015 and will continue till summer 2016. Details on the possible laboratory work envisioned in FEBEX-DP are available in Gaus and Kober (2014).

Data synthesis and post-dismantling modeling:

Starting in early 2016, 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.

It is expected that UFD researchers will participate in the pre- and post-dismantling modeling and also in the analytical work on samples (see Section 6.1.2).

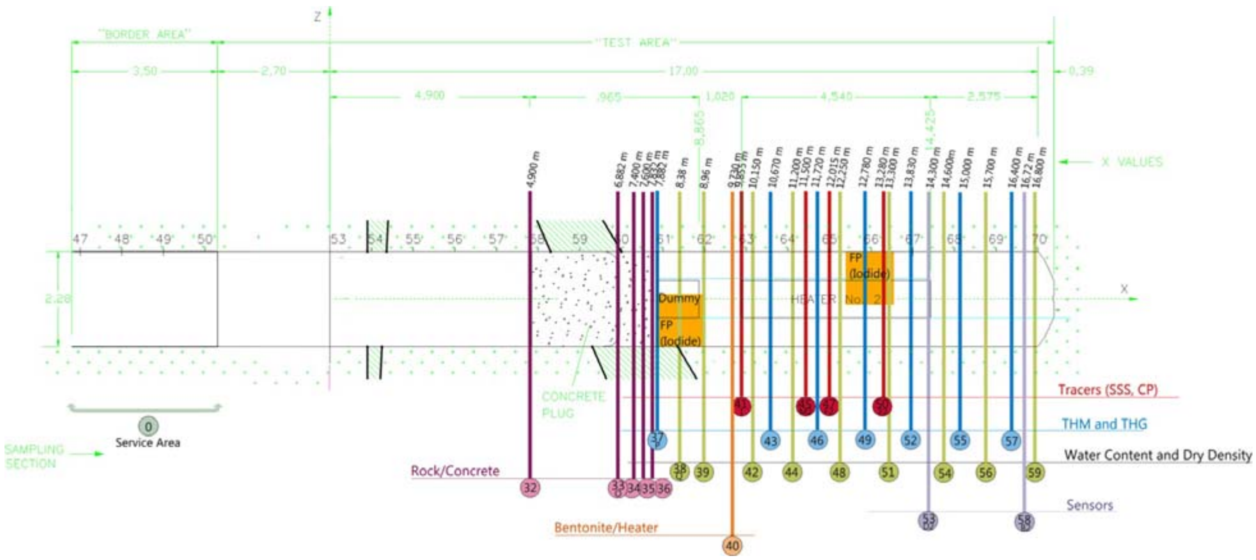

Figure 3-39. Sampling cross-sections planned for FEBEX-DP Project (from NAGRA, 2014)

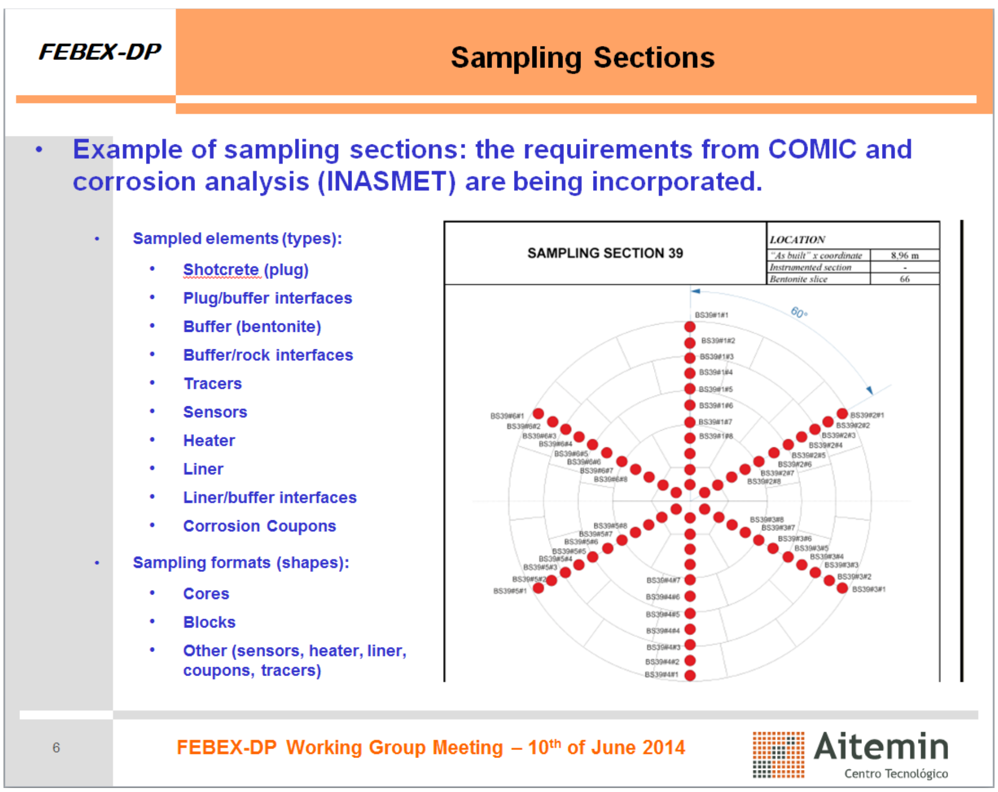

Figure 3-40. Radial sample distribution planned for FEBEX-DP Project (from NAGRA, 2014)

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 currently participate in the test design and sampling plan development (Section 6.1.2).

Outlook:

The FEBEX-DP Project has just started. DOE/UFD is expected to participate in the project until the end of 2016, when a final synthesis report is expected on the project findings.

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3.3.3 Other Experiments at Grimsel Test Site, Switzerland

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 3-41). 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.

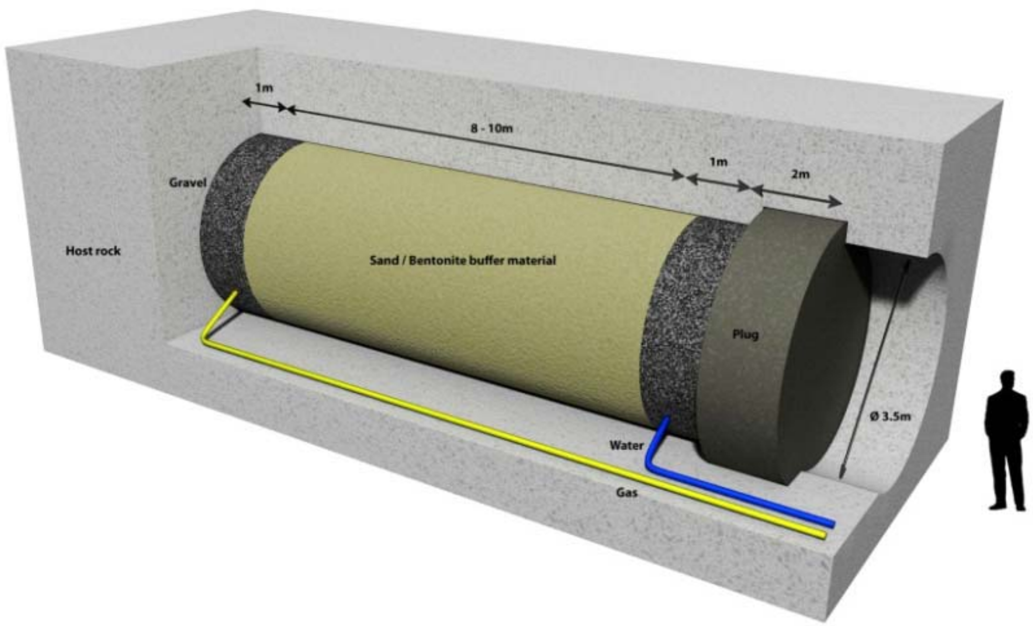

Figure 3-41. GAST Experiment at Grimsel Test Site: Schematic picture of repository seal design with 8–10 m long sand/bentonite plug in between two gravel packs and a concrete plug for reinforcement (from http://www.grimsel.com/gts-phase-vi/gast/gast-introduction).

3.4 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 3-42).

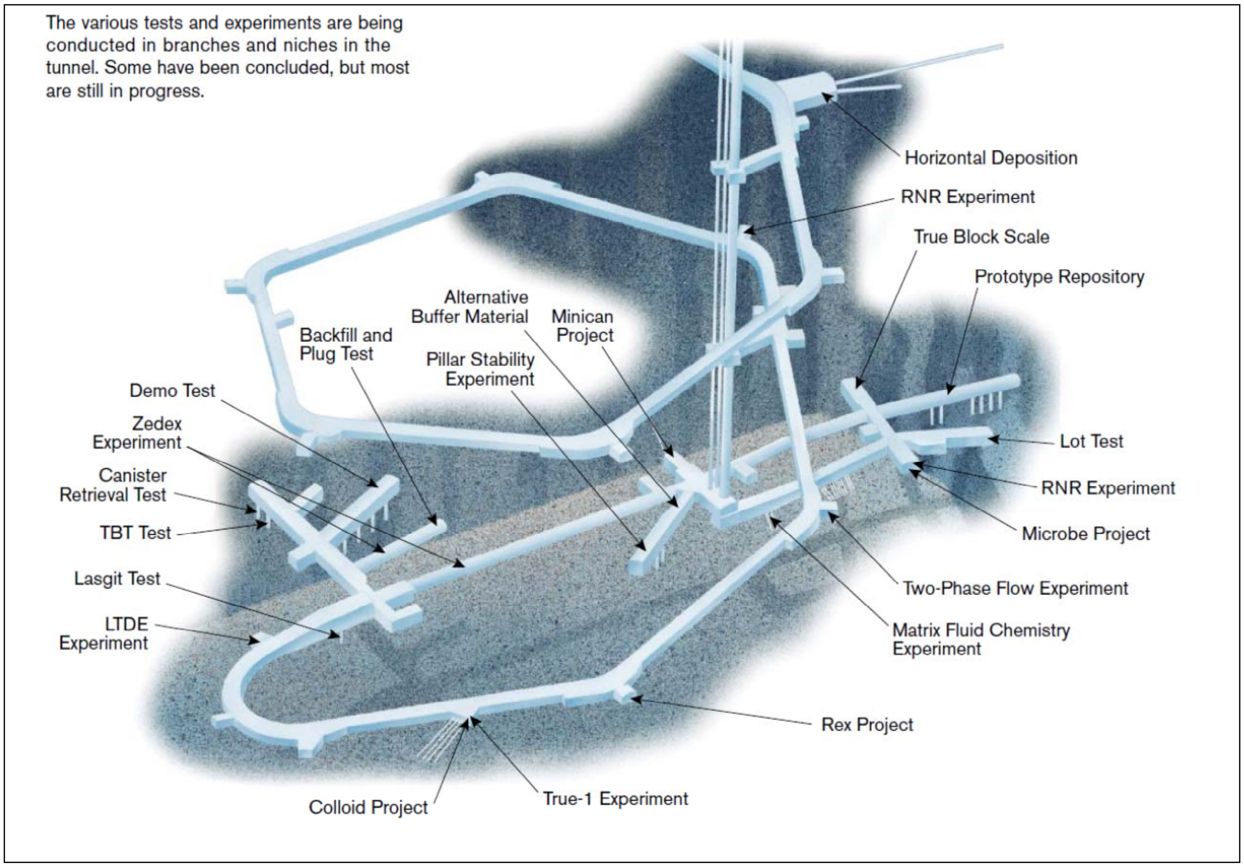

Figure 3-42. Layout of Äspö HRL and location of main experiments (from Birkholzer, 2012)

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. Prominent modeling tasks conducted currently are: (see more information in Sections 3.4.2 through 3.4.4 below)

<u>GWFTS Task Force:</u>

- Modeling of the Bentonite Rock Interaction Experiment (BRIE) at Äspö HRL (jointly with EBS Task Force)
- Modeling of transport experiments such as the Long Term Diffusion Experiment at Äspö HRL or the REPRO (Rock Matrix Retention Properties) Experiment at Onkalo URL in Finland

<u>EBS Task Force:</u>

- Modeling of the Bentonite Rock Interaction Experiment (BRIE) at Äspö HRL (jointly with GWFTS Task Force)
- Modeling of one of the two outer deposition holes in the Prototype Repository at Äspö HRL

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. UFD researchers are now actively engaged in the GWFTS task force and conduct simulation work supporting the interpretation of the BRIE experiment. Other participating organizations in the GWFTS and/or EBS Task Forces are SKB, POSIVA, KAERI, CRIEPI, JAEA, NAGRA, BMWi/KIT, NDA, NWMO, and RAWRA.

3.4.2 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 3-43 and 3-44). 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 are participating in the modeling analysis of the BRIE experiment (see Section 6.1.5).

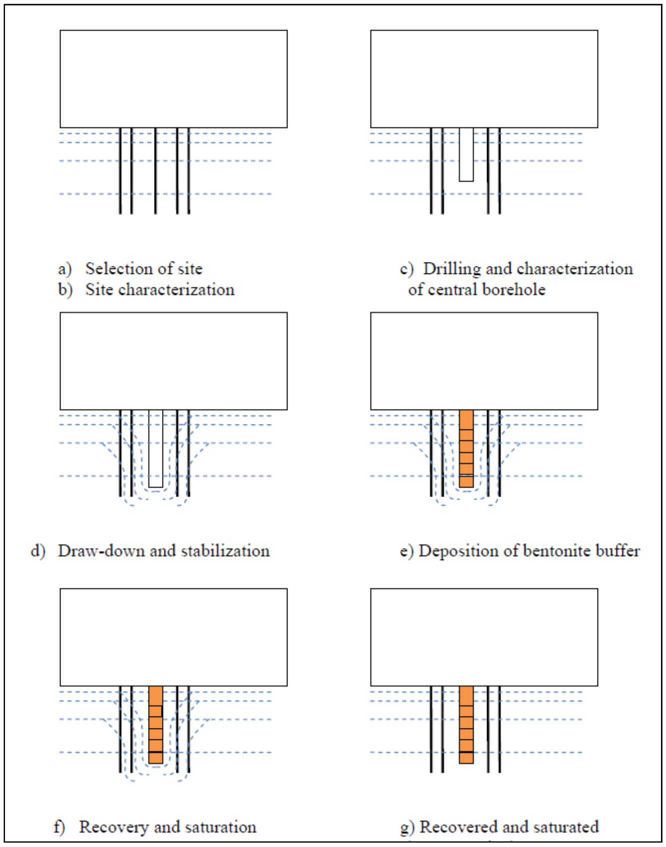

Figure 3-43. Schematic stages of the BRIE Experiment at Äspö HRL (from Bockgård et al., 2012)

Figure 3-44. 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)

3.4.3 Long-Term Diffusion Sorption Experiment (LTDE-SD)

The Long-Term Diffusion Sorption Experiment, completed in 2010, is under consideration as a new modeling task in the GWFTS Task Force. The experiment is 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 3-45). 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.

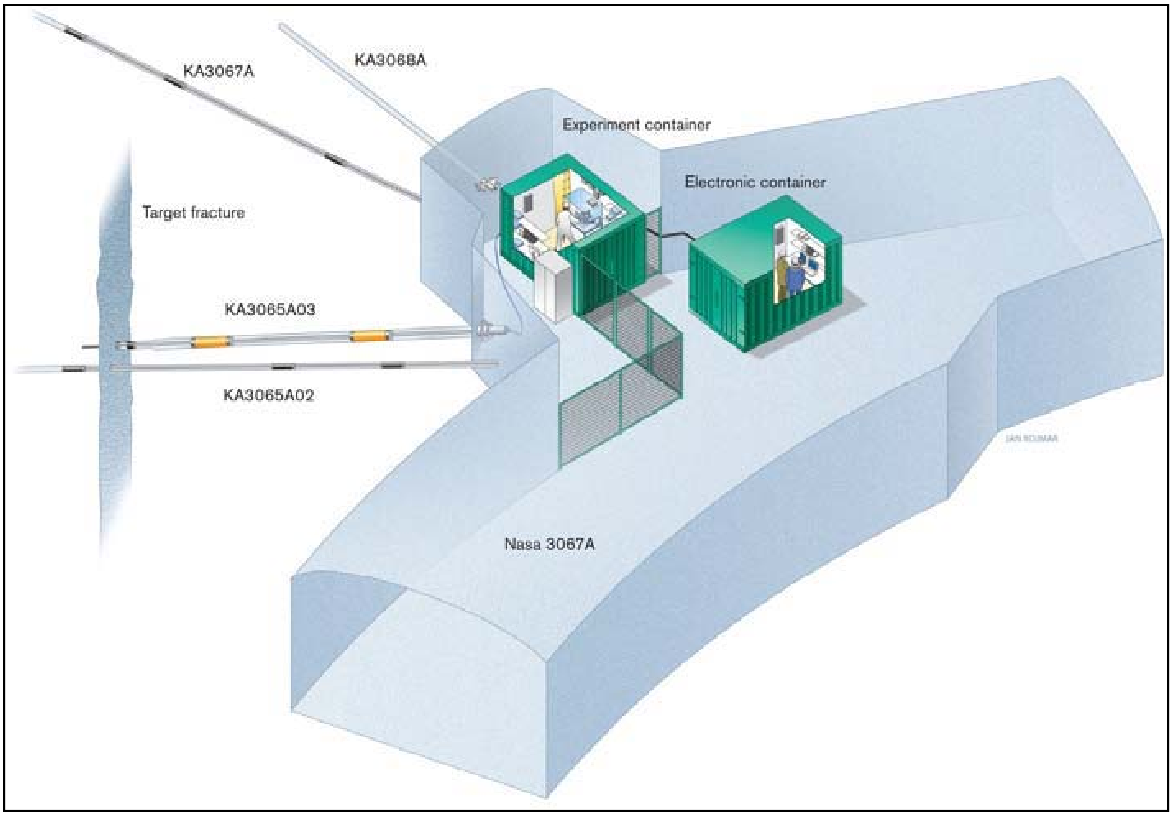

Figure 3-45. Schematic setup of LTDE-SD at Äspö HRL (from SKB, 2011a)

3.4.4 Prototype Repository

In 2000, SKB started the planning and installation of a so-called Prototype Repository as a full-scale demonstration of the integrated function of the repository, and a reference for testing predictive models concerning individual components as well as the complete repository system. The test area is located in the innermost section of the TBM tunnel at the –450 m level. The layout involves a total of six deposition holes, four in an inner and two in an outer section—see Figure 3-46. Canisters with dimension and weight according to the current plans for the final repository, and with heaters to simulate the thermal energy output from the spent nuclear fuel, have been positioned in the holes and surrounded by bentonite buffer. The deposition holes were placed with a center distance of 6 m. This distance was evaluated considering the thermal diffusivity of the rock mass and the maximum acceptable temperature of the buffer. The deposition tunnel was backfilled with a mixture of bentonite and crushed rock (30/70). A massive concrete plug, designed to withstand full water and swelling pressures, separates the test area from the open tunnel system, and a second plug separates the two sections. This layout provides two more or less independent test sections. The monitoring system is comprised of a dense network of sensors for temperature, total pressure, pore-water pressure, relative humidity and resistivity, as well as some rock mechanical measurements. The heaters of the inner section were turned on in 2001; those in the outer section in 2004. This was followed by several years of monitoring, offering a very valuable data set of early-stage, full-scale repository evolution.

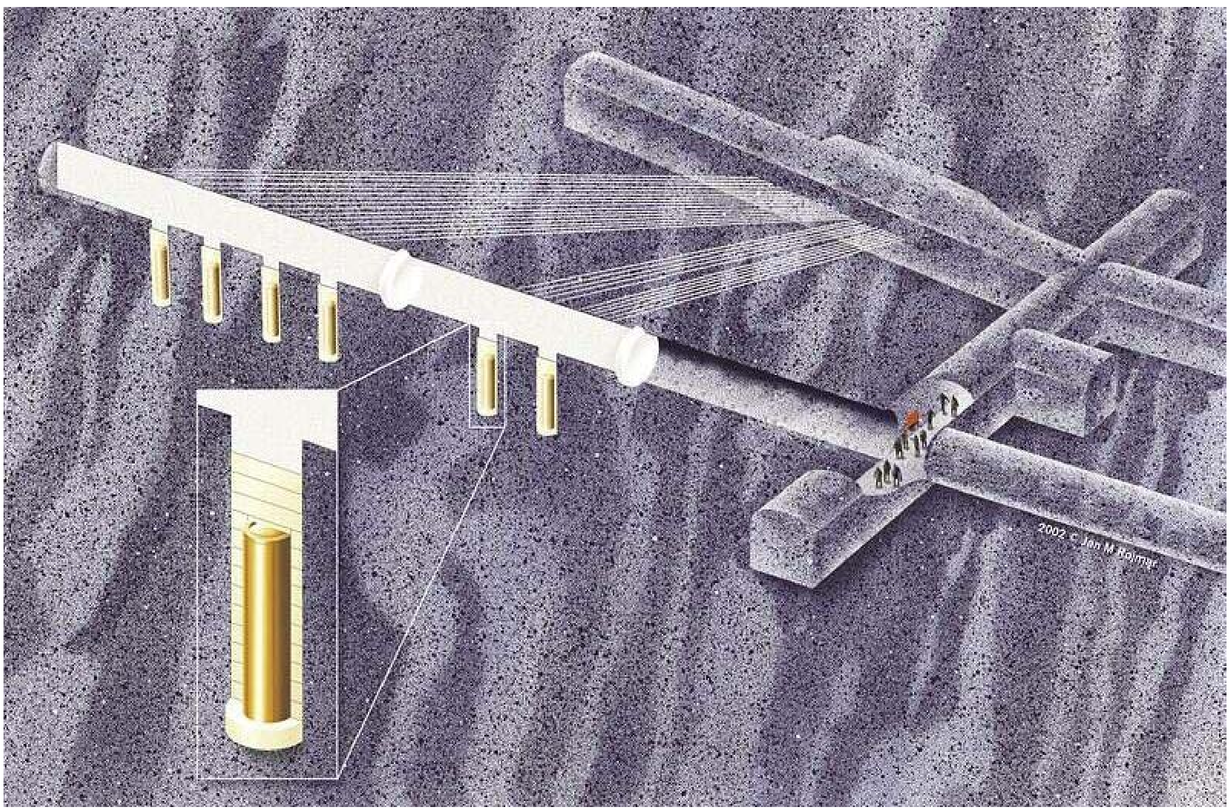

Figure 3-46. Schematic layout of Prototype Repository at Äspö HRL (from SKB, 2011a, 2011b)

In 2011, SKB excavated the outer section of the Prototype Repository while extensive samplings were performed. Approximately 1,000 samples on the backfill and about 3,000 samples on the buffer were taken to determine water content and density. The two canisters were lifted up and transported to SKB's Canister Laboratory in Oskarshamn for additional investigations. The main objectives of dismantling the outer section were to (1) investigate the density and water saturation of the buffer and backfill, (2) investigate the interface between buffer – backfill and between backfill – rock surfaces, after 7 years of wetting, (3) measure and examine the canisters (positions, mechanical stress, corrosion), (4) investigate the bedrock after dismantling, (5) study biological and chemical activities in the buffer and backfill, and (6) study possible changes of the buffer material caused by temperature and saturation processes. The observations made in one of the excavated deposition holes (Figure 3-47) are the focus of one modeling task of the EBS Task Force, the objective being to verify the THM processes occurring during heating and resaturation, and validation against the post-mortem analysis.

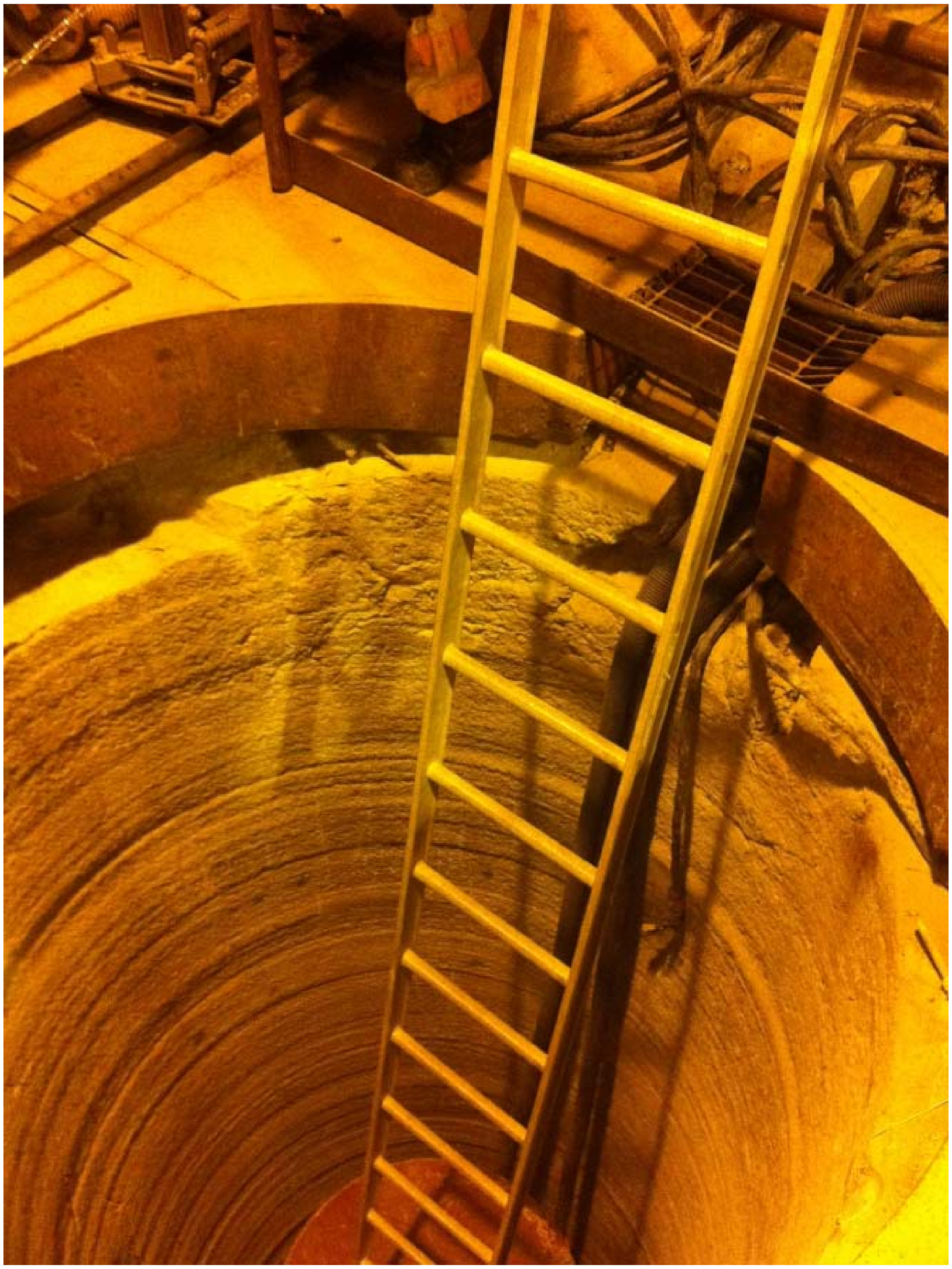

Figure 3-47. Prototype Repository at Äspö HRL: Photo of excavated deposition hole

3.4.5 SKB Task Force Summary

Benefits of Participation:

- Access to **several** sets of experimental data from **one** URL in crystalline rock
- Opportunity to perform **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)

Status of Participation:

DOE joined both task forces in January 2014. UFD researchers are actively engaged in the interpretation and modeling of a bentonite-rock experiment (Section 6.1.5).

Outlook:

With DOE's membership in the task forces just recently formalized, UFD's collaboration portfolio with SKB is still in development. In addition to BRIE, there may be other valuable tasks, a review of which will be continued in FY15.

Contact Information:

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Antonio Gens, EBS Task Force for THM, from UPC, Spain
Urs Maeder, EBS Task Force for THC, University of Bern, Switzerland

3.5 NEA's Cooperative Initiatives

The previous sections describe initiatives that foster active research with other international disposal programs, provide access to field data, and/or may allow participation in ongoing and planned field experiments in URLs (Sections 3.1 to 3.4). Here we briefly touch on NEA's international collaboration initiatives where the focus is less on active collaboration thanon the exchange of information and shared approaches.

3.5.1 NEA's Clay Club

In 1991, the Nuclear Energy Agency (NEA) established a "Working Group on the Characterization, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations," known more commonly as the "Clay Club" (http://www.oecd-nea.org/rwm/clayclub/). Since 2000, the Clay Club has operated under the umbrella of NEA's Integration Group for the Safety Case (IGSC), an international forum on confidence-building in repository technical safety cases and on the underlying methodological and scientific bases for the purpose of decision-making in repository development. The Clay Club promotes the exchange of information and shared approaches and methods to develop and document an understanding of clay media as a host rock for a repository. The Clay Club generally establishes the program of work at its own initiative, based on experience and progress in repository programs of its member countries. The work program and products are presented at each IGSC plenary meeting. The Clay Club may also carry out specific tasks at the request of IGSC dealing with, for instance, the analysis of performance of clays for safety assessment purposes. The Clay Club chooses among a variety of mechanisms for its work program, including, for example: to install task-oriented expert groups; to organize workshops; to hire dedicated consultants and specialists; to collaborate in conferences; or a combination of these. A high priority is placed on making the results of Clay Club projects publicly available, using printed and/or electronic publications. The Clay Club working group is composed of senior technical experts with experience in assembling or reviewing the understanding of argillaceous media as host rocks for deep geologic disposal projects. Members represent waste-management agencies, regulatory authorities, academic institutions, and research and development institutions.

The work program and modus operandi of the Clay Club emphasize the pooling of resources, the sharing and synthesis of understanding and experiences, and the communication of findings to various audiences. Clay Club projects are established most often at the initiative of the members; work may also be undertaken on specific topics at the request of the IGSC. The topics of work reflect issues of common interest, considering the experience, progress and challenges of national program. Decisions on projects are made on a consensus basis, taking into account the importance and urgency of the issue, the breadth of interest (i.e., the number of national program for whom the issue is considered a key issue), and the necessary resources and schedules to accomplish the work proposed. Communication within the group takes place through plenary meetings, which occur on at least an annual basis.

In general, the Clay Club addresses recommendations, trends, and information gaps concerning the characterization, evolution, modeling, and performance of argillaceous media, for example regarding:

- Understanding (and development of associated conceptual models) of argillaceous rocks through site characterization and expert evaluation, including both field and laboratory work on key issues
- Quality (characterization, understanding and conceptualization capability) and limitations of the information that is available
- Performance assessment and supporting models, including model abstraction and simplification as well as the traceability of related data and information

- Links and potential knowledge transfer between the understanding of clay as a host material and its use in engineered barrier systems of geologic repositories
- Relevant progress in R&D on clay materials in other fields or industries, such as petroleum exploration and CO_2 sequestration

Examples of topics that have been (or are being) addressed are:

- Catalogue of characteristics of the various argillaceous media;
- Relevant FEPs
- Use of natural tracers to support long-term dominance of diffusion;
- Role and influence of faults and fractures at repository depths
- The quality and limitations of the information that is available
- Potential for self- sealing of fractures in clay rocks
- Imaging and observations of clays at the microscopic level (current)
- Anomalous heads in clay media (current)
- Micro-mechanical models (current)

Membership in the Clay Club requires no formal agreement, but rather a simple expression of interest, acceptance by current Clay Club members, and a voluntary annual financial contribution. Each member organization sends a representative to the annual meetings and provides a report on ongoing activities. Clay Club members are expected to: promote Clay Club activities in their own organization; provide relevant data and bibliographic material to support Clay Club initiatives; and, as appropriate and on an ad hoc basis, make human or financial resources available to the Clay Club initiatives. In contrast to other international initiatives (such as the Mont Terri Project, DECOVALEX, or SKB's Task Forces), the Clay Club is not about active R&D collaboration, but rather about having a regular forum for in-depth discussion and information exchange. Current members are institutions from Belgium, Canada, France, Germany, Hungary, Japan, Netherlands, Spain, Switzerland, and United Kingdom. DOE has been contemplating membership in the past, but so far has not ultimately decided on participation.

3.5.2 NEA's Salt Club

The Salt Club brings together nations currently considering rock salt as a candidate medium for deep geologic disposal of HLW and long-lived radioactive waste (http://www.oecd-nea.org/rwm/saltclub/). The club's mission is to develop and exchange scientific information on rock salt as a host rock formation for deep geologic repositories. By promoting information and knowledge exchange, the Salt Club also intends to stimulate interest in other nations with appreciable rock salt deposits to consider rock salt as a viable repository medium. In addition to the technical aspects, the working group also aims at transferring obtained knowledge to programs at different phases of development, fostering education and training of future subject-matter experts in the field of rock salt, and cooperating with other NEA working groups (e.g., the Forum on Stakeholder Confidence, FSC) to engender public acceptance and building stakeholder confidence. The Salt Club working group is composed of senior technical experts with experience in assembling or reviewing the understanding of salt formations as host rock for deep geologic disposal projects. Members represent waste management agencies, regulatory authorities, academic institutions, and research and development institutions. Salt Club members have a level of seniority in their organizations such that they are able to mobilize resources to contribute to Salt Club initiatives. DOE is a current member of the Salt Club; other members are Sandia National Laboratories (SNL), Los Alamos National Laboratory (LANL), and institutions from Germany, the Netherlands, and Poland.

The club started in 2011 as a NEA working group, comprised of scientists and experts in developing disposal in geologic rock salt formations. The official kick-off meeting for the Salt Club took place on

April 20, 2012, at the OECD NEA headquarters in Paris to discuss initial work activities, schedules and other project details. The Salt Club has the following areas of interest:

- Geomechanical issues (coupled processes, excavation damaged zone (EDZ) behavior, rock mechanic issues, backfilling, sealing and plugging of rooms, drifts, shafts)
- Brine and gas migration
- Actinide and brine chemistry
- Microbial activities in rock salt
- Geochemical issues (radionuclide chemistry, modeling, natural analogs)
- Technical/technological and engineering issues (construction, operation, closure)
- Performance of geotechnical barriers
- Contributions to the Safety Case (e.g. FEP catalog, scenarios, performance assessment issues, uncertainties, use of natural analogs)

Similar to the Clay Club, the Salt Club is not about active R&D collaboration, but rather about providing a regular forum for in-depth discussion and information exchange.

3.5.3 NEA's Thermochemical Database Project

The purpose of the international Thermochemical Database Project (TDB) is to make available a comprehensive, internally consistent, quality-assured and internationally recognized chemical thermodynamic database of selected chemical elements, in order to meet the specialized modeling requirements for safety assessments of radioactive waste disposal systems. The unique feature of the TDB project is that the data are evaluated and selected by teams of leading experts drawn from universities and research institutes around the world, through a critical review of the existing primary experimental sources. Detailed TDB reports document the process leading to the selected values. Participating countries are as follows: Belgium, Canada, Czech Republic, Finland, France, Germany, Japan, Spain, Sweden, Switzerland, United Kingdom, and the United States.

The project has operated in five phases over almost two decades. During the first part of the project, a high priority was assigned to the critical evaluation of the data of inorganic compounds and complexes of the actinides uranium, americium, neptunium, and plutonium, as well as the inorganic compounds and complexes of technetium. The second phase provided for further needs of the radioactive-waste-management programs by updating the existing database and applying the TDB methodology to new elements present in radioactive waste (as fission or activation products): nickel, selenium and zirconium, and also simple organic complexes. The third phase started in 2003, with three new reviews on thorium, tin, and iron (part 1), and with the constitution of an expert team for the preparation of guidelines for the evaluation of thermodynamic data for solid solutions. The fourth phase (2008-2013), included three reviews concerning molybdenum, iron (part 2) and ancillary data, and the initiation of two state-of-the-art reports on cement minerals and high-ionic-strength solutions. The program for the current fifth phase (2014-2018) of the Thermochemical Database (TDB) Project comprises the following activities:

- Completion of the reviews from the fourth phase
- Preparation of an update of the phase II actinide volumes, including technetium
- Preparation of a state-of-the-art report on the thermodynamic properties of cement minerals
- Preparation of a state-of-the-art report on thermodynamic considerations for actinides in high-ionic-strength solutions

DOE has been participating in the TDB Project for a while, and is currently represented by scientists from Lawrence Livermore National Laboratory.

4. BILATERAL COLLABORATION OPPORTUNITIES

Access to data from international field experiments and participation of UFD researchers in collaborative field studies can also be facilitated via direct informal or semi-formal agreements between national laboratories and international partners. Several UFD scientists have close relationships with their international counterparts, resulting from workshops and symposia meetings, or from collaboration outside of UFD's scope. International disposal programs are aware of the technical capabilities of UFD scientists and are generally quite open to including them in their ongoing research teams. This may require (MoUs) or other types of bilateral agreements. The U.S. DOE has several such bilateral agreements in place, among those the Joint Fuel Cycle Studies (JFCS) agreement with the Republic of Korea, with the German Federal Ministry of Education and Research (BMWi), with Japan under the JNEAP (Joint U.S.–Japan Nuclear Energy Action Plan) agreement, and with France as a result of a recent MoU with ANDRA. The subsections below give a short description of selected bilateral collaboration opportunities (providing access to valuable data and major field experiments). The first two opportunities with the Republic of Korea and Germany have already resulted in close collaborative research work between UFD scientists and their international counterparts; the others describe opportunities for future collaboration. This list will be amended and updated as new opportunities arise.

4.1 Experiments at KURT URL, Republic of Korea

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. KURT stands for KAERI Underground Research Tunnel, with KAERI being the Korea Atomic Energy Research Institute. Using KURT, KAERI intends to obtain information on the geologic environment and the behavior and performance of engineered barriers under repository conditions. KURT has a total length of 255 m with a 180 m long access tunnel and two research modules with a total length of 75 m. The maximum depth of the tunnel is 90 m from the peak of a mountain. The horseshoe shape tunnel is 6 m wide and 6 m high (Figure 4-1). The tunnel construction at KURT started in March 2005 and was completed in November 2006. An expansion of the tunnel is currently under way and expected to be completed in November 2014. Figure 4-2 shows a preliminary design of the expansion, which would allow for additional several hundred meters of tunnel length for further site characterization and *in situ* testing. The host rock is granite, which is one of the potential host rock types for an HLW disposal repository in Korea. The utilization of radioactive material in KURT is not allowed.

Compared to other URLs, including those discussed in Section 3 and Section 4 above, KURT is a relatively new facility. The first 5-year research phase started in 2006 after successful completion of the facility. Past or current research works has included (1) geologic characterization and long-term monitoring, (2) development and testing of site investigation techniques, (3) solute and colloid migration experiments, (4) EDZ characterization, (5) borehole heater tests, and (6) investigation of correlation between streaming potential (Section 6.2.2) and groundwater flow (Figure 4-3). A second 5-year research phase, which started in 2012, comprises additional site characterization work related to the tunnel expansion and *in situ* long-term performance tests on a 1/3 scale engineered barrier system at KURT. The focus of the site characterization work is a major water-conducting feature (MWCF), which was initially identified from surface boreholes and which will soon be accessed from the new expansion tunnels. The hydrogeological, geochemical, and transport properties of the MWCF will be characterized, before, during, and after excavation.

The KURT site offers one unique feature with regards to *in situ* borehole characterization and deep borehole disposal R&D. The site hosts an existing deep (1 km) borehole drilled into granitic bedrock, which provides a unique opportunity for developing and testing techniques for *in situ* borehole characterization in fractured crystalline rocks. The DB-2 borehole was drilled from the surface to a depth just outside of the KURT facility (Figure 4-4) to better understand the deep geologic, hydrogeological, and chemical characteristics around the KURT site, and to specifically explore the MWCF. The deep borehole could offer possibilities of collaboration regarding deep borehole disposal concepts. The Republic of Korea and KAERI are interested in further exploration of deep borehole disposal concepts.

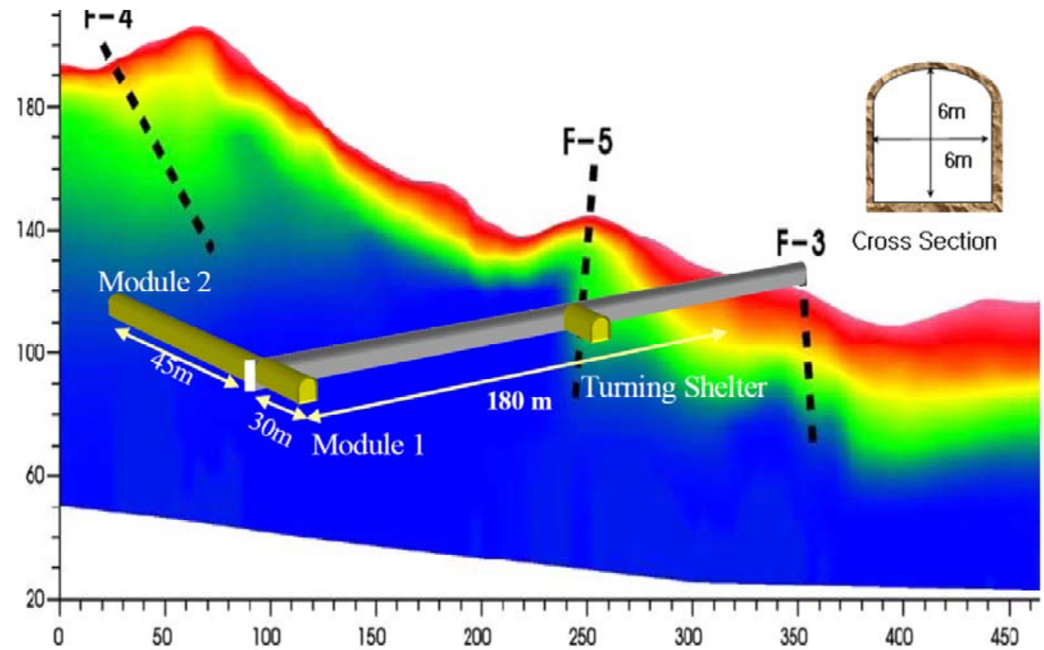


Figure 4-1. Current layout of the KURT URL in Daejeon, Korea (from KAERI, 2011)

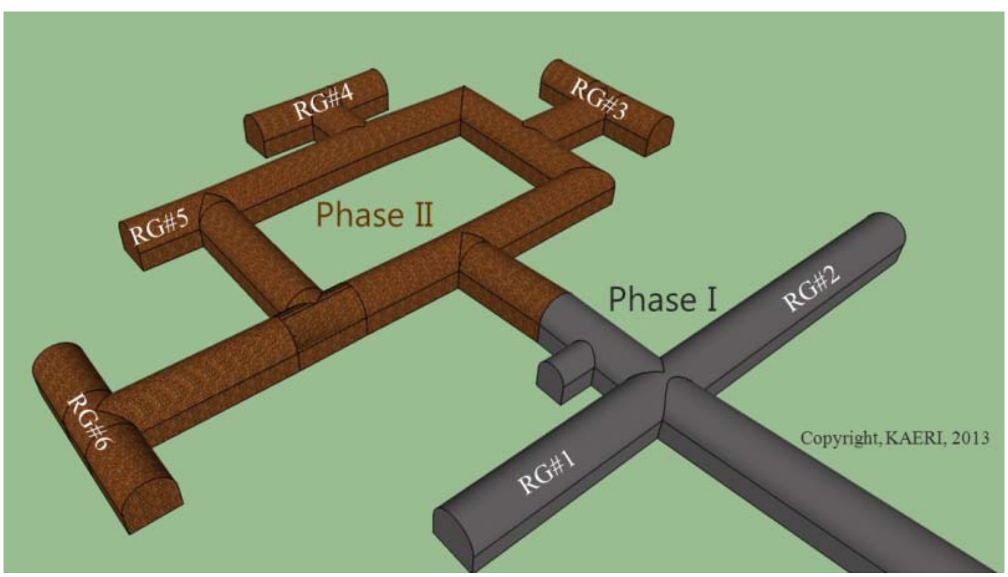


Figure 4-2. Preliminary layout for tunnel extension of KURT (from Wang et al., 2014)

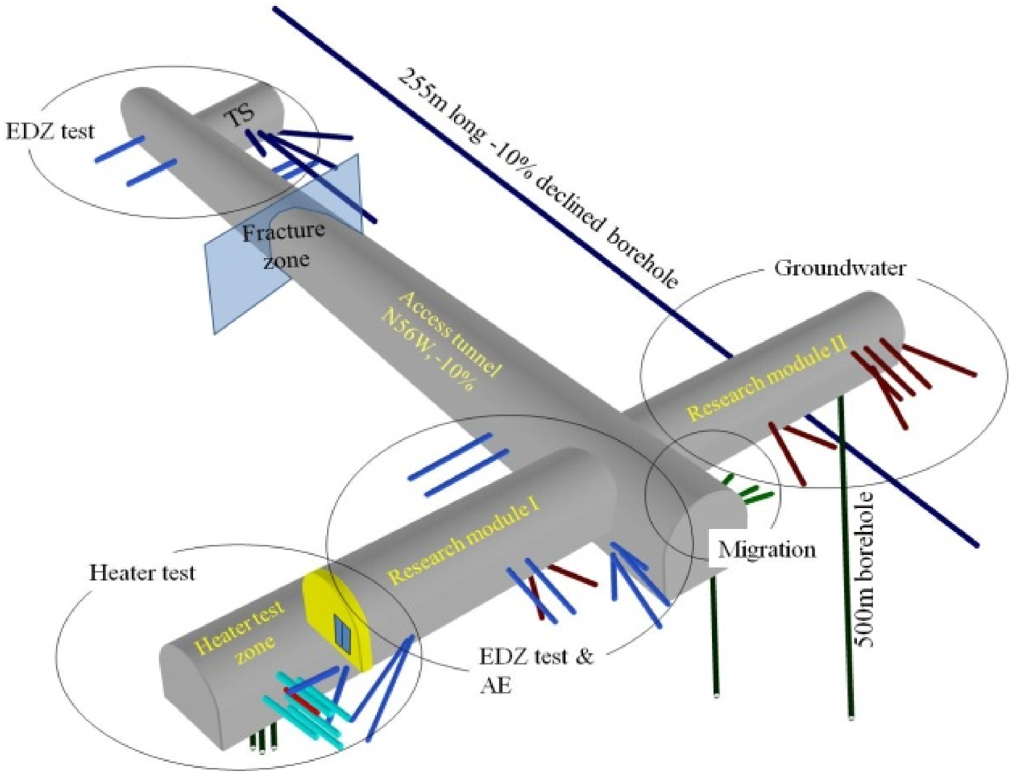


Figure 4-3. Location of *in situ* tests and experiments with related boreholes at KURT (from Wang et al., 2014)

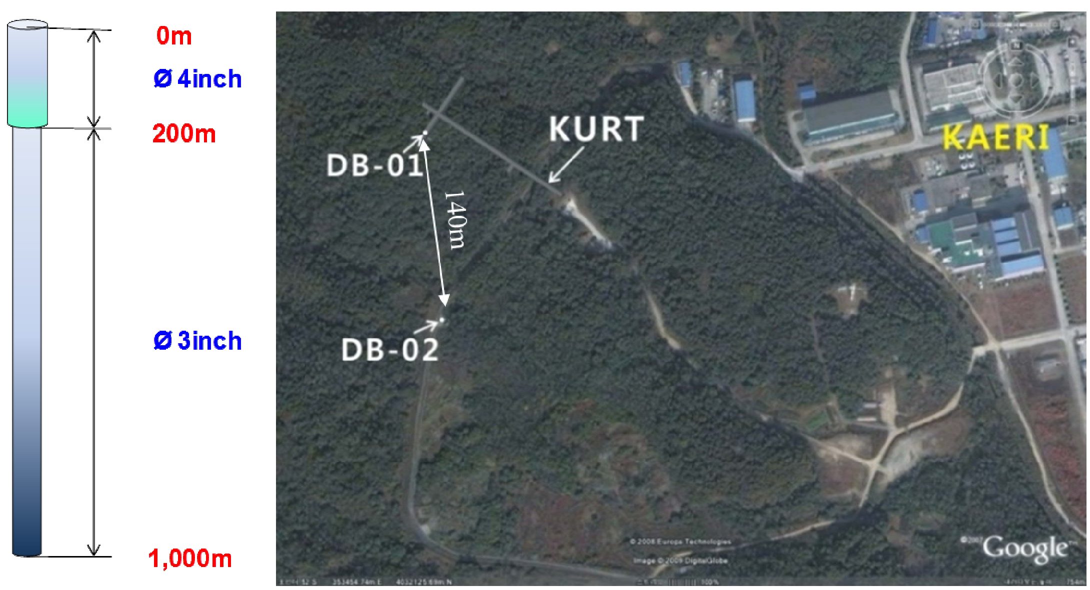


Figure 4-4. Specification of DB-2 borehole and its location near KURT site (from Wang et al., 2014)

In general, KAERI is open to international collaboration and is looking for new ideas and experimental designs for future tests. A few years ago, a formal commitment to collaboration on the management of nuclear fuel was established between the United States and the Republic of Korea (ROK). The agreement, called the Joint Fuel Cycle Studies (JFCS), between the U.S. Department of Energy, the ROK Ministry of Education, Science & Technology, and the ROK Ministry of Knowledge Economy, focuses mainly on three areas of fuel-cycle technologies (electrochemical recycling, safeguards, and fuel cycle alternatives), but has also some research elements related to geologic disposal. Researchers at SNL and KAERI have developed a multi-year plan for joint field testing and modeling to support the study of high-level nuclear waste disposal in crystalline geologic media, which includes sharing of KURT site characterization data. There are two specific collaborative tasks, as follows: (1) streaming potential (SP) testing regarding correlation with groundwater flow, and (2) technique development for *in situ* borehole characterization. For Task 1, KAERI and SNL have completed the experimental design and conducted a first set of preliminary laboratory tests. *In situ* testing is planned at KURT once the extension is completed. For Task 2, KAERI and SNL have developed a roadmap for the development of site-characterization techniques in fractured crystalline rocks, especially the *in situ* hydrological and geochemical measurements in boreholes. More detail on these collaborative tasks is given in Section 6.2.2.

4.2 Salt Research Collaboration with German Researchers

DOE/UFD scientists and their German colleagues in academia and other research laboratories collaborate closely on various R&D issues related to disposal of radionuclide waste in salt. A MoU was signed a few years ago between DOE and the German Federal Ministry of Economics and Technology (BMWi) to cooperate in the field of geologic disposal of radioactive wastes (MoU date: November 2011). Four U.S. –German Salt workshops have been held so far to advance collaboration, starting with a preparatory workshop on May 25–27, 2010, in Jackson Mississippi, followed by Peine, Germany, (November 9–10, 2011), Albuquerque, New Mexico (October 8–11, 2012), and Berlin, Germany (September 16–17, 2013) (Hansen et al., 2013). The overriding premise for U.S./German collaborations is to advance the scientific basis for salt repositories. Today, scientists from both countries have started cooperative work in several areas, including coupled-salt-mechanics modeling, safety case aspects, plugging and sealing of a salt repository, and repository design (see Section 7.1). As opposed to argillite or crystalline host rocks, the United States has an operating repository for transuranic waste, the Waste Isolation Pilot Plant (WIPP), which could be made available for generic R&D on disposal of high-level waste in a bedded salt formation. Germany, on the other hand, is currently not in a position of continued work in its URLs, despite having a long history of conducting field experiments at the Gorleben or Asse salt domes. Therefore, some of the collaborative discussions between U.S./German scientists include potential uses of an underground research space to be developed at the Waste Isolation Pilot Plant (WIPP).

Germany has a long history of salt R&D. The country started in 1979 to conduct exploration work at the Gorleben salt dome to evaluate its suitability for waste disposal (Figure 4-5). However, a moratorium on further exploration at the Gorleben site was imposed in 2000, mainly due to political controversy. While the moratorium has now been lifted, R&D activities at Gorleben have not yet resumed, and it is questionable whether and when further underground testing at this URL might be conducted. Another mine, the Asse II mine, was also used as a research space in the past, between 1965 and 1995, with some major experiments such as the long-term TSDE (*Thermal Simulation for Drift Emplacement*) experiment. As shown in Figure 4-6, the TSDE experiment comprised two parallel drifts, each of which housing three electrical heaters to simulate emplacement of heat-producing waste. A significant amount of data was collected over several years in 20 monitoring cross sections: temperature, stress changes, displacement, convergence, and porosity of crushed salt, among others. Data from the TDSE experiment are currently used by UFD scientists to validate the large-scale applicability of coupled THM models (Rutqvist et al., 2014b). Note that between 1967 and 1978, low-level and intermediate-level radioactive waste was placed in storage in other parts of the Asse II mine. Research was eventually stopped; between 1995 and 2004, all underground tunnels and cavities were filled with salt. Today, the Asse II mine is the subject of major controversy because of security concerns regarding water inflow and salt stability.

Figure 4-5. View of one of the underground tunnels at Gorleben site at the 840 m level (from BMWi, 2008)

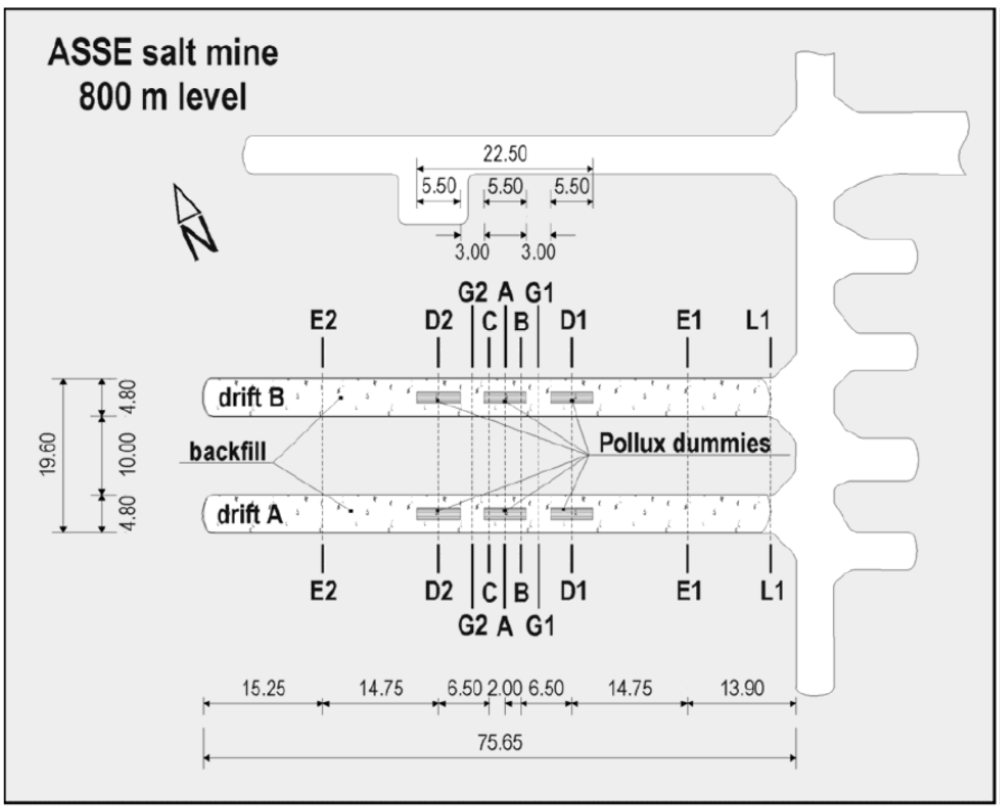


Figure 4-6. Schematic view of the two drift tests used in the TSDE experiment (800 m level of the Asse salt mine) (from Ruqvist et al., 2014)

4.3 Collaboration Opportunities at ANDRA's LSMHM URL, France

The major underground disposal research facility in France is ANDRA's LSMHM URL sited near Bure in the Meuse and Haute-Marne districts in the east of France, co-located with the proposed French disposal site Cigeo. R&D at Bure aims at studying the feasibility of reversible geologic disposal of high-level and long-lived intermediate-level radioactive waste in the Callovo-Oxfordian clay formation. This facility was licensed in August 1999, and its construction (access shafts, basic drift network with underground ventilation) was finalized in 2006. As shown in Figure 4-7, the URL consists of two shafts sunk down to a depth of about 500 m. A network of about 900 m of tunnels and drifts is used for various scientific experiments, engineering technological demonstrations, and the testing of industrial solutions for construction and operation (Figure 4-8). A recent MoU between ANDRA and DOE can be a starting point for collaborative work in clay/shale disposal at the Bure URL, though currently there are no ongoing joint R&D projects between U.S. and French scientists related to the Bure URL.

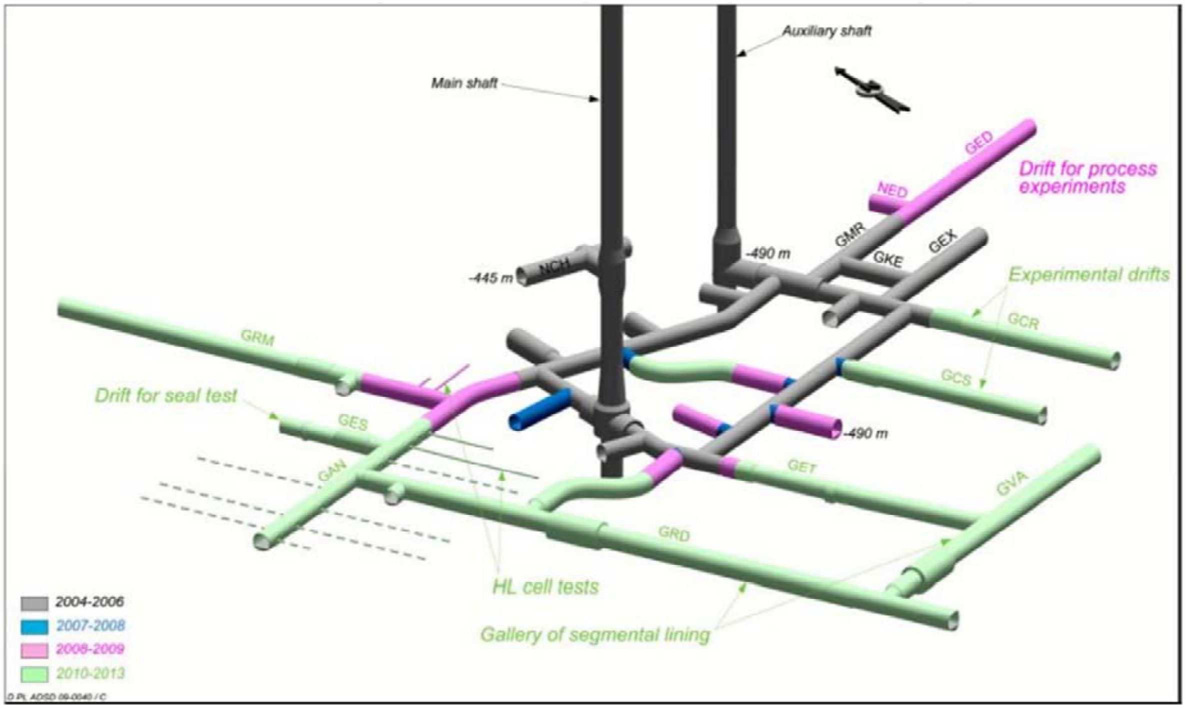


Figure 4-7. Layout of the LSMHM URL at Bure, France (from Lebon, 2011)

Figure 4-8. LSMHM URL at Bure, France
(from http://www.andra.fr/download/andra-international-en/document/355VA-B.pdf)

4.4 Collaboration Opportunities with JAEA's URLs in Japan

Opportunities for active collaborative R&D with Japan exist not only at the Horonobe URL in sedimentary rock (see Section 3.1.5), but also at this nation's second URL at the Mizunami Underground Research Laboratory, which resides in crystalline rock (Figure 4-9). Japan and the United States entertain close collaboration on issues related to nuclear energy under the JNEAP (Joint U.S.–Japan Nuclear Energy Action Plan) agreement. JNEAP has a Waste Management Working Group that meets in regular intervals to discuss joint R&D on, among other topics, waste disposal issues. Japanese research institutions are also a frequent partner in many of the cooperative initiatives that DOE has joined in recent years (see Section 3, Table 3.1), and both nations collaborate on the DECOVALEX task featuring JAEA's Horonobe EBS experiment. There are currently no joint activities related to experimental work at the Mizunami URL.

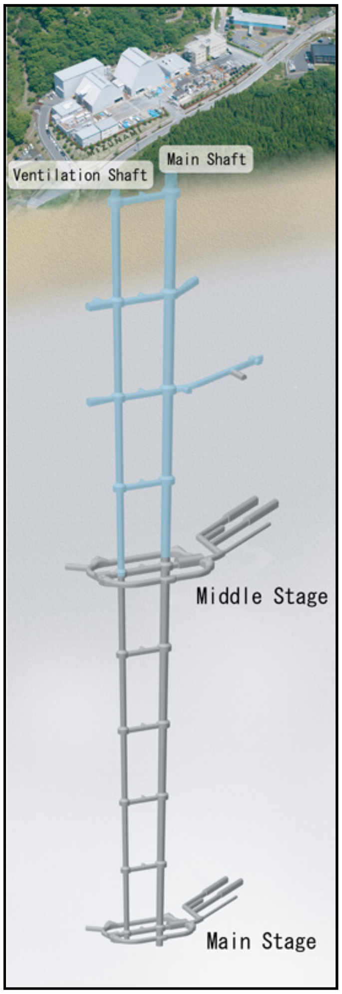


Figure 4-9. Layout of the Mizunami Underground Research Laboratory in Japan, and photo of tunnel shaft construction (from http://www.jaea.go.jp/04/tono/miu_e/)

4.5 Collaboration Opportunities at HADES URL, Belgium

Belgium is another country with a strong R&D program in geologic disposal and a long history of experimental work in an underground research laboratory. The HADES (High Activity Disposal Experimental Site) URL is located in a secured area belonging to one of Belgium's nuclear power plants, which also hosts other nuclear research facilities. HADES is essentially a several-hundred-meter-long tunnel in the soft Boom Clay rock formation, accessible by two shafts located at each end (Figure 4-10). The tunnels were drilled in stages, starting with a first section in 1982, followed by additions in 1987 and 2001. Each of these sections was secured with different types of ground support, reflecting increased knowledge about the structural behavior of the host rock. Most interesting to DOE's program is probably the PRACLAY heater experiment, and to a lesser degree long-term clay diffusion experiments, both of which are discussed in more detail below. The Belgium organizations involved in conducting and interpreting these experiments (SCK/CEN, EIG Euridice, ONDRAF/NIRAS) have long-standing relationships with DOE/UFD scientists; they are open to participation with UFD research groups and have already invited researchers to provide THM modeling expertise to the PRACLAY project team. However, there are currently no joint activities related to the HADES URL.

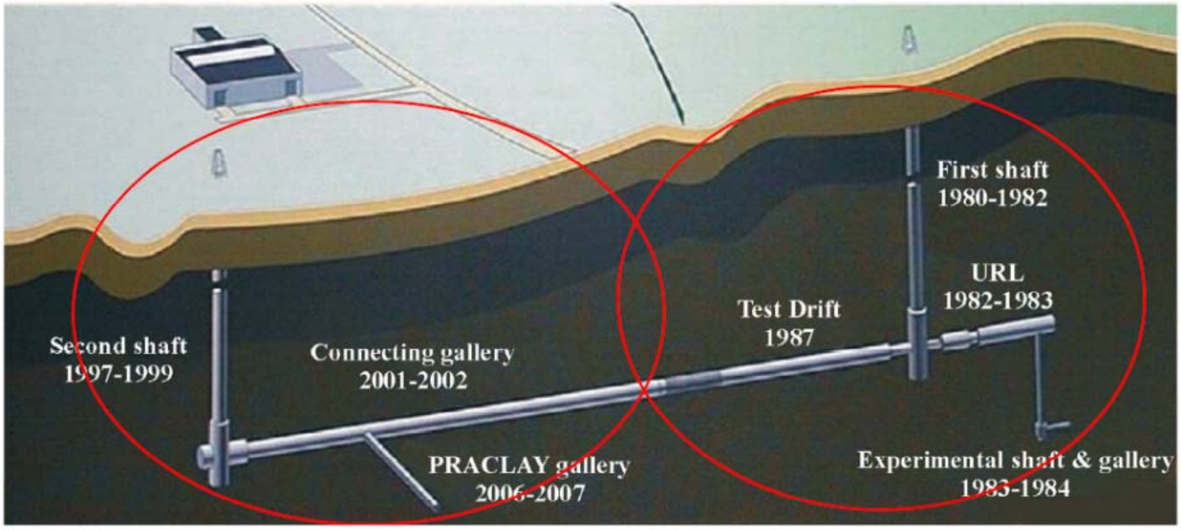


Figure 4-10. Layout of the HADES URL in Mol, Belgium (from Li, 2011)

4.5.1 PRACLAY Test

The PRACLAY Heater Test is a full-scale validation and confirmation experiment conducted at the HADES URL, excavated at 223 m depth in Boom Clay, a tertiary clay formation in Mol, Belgium. The heater test, which starts its heating phase in late 2014, involves a 30 m gallery section heated for 10 years with many monitoring sensors (Figures 4-11, 4-12, and 4-13), for the purpose of investigating the thermo-hydro-mechanical (THM) behavior of near-field plastic clay under the most "mechanically critical" conditions that may occur around a repository (Van Marcke and Bastiaens, 2010). For plastic clay under the influence of temperature change, these are undrained conditions, which then generate a higher pore-pressure increase and a higher possibility of near-field damage. For this objective, a hydraulic seal has been installed at the intersection between the planned heated and unheated sections of the gallery. This installation makes up the Seal Test, which was initiated in 2010, and allows for testing the functionality of the hydraulic seal under heated repository conditions.

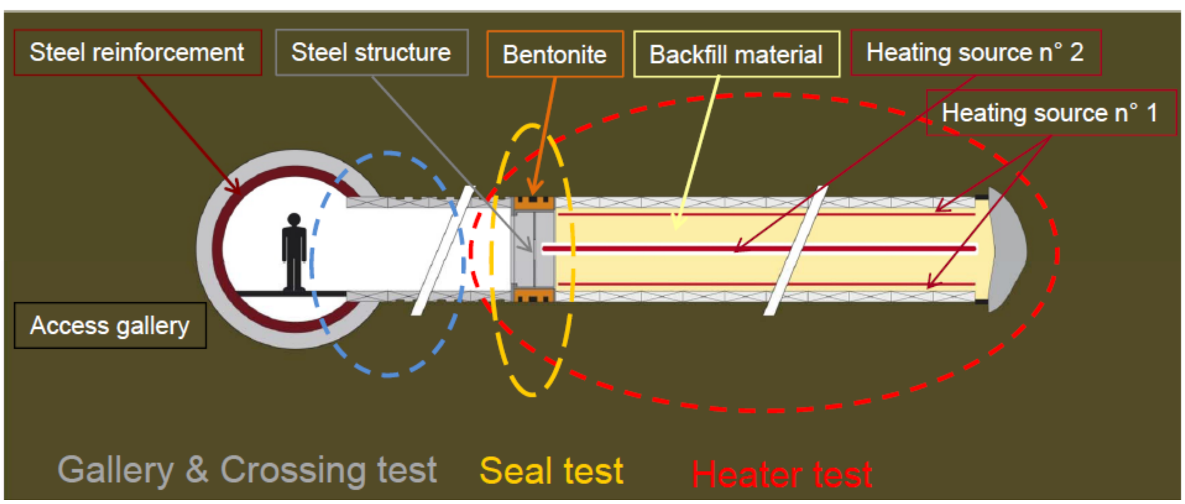


Figure 4-11. Layout of the PRACLAY *in situ* experiment at HADES URL (from Li, 2011)

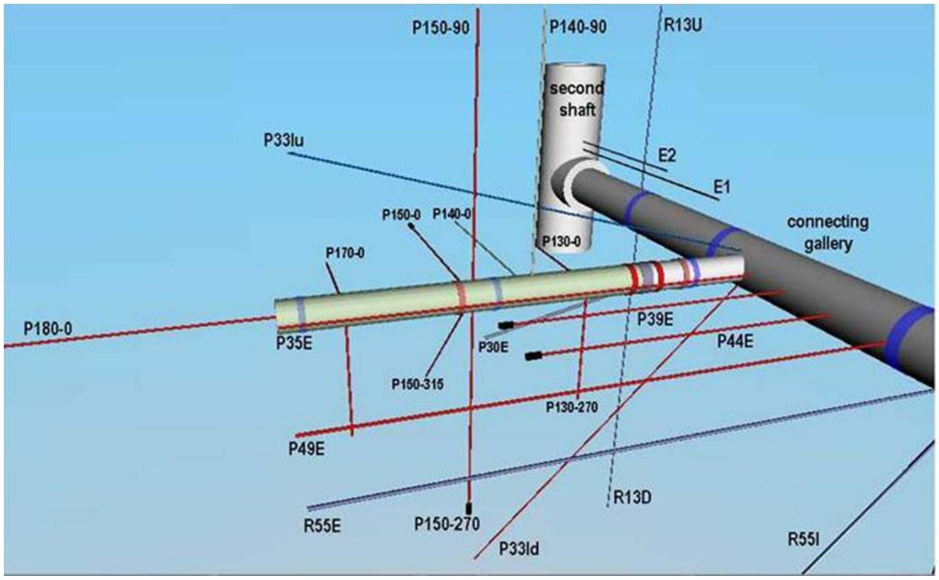


Figure 4-12. PRACLAY *in situ* experiment at HADES URL: Configuration of boreholes for pressure, stress, displacement, and water chemistry measurements (from Li, 2011)

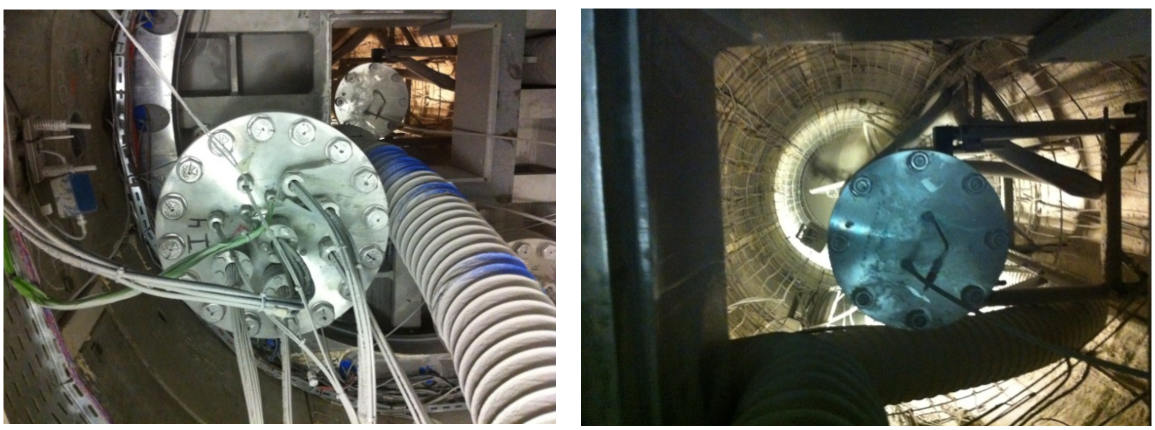


Figure 4-13. PRACLAY *in situ* experiment at HADES URL: Photo on left shows hydraulic seal from the outside, with an access hole to the right which soon will be closed. Photo on right was taken from access hole into the heater gallery section, which is currently being backfilled.

4.5.2 Radionuclide Migration Experiments

The Belgium waste management program has been conducting a suite of long-term radionuclide migration *in situ* experiments in dense clays at their HADES URL near Mol. Two of these experiments, named CP1 (Figure 4-14) and Tribicarb-3D, have been ongoing for 23 and 16 years, respectively, and offer valuable data on the slow diffusion-controlled migration of radionuclides in clay rock. Because of their duration, they offer unique test cases for model and process validation. Recently, two other ongoing large-scale migration experiments were initiated at HADES. The TRANCOM test involves colloid transport with C-14 labeled humic substances. The RESEAL shaft seal experiment investigates transport of iodine-125 through the disturbed zone and the interface between Boom Clay and bentonite.

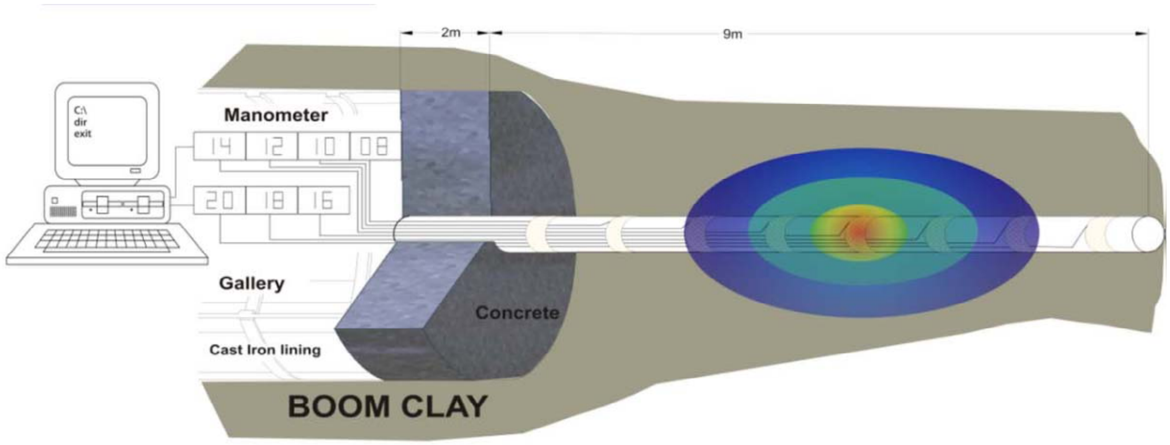


Figure 4-14. Schematic of CP1 Diffusion Experiment at HADES URL (from Maes et al., 2011)

4.6 Collaboration Opportunities at Onkalo URL, Finland

The Onkalo URL in Finland is located at a site chosen to potentially co-host a repository. Thus, it is not only an underground research laboratory, but also an underground characterization facility. It is constructed in crystalline bedrock to the anticipated repository depth of 430–440 m. Construction began in 2004 and is ongoing, but actual underground tests were already started in 2007. Figure 4-15 shows the layout of the URL, with an access tunnel and three shafts. The access tunnel takes the form of a spiral on an approximately 1 in 10 incline downward, and reaches the technical facilities level at about 437 m. The three shafts consist of one personnel shaft and two ventilation shafts. Details may be found in Posiva (2011) and Aalto et al. (2009). There are currently no joint activities between DOE and the Finnish waste management program related to the Onkalo URL.

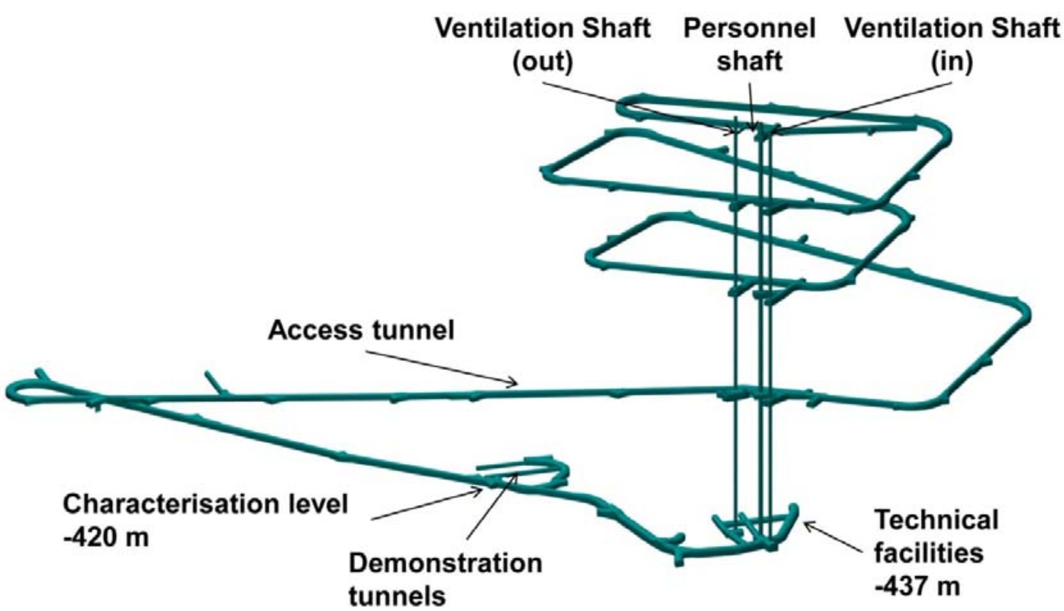


Figure 4-15. Layout of the Onkalo URL in Finland (from Äikäs, 2011)

5. SELECTION OF INTERNATIONAL COLLABORATION TASKS

As discussed in Sections 3, DOE joined five multinational and multipartner initiatives that promote active international collaboration with specific focus on URL field experiments and related data: the DECOVALEX project, the Mont Terri Project, the Colloid Formation and Migration Project, the FEBEX-DP Project, and the SKB Task Forces. UFD researchers are now in a position that allows participation in planning, conducting, and interpreting the many past and ongoing field experiments associated with these five initiatives, and they do so in close collaborative partnership with international scientists. DOE also reached out to—and explored options of collaboration with—individual international disposal programs, such as the Republic of Korea's KAERI, Germany's BMWi, France's ANDRA, Japan's JAEA, Belgium's SCK/CEN, and Finland's POSIVA (Section 4).

With many collaboration opportunities available to UFD, the campaign in FY12 started a planning exercise to identify the most relevant and promising ones, and to select and develop a set of activities that align with current goals, priorities, and funding plans of the UFD. In a general sense, the benefits of international collaboration are obvious: UFD can gain substantial value from the knowledge, data, and modeling capabilities that international partners have developed over decades of research. However, the benefit of international collaboration needs to be evaluated 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 previous progress 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 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]).

A summary table was developed to provide a basis for planning and selection of international activities. Table 5-1 below is an updated version of this summary table; it lists the most relevant ongoing or planned field experiments conducted in international URLs, provides information on how UFD participation can be achieved, which research areas would be the main benefactor (generally either the Engineered barrier System, EBS, or Natural Barrier System, EBS), the key FEPs addressed (including a link to roadmap and FEPs importance ranking; using the *Used Fuel Disposition Campaign Disposal Research and Development Roadmap, FCRD-USED-2011-000065 Rev 0, March 2011* [Nutt, 2011]), and finally information on the experimental schedules.

Three workshops were held in FY11 and FY12 to inform the DOE leadership and UFD scientists about existing or future international opportunities, and align UFD work-package activities with international initiatives. The first workshop was a session held in conjunction with the UFD Working Group Meeting in Las Vegas, July 12–14, 2011, at this point mostly for informative purposes. The second workshop, held in Las Vegas on April 11, 2012, was a full-day meeting to review the current and planned work scope within UFD work packages for possible leveraging with the international programs, and to develop an initial set of R&D activities that align with goals, priorities, and funded plans of the UFD program. A third workshop was a session held in conjunction with the UFD Working Group Meeting in Las Vegas, May 15–17, 2012, to inform UFD researchers about the outcome of the full-day planning workshop.

Today, two years after its initiation, the international disposal program within UFD has established a balanced portfolio of selected collaborative R&D activities in disposal science, addressing relevant R&D challenges and open research questions as follows:

- 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? In a clay host rock, can bentonite mixtures be developed that allow for gas pressure release while maintaining sealing properties for water? In fractured granite, 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 granites 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?
- Demonstration of Integrated System Behavior: Can the behavior of an entire repository system, including all engineered and natural barriers and their interaction, be demonstrated, and is the planned construction/emplacement method feasible?

Table 5-2 summarizes the FY14 portfolio of UFD activities related to relevant ongoing or planned experiments in international URLs. As described in the following sections, these selected activities have made significant advances over the past two years. The joint R&D with international researchers and the access to relevant data/experiments from a variety of URLs and host rocks have helped UFD researchers to significantly improve their understanding of the current technical basis for disposal in a range of potential host-rock environments and has contributed to testing and validating predictive computational models for evaluation of disposal-system performance in a variety of generic disposal-system concepts.

In FY15, UFD will make an effort to re-evaluate its international research portfolio, in a process similar to the initial planning phase in 2012. As research priorities and boundary conditions change, and as new opportunities for collaboration develop, one objective will be to reassess the relevance of ongoing activities in light of new possibilities for cooperation. Another discussion point will be whether DOE/UFD should move from a mostly participatory role in ongoing URL experiments conducted by other nations, to a more active role in developing its own experimental program specifically tailored to its needs. Some collaborative initiatives like the Mont Terri Project definitely provide the opportunity to project partners, such as DOE, to conduct their own experimental work. As mentioned earlier in this document, other international partners can be found if the proposed work aligns well with the interests 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.

Table 5-1. Participation of International Programs in Cooperative Initiatives Related to URLs: Status September 2014. The FEP ranking is based on Tables 7 and 8 in Nutt (2011). Table entries are sorted by URLs.

URL	Relevant Ongoing or Planned Experiments (Selected)	Cooperation Mode	Main Focus	FEPs Ranking	Test Period
Mont Terri, Switzerland (Opalinus Clay)	FE: Full-scale heater test demonstration experiment	Via Mont Terri Project	Both EBS and NBS NBS: Many aspects of near-field shale repository evolution, such as EDZ creation, desaturation and resaturation, thermal effects, pore-pressure increase after backfilling and heating EBS: Performance of EBS backfilling and lining technology	Geosphere FEPS (for shale): 2.2.01: Excavation Disturbed Zone (EDZ) >> High (Shale) 2.2.07: Mechanical Processes >> Medium (Shale) 2.2.08: Hydrologic Processes >> Medium (Shale) 2.2.11: Thermal Processes >> Medium (Shale) Engineered System FEPS: Buffer/Backfill materials 2.1.04.01: Buffer/Backfill >> High 2.1.07.02, .03., .04., .09: Mechanical Processes >> Medium 2.1.08.03, .07, .08: Hydrological Processes >> Medium 2.1.11.04: Thermal Processes >> Medium Engineered System FEPS: Seal/liner materials 2.1.05.01: Seals >> Medium 2.1.07.02, .08., .09: Mechanical Processes >> Medium 2.1.08.04, .05, .07, .08, .09: Hydrological Processes >> Low	Test is in final installation stage; heating to start in early 2015
Mont Terri, Switzerland	HE-E: Half-scale heater test in VE test section (VE = Ventilation Experiment)	Via DECOVALEX Project	Mostly EBS EBS: Non-isothermal resaturation behavior in bentonite backfill NBS: Interaction of near-field shale rock with EBS components	Geosphere (for shale): 2.2.01: Excavation Disturbed Zone (EDZ) >> High (Shale) 2.2.07: Mechanical Processes >> Medium (Shale) 2.2.08: Hydrologic Processes >> Medium (Shale) 2.2.11: Thermal Processes >> Medium (Shale) 2.2.09: Chemical Processes - Transport >> Medium-High Engineered System FEPS: Buffer/Backfill materials 2.1.04.01: Buffer/Backfill >> High 2.1.07.02, .03., .04., .09: Mechanical Processes >> Medium 2.1.08.03, .07, .08: Hydrological Processes >> Medium 2.1.11.04: Thermal Processes >> Medium	Heating phase: June 2011 through 2018
Mont Terri, Switzerland	MB: Mine-by Test for full-scale HM validation	Via Mont Terri Project	NBS Excavation-generated response in the argillaceous clay host rock near a mined tunnel, including changes in the near-field hydrologic properties	Geosphere FEPS (for shale): 2.2.01: Excavation Disturbed Zone (EDZ) >> High (Shale) 2.2.07: Mechanical Processes >> Medium (Shale) 2.2.08: Hydrologic Processes >> Medium (Shale)	2008 – 2009

URL	Relevant Ongoing or Planned Experiments (Selected)	Cooperation Mode	Main Focus	FEPs Ranking	Test Period
Mont Terri, Switzerland	HG-A: Gas path host rock and seals	Via Mont Terri Project	Mostly NBS Investigation of EDZ as preferential flow path for gases generated from corrosion	Geosphere FEPS (for shale): 2.2.01: Excavation Disturbed Zone (EDZ) >> High (Shale) 2.2.08: Hydrologic Processes >> Medium (Shale) 2.2.12: Gas sources and effects >> Low	Ongoing since 2006 in various stages with hydraulic and gas injection tests
Mont Terri, Switzerland	DR-A: Diffusion, retention and perturbations	Via Mont Terri Project	NBS Long-term diffusion behavior of sorbing and non-sorbing radionuclides in clay	Geosphere FEPS (for shale) 2.2.05: Flow and Transport Pathways >> Medium (Shale) 2.2.08: Hydrologic Processes >> Medium (Shale) 2.2.09: Chemical Processes - Transport >> Medium (Shale)	2011 - 2013
Grimsel Test Site, Switzerland	CFM: RN tracer test	Via CFM Project	NBS Transport behavior of a tracer/radionuclide “cocktail” in a shear zone. Test includes conservative tracers, weakly sorbing solutes, strongly sorbing solutes and bentonite colloids	Geosphere FEPS (for crystalline rock) 2.2.05: Flow and Transport Pathways >> Medium (Crystalline) 2.2.08: Hydrologic Processes >> Low (Crystalline) 2.2.09: Chemical Processes - Transport >> Medium (Crystalline)	Several tests in 2009 through 2012
Grimsel Test Site, Switzerland	CFM: RN-Doped Plug Experiment	Via CFM Project	NBS: Similar to above test, but this time involving at radionuclide-doped bentonite plug which erodes and induces colloid-facilitated transport	Geosphere FEPS (for crystalline rock) 2.2.05: Flow and Transport Pathways >> Medium (Crystalline) 2.2.08: Hydrologic Processes >> Low (Crystalline) 2.2.09: Chemical Processes - Transport >> Medium (Crystalline) Engineered System FEPS: Buffer/backfill materials 2.1.04.01: Buffer/Backfill >> High 2.1.09.51-59, .61: Chemical Processes -Transport >> Low to Medium	Started in May 2014
Grimsel Test Site, Switzerland	FEBEX-DP: Full-scale heater test dismantling project	Via FEBEX-DP Project	Mostly EBS Long-term performance of the bentonite backfill 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	Engineered System FEPS: Buffer/Backfill materials 2.1.04.01: Buffer/Backfill >> High 2.1.07.02, .03., .04., .09: Mechanical Processes >> Medium 2.1.08.03, .07, .08: Hydrological Processes >> Medium 2.1.11.04: Thermal Processes >> Medium Geosphere FEPS (for crystalline rock) 2.2.01: Excavation Disturbed Zone (EDZ) >> Medium (Crystalline) 2.2.07: Mechanical Processes >> Low (Crystalline) 2.2.08: Hydrologic Processes >> Low (Crystalline) 2.2.11: Thermal Processes >> Low (Crystalline)	Heater test ongoing since 1997; dismantling to be conducted in Summer 2015

URL	Relevant Ongoing or Planned Experiments (Selected)	Cooperation Mode	Main Focus	FEPs Ranking	Test Period
Grimsel Test Site, Switzerland	GAST: Gas permeable seal experiment	Possibly via MoU with NAGRA	EBS Demonstrate the performance of repository seals and to improve the understanding of water and gas transport through these sealing systems. The experiment involves specially designed backfill and sealing materials such as high porosity mortars or sand/bentonite (S/B) mixtures.	Engineered System FEPS: Buffer/Backfill materials 2.1.04.01: Buffer/Backfill >> High 2.1.08.03, .07, .08: Hydrological Processes >> Medium 2.1.12.01, .02, .03: Gas sources and effects >> Medium	2010 - 2015
Äspö Hard Rock Laboratory, Sweden	BRIE: Bentonite rock interaction experiment	Via SKB Task Forces	Both NBS and EBS Understand the exchange of water and potential bentonite erosion at the interface between backfill and flowing fractures	Engineered System FEPS: Buffer/Backfill materials 2.1.04.01: Buffer/Backfill >> High 2.1.08.03, .07, .08: Hydrological Processes >> Medium Geosphere FEPS (for crystalline rock) 2.2.05: Flow and Transport Pathways >> Medium (Crystalline) 2.2.08: Hydrologic Processes >>Low (Crystalline)	Ongoing since 2012
Äspö Hard Rock Laboratory, Sweden	LTDE-SD: Long-term sorption diffusion experiment	Via SKB Task Forces	NBS Diffusion and sorption in a conducting fracture and adjacent matrix (sorbing and non-sorbing tracers)	Geosphere FEPS (for crystalline rock) 2.2.05: Flow and Transport Pathways >> Medium (Crystalline) 2.2.08: Hydrologic Processes >>Low (Crystalline) 2.2.09: Chemical Processes - Transport >> Medium (Crystalline)	Completed in 2010 with 6 months test duration
Äspö Hard Rock Laboratory, Sweden	Prototype Repository: full-scale prototype tunnels with six deposition holes	Via SKB Task Forces	Mostly EBS, also NBS Demonstration of the integrated function of the repository and a full-scale reference for test of predictive models concerning individual components as well as the complete repository system. Includes heaters and backfill.	Geosphere FEPS (for shale): 2.2.01: Excavation Disturbed Zone (EDZ) >> High (Shale) 2.2.07: Mechanical Processes >> Medium (Shale) 2.2.08: Hydrologic Processes >> Medium (Shale) 2.2.11: Thermal Processes >> Medium (Shale) Engineered System FEPS: Buffer/Backfill materials 2.1.04.01: Buffer/Backfill >> High 2.1.07.02, .03., .04., .09: Mechanical Processes >> Medium 2.1.08.03, .07, .08: Hydrological Processes >> Medium 2.1.11.04: Thermal Processes >> Medium	Since 2001. Outer test section opened and retrieved in 2011.

URL	Relevant Ongoing or Planned Experiments (Selected)	Cooperation Mode	Main Focus	FEPs Ranking	Test Period
Tournemire, France	SEALEX: Long-time sealing experiment for different materials	Via DECOVALEX	Mostly EBS Long-term isothermal HM(C) behavior and hydraulic performance of swelling clay-based seals	Engineered System FEPS: Seal/liner materials 2.1.05.01: Buffer/Backfill >> Medium 2.1.07.02, .08., .09: Mechanical Processes >> Medium 2.1.08.04, .05, .07, .08, .09: Hydrological Processes >> Medium (Flow through seals) 2.1.09.01, .03, .09, .13: Chemical Processes - Chemistry >> Medium	2011 - 2015
Bedrichov Tunnel, Czech Republic	Flow patterns and tracer transport in fractured granite	Via DECOVALEX	NBS Flow patterns and tracer transport behavior within fractured crystalline rock	Geosphere (for crystalline rock): 2.2.02: Host Rock Properties >> High (Crystalline) 2.2.05: Flow and Transport Pathways >> Medium (crystalline) 2.2.08: Hydrologic Processes >> Medium (Crystalline)	Hydrogeologic characterization and monitoring ongoing
Horonobe URL, Japan	EBS experiment: Vertical heater and buffer test (planned)	Via DECOVALEX	Mostly EBS EBS: Non-isothermal resaturation behavior in bentonite backfill NBS: Interaction of near-field shale rock with EBS components	Geosphere (for shale): 2.2.01: Excavation Disturbed Zone (EDZ) >> High (Shale) 2.2.07: Mechanical Processes >> Medium (Shale) 2.2.08: Hydrologic Processes >> Medium (Shale) 2.2.11: Thermal Processes >> Medium (Shale) Engineered System FEPS: Buffer/Backfill materials 2.1.04.01: Buffer/Backfill >> High 2.1.07.02, .03., .04., .09: Mechanical Processes >> Medium 2.1.08.03, .07, .08: Hydrological Processes >> Medium 2.1.11.04: Thermal Processes >> Medium	Start of heating phase in late 2014
KURT URL, Korea	Streaming potential (SP) testing and correlation with groundwater flow	Via MoU with KAERI	NBS: Flow patterns in fractured crystalline rock	Geosphere (for crystalline rock): 2.2.02: Host Rock Properties >> High (Crystalline) 2.2.05: Flow and Transport Pathways >> Medium (crystalline) 2.2.08: Hydrologic Processes >> Medium (Crystalline)	*In situ* testing will be conducted once the KURT extension is complete, probably in 2015
KURT URL, Korea	Development of techniques for *in situ* borehole characterization and monitoring	Via MoU with KAERI	NBS: Relevance to deep borehole disposal	Geosphere FEPS (for borehole): 2.2.01: Excavation Disturbed Zone (EDZ) >> High (Borehole) 2.2.07: Mechanical Processes >> Low (Borehole) 2.2.08: Hydrologic Processes >> Medium (Borehole) 2.2.11: Thermal Processes >> Medium (Borehole) 2.2.09: Chemical Processes - Chemistry >> Medium-High (Borehole) 2.2.09: Chemical Processes - Transport >> Medium-High (Borehole) 2.2.02: Host Rock (properties) >> High (Borehole) 2.2.05. Flow and Transport Pathways >> Medium (Borehole)	Ongoing

URL	Relevant Ongoing or Planned Experiments (Selected)	Cooperation Mode	Main Focus	FEPs Ranking	Test Period
HADES URL, Belgium	PRACLAY: Full-scale seal and heater experiment	Possibly via bilateral collaboration with SCK/CEN	Mostly NBS Many aspects of near-field boom clay repository evolution, such as EDZ creation, desaturation and resaturation, thermal effects, pore-pressure increase after backfilling and heating	Geosphere FEPS (for shale): 2.2.01: Excavation Disturbed Zone (EDZ) >> High (Shale) 2.2.07: Mechanical Processes >> Medium (Shale) 2.2.08: Hydrologic Processes >> Medium (Shale) 2.2.11: Thermal Processes >> Medium (Shale)	Heating phase to start late 2014
HADES URL, Belgium	RN Migration: Long-running RN diffusion tests	Possibly via bilateral collaboration with SCK/CEN	NBS Diffusion-controlled migration of radionuclides in clay rocks	Geosphere FEPS (for shale) 2.2.05: Flow and Transport Pathways >> Medium (Shale) 2.2.09: Chemical Processes - Transport >> Medium (Shale)	Ongoing since more than two decades

Table 5-2. Current or Planned Work Package Activities with International Collaboration and Focus on URL Experiments (sorted by URL)

URL	Relevant Ongoing or Planned Experiments (Selected)	Cooperation Mode	UFD Participation
Mont Terri, Switzerland (Opalinus Clay)	• FE: Full-scale heater test demonstration experiment • HE-E: Half-scale heater test in VE test section • MB: Mine-by experiment • HG-A: Gas path host rock and seals • DR-A: Diffusion, retention and perturbations	• Mont Terri Project • DECOVALEX • Mont Terri Project • Mont Terri Project • Mont Terri Project	• Ongoing, LBNL • Ongoing, LBNL • Completed, LBNL • Ongoing, LBNL • Completed, LBNL
Grimsel Test Site, Switzerland (Granite)	• CFM: RN tracer test and RN-doped plug experiment • FEBEX-DP: full-scale heater test dismantling • GAST: Gas permeable seal experiment	• CFM • FEBEX-DP • Bilateral NAGRA	• Ongoing, LANL, LLNL • Planned, SNL, LANL, LBNL • Not currently planned
Äspö Hard Rock Laboratory, Sweden (Granite)	• BRIE: Bentonite rock interaction experiment • Prototype Repository: full-scale prototype tunnels • LTDE: Long-term sorption diffusion experiment	• SKB Task Forces • SKB Task Forces • SKB Task Forces	• Ongoing, LANL • Likely • Not currently planned
Tournemire, France (Argillite)	• SEALEX: Long-time sealing experiment for different materials	• DECOVALEX	• Not currently planned
Bedrichov Tunnel, Czech Republic (Granite)	• Flow patterns and tracer transport in fractured granite	• DECOVALEX	• Ongoing, SNL
Horonobe URL, Japan (Sedimentary rock)	• EBS experiment: Vertical heater and buffer test (planned)	• DECOVALEX	• Ongoing, LBNL
KURT URL, Korea (Crystalline rock)	• Streaming potential (SP) testing regarding correlation with groundwater flow • Technique development for *in situ* borehole characterization	• MoU KAERI • MoU KAERI	• Ongoing, SNL • Ongoing, SNL
HADES URL, Belgium (Boom Clay)	• PRACLAY: Full-scale seal and heater experiment • RN Migration: Long-running RN diffusion tests	• Bilateral SCK/CEN • Bilateral SCK/CEN	• Not currently planned • Not currently planned

6. STATUS OF INTERNATIONAL COLLABORATION ACTIVITIES WITH FOCUS ON URL EXPERIMENTS

Here we give brief descriptions of ongoing international collaboration activities involving UFD scientists. The section is dedicated to R&D work with primary focus on participation in, and analysis of, URL experiments, as described in Table 5-2. We start with research work addressing issues related to near-field perturbation and engineered barrier integrity, followed by R&D on characterizing and understanding fluid flow and radionuclide transport processes in the host rock. Example R&D results will be presented, albeit without providing exhaustive explanations. We intend to merely illustrate technical achievements made in various areas. All necessary detail can be found in the references given throughout the text. Ongoing international collaboration activities unrelated to URLs are briefly described in Section 7.

6.1 Near-Field Perturbation and EBS Integrity

6.1.1 THM Modeling of Heater Experiments

On behalf of DOE, LBNL has been participating in the DECOVALEX-2015 Project since 2012 as one of the international modeling teams working on Task B1, the HE-E Heater Test at Mont Terri (Section 3.1.4) and Task B2, the Horonobe Engineered Barrier Experiment (Section 3.1.5). LBNL also contributes to the design and scoping simulations for the FE Heater Test at Mont Terri. As described in Section 4 of the milestone report entitled "*Investigation of Coupled Processes and Impact of High Temperature Limits in Argillite Rock,*" FCRD-UFD-2014-000493, (Zheng et al., 2014), the TOUGH-FLAC simulator developed at LBNL is the primary analysis tool, because this simulator has the required capabilities to model a large variety of problems associated with nuclear waste disposal for various engineering and natural systems. TOUGH-FLAC can simulate coupled THM processes under multiphase flow conditions through a sequential coupling of the TOUGH2 multiphase flow simulator with the FLAC3D geomechanical code (Rutqvist et al., 2002; Rutqvist, 2011). TOUGH-FLAC has recently been modified for applications related to bentonite-backfilled repositories in clay host formations (Rutqvist et al., 2014a). Major improvements include implementation of the Barcelona Basic Model (BBM) for the mechanical behavior of unsaturated soils and applied to modeling of bentonite backfill behavior (Alonso et al., 1990).

6.1.1.1 Status of Participation in DECOVALEX Task B1

Eight international modeling teams are participating in Task B1 of DECOVALEX-2015. Instead of starting directly with the interpretation and simulation of the rather complex HE-E heater experiment, Task B1 included several modeling steps of increasing complexity: (1) the study of THM processes in the host rock, using data from an earlier borehole heater test (HE-D experiment); (2) the study of THM processes in the buffer materials, using data from laboratory experiments (Ciemat Column Experiments), and (3) the study of the ongoing HE-E experiment considering the host rock as well as the buffer material, initially as a predictive exercise, then as an interpretative effort with comparison to monitoring data (Garitte and Gens, 2012). Regarding the HE-E experiment, the main objective is to test model capabilities addressing the evolution of EBS components and the near-field Opalinus Clay in the early post-closure perturbation period, with emphasis on thermal evolution, resaturation, and evolution of swelling pressure in bentonite backfill.

The first step of modeling the HE-D experiment started in 2012 and was completed in November 2013. LBNL's modeling of the HE-D experiment and comparison of the TOUGH-FLAC modeling results to those of other DECOVALEX modeling teams were reported in the FY2013 milestone report entitled

"*THM and Reactive Transport Model Development and Evaluation: International Activities*," FCRD-UFD-2013-000372 (Rutqvist et al., 2013). Simulating the THM behavior in this test allowed initial model comparison and validation without the complicating THM interaction with engineered barrier components. The second step, a study of bentonite properties through modeling of laboratory experiments, has recently been completed. This work is described in the FY14 milestone report entitled "*Investigation of Coupled Processes and Impact of High Temperature Limits in Argillite Rock*," FCRD-UFD-2014-000493 (Zheng et al., 2014). The predictive and finally interpretive modeling of the HE-E experiment (the final step of Task B1) has just started. Below, we provide a brief description of the LBNL modeling studies conducted for the HE-D heater test and for the CIEMAT column experiments.

The HE-D experiment was conducted at the Mont Terri URL between March 2004 and June 2005 by heating of Opalinus Clay from two heaters placed in a horizontal borehole (Wileveau, 2005; Gens et al., 2007). About 30 temperature sensors, 10 water pressure sensors, and 3 extensometers were placed around this heating borehole (Figure 6-1). Approximately one month after installation, the heaters were switched on with a total power of 650 W (325 W per heater). The heaters were then left under constant power for 90 days. Afterwards, the power was increased threefold, to 1950 W (975 W per heater), and maintained at that level for a further 248 days. At the end of this second heating stage, the heaters were switched off and the clay was allowed to cool down. Temperature, pore pressure, and deformation were measured throughout.

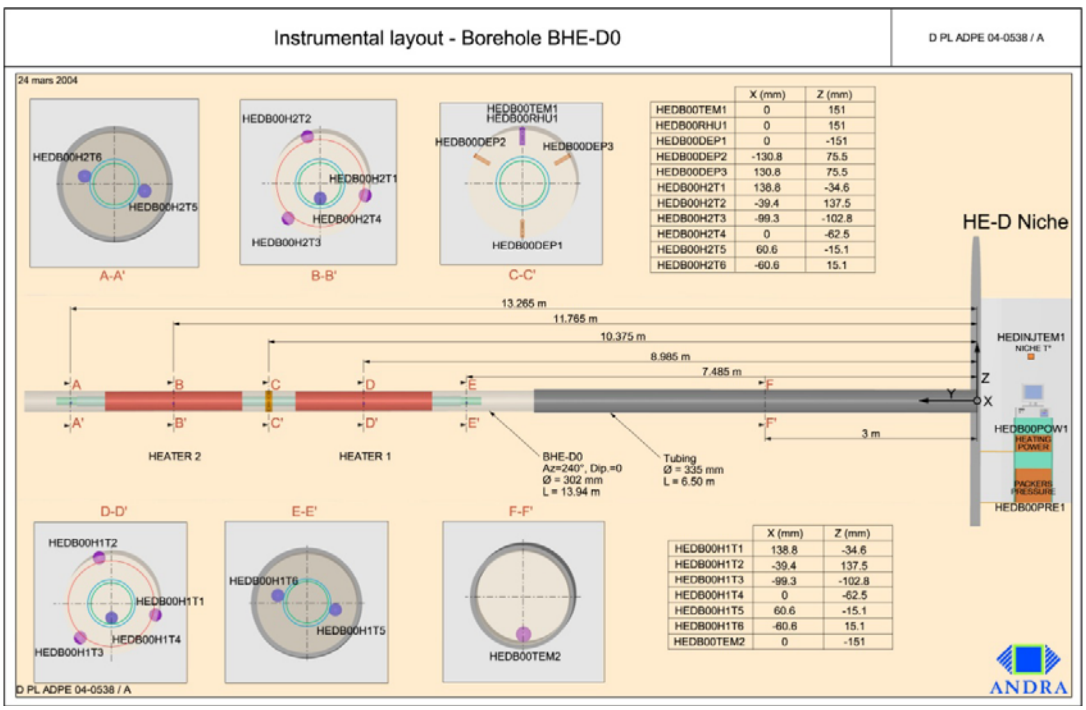


Figure 6-1. Layout of the heater borehole of the HE-D Heater Test at Mont Terri URL (from Garitte and Gens, 2012)

LBNL modeled the HE-D experiment using the TOUGH-FLAC simulator. Anisotropic material models were employed to account for the effect of sedimentation planes found in the Opalinus Clay. Figure 6-2 shows typical simulation results at two temperature monitoring points near the heaters, and one strain gage at another location in the perturbed rock mass. The simulation shows a correlation between temperature and fluid pressure as a result of thermal pressurization, which is caused by the differences in the coefficient of thermal expansion between the fluid and the solid rock. Temperature is in good agreement with measured data when an anisotropic thermal conductivity is used. Simulated pressure and strain are also in reasonable agreement with the measurements. The radial strain shows mainly compression during heating as rock is expanded from the heated borehole.

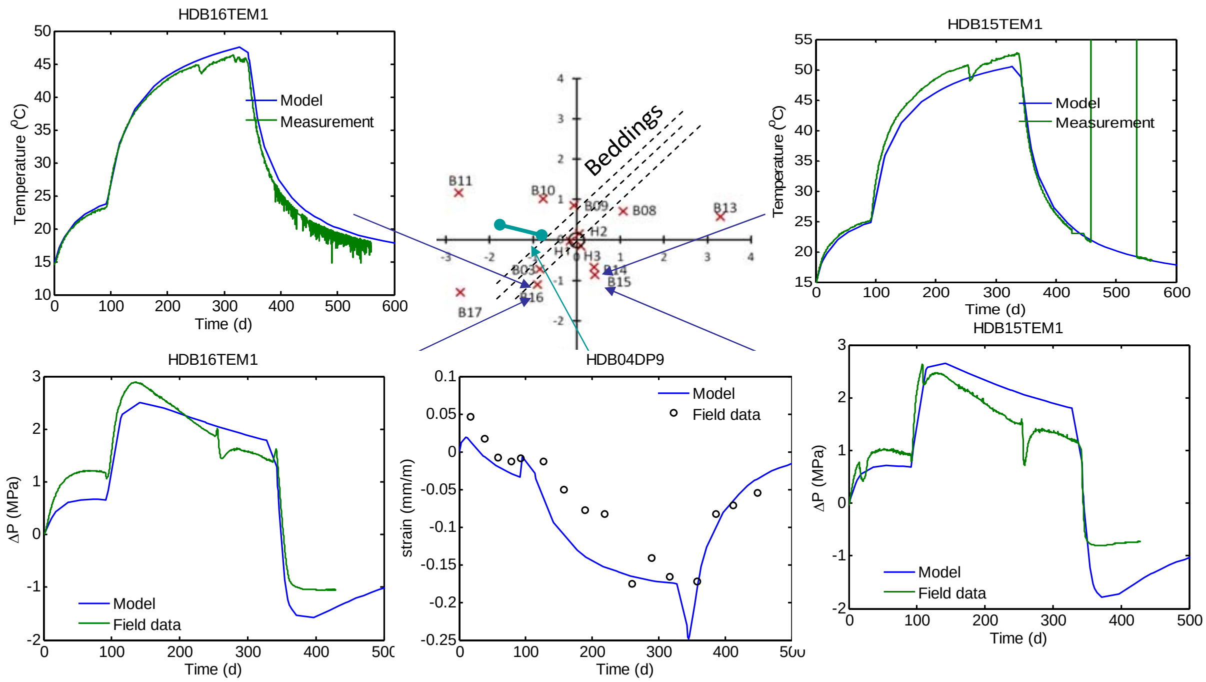


Figure 6-2. Comparison of simulated and measured temperature and pressure at two monitoring points (B15 and B16) and strain at another location close to the heater (from Rutqvist et al., 2013)

Figure 6-3 gives a comparison of simulation results from the eight teams involved in modeling the HE-D experiment of DECOVALEX-2015. Two temperature sensors are depicted in Figure 6-3, located, respectively, at a distance of 1.11 m away from the centre of the heater parallel to bedding (HEDB03), and at a distance of 0.775 m away from the center of the heater perpendicular to bedding (HEDB14). Despite the different distances to the heater, both sensors show a similar course of temperature evolution over time, which illustrates the effect of anisotropic heat conduction in the Opalinus Clay. Overall, the figure demonstrates good agreement between the results of the different groups. Furthermore, the temperature observations are well enveloped by the modeling results of the eight teams. The largest disagreement is observed at sensor HEDB14, where the simulated temperature is strongly overestimated by one of the international modeling teams. This particular simulation was conducted with an axisymmetric model in which thermal anisotropy cannot be considered. The comparative evaluation shown in Figure 6-3 is a good example of the value that DECOVALEX-type model comparison studies can provide to system understanding and model validation. The fact that several individual research groups with their own simulation tools and conceptual understanding arrive at similar model predictions enhances confidence in the robustness of THM models. And 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.

The CIEMAT column experiments tested the thermal hydration behavior in two buffer materials, granular bentonite (or bentonite pellets) and a sand/bentonite mixture (Figure 6-4). The design of the column experiments mimicked the HE-E conditions, with the height of the column equal to the thickness of the buffer filled between the canister and the host rock. A heater was placed at the bottom and a cooler at the top of each column, so that the column was heated while the top remained at an ambient temperature of

~21.5°C. Sensors were installed at distances of 10 cm, 22 cm, and 40 cm from the heater to measure temperature and relative humidity. The experiment was conducted in several stages with changing boundary/heating conditions, as illustrated in Figure 6-4. The simulation objective was to predict the transient fluid-flow and heat-transfer processes that occur in the experiment, and to calibrate the evolution of flow and thermal properties of the two hydrating buffer materials against the experimental measurements.

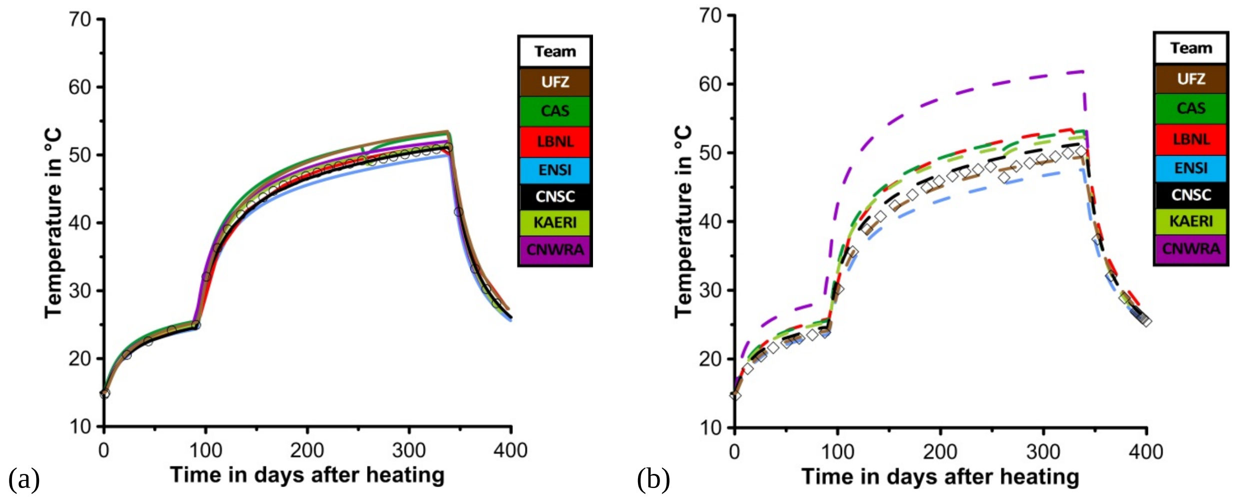


Figure 6-3. Comparison of measurements and model results of for the temperature evolution over time at sensors HEDB03 (a) and HEDB14 (b) (from Graupner et al., 2013).

Figure 6-5 shows selected simulation results after model calibration by the LBNL team. After heating is initiated, the temperature at the 10 cm location increases rapidly to ~30°C. Further step-wise increases occur when the insulation is changed and later as the heater temperature is raised to 140°C. The simulated relative humidity at 10 cm also increases rapidly after heating starts, due to the increase in temperature and the vapor flowing up from the bottom. There are complex couplings at play. When temperature increases at the 10 cm location, the relative humidity becomes larger as the capillary pressure drops, even if the water saturation remains unchanged. However, heating also causes the vapor pressure to increase near the heater, which drives vapor flowing up and contributes to the increased relative humidity at the 10 cm location during the early stage of heating. Over time, the relative humidity decreases at the 10 cm location. This is because further heating causes the drying at the 10 cm location with the vapor flowing further up. This upflow of vapor is evidenced by the continuous increase in relative humidity at the 22 cm and 40 cm locations, which in part is also caused by as a result of liquid water flowing downward from the top of the cell via gravity and capillary forces. Overall, the simulated temperatures and relative humidity values at three locations are in a good agreement with the measured ones.

The simulations for the CIEMAT column experiments demonstrate the complexity of the coupled processes involved in the temperature and hydration behavior of heated bentonite. Results also indicate the importance of adequately understanding experimental boundary conditions, such as the water intake of the experimental column or the substantial heat loss from the equipment that has to be considered in order to characterize the thermal properties of the buffer material. Modeling teams learned that one can obtain a unique solution for back-calculating the thermal and hydraulic properties of the buffer material by evaluating the transient temperature and moisture responses in addition to steady-state profiles. By accounting for the enhanced permeability of gas and the temperature dependency of the capillary pressure, the models can reasonably reproduce the evolution of relative humidity along the column in the experiments.

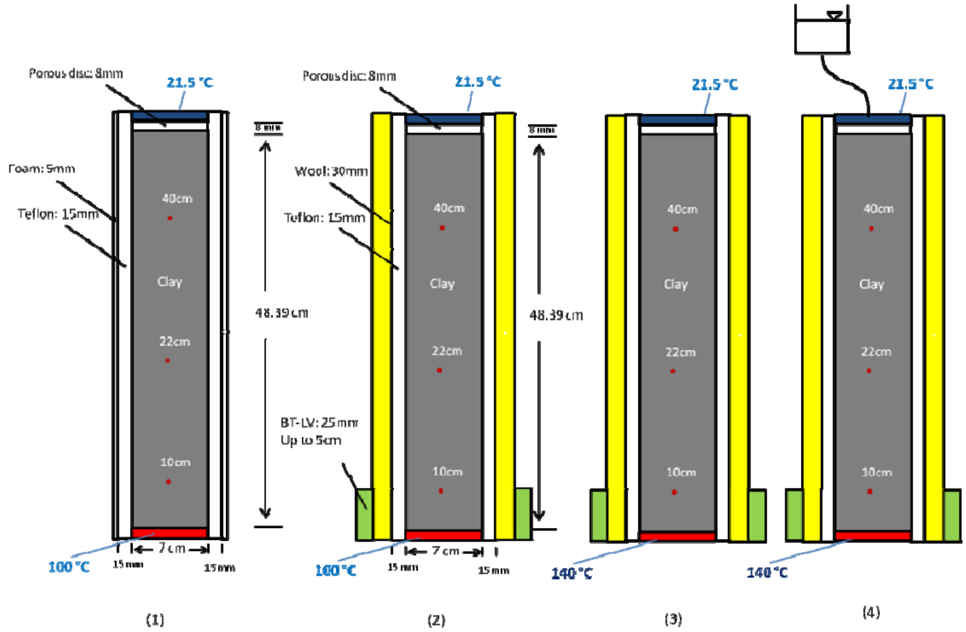


Figure 6-4. Schematic of experimental setups of column experiment in sequential steps: (1) Heating at temperature of 100 ˚C from 0 to 1566 hours, (2) heating with new insulation layer from 1566 to 3527 hours, (3) heating at 140 ˚C from 3527 to 5015 hours, (4) heating with hydration valve open after 5015 hours. (from Zheng et al., 2014)

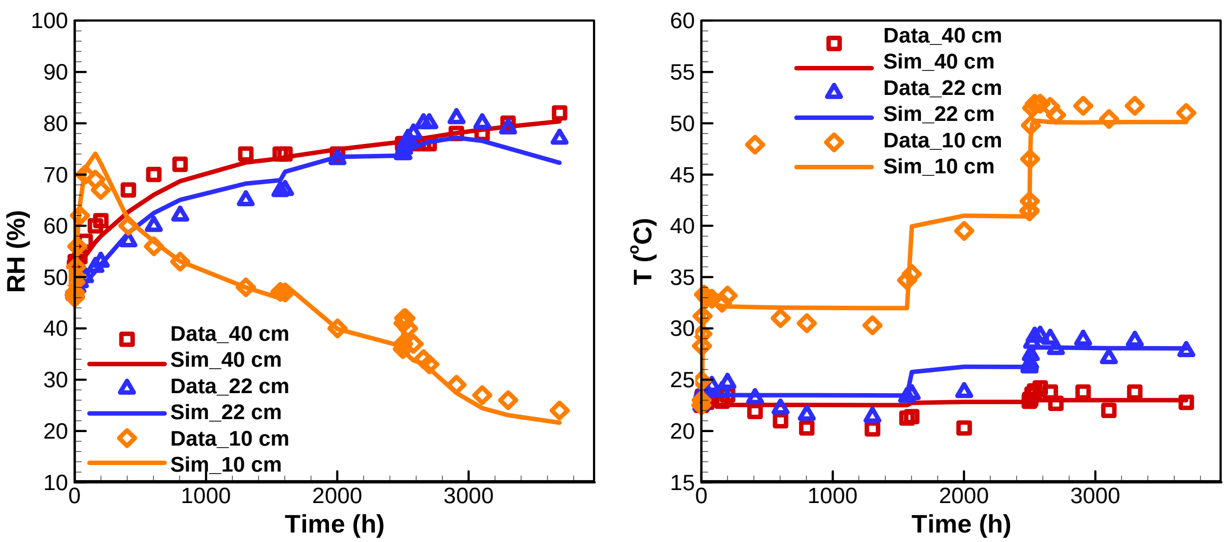


Figure 6-5. Simulated and measured relative humidity (RH) and temperature (T) as a function of time after heater was turned on. (from Zheng et al., 2014)

6.1.1.2 Status of Participation in DECOVALEX Task B2

Task B2 focuses on coupled THMC modeling of a planned full-scale EBS experiment to be conducted by the Japan Atomic Energy Agency (JAEA) at the Horonobe URL in Japan (Section 3.1.5). As a first modeling step, participating teams were asked to simulate a simplified 1D benchmark test with exact properties and boundary conditions given by the JAEA. This step allowed teams to get familiar with the problem setup and to conduct an initial model comparison for a simpler test problem before simulating the complex full-scale EBS experiment. The benchmark is a one-dimensional representation of the heater, buffer, and rock extending from the center of the overpack (heat source) out to 25 m. As shown in Figure 6-6, this includes 0.41 m of overpack, 0.72 m of bentonite buffer, and 23.87 m of rock. Figures 6-7 and 6-8 show selected simulation results, demonstrating good agreement between the five modeling teams participating in Task B2. Teams have now moved to the next modeling step, which is to conduct initial model predictions for the full-scale Horonobe EBS experiment. Results are reported in Rutqvist et al. (2013) and Zheng et al. (2014).

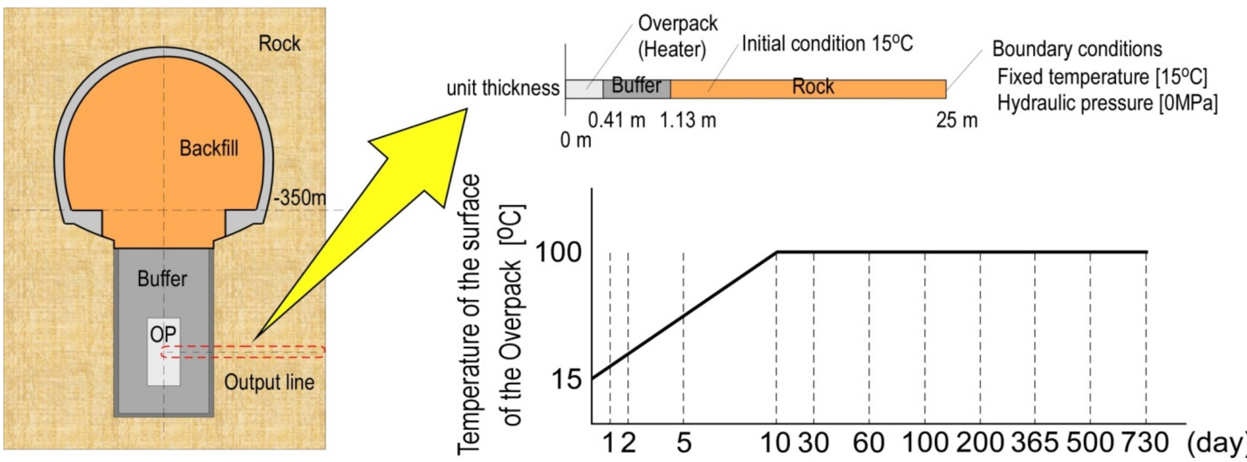


Figure 6-6. Definition of 1D benchmark test for Task B2 (from Rutqvust t al., 2013)

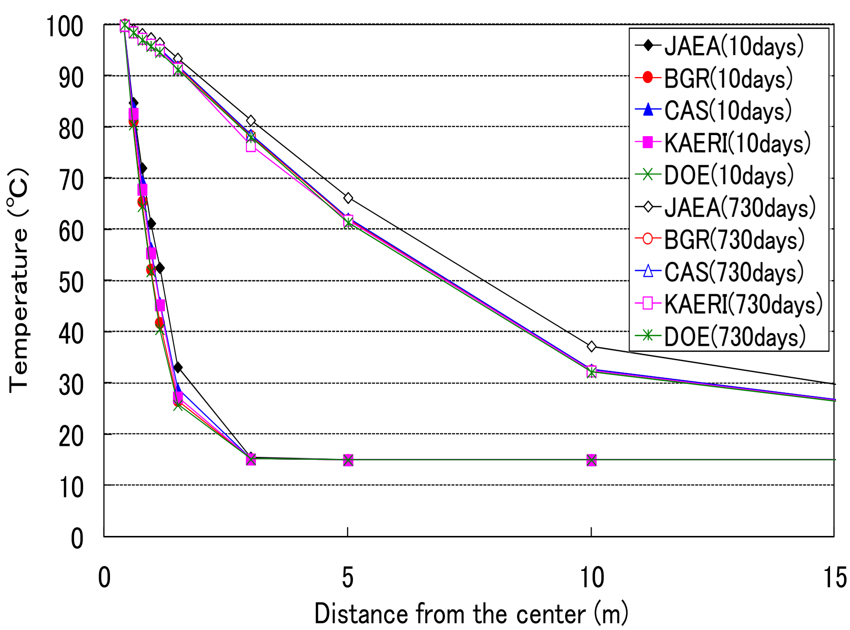


Figure 6-7. Task B2 Benchmark test: Comparison of simulated temperature as a function of distance from the center, for two time steps at 10 days and 730 days (from Zheng et al., 2014)

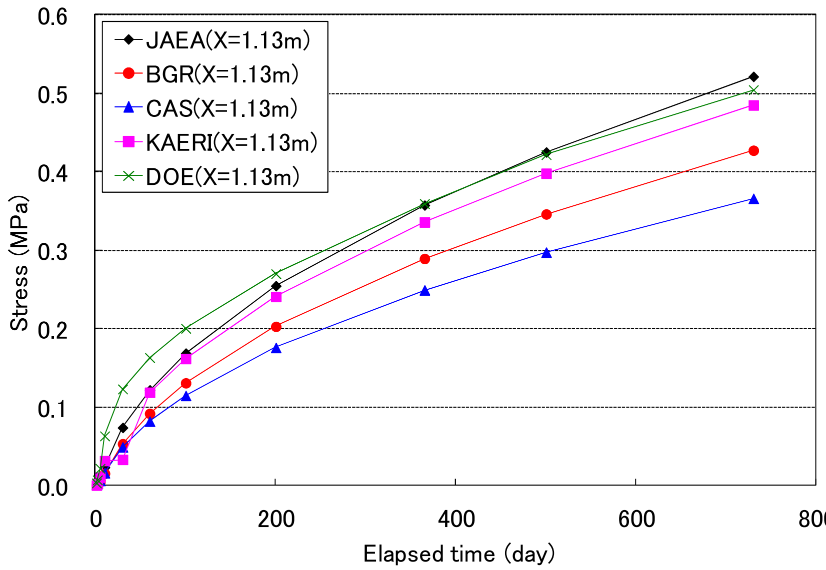


Figure 6-8. Task B2 Benchmark Test: Comparison of the simulated stress change at X=1.13m (from Zheng et al., 2013)

To conduct the predictive simulations for the Horonobe EBS experiment, the LBNL team developed a half symmetric 3D model, which includes half of the tunnel and half of the deposition hole (Figure 6-9), and explicitly represents all relevant materials, including mudstone rock, buffer, backfill, a sand layer at the rock/buffer interface, concrete lining, and plug. Preliminary simulations of the expected THM response were conducted for a heating period of about 2 years. Selected results of temperature evolution are shown in Figures 6-10 for points located in the buffer and near-field rock. When keeping the heater temperature constant at 100°C, the simulation shows that the temperature at the buffer-rock interface (P3, P4 in Figure 6-10) increases to about 60°C after 2 years. As a next step in Task B2, modeling teams will finalize and compare their predictive THM simulations, and will then evaluate their robustness against an initial set of measurements to be provided by JAEA in 2015.

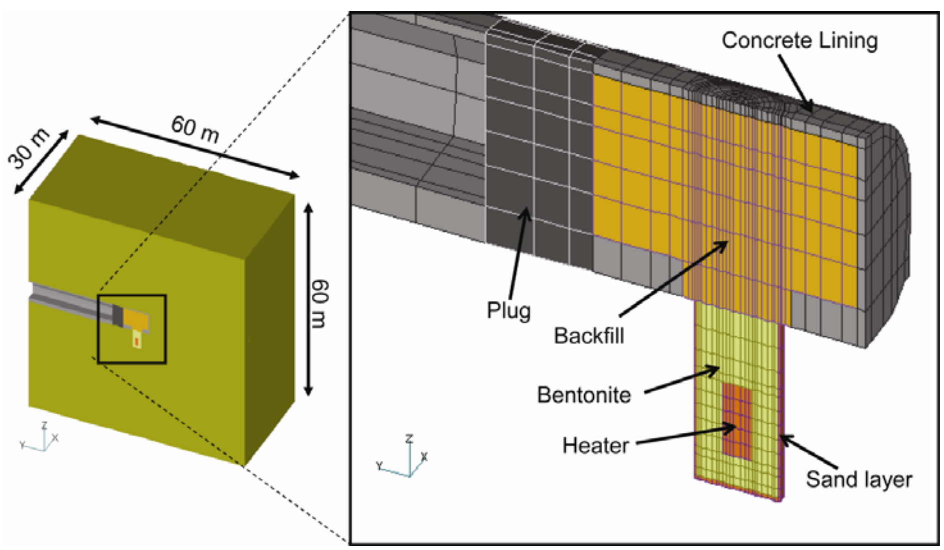


Figure 6-9. TOUGH-FLAC 3D numerical grid of the Horonobe EBS experiment (from Zheng et al., 2014)

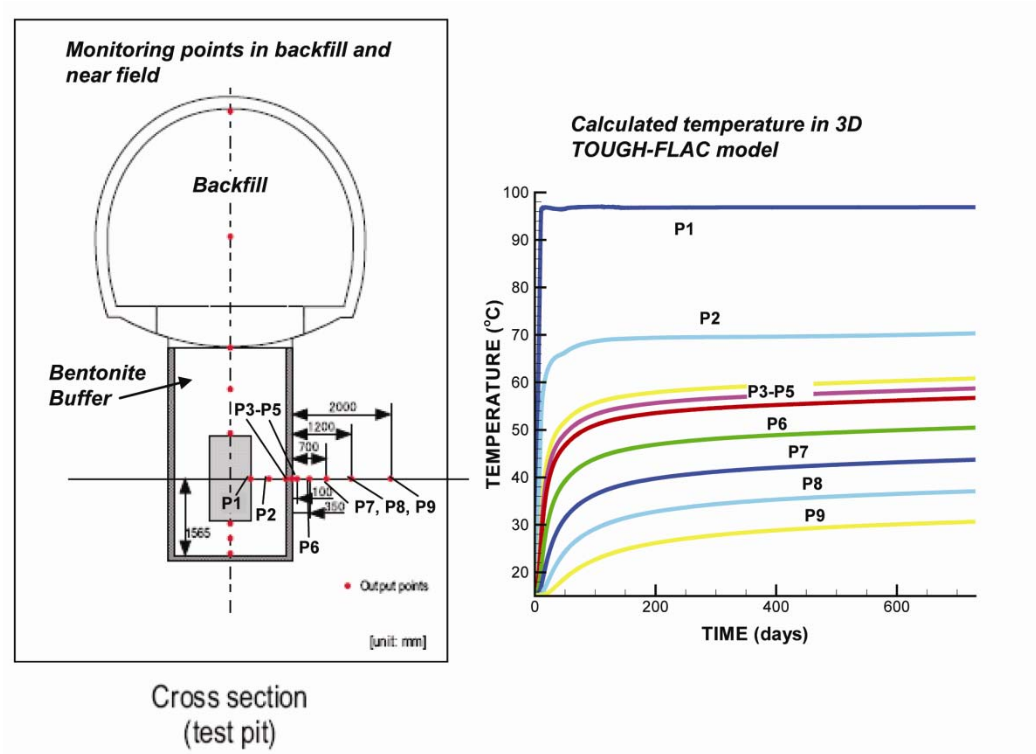


Figure 6-10. EBS Experiment: TOUGH-FLAC simulation results of temperature in the buffer and rock (from Zheng et al., 2014)

6.1.1.3 THM Modeling of FE Heater Test at Mont Terri

Enabled by DOE's formal partnership in the Mont Terri Project, LBNL is one of seven international modeling teams conducting THM simulations for the design of the FE Heater Test and for the evaluation of monitoring data. As mentioned in Section 3.2.2, this experiment will soon start its heating phase as one of the largest and longest-duration heater tests worldwide, with focus on both the EBS components and the host-rock behavior. Due to the 1:1 scale of the experiment, it will be possible to achieve realistic temperature, saturation, and stress gradients in the emplacement tunnel and the host rock, which is extremely useful for THM model validation.

Over the past 2 years, modeling teams have conducted design predictions for the FE Heater Test, developing conceptual models and selecting material properties from available literature (papers and reports) on lab experiments and previous Mont Terri *in situ* tests. Several sets of scoping simulations were conducted to probe the relevance of coupled processes, evaluate their significance and parameter range, compare conceptual models, test sensitivity to input parameters, and summarize lessons learned before the onset of the experiment (parameter ranges, importance, expected response). This initial step was complemented with a restricted benchmark test for code comparison, in which properties and model geometry were defined by NAGRA. With the onset of heating planned for early 2015, teams will soon move into the modeling phase with evaluation, interpretation, and validation using measured data from the FE Heater Test.

In collaboration with NAGRA and other teams, LBNL has developed a sophisticated 3D TOUGH-FLAC model for the THM design predictions. This work is described in the FY14 milestone report entitled "*Investigation of Coupled Processes and Impact of High Temperature Limits in Argillite Rock,*" FCRD-

UFD-2014-000493 (Zheng et al., 2014). The host rock is modeled with anisotropic properties considering bedding planes in the Opalinus Clay. An inclined TOUGH-FLAC mesh was created to accurately represent anisotropic thermal and hydrological behavior. Anisotropic mechanical material behavior is simulated using the FLAC3D ubiquitous joint model, with initial properties derived from excavation design analysis conducted by another FE Heater Test modeling team (Nater, 2012). In the ubiquitous joint model, weak planes are assumed along the bedding planes of the Opalinus Clay; in other words, the shear strength properties are different in the direction of bedding versus the direction across bedding. Bentonite behavior is accounted for with the Barcelona Basic Model (BBM). Figure 6-11 presents the 3D TOUGH-FLAC numerical grid of the FE experiment. This model grid includes all vital material components for the modeling of the FE experiment, including layered Opalinus Clay host rock, excavation-disturbed zone, tunnel, three heaters, bentonite buffer, concrete liner, and concrete plug. As in the real test, the predictive simulations start with an open tunnel at atmospheric pressure for 1 year, creating a pressure drop and hydraulic gradient around the tunnel. Thereafter, the model assumes instantaneous emplacement of the heater and buffer, and the heating period is simulated.

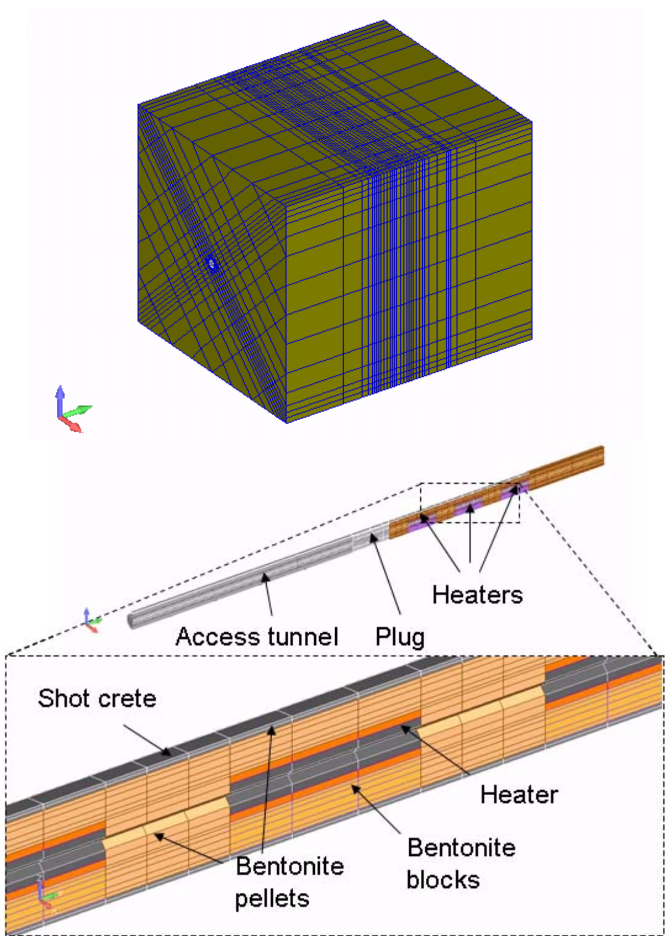
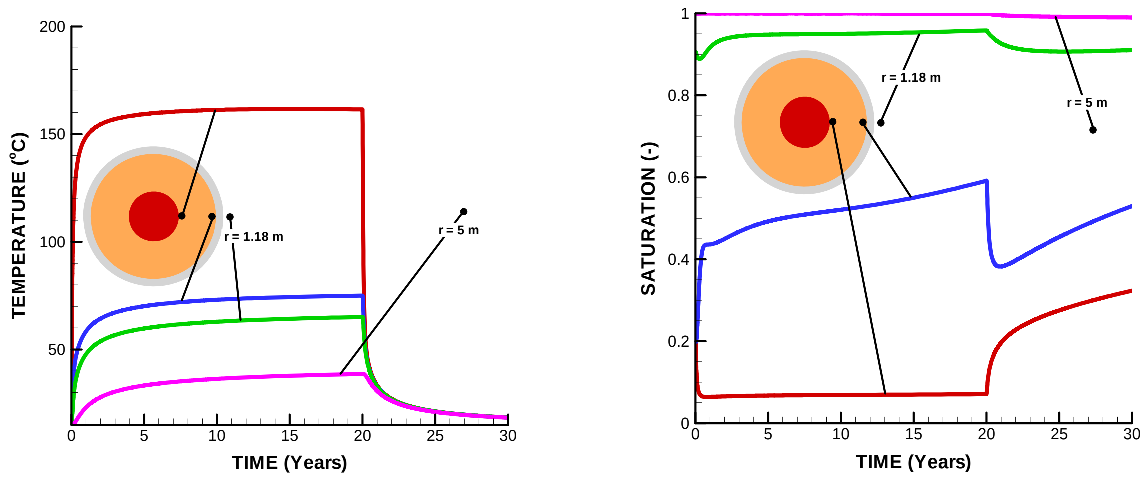


Figure 6-11. TOUGH-FLAC 3D numerical grid of the FE experiment (from Zheng et al., 2014)

Figure 6-12 shows LBNL's initial prediction of temperature and saturation evolution, assuming the full 1500 W power in each heater operating over a 20-year period. In this case, the peak temperature at the buffer is as high as 160°C, i.e., considerably higher than the targeted 125°C to 135°C. In the experiment, the temperature should not exceed 150°C, because this could be damaging for some of the monitoring sensors. The high peak temperature at the canister surface is caused by the combined effects of low thermal conductivity of the buffer and the rock, as well as the high vapor diffusion coefficient that keeps the buffer dry around the heater. Modeling teams then explored alternative heating schemes, including staged heating, to better accommodate the targeted temperature constraints.



(a) (b)

Figure 6-12. Model prediction of (a) temperature and (b) liquid saturation for full power of 1500 W at each heater (from Zheng et al., 2014)

6.1.1.4 Summary of Heater Test Modeling in Argillite Rocks

Over the past few years, UFD researchers have greatly benefited from participating in international activities for developing expertise and testing advanced models for coupled THM processes. As described below, LBNL scientists are now utilizing data and results from laboratory and field studies that have been and are being conducted with millions of R&D investments provided by international partners. UFD simulators are being verified and validated against these experimental studies, providing a robust modeling and experimental basis for the prediction of the complex long-term THM and THMC evolution of a multi-barrier waste repository system involving backfilled emplacement tunnels and argillite host formations. Specific FY2014 accomplishments of UFD scientists include:

- Validation of TOUGH-FLAC and characterization of THM properties was achieved for two types of bentonite-based buffer materials through modeling of CIEMAT laboratory column experiments.
- Benchmarking associated with the DECOVALEX-2015 Horonobe EBS Experiment demonstrated good agreement of UFD models with results of other international modeling teams, providing code-to-code verification of TOUGH-FLAC.
- Full-scale 3D models were developed for the Horonobe EBS Experiment and the Mont Terri FE Heater Test and initial model predictions of temperature and saturation evolutions were conducted for later comparison with measurements.

Future collaborative work in this area will utilize the full-scale 3D models of the three *in situ* heater experiments—the Mont Terri HE-E experiment, the Horonobe EBS experiment, and the Mont Terri FE experiment—for further comparison of simulation results with measurements and with the results of other international modeling teams.

6.1.2 Plans for UFD Participation in FEBEX-DP Experiment

As described in Section 3.3.2, the FEBEX-DP project provides a unique opportunity to evaluating the long-term behavior of an engineered barrier that underwent continuous heating with natural resaturation for about 18 years. The project has just started with a kick-off meeting on June 10, 2014, and DOE is in the process of defining the detailed R&D activities to be undertaken by UFD scientists. Preliminary plans envision LBNL participation in the pre- and post-dismantling modeling, with particular focus on the chemical alteration of the bentonite and how it is affected by THM processes such as hydration, thermal osmosis, and swelling.

UFD scientists also plan to participate in the sampling and analysis campaign of bentonite interfaces with other EBS components (i.e., metals, cement). LANL scientists will perform initial forensic analysis of selected samples (focusing on bentonite-metal, bentonite, and bentonite-cement segments) to understand the alterations that took place during the 18-year experiment. Following the forensic analyses, a series of hydrothermal experiments will be conducted to expand the thermal knowledge of this particular bentonite system and compare the results to ongoing LANL experiments conducted on other bentonite systems. Results from these hydrothermal experiments will elucidate bentonite alterations during long-term heating under controlled conditions beyond what was observed in the FEBEX project.

LBNL and SNL plan to collaborate on the study of micro-cracks in FEBEX-DP samples. Micro-cracks could have formed during heating and drying, but then might have healed during hydration. Such a study will not only facilitate better understanding of potential flow paths in bentonite, but will also shed light on the self-healing of excavation disturbed zone (EDZ) in the argillite host rocks, because of the similarity in the controlling processes. LBNL will use the synchrotron light source at LBNL to examine the micro-cracks at a resolution of ~750 nm. These microCT images will provide a dynamic of the evolving micro-cracks. In a second step, the microCT results will be used by SNL to select target locations for FIB/SEM analysis and serial sectioning to image micro-cracks at a smaller scale but higher resolution. Together, these tests will yield a multiscale characterization of micro-crack behavior.

6.1.3 HM Modeling of Mine-by Test at Mont Terri

Constitutive relationships refer to relationships among hydraulic, mechanical, thermal, and mechanical properties. The stress–strain relationship is the most fundamental part of constitutive relationships for geomechanical models. Hooke's law has been generally used to describe this stress–strain relationship for elastic mechanical processes. However, Hooke’s law assumes a constant proportionality between stress and strain, an assumption that has been challenged in many studies because relevant mechanical properties are stress-dependent (Liu et al., 2012). To incorporate this stress dependency, Liu et al. (2009) developed a modification of Hooke's law referred to as the “Two-Part Hooke’s Model” or “TPHM,” as opposed to the standard “Single-part Hooke’s Model” or “SPHM.” Liu et al. (2009) argued that different varieties of Hooke's law should be applied within regions of the rock having significantly different stress–strain behavior, and that a rock body could be conceptualized in to two distinct parts. These two parts are called a “hard part,” which undergoes only small deformation, and a “soft part,” which undergoes large deformation. This approach permits the derivation of constitutive relationships between stress and a variety of mechanical and/or hydraulic rock properties.

In FY12, LBNL implemented the TPHM into the TOUGH-FLAC code, and started testing the usefulness and validity of the new constitutive relationship for coupled HM behavior of argillites rock by the comparison with field observations at Mont Terri. The first step was to conduct 2D simulations of tunnel displacement and EDZ evolution using an earlier Mine-by experiment, known as the ED-B tunnel, conducted in 1997 and 1998. Figures 6-13 and 6-14 show sample results of the 2D simulations using the

TPHM. The first figure is a comparison of the displacement magnitude at different locations around the tunnel, between the measurements in the field and the TPHM as well as SPHM, respectively. It is evident that the TPHM model results are significantly different from those obtained from traditional (SPHM) approaches and agree very well with the field observations. The second figure shows results from EDZ damage simulations using the TPHM. A fine-grid numerical approach, based on an explicit incorporation of small-scale heterogeneity of mechanical properties, was used to simulate the fracturing process in a rock mass as a function of time. The failure results shown in Figure 6-14 are in qualitative agreement with the conceptual model of EDZ fractures at Mont Terri, such as steeply inclined unloading joints and shear fractures on both side walls of a mined tunnel in Opalinus Clay. More details on the TPHM and its application to the ED-B Tunnel are provided in Section 2 of the *Report on Modeling Coupled Processes in the Near Field of a Clay Repository,* FCRD-UFD -2012- 000223, August 2012 [Liu et al., 2012]).

In FY13, LBNL conducted a full 3D modeling study evaluating the TPHM approach in comparison with the three-dimensional HM response observed during the Mine-by Test recently conducted at Mont Terri (Section 3.2.3). The data were made available to LBNL as a result of DOE's membership in the Mont Terri Project. The simulations were conducted using the geomechanical simulator FLAC3D (Itasca, 2009) into which the TPHM was implemented. The FLAC3D model for the Mine-by niche has dimensions 40 m × 46 m × 44 m, discretized with a total of 100,256 zones (grid cells). The tunnel excavation, which lasted over four weeks, was represented in the model as 20 excavation steps. For each step, the simulations assumed that excavation was advanced by about 1 m and that a concrete liner was installed simultaneously. Each excavation step was modeled in two stages. In the first stage, the model was run to mechanical equilibrium to simulate a rapid (undrained) excavation process for the given excavation step. In the second stage, a constant pore pressure (atmospheric pressure) was fixed at the excavation surface, and transient water flow was simulated for the time period of the corresponding excavation step.

Three-dimensional pore-pressure and damage-zone distributions around the niche, as predicted from the TPHM model, are shown in Figure 6-15 for three excavation stages. A low-pressure zone forms near the excavated tunnel, corresponding to the damage zone, where the value of pore pressure is equal to the atmospheric pressure in the niche. A sharp increase in pore pressure can be seen beyond the advancing excavation face, outside of the damage zone, about 11 m (2.5 diameters of the Mine-by niche) ahead of the excavation. This overpressure forms as a result of complex HM processes: Stress increases at the edge of the EDZ to compensate for the fact that the damage zone is not effective in supporting the overburden. This stress increase results in compression of the argillite rock, which in turn increases pore pressure because the permeability is too low to provide immediate pressure relief. Beyond this high pore-pressure zone, the unloading effect due to excavation and the associated damage zone disappears, and the natural pore pressure in the formation is essentially undisturbed.

Figure 6-16 shows how the measured data from the Mine-by test have been used to test the new TPHM model and to compare it to the existing SPHM approach. The deformation of surrounding rock matrix becomes visible at about 11 m before the Mine-by excavation front. The calculated inward displacements based on the TPHM are larger than those predicted with SPHM. Clearly, the TPHM model results represent a better match to measured data. These results show that the TPHM model provides a more realistic representation of the deformation pattern, because it takes into account the mechanical behavior of "soft" features within the rock mass. Similar results were obtained for the measured pore-pressure increases ahead of the advancing front, with the TPHM being the superior model. More details on TPHM application to the Mont Terri Mine-by Test are provided in Section 2 of the *Report on THMC Modeling of the Near Field Evolution of a Generic Clay Repository: Model Validation and Demonstration,* FCRD-UFD-2013-000224, August 2013 [Liu et al., 2013]).

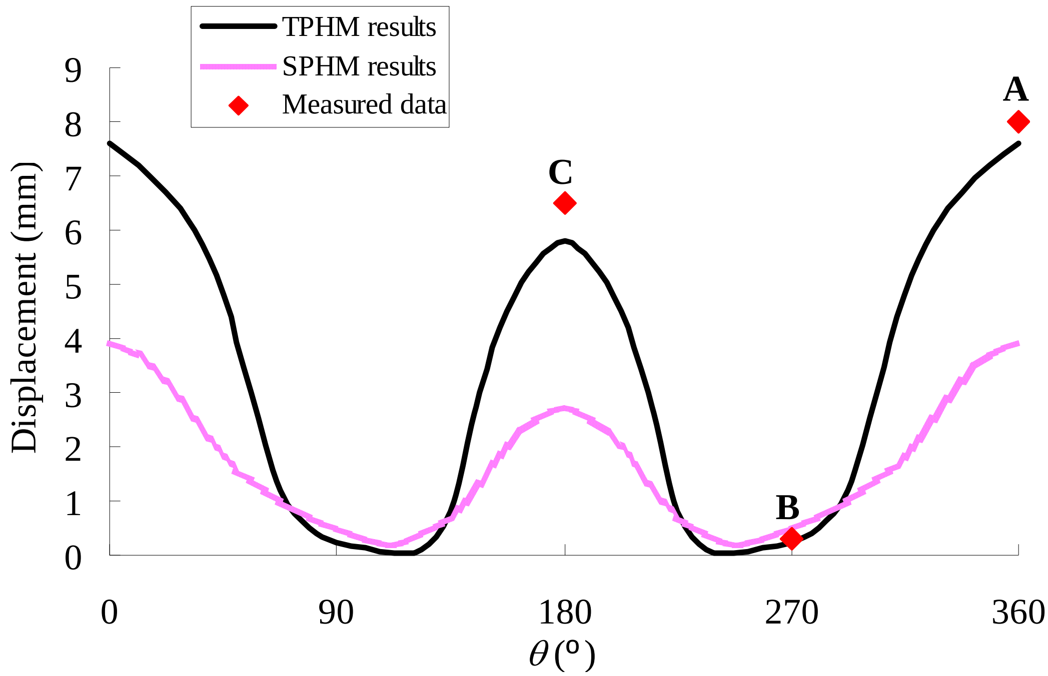


Figure 6-13. Displacement variation (magnitude) at points around the ED-B Tunnel at Mont Terri (from Liu et al., 2012)

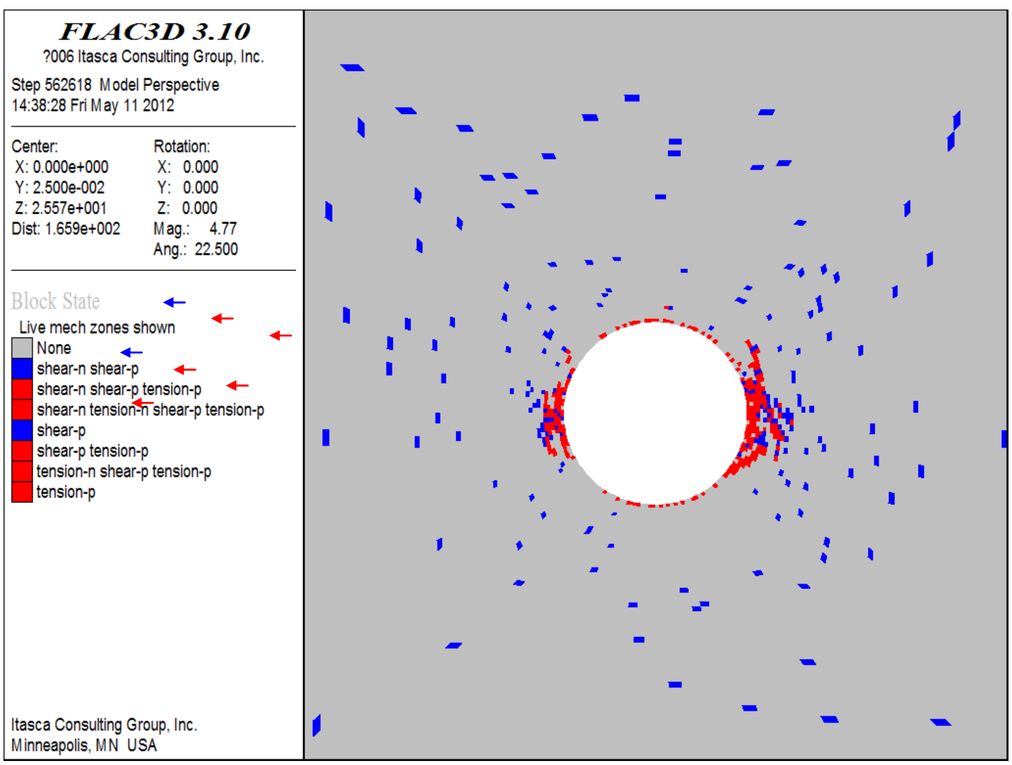


Figure 6-14. Failure type in the EDZ surrounding the ED-B Tunnel at Mont Terri simulated by TPHM (tension failure marked by RED color and shear failure marked by BLUE color) (from Liu et al., 2012)

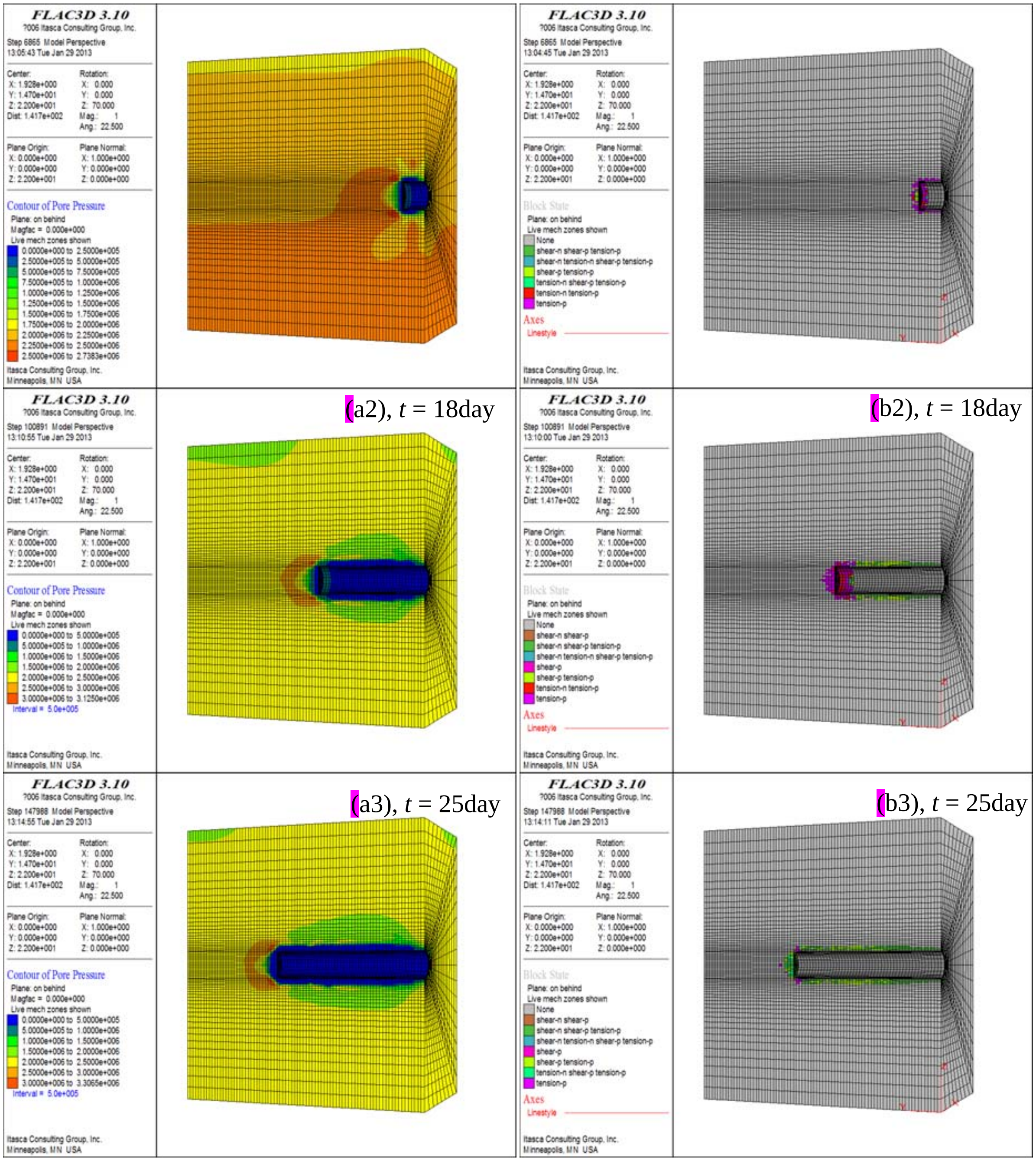
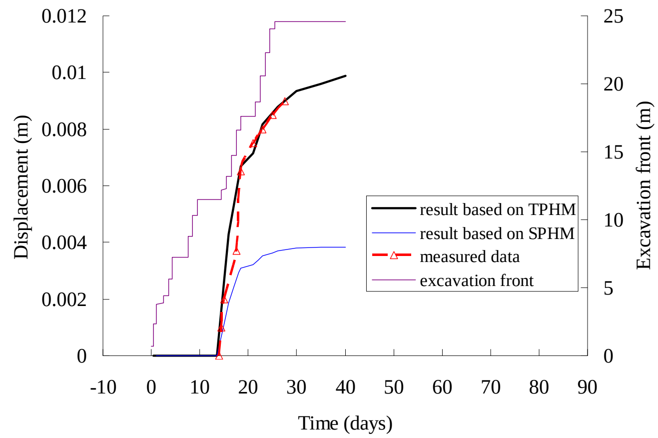
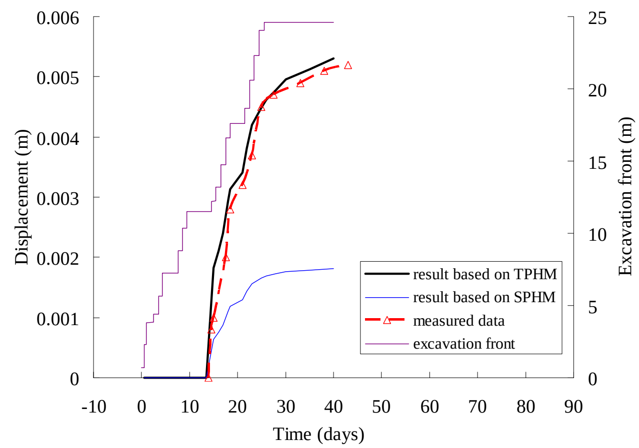


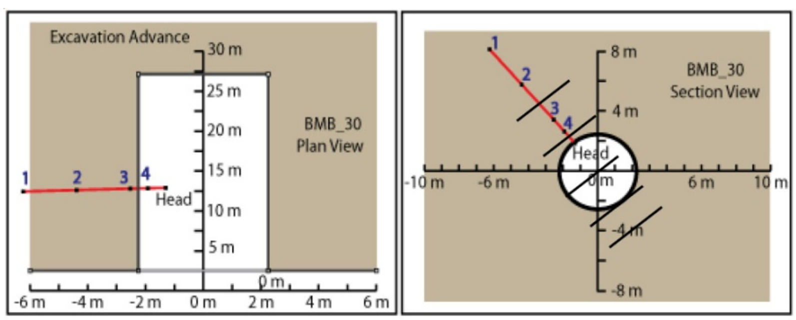
Figure 6-15. Simulation results based on TPHM for a vertical cross-section along the Mine-by niche: (a) pore pressure contours (Pa) and (b) the damage zone (and mode) (from Liu et al., 2013)



(a) displacement at sensor BMB30_4



(b) displacement at sensor BMB30_1



(c) the locations of displacement monitoring sensors (BMB30)

Figure 6-16. Excavation advancing and (simulated and observed) inward displacements as a function of time (from Liu et al., 2013)

The Mine-by simulations are now completed. Simulation results have shown that the pore pressure disturbance in the argillite formation at Mont Terri becomes visible at about 2 ½ tunnel diameters ahead of the Mine-by excavation advancing face (along the longitudinal direction of the niche). The results also demonstrate that there exists a good correlation between the EDZ and the pore-pressure evolution, which has important practical applications for monitoring EDZ evolution with pore-pressure sensors. The excellent agreement between observed displacement and pore-pressure histories at several locations and those predicted with TPHM clearly indicate that TPHM captures the complex hydro-mechanical responses to the excavation.

6.1.4 DFN Modeling of the HG-A Experiment at Mont Terri

To more accurately characterize and model EDZ evolution and its impact on flow and transport, LBNL has developed a new modeling approach for studying hydro-mechanical coupled processes, including fracture development, within geologic formations. This is accomplished through the novel linking of two codes: TOUGH for subsurface multiphase flow based on the finite volume method, and RBSN (Rigid-Body-Spring-Network) for discrete (lattice) representation of material elasticity and dynamic fracture development/propagation. The RBSN formulation is based on the concept of the Rigid-Body-Spring model, first introduced by Kawai (1978), in which the material constitution is represented as a collection of rigid bodies connected by spring sets. TOUGH is used to simulate relevant scalar quantities (e.g., temperature, pressure, and degree of saturation) associated with fluid flow and heat transport, whereas RBSN accounts for mechanical quantities (e.g., displacement, strain, and stress) of interest. The TOUGH-RBSN simulator predicts fracture evolution, as well as mass transport through fractured porous rock, under dynamically changing thermal-hydrologic and -mechanical conditions. The modeling approach is facilitated by a Voronoi-based discretization technique common to both codes, capable of representing discrete fracture networks embedded in a porous matrix. Further details on this method and UFD-related applications are provided in Section 3 of the *Report on Investigation of Coupled Processes and Impact of High Temperature Limits in Argillite Rock*, FCRD-UFD-2014-000493, August 2014 [Zheng et al., 2014]).

In FY13, LBNL started testing its new capabilities using data from the ongoing HG-A experiment at Mont Terri (Section 3.2.5). This experiment examines gas paths through the near-field host rock affected by the evolution of the damage zone. Several hydraulic and gas injection tests have been conducted, and a detailed discrete fracture mapping study was performed. The test is therefore a valuable testbed for discrete fracture and THM modeling capabilities. However, application to the HG-A experiment required a modification to the standard RBSN approach to account for anisotropic elastic properties of the RBSN spring sets. In the standard RBSN, the spring sets are oriented randomly as defined by the Voronoi element structure. In the new scheme, by comparison, all the spring sets are aligned with the principal bedding direction. The spring coefficients are defined in global fabric coordinates, where two orthogonal axes are normal and parallel to bedding, respectively. The anisotropic modeling scheme was validated through comparison with uniaxial compression tests for transversely isotropic rock specimens from Mont Terri. Cylindrical core samples were subjected to unconfined uniaxial compression, in which the loading direction formed an angle relative to the bedding plane. TOUGH-RBSN simulations were conducted for seven cases of fabric orientation relative to core sample axis with $\beta = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ$. Selected damage patterns are shown in Figure 6-17.

So far, the TOUGH-RBSN simulation for the HG-A experiment have focused on the initial excavation damage observed in the micro-tunnel (Figure 6-18). The partial damage and exfoliations observed along the tunnel have been mainly attributed to the anisotropic strength characteristics of the rock. The relative weakness of the rock orthogonal to the bedding and the weakness near faults intercepting the tunnel, as depicted in Figure 6-18, result in the nonuniform damage around the excavation wall. Simulated damage patterns are shown in Figure 6-19. Damage zones are more prominent at the tunneling wall tangential to the bedding planes, similarly to the failure characteristics seen in Figure 6-18. For identification of failure modes, individual fracture segments are drawn in different colors: blue and red segments represent tensile and shear failure modes, respectively. Tensile fracturing is concentrated at the borehole boundary, due to the lack of constraints against the pore pressure acting towards the center of the tunnel. This failure feature can be supported by observation of the deformation around the borehole. Figure 6-19c depicts the deformed shape of the tunnel, in which the deformation is exaggerated for better visibility. Voronoi cells adjacent to the borehole come off the body, which indicates tensile failure. Next, the HG-A simulations will attempt to simulate the hydraulic and gas injection tests conducted at the site, in particular those that may have caused additional damage in the EDZ. Long-term plans consider the possibility of using

TOUGH-RBSN for damage modeling related to long-term gas generation from canister corrosion in low-permeable backfill, a topic currently discussed as a modeling task in the next DECOVALEX Project phase.

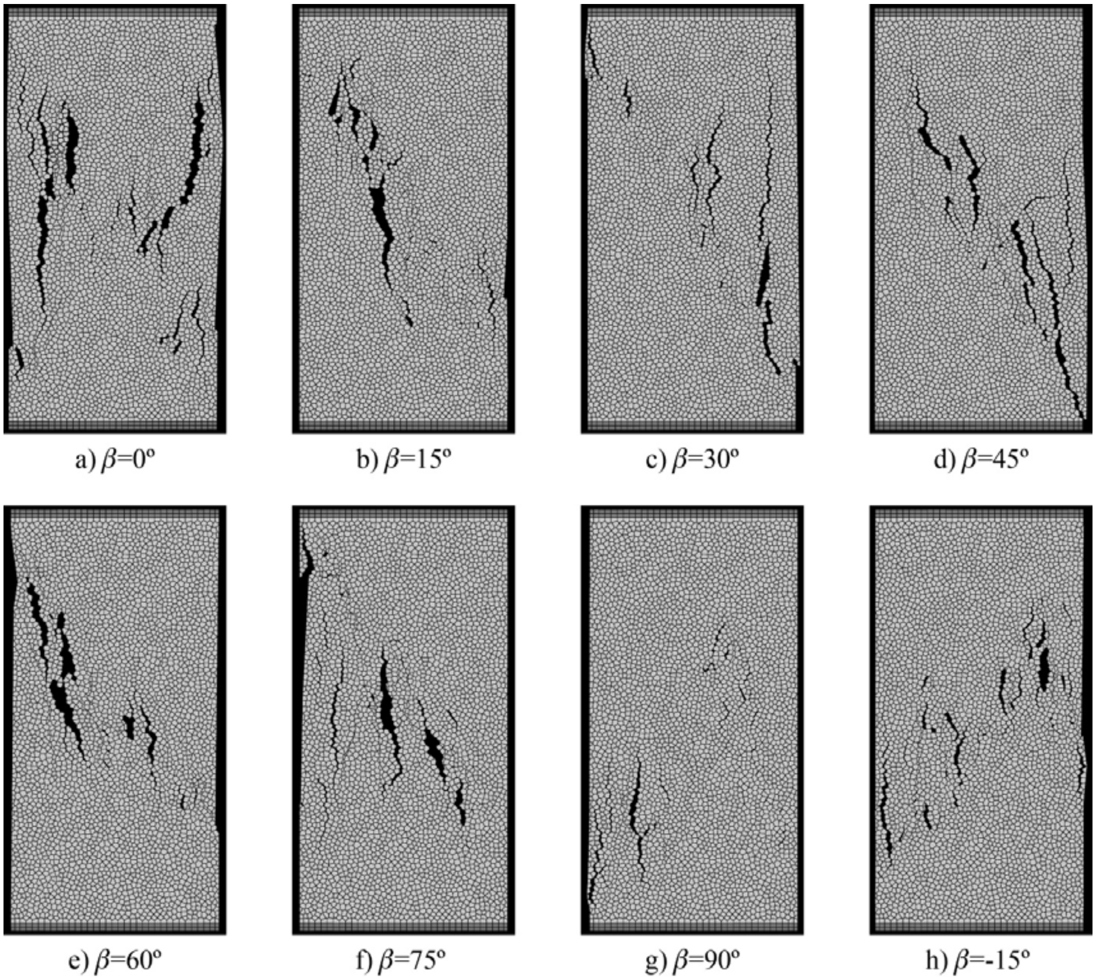
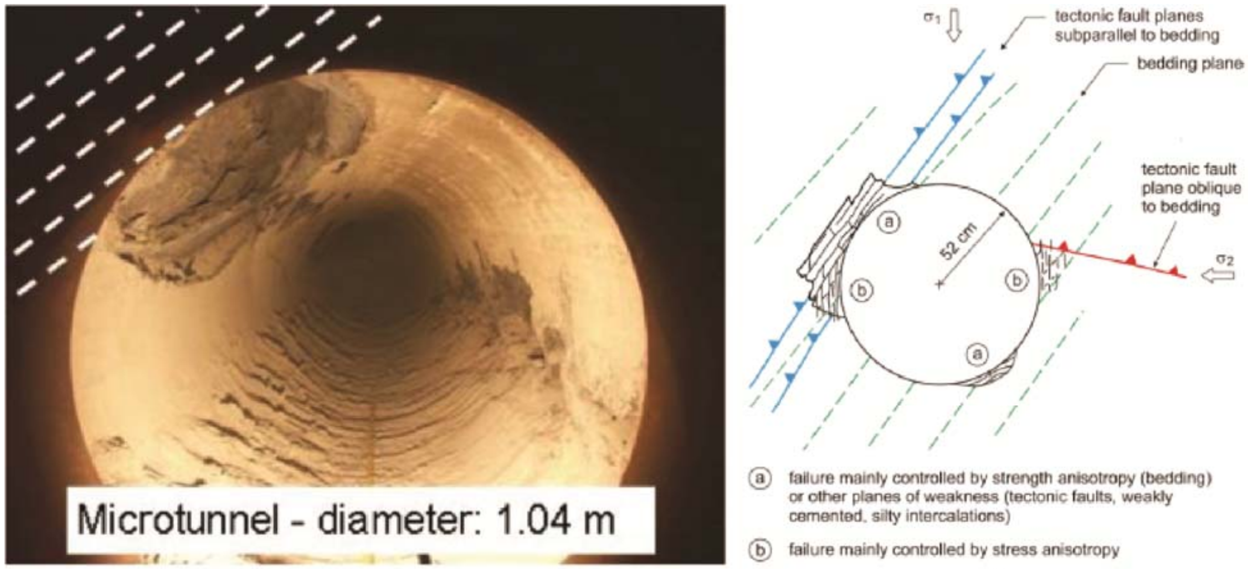


Figure 6-17. Fracture patterns of the specimens with various orientations of fabric forming the angle of β with the loading axis. Note that the positive angle indicates counter-clockwise rotation from the vertical orientation. (from Zheng et al., 2014)



a) b)

Figure 6-18. a) Excavation damage viewing from the HG-A Niche towards back end (from Marschall et al., 2006); and b) Conceptual diagram of the damage zone (from Lanyon et al., 2009)

a) b) c)

Figure 6-19. a) Discretization of the computational domain for the HG-A test simulation; b) nonuniform fracture pattern around the tunnel; and c) deformed shape of the borehole (from Zheng et al., 2014)

6.1.5 DFN Modeling of BRIE Experiment at Äspö Hard Rock Laboratory (LANL)

Researchers at LANL have been developing novel discrete fracture network (DFN) approaches for modeling flow and transport in the near- and far-field domains of sparsely fractured crystalline formations (e.g., Section 2 in Milestone Report "*Crystalline and Crystalline International Disposal Activities,*" FCRD-UFD-2014-000495 [Dittrich et al., 2014]). In FY14, LANL has started applying these capabilities to the ongoing BRIE Experiment at Äspö Hard Rock Laboratory, where the water-bearing fractures have been mapped and their interaction with the bentonite backfill in a vertical deposition hole is being measured (Section 3.4.2). The main objectives of the work are to test and refine the DFN modeling capability using the BRIE site as a well-characterized demonstration site. This work is part of SKB's Task Force on Groundwater Flow and Transport.

The scope of the BRIE modeling task is to simulate wetting of the bentonite in the emplacement boreholes. This requires that flow in the fracture network near the boreholes also be modeled. The DFN grids are locally two-dimensional whereas the emplaced bentonite requires a conventional three-dimensional space-filling grid. As a preliminary step in the BRIE modeling, LANL's DFN modeling capability needed to be extended to allow for hybrid DFN/volume grids. The procedure used to create hybrid DFN/volume meshes is illustrated for a simple demonstration example in Figure 6-20. In this example, the interior of a cylinder is to be meshed and merged with a DFN grid in the nearby rock volume. A DFN is first generated using the procedures described previously (Painter et al., 2012; Hyman et al., 2014). The generated DFN ignores the volume to be meshed. However, before the DFN is meshed, interfaces between fractures and the cylinder to be meshed are identified. A two-dimensional mesh is then created on each fracture in a way that conforms to the fracture intersections and to the fracture-volume interfaces (Figure 6-20A). In the second step, nodes on the fractures within the volume to be meshed are removed (Figure 6-20B). A tetrahedral mesh that conforms to the fracture intersection is then created within the cylinder. In the final step, the tetrahedral mesh and the DFN mesh are merged and duplicate nodes removed (Figure 6-20C). The LaGriT software (Los Alamos Grid Toolbox, 2011) was used to execute the meshing calculations.

Using the hybrid procedure explained above, the LANL team developed a BRIE model for a 40 m × 40 m × 40 m cube to simulate flow in the fractured granite surrounding two BRIE boreholes as well as flow in the bentonite-filled boreholes themselves. One typical meshed realization of the BRIE DFN with three deterministic fractures and two BRIE boreholes is shown in Figure 6-21. For this preliminary simulation, the lower cutoff for fracture length was increased to 1.0 m to reduce the size of the network, with appropriate adjustments to the fracture density. The network contains approximately 3500 stochastically generated fractures. Initial results for rewetting of the BRIE experiment boreholes for two realizations of the DFN are shown in Figure 6-22 at 3 months, 6 months, and 12 months. Little difference is noted between the two realizations. Both realizations show a steep gradient in liquid saturation in the bentonite near where it intersects with fractures. Away from that intersection, the bentonite is rewetting relatively uniformly. This dependence of saturation on distance from the fracture intersection is attributed to the shape of the capillary pressure versus saturation curve, which provides for strong suction at lower saturation values (Section 3 in Dittrich et al., 2014). The two realizations of the DFN with boreholes in place is an important demonstration of an advanced modeling capability combining volume and DFN meshes, and incorporating complex geometries. Comparison of simulated and measured saturation values in the BRIE borehole is under way.

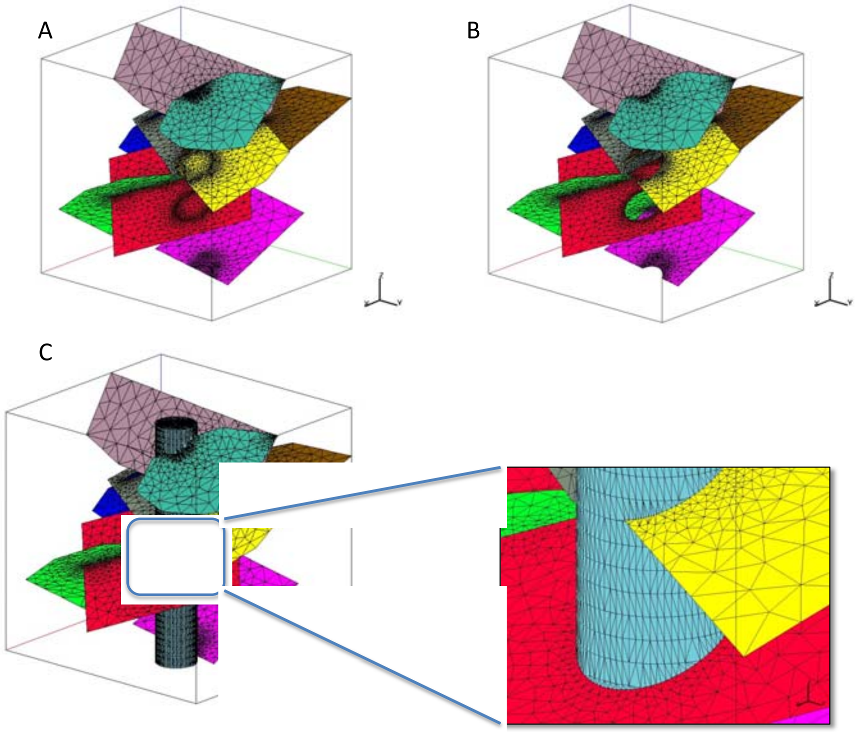


Figure 6-20. Example showing the creation of a hybrid tetrahedral/DFN mesh. Such hybrid meshes were required to model the rewetting of bentonite in the BRIE. (from Dittrich et al., 2014)

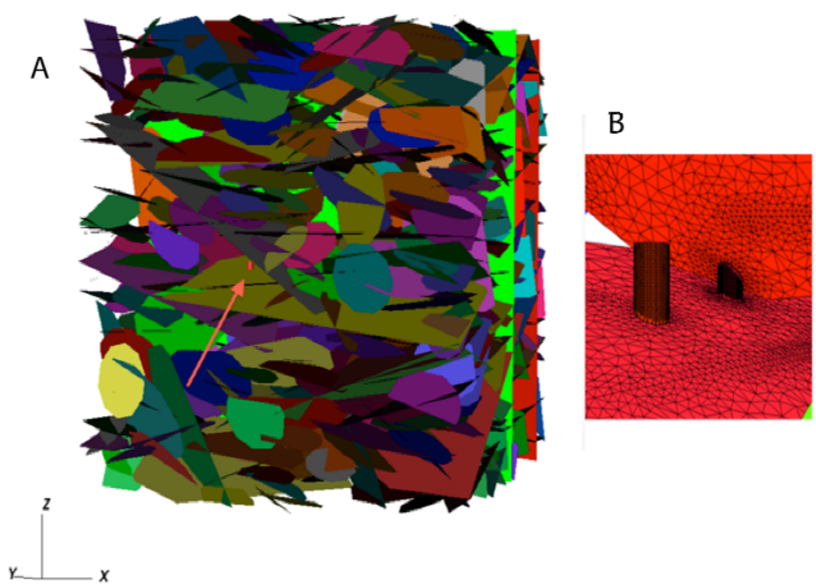


Figure 6-21. Computational mesh for the three-dimensional model of the BRIE experiment. The DFN and boreholes are shown in A. The arrow indicates the position of one of the boreholes. A detail from the computational mesh showing the merged DFN and tetrahedral mesh is shown in B. (from Dittrich et al., 2014)

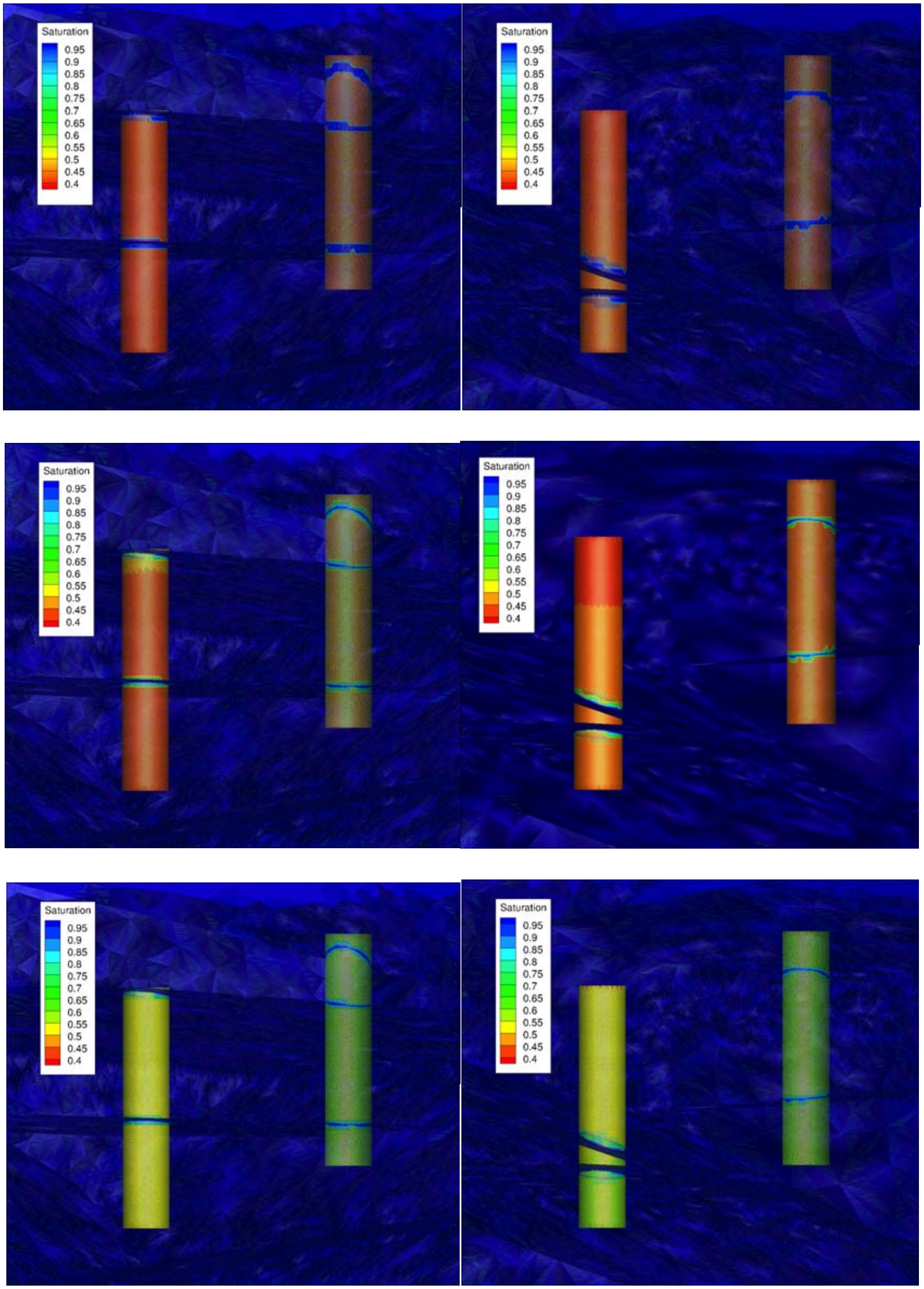


Figure 6-22. Details from two simulations of rewetting of the BRIE experiment boreholes. Results from one realization of the DFN are shown in each of the two columns. The top row is at 3 months, the middle row is at 6 months, and the bottom row is after one year of rewetting. (from Dittrich et al., 2014)

6.2 Fluid Flow and Radionuclide Transport

6.2.1 Using Environmental Tracers to Estimate Fracture-Network Properties: Application to the Bedrichov Tunnel Experiment

Since 2012, SNL scientists have participated as DOE's modeling team in the interpretation and modeling of DECOVALEX Task C2, which is the Bedrichov Tunnel Experiment in the Czech Republic (see Section 3.1.7). The task utilizes a dataset of environmental tracers and discharge in the Bedrichov Tunnel. The expectation is that environmental tracers can provide valuable information for constraining parameters controlling flow and transport and making better predictions of contaminant transport in fracture network systems. The high-resolution groundwater discharge data measured in the Bedrichov Tunnel—along with measurements of stable isotopes of water, tritium, tritiogenic ^{3}He and other noble gases, as well as dissolved chlorofluorocarbons—provide a unique data set against which to test and calibrate numerical models of groundwater flow and solute transport in fractured media. The goal of Task C2 is to model groundwater flow and transport of environmental tracers in the fracture systems surrounding the Bedrichov Tunnel and utilize this data to constrain fracture-network parameters.

Consistent with the modeling steps defined for Task C2, SNL scientists first developed a lumped parameter model for stable isotope, tritium and CFC-12 transport at the Bedrichov Tunnel site and compared model results to measured data. The lumped parameter model consistently predicts heavier isotopic values observed at the site, indicating preferential recharge of winter precipitation (Figure 6-23). PFLOTRAN, a multiphase, multicomponent reactive flow and transport simulator, was then used to simulate multiple environmental tracer concentrations in heterogeneous 2D and 3D domains (Figure 6-24). Fracture-zone permeability was calculated by matching the steady tunnel discharge to the appropriate values given in the description of Task C2. The modeling results demonstrate the usefulness of both the lumped parameter model and the PFLOTRAN code for evaluating flow and transport behavior in fractured crystalline rocks.

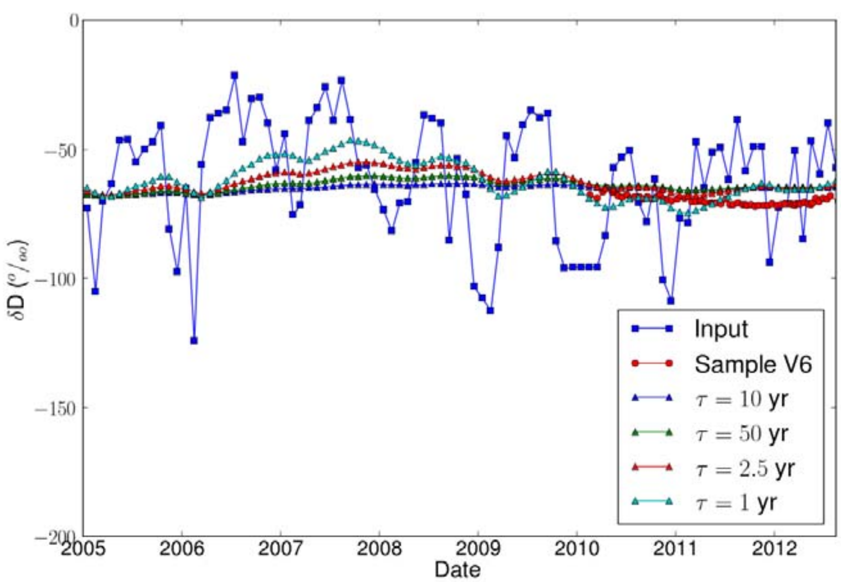


Figure 6-23. Measured and modeled stable isotope composition for the Bedrichov collection canal using the exponential age distribution (from Wang et al., 2014)

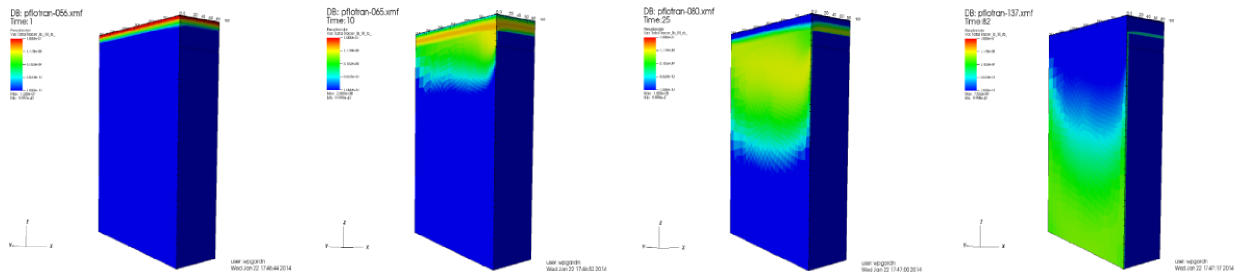


Figure 6-24. Transport sequence of tracer migration from a selected PFLOTRAN simulation run. Note that tracer concentration is contoured in log scale. Fracture plane on left side of domain, tunnel on right (front) of domain. (from Wang et al., 2014)

The comparison of modeling results among the participating DECOVALEX teams from Germany and the Czech Republic has improved confidence in the intended use of the modeling tools. SNL's work FY14 work on the Bedrichov Tunnel Experiment is described in Section 2 of the Milestone Report "*Fluid Flows in Fractured Crystalline Rock – International Collaborations*," FCRD-UFD-2014-000499 (Wang et al., 2014).

6.2.2 R&D Cooperation with KAERI at the KURT URL

As part of ongoing bilateral collaboration between DOE and the Republic of Korea (Section 4.1), researchers at SNL have developed a multi-year plan for joint field testing and modeling to support the study of high-level nuclear waste disposal in crystalline geologic media. The work for FY14 focused on two tasks: (1) streaming potential (SP) testing to better understand groundwater flow and transport, and (2) technique development for *in situ* borehole characterization. Brief descriptions are given below; for more detail, we refer to Section 3 of Milestone Report "*Fluid Flows in Fractured Crystalline Rock – International Collaborations*," FCRD-UFD-2014-000499 (Wang et al., 2014).

The SP method is a geophysical technique that is sensitive to the movement of groundwater in real time. The method is based on the fact that the streaming of water through pores and fractures in the ground can produce a natural electrical potential (called streaming potential) along the flow path. Therefore, unlike other geophysical methods, there is a direct relation between SP signal and groundwater flow. A number of recent studies have used the SP method for quantifying groundwater flow properties associated with porous media (e.g., aquifer transmissivity and storativity).

In contrast, only preliminary studies have been conducted testing the suitability of the SP method when dealing with discrete fractures and anisotropic flow patterns (Hunt and Worthington, 2000; Wishart et al., 2006; Suski et al., 2008). The objective of the collaborative R&D between SNL and KAERI is to obtain a mechanistic understanding of the coupling of electrochemical processes with hydrologic flows in fractured rock. As a first step, laboratory-scale testing of groundwater flow and transport with SP signal monitoring is being conducted by KAERI in a sand box of dimensions 1 m long × 0.5 m wide × 0.4 m high (Figure 6-25). Results of a preliminary experiment with water drainage and SP measurements are shown in Figure 6-26. As the water table decreases, the self-potential also decreases, which means that the installed device is sufficiently sensitive to detect the change of self-potential in the test box. Ongoing and planned laboratory experiments are, respectively, a hydraulic test with fixed gradient to examine whether SP can be used to estimate hydraulic conductivity and a tracer test to establish possible correlation between SP and solute concentration. Plans also exist to transfer the test equipment into the field to measure EDZ properties at the Korea Underground Research Tunnel (KURT) once the extension of the facility is completed. This testing will directly support UFD efforts on developing advanced methods for characterizing an excavation-disturbed zone (EDZ). KAERI will be responsible for instrumentation, field testing and data acquisition of the *in situ* experiment. SNL and KAERI will work jointly on experimental design and data interpretation.

Figure 6-25. Sand box for SP sand box experiments (from Wang et al., 2014)

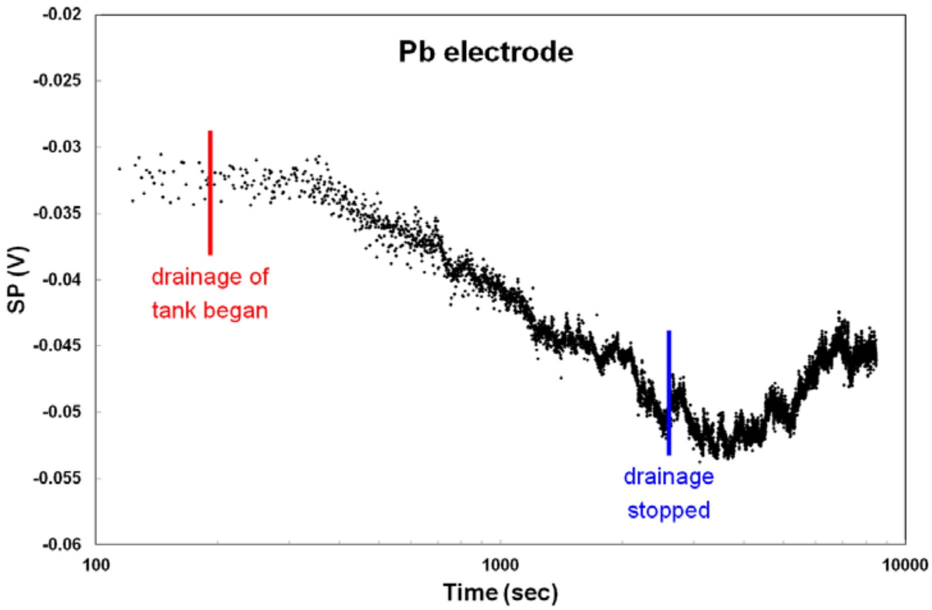


Figure 6-26. Change of SP in the sand box during drainage of water (from Wang et al., 2014)

As mentioned above, KAERI and SNL are collaborating on a second task: technique development and demonstration for *in situ* borehole measurements. Key techniques have been identified and demonstration of selected techniques is currently planned in the DB-2 borehole, which was recently drilled from the surface to a depth of 1,000 m just outside of the KURT facility (Section 4.1). Key techniques have been identified by KAERI and SNL, grouped into the following main categories (Wang et al., 2014):

Development of *in situ* measurement and data acquisition techniques

Objectives:

Better understanding of deep hydrogeological and geochemical characteristics and uncertainty reduction in evaluating deep geologic environments of granitic area

Key techniques:

1. Development of *in situ* measurement equipment for hydrological and hydrochemical parameters at high pressure conditions in a deep borehole
2. Development of groundwater sampling and monitoring technique from very low water conductivity zone of a deep borehole
3. Development of techniques for remote measurement of hydrochemical and hydrological properties from a deep borehole
4. Alternative techniques for earthquake and micro-movement observation in a deep borehole

Development of rock mechanical investigation techniques

Objectives:

Evaluation of mechanical characteristics and construction of rock mechanical models in deep geologic environments of granitic area

Key techniques:

1. Development of an in situ rock stress measurement strategy
2. Techniques for mechanical tests in deep boreholes to determine in situ stress state
3. Evaluation techniques for geomechanical development and long-term behavior of the excavation disturbed zone and the surrounding rock mass in a deep borehole
4. Evaluation techniques for geochemical development and long-term behavior of the excavation disturbed zone and the surrounding rock mass in deep borehole

Development of evaluation techniques for microbiological and biogeochemical effect in deep environment

Objectives:

Evaluation of microbiological and biogeochemical effects in deep environments of granitic area and development of the integrated biochemical and geochemical modeling tools

Key techniques:

1. Evaluation techniques for microbiological and biogeochemical effects on the variation of hydrological properties of the fracture network in deep environments
2. Evaluation techniques for microbiological effects on oxidation-reduction conditions in deep environments

Development of evaluation techniques for solute migration and natural analogue study

Objectives:

Evaluation of solute migration properties in deep geologic environments of granitic areas

Key techniques:

1. Techniques for the characterization of the transport property of a water-conductive fractured zone and the hydraulic connectivity among fractures in a crystalline rock
2. Techniques for natural analogue studies using deep boreholes

More detail on these key techniques is given in Section 3.1.6 of Milestone Report "*Fluid Flows in Fractured Crystalline Rock – International Collaborations*," FCRD-UFD-2014-000499 (Wang et al., 2014). KAERI and SNL will continue to discuss target investigation items and their priority based on the key techniques proposed above. Selected key techniques may be used for further testing in the deep borehole DB-2 near the KURT site.

6.2.3 Diffusion-Reaction Modeling of the DR-A Experiment at Mont Terri

UFD researchers have also utilized international collaboration to test modeling approaches for radionuclide diffusion processes in compacted clay-based materials. In such materials (e.g., clay-rich rocks or compacted bentonite), the negatively charged clay particles are balanced by a cation-enriched electrical double layer (EDL). Radionuclide diffusion is affected by these electrochemical effects. While anions are likely to be excluded from this layer at high degrees of compaction, their concentration is decreased in the double layer even at lower degrees of compaction, and the tortuosity of the compacted clay with respect to chloride changes as well. Both of these contribute to slower diffusive transport rates of ions through compacted clay-rich materials (Bourg et al., 2003; Bourg et al., 2006; Leroy et al., 2006; Gonçalvès et al., 2007), an effect that becomes increasingly important as the compaction increases. For realistic performance predictions of radionuclide transport in the EBS and near-field rock, it is important to develop rigorous and yet practically useful approaches to modeling such diffusive processes.

LBNL has been pursuing two separate but related approaches to modeling ion diffusion through compacted clays. The first makes use of a Donnan equilibrium approach, in which a mean electrostatic potential is defined for the electrical double layer that balances the fixed negative charge of the clays. The volume of the EDL required for mass-balanced-based transport calculations is the product of the surface area of the clays and the width of the EDL, normally calculated as some multiple of the Debye length. The second approach involves the use of the Nernst-Planck and Poisson-Boltzmann equation (termed the Poisson-Nernst-Planck or PNP equation), which resolves the electrical potential as a function of distance from the charged clay surfaces. Both approaches predict that the electrical potential in the space between two clay layers does not decay to zero when the clay layers or interlamellae are closely spaced, and thus the water within the space does not have the same properties as "bulk water." A recent improvement of both methods now allows dynamic calculation of the width and the composition of the electrical double layer (or micro) porosity as a function of ionic strength (and other geochemical properties). Further details on this method and applications are provided in Section 6 of the Milestone Report "*Investigation of Coupled Processes and Impact of High Temperature Limits in Argillite Rock*," FCRD-UFD-2014-000493 (Zheng et al., 2014).

During the past two years, LBNL has been one of the international research teams involved in the DR-A Diffusion, Retention and Perturbation Experiment of the Mont Terri Project. As mentioned in Section 3.2.5, one of the geochemical perturbations investigated in this experiment was a dynamic change in ionic strength, which provides an extremely valuable set of validation data to test LBNL's new diffusive transport modeling capabilities with dynamic calculation of the EDL. We recall that the DR-A test consisted of a single borehole drilled in the Opalinus Clay that contained an ionic strength cocktail and anions, cations, and nonreactive tracers like tritium (HTO), operated in two stages: In the first stage 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 (1.135M) was circulated in the borehole without diluting the tracers (HTO, iodine, and bromine) in the cocktail. The higher ionic strength solution was allowed to diffuse out of the borehole through Day 412.

The diffusion simulations for the DR-A test conducted by LBNL assume a fixed total porosity for the Opalinus Clay, but with dynamic partitioning between the "bulk" and "EDL" porosities governed by the Debye length (which in turn is determined by the ionic strength, and thus variable over the course of the 412 day experiment). Selected results from the simulations, including the increase in ionic strength in the borehole-reservoir system at Day 189, are shown in Figure 6-27 in comparison to the measured data. One expects that the increase in ionic strength will lead to a decrease in the thickness of the EDL, and thus an increase in bulk versus EDL porosity. An increase in bulk porosity, in turn, is expected to allow for more effective diffusion of anions, and thus an increase in rate of loss from the borehole. Indeed, the anion (iodide and bromide) concentrations in the borehole show an increase in the rate of loss from the borehole starting about Day 189, the time when the ionic strength was increased. The simulation results also show an increase in the rate of loss from the borehole (solid blue red for iodide), albeit slightly less pronounced, which is likely the result of the use of the same diffusion coefficients for the iodide and bromide in the EDL and bulk porosity. One expects that diffusion rates of anions in the EDL are smaller because of the greater tortuosity for the negatively ions versus the bulk fluid. The comparison between simulations and test results provides evidence that the electric double layer influences anion diffusion rates in the Opalinus Clay, that these rates are also affected by ionic strength, and that the new modeling approaches developed by LBNL can account for all relevant influences and effects on ion diffusion.

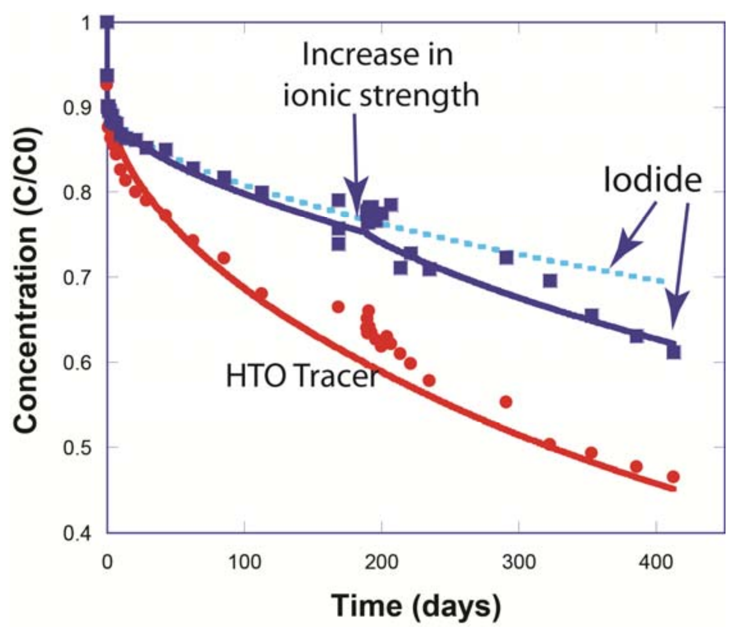


Figure 6-27. Evolution of concentration in the borehole with comparison of data (symbols) versus simulation results (solid lines) for the DR-A test through Day 412. The pale blue dashed line represents simulation results for anion diffusion where the EDL thickness and porosity is not affected by ionic strength. (from Zheng et al., 2014)

6.2.4 Interpretative Analysis of Colloid Migration and Radionuclide Transport for CFM Experiments

For the past several years, researchers at LANL have been working on developing an improved understanding and predictive capability for colloid migration and colloid-associated radionuclide transport in crystalline formations (Arnold et al., 2011; Kersting et al., 2012). In FY13 and FY14, LANL scientists conducted quantitative interpretation of radionuclide transport and colloid breakthrough from four colloid-facilitated transport tests performed as part of the CFM Project between 2008 and 2012 at the Grimsel Test Site in Switzerland (Section 3.3.1). These tests provide valuable data on how colloids released as a result of swelling and erosion of a bentonite plug will transport radionuclides through a preferred flow path such as a shear zone. Initial model interpretations conducted in FY13 (Section 2 in Wang et al., 2013) to analyze the tri- and tetravalent homologue and actinide breakthrough curves in these tests were refined in FY14, with emphasis on evaluating alternative descriptions of the desorption process of the solutes from the bentonite colloids and determining which description best explains the test observations. This activity constitutes DOE/UFD's formal contribution to the CFM project. In collaboration with the Karlsruhe Institute of Technology (KIT) in Germany, LANL complemented the field-based colloid simulations with laboratory experiments on colloid-facilitated transport of americium (Am). These experiments were conducted in small columns packed with weathered fracture fill material (also known as fault gouge) collected in the shear zone of the Grimsel Test Site, using bentonite colloids processed from a sample of FEBEX bentonite. Both activities are described in detail in Sections 5 and 6 of Milestone Report "*Crystalline and Crystalline International Disposal Activities*," FCRD-UFD-2014-000495 (Dittrich et al., 2014). A brief summary of the field data analysis is given below.

The interpretation of breakthrough curves in the CFM tracer tests was conducted using a semi-analytical model referred to as RELAP (REactive transport LAPlace transform) (Reimus et al., 2003) as well as a more sophisticated 2D numerical model (Reimus, 2012). RELAP uses a Fourier transform inversion method to solve the Laplace-domain transport equations in either a single- or a dual-porosity system. The model can account for diffusion between fractures and matrix, as well as linear, first-order reactions in both fractures and matrix. The very rapid execution of the model makes it ideal for the numerous simulations needed for transport parameter estimation. For each test, RELAP was first applied to fit the conservative tracer extraction breakthrough curves by adjusting the mean residence time and Peclet number in the shear zone (Peclet number is transport distance divided by longitudinal dispersivity) as well as the fractional tracer mass participation in each test. In addition to providing estimates of shear-zone transport parameters for the conservative tracers, RELAP was also used to estimate colloid transport parameters (filtration and resuspension rate constants). These estimates were obtained by assuming that the mean residence time, Peclet number, and fractional mass participation estimated for the conservative tracers also applied to the colloids, and then the filtration-rate parameters were adjusted to fit the colloid data. The resulting best-fitting parameters from RELAP were used as initial parameter estimates in a 2-D numerical model that could account for processes that RELAP does not explicitly account for. The most important of these processes were the variable injection flow rates observed in one of the field experiments and the simultaneous transport of colloids and reactive solutes in all the tests (RELAP does not account for interacting species).

It was found that once appropriate mean residence times, Peclet numbers and fractional mass participations were determined for the conservative tracer breakthrough curves in each test, and filtration parameters were determined for the colloids, the model fits to the colloid-facilitated solute breakthrough curves were sensitive mainly to the desorption-rate constants of the solutes from the colloids. The best fits to the field data were obtained when (1) the rate constants for solute adsorption to the shear-zone surfaces were large enough that the solutes rapidly adsorbed to these surfaces after they desorbed from the colloids and (2) the rate constants for solute desorption from the shear-zone surfaces were small enough that the solutes effectively did not desorb from these surfaces for the remainder of the tests. Under these conditions, the shear zone surfaces act as a fast and irreversible sink once desorption from colloids occurs. Because the tri- and tetravalent solute desorption process from colloids appeared to be so important, LANL researchers implemented into their models alternative descriptions of the solute associations with the colloids and tested these against the measured breakthrough curves from the CFM experiments. Figure 6-28 shows sample results for the model fit to the breakthrough curves for the conservative dye tracers and colloids. Overall, the simulated and measured breakthrough curves show excellent agreement, indicating the relevant processes driving colloid-facilitated transport are reasonably accounted for in the RELAP analysis, at least at the scale of the CFM test facility. As discussed in Dittrich et al. (2014), upscaling to repository scale presents further challenges.

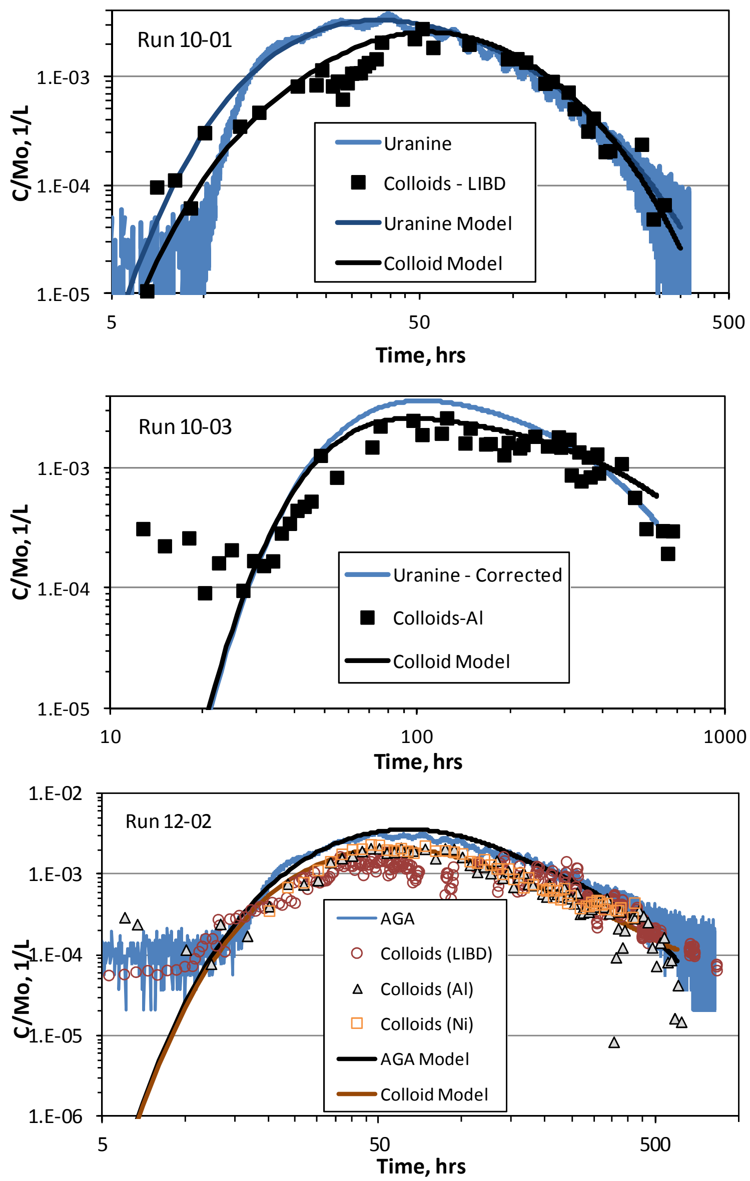


Figure 6-28. Simulated and experimental breakthrough curves for the conservative dye tracers and colloids in CFM Runs 10-01, 10-03 and 12-02. Three colloid breakthrough curves are shown for Run 12-02 because three analytical methods were used to quantify the colloid concentrations. (from Dittrich et al., 2014)

6.2.5 Plutonium Adsorption and Desorption Experiments Related to CFM

In FY14, in support of the international collaboration with the CFM Project, researchers at LLNL continued their laboratory experiments and interpretation work on plutonium adsorption and desorption to bentonite. Due to its swelling properties, plasticity, ion exchange, sorption and sealing capability, bentonite is a suitable candidate for backfill material in nuclear waste repository scenarios. However, as discussed in the Section 6.2.4, one of the concerns with the use of bentonite is that it can form colloidal particles, which may enhance the migration of radionuclide species (Geckeis et al., 2004; Kersting et al., 1999). As a result, radionuclide (including Pu) adsorption to mineral colloids has been the subject of considerable research. In contrast, desorption reactions have been far less well studied. The aim of LLNL's FY14 activities has been two-fold: (1) to provide information on Pu adsorption/desorption to FEBEX bentonite, a backfill material used at the Grimsel Test Site, and (2) to determine if the linearity observed for Pu(V) sorption to a pure clay mineral is replicated for Pu(IV) sorption to a multicomponent clay rock. To this extent, the sorption behavior of Pu(IV) to FEBEX bentonite was examined in laboratory experiments across a wide range of initial concentrations (10^{-7} – 10^{-16} M) over a 120 d period. In addition, LLNL performed long-term (10 month) adsorption experiments with Pu(V) to better constrain the slow apparent rates of reduction on bentonite. The experimental setup and results are described in Milestone Report "*Plutonium Adsorption and Desorption from Bentonite: Progress Report,*" FT-14LL080771 (Begg et al., 2014).

LLNL's experiments demonstrate the control that the montmorillonite in bentonite exerts on the adsorption behavior of Pu, provides long-term adsorption data useful for the interpretation of colloid transport experiments at the Grimsel test site, and validates the extrapolation of Pu(IV) experiments performed at concentrations of 10^{-10} M Pu to concentrations typically found in the environment at timescales relevant for groundwater transport. A numerical model was developed to describe the adsorption and desorption behavior of Pu with montmorillonite colloids. In future work, LLNL scientists plan to apply this numerical model to data generated in the recent colloid-transport experiments performed within the CFM Project at the Grimsel Test Site (Section 3.3.1).

6.3 Summary Table

Table 6-1 provides a summary list of ongoing R&D activities by UFD scientists in collaboration with international peers and focus on field data sets. For each activity, the table provides the respective section in this report, the current status, and the UFD milestone feeder report providing more detail.

Table 6-1. Summary of FY14 Work Packages Activities with International Collaboration and Focus on URL Experiments

Work Package Activity	Report Section	Status	UFD Milestone
THM Modeling of HE-E Heater Test at Mont Terri	6.1.1.1	Modeling steps 1 and 2 for DECOVALEX Task were finalized in late FY14 (THM modeling of HE-D borehole heater test and Ciemat laboratory experiments). Predictive simulations for HE-E experiment have started.	FRDC-UFD-2014-000493, Sections 4.2 and 4.3, Zheng et al. (2014)
THM Modeling of EBS Experiment at Horonobe	6.1.1.2	Simplified benchmark simulations were finalized in FY14. Predictions for full-scale heater experiment are ongoing.	FRDC-UFD-2014-000493 Section 4.4, Zheng et al. (2014)
THM Modeling of FE Heater Test at Mont Terri	6.1.1.3	Design predictions for FE Heater Test have been finalized and shared with other modeling teams.	FRDC-UFD-2014-000493 Section 4.5, Zheng et al. (2014)
FEBEX-DP Work Plan Development	6.1.2	Initial draft work plans were developed for DOE's participation in sample analysis and pre/post-dismantling modeling.	Not reported
HM Modeling of Mine-by Test at Mont Terri	6.1.3	Substantial work conducted in FY12 and FY13 to test new constitutive model for stress-strain relationship in comparison with Mont Terri data (displacement, EDZ behavior, etc.). Works is completed.	FRDC-UFD-2013-000244 Section 2, Liu et al. (2013)
DFN Modeling of HG-A Experiment at Mont Terri	6.1.4	New coupled flow and dynamic fracture simulation framework was applied to EDZ characteristics observed in HG-A micro-tunnel.	FRDC-UFD-2014-000493 Section 3.4, Zheng et al. (2014)
DFN Modeling of BRIE Experiment at Äspö Hard Rock Laboratory	6.1.5	BRIE model with discrete fracture network surrounding volume grid for bentonite-filled boreholes was generated and preliminary simulations were conducted.	FRDC-UFD-2014-000495 Section 3, Dittrich et al. (2014)
Using Environmental Tracers to Estimate Fracture Network Properties: Bedrichov Tunnel Experiment	6.2.1	Simple lumped-parameter models as well as high-fidelity PFLOTRAN simulations were conducted to evaluate flow and transport behavior at the site and compare results to measured data.	FRDC-UFD-2014-000499 Section 2, Wang et al. (2014)
Work Plan for R&D Cooperation with KAERI at KURT	6.2.2	Laboratory experiments and modeling on Streaming Potential Methods were performed. A work plan has been developed to identify and test techniques for *in situ* borehole measurements.	FRDC-UFD-2014-000499 Section 3, Wang et al. (2014)
Diffusion-Reaction Modeling of DR-A Experiment at Mont Terri	6.2.3	New modeling capabilities (for electrical double layer effects on diffusion) were applied to and compared with results from DR-A Experiment. Work is completed.	FRDC-UFD-2014-000493 Section 6.4, Zheng et al. (2014)
Interpretative Analysis of Colloid Migration and Radionuclide Transport for CFM Experiments	6.2.4	Substantial work was conducted interpret via semi-analytical and numerical modeling the observed breakthrough curves from several colloid-facilitated transport experiments conducted at Grimsel Test Site	FRDC-UFD-2014-000495 Section 6, Dittrich et al. (2014)
Plutonium Adsorption and Desorption Experiments Related to CFM	6.2.5	A series of laboratory experiments were completed to measure plutonium adsorption and desorption to bentonite.	FT-14LL0807071 Begg et al. (2014)

7. BRIEF STATUS OF OTHER INTERNATIONAL COLLABORATION ACTIVITIES

This section provides brief descriptions of ongoing international collaboration activities that are not directly associated with access to field data or participation in URL field experiments. As with the remainder of this report, the focus here is on active collaboration in specific R&D projects, not on conferences, meetings, or other types of information exchange.

7.1 Collaborative Salt Repository Research with Germany

There are ongoing collaborative efforts between scientists from the U.S. and Germany regarding salt as a host rock for radioactive waste. In FY14, these collaborative efforts focused on: (1) selected aspects of the safety case for salt disposal of high-level waste, (2) plugging and sealing of a salt repository, (3) salt mechanics modeling, and (4) repository design including potential uses of an underground research laboratory (URL) at the Waste Isolation Pilot Plant (WIPP). Details of the collaborations in each of these areas are summarized below (mainly based on Milestone Report "*Status of UFD Campaign International Activities in Disposal Research at SNL*," FCRD-UFD-2014-000510, McMahon, 2014):

Safety Case for Heat-Generating Waste Disposal in Salt

- Subject matter experts from SNL and Germany are compiling a comprehensive Features, Events, and Processes (FEPs) catalogue for disposal of heat-generating waste in salt (Freeze et al., 2014).
- SNL is beginning to develop a generic safety case for disposal of heat-generating waste in bedded salt. Collaborators discussed elements of the safety case including handling uncertainties and the qualitative contribution of analogs. This progress along with Germany's preliminary safety analysis for the Gorleben site ("Vorläufige Sicherheitsanalyse Gorleben" or VSG) provides a strong technical basis for a safety case for disposal of heat-generating nuclear waste in salt.

Plugging and Sealing

- U.S. and German researchers are collaborating on the design and evaluation of plugs and seals in a salt repository. Sealing capability for both shafts and drifts has to be demonstrated in the laboratory and at full-scale *in situ*.
- Real-time and full-scale drift-seal demonstrations are ongoing in the Morsleben repository, in the European project full-scale Demonstration of Plugs and Seals (DOPAS) project, and in the BMWi research and development (R&D) project "Shaft seals for repositories for high-level radioactive waste" or in German "Schachtverschlüsse für Endlager für hochaktive Abfälle" (ELSA). The ELSA project develops concepts for shaft seals and demonstrates functional elements using laboratory and medium-scale tests. One of the key overarching research areas pertaining to plugging, sealing, testing, and modeling involves reconsolidation of granular salt, particularly in the horizontal orientation.

Salt Mechanics Modeling and Benchmarking

- A joint benchmarking study on HM processes in salt between German groups and SNL has been officially extended to include two additional benchmarking problems based on *in situ* full-scale tests conducted in the early 1980s at WIPP. Modeling will compare an isothermal mining development test (WIPP Room D) to a heated "overtest" for simulated defense high-level waste (WIPP Room B).

- In concert with benchmark modeling of the full-scale field tests, German research groups are conducting approximately 140 laboratory experiments on WIPP salt. Back-calculations of the various lab tests with different boundary conditions demonstrate the ability of the models to describe different phenomena and their dependencies under different and well-controlled conditions. Back-calculations of these lab tests are not only performed for parameter determination, but also as a check of model capability to describe the deformation behavior of bedded WIPP salt.

Salt THM Modeling and Benchmarking

- Researchers from LBNL have been collaborating with a research group led by Professor Lux in Germany at the Clausthal University of Technology (TUC) on modeling coupled THM processes in salt. LBNL incorporated into the TOUGH-FLAC simulator an advanced geomechanical constitutive model for rock salt developed by the TUC group (the Lux/Wolters model), a model that can handle creep, damage, sealing, and healing of the salt as a function of stress, temperature, and pore pressure. Using the TOUGH-FLAC simulator, LBNL and TUC are now working on THM benchmarking studies. One ongoing benchmark problem involves modeling of the TSDE (Thermal Simulation for Drift Emplacement) test conducted in the Asse Mine, Germany. More details are provided in Milestone Report "*Modeling Coupled THMC Processes and Brine Migration in Salt at High Temperatures*," FCRD-UFD-2014-000341 (Rutqvist et al., 2014b).

Repository Design and Use of the Underground Research Laboratory (URL)

- The international salt repository community has significant experience in collaborative monitoring projects, which were revisited in a recent U.S./German Salt Workshop held September 16–17, 2013 in Berlin, Germany. Workshop participants examined possible uses of the new research tunnels in the WIPP underground setting. Several potential activities were discussed in breakout sessions, and feedback included a sense of duration, cost, and merit among the many potential uses. A more formal and rigorous review process of underground research activities at WIPP would be expected in order to guide development of the facility as an underground research laboratory.

7.2 Thermodynamic Database Evaluations

Thermodynamic data are essential for understanding, evaluating, and modeling geochemical processes, such as speciation solubility, reaction paths, or reactive transport. The data are required to evaluate both equilibrium states and the kinetic approach to such states. However, thermodynamic databases are often limited and do not span the range of conditions that may exist under the various generic repository scenarios (salt, deep borehole, etc.). For example, previously developed thermodynamic data overstate the stabilities of smectites and illites. While this is adequate for both tuff and salt host rock, the databases have some deficiencies with respect to other repository designs, such as those in clay/shale, or those that include a clay/bentonite buffer. Data that continue to come out of the NEA thermochemical database review program were not incorporated into the previous DOE thermodynamic databases. Furthermore, NEA data are also limited and do not account for pressure extrapolations applicable to deep borehole repositories. Ion exchange data and surface complexation processes are also lacking in most current thermodynamic databases.

Scientists at LLNL have collaborated with the international research community to improve thermodynamic databases and models that evaluate the stability of EBS materials and their interactions with fluids at various physico-chemical conditions relevant to subsurface repository environments. The development and implementation of equilibrium thermodynamic models are intended to describe chemical and physical processes such as solubility, sorption, and diffusion. As part of this work, LLNL scientists have continued participating in the NEA Thermochemical Database (TDB) Project (see Section 3.5.3). Furthermore, LLNL has revised previously developed thermodynamic databases and expanded them to cover the needs of the repository types currently under consideration by the UFD (i.e., clay, granite, deep borehole). In another collaborative effort, LLNL scientists have worked with colleagues from the Helmholtz Zentrum Dresden-Rossendorf in Germany to develop improved thermodynamic data for high-ionic-strength conditions and surface-complexation models. Progress made on these tasks is documented in the Milestone Report "*Thermodynamic Evaluations Progress*," M4FT-14LL0806039 (Zavarin et al., 2014).

8. SUMMARY

Active collaboration with international programs, initiatives, or projects is considered very beneficial to UFD's disposal research program, providing access to the decades of experience that some international programs have gained in various disposal options and geologic environments. The first part of this report discusses opportunities for active international collaboration, with focus on both NBS and EBS aspects and those opportunities that involve field experiments in international URLs. Section 3 contains a summary of currently existing international opportunities resulting from DOE's formal "membership" in international collaborative initiatives, such as the DECOVALEX Project, the Mont Terri Project, the Colloid Formations and Migration Project, the FEBEX-DP Project, and the SKB Task Forces. Benefits of DOE participation include (1) access to experimental data from many past, ongoing, and future *in situ* tests conducted in several URLs in different host rocks, (2) active research participation in international groups that conduct, analyze, and model experiments, and (3) the opportunity to conduct own experiments in international URLs. Additional cooperation possibilities are discussed in Section 4; these comprise bilateral collaborations options with international disposal programs.

With many collaboration opportunities available to UFD, the campaign in FY12 started a planning exercise to identify the most relevant and promising opportunities, and to select and initiate several cooperative R&D activities that align with its goals and priorities. The following criteria were applied: (1) Focus on activities that complement ongoing disposal R&D within UFD, (2) 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, (3) 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), (4) Focus on collaboration opportunities for active R&D participation.

During the past two years, UFD scientists initiated various collaborative projects to address high-priority R&D challenges related to near-field perturbation, engineered barrier integrity, flow and radionuclide transport, and integrated system behavior. The second part of this report provides an overview of this collaborative R&D portfolio and explains how UFD scientists benefit from collaboration with international peers. Section 5 describes the planning process that led to the selection of specific activities. Section 6 then gives a detailed description of projects that make use of international field experiments, and Section 7 briefly mentions other active cooperation projects. Overall, this report attests to the fact that DOE/UFD has in a very short time frame developed a balanced portfolio of international research collaborations that have already led to substantial technical advances (i.e., several science and engineering tools developed in UFD were tested in comparison with data from international experiments). UFD scientists have utilized data and results from laboratory and field studies that have been and are being conducted with millions of R&D investments provided by international partners. UFD's advanced simulation models are being verified and validated against these experimental studies, providing a robust modeling and experimental basis for the prediction of the complex processes defining the performance of a multibarrier waste repository system. Promising opportunities exist for further expansion of the program and are mentioned in the report.

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10. REFERENCES

Aalto, P., Aaltonen, I., Ahokas, H., Andersson, J., Hakala, M., Hellä, P., Hudson, J.A., Johansson, E., Kemppainen, K., Koskinen, L., Laaksoharju, M., Lahti, M., Lindgren, S., Mustonen, A., Pedersen, K., Pitkänen, P., Poteri, A., Snellman, M., Ylä-Mella, M. (2009) *Programme for Repository Host Rock Characterization in ONKALO (ReRoc)*, Posiva Oy Working Report 2009-31.

Äikäs, T. (2011) *Towards Implementation*, Presentation given at the HADES Workshop, "30 Years of Underground Research Laboratory," May 23-25, 2011, Antwerp, Belgium.

Alonso, E.E., Gens, A., Josa, A. (1990) *A Constitutive Model for Partially Saturated Soils*, Géotechnique, 40(3), 405-430.

Arnold, B.A., Reimus, P.W., James, S.C. (2011) *Flow and Transport in Saturated Media: FY2011 Status Report*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-USED-2011-000311, Sandia National Laboratories and Los Alamos National Laboratory.

Barnichon J.D. (2011) *IRSN proposal - the SEALEX In Situ Tests*, Presentation given at 7th DECOVALEX 2011 Workshop, April 2011, Helsinki, Finland.

Barnichon J.D., Millard, A. (2012) *Task A: the SEALEX In Situ Experiments*, Presentation given at 1st DECOVALEX 2015 Workshop, April 2012, Berkeley, CA.

Begg, J.D., Zavarin, M., Tumey, S.J., Kersting, A.B. (2014) *Plutonium Adsorption and Desorption from Bentonite: Progress Report*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FT-14LL0807071, Lawrence Livermore National Laboratory.

Birkholzer, J.T. (2011) *Disposal R&D in the Used Fuel Disposition Campaign: A Discussion of Opportunities for Active International Collaboration*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-USED-2011-000225, Lawrence Berkeley National Laboratory.

Birkholzer, J. (2012) *Status of UFD Campaign International Activities in Disposal Research*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-UFD-2012-000295, Lawrence Berkeley National Laboratory.

Bockgård, N., Vidstrand, P., Åkesson, M. (2012) *Task 8, Modeling the interaction between engineered and natural barriers - An assessment of a fractured bedrock description in the wetting process of bentonite at deposition tunnel scale*, Task Description for GWFTS Task Force, SKB, Internal Report.

Bossart, P., Thury, M. (2007) *Research in the Mont Terri Rock laboratory: Quo vadis?* Physics and Chemistry of the Earth, Parts A/B/C, 32(1-7), 19-31.

Bossart, P. (2012) *Welcome to Technical Meeting 8-9 February 2012*, Presentation given at the Mont Terri Technical Meeting TM-30, February 8-9, 2012, Saint Ursanne, Switzerland.

Bossart, P. (2014a) *Enclosure – Steering Meeting SM-64*, Presentation given at the Mont Terri Steering Meeting SM-64, March 27, 2014, Tournemire URL, France.

Bossart, P. (2014b) *Enclosure – Steering Meeting SM-65*, Presentation given at the Mont Terri Steering Meeting SM-65, May 15, 2014, Horonobe URL, Japan.

Bourg, I.C., Bourg, A.C.M., Sposito, G. (2003) *Modeling Diffusion and Adsorption in Compacted Bentonite: a Critical Review*, J. Contam. Hydrol. 61, 293–302.

Bourg, I.C., Sposito, G., Bourg, A.C.M. (2006) *Tracer Diffusion in Compacted, Water-Saturated Bentonite*, Clays Clay Miner., 54, 363–374.

Bragg-Sitton, S.M, Birkholzer, J., MacKinnon, R., McMahon, K., Saltzstein, S., Sorenson, K., Swift, P. (2014) *Used Fuel Disposition Campaign Campaign Implementation Plan*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-UFD-2014-000047, Draft.BMWi (2008) *Final Disposal of High-level Radioactive Waste in Germany – The Gorleben Repository Project*, Federal Ministry of Economics and Technology (BMWi), Germany, October, 2008.

Cuss, R. (2010) *Large Scale Gas Injection Test (LASGIT): Progress to May 2010*, Presentation given at 6th DECOVALEX 2011 Workshop, October 2010, Wuhan, China.

Dittrich, T., Gable, C.W., Karra, S., Makedonska, N., Painter, S.L., Reimus, P. (2014) *Crystalline and Crystalline International Disposal Activities*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-UFD-2014-000495, Los Alamos National Laboratory.

Freeze, G., Sevougian, S.D., Leigh, C., Gross, M., Wolf, J., Monig, J., Buhmann, D. (2014) *Development a Salt Repository FEP Catalogue*. SAND2014-2423. Sandia National Laboratories, Albuquerque, NM.

Garitte B. (2010) *New In Situ Experiments at Mont Terri*, Presentation given at 6th DECOVALEX 2011 Workshop, October 2010, Wuhan, China.

Garitte B. and several others (2011) *HE-E experiment - In Situ Heater Test*, Presentation given at 7th DECOVALEX 2011 Workshop, April 2011, Helsinki, Finland.

Garitte, B., Gens, A. (2012) *DECOVALEX-2015: Description of Task B1, THM Processes in Argillaceous Rocks and the Engineered Barrier*, DECOVALEX Task Description Report, Modeling Step 1, August 2012.

Gaus, I., Garitte, B., Senger, R., Gens, A., Vasconcelos, R., Garcia-Sineriz, J.-L., Trick, T., Wieczorek, K., Czaikowski, O., Schuster, K., Mayor, J.C., Velasco, M., Kuhlmann, U., Villar, M.V. (2014) *The HE-E Experiment– Layout, Interpretation, and THM Modeling*, NAGRA Arbeitsbericht NAB 14-53, May 2014, Switzerland.

Gaus, I., Kober, F. (2014) *FEBEX-DP Project Plan*, NAGRA, Switzerland.

Geckeis, H., Schafer, T., Hauser, W., Rabung, T., Missana, T., Degueldre, C., Mori, A., Eikenberg, J., Fierz, T., Alexander, W.R. (2004) *Results of the colloid and radionuclide retention experiment (CRR) at the Grimsel Test Site (GTS), Switzerland - impact of reaction kinetics and speciation on radionuclide migration*. Radiochim Acta, 92, 765-774.

Gens, A., Garitte, B., Wileveau, Y. (2007) *In situ Behaviour of a Stiff Layered Clay Subject to Thermal Loading: Observations and Interpretation*, Geotechnique, 57, 207-228.

Gonçalvès, J., Rousseau-Gueutin, P., Revil, A. (2007) *Introducing Inter-acting Diffuse layers in TLM Calculations: A Reappraisal of the Influence on the Swelling Pressure and the Osmotic Efficiency of Compacted Bentonites*, Journal of Colloid Interface Science 316, 92-99.

Hansen, F., Steininger, W., Biurrun, E. (2013) *Proceedings of the 4th US/German Workshop on Salt Repository Research, Design and Operation*. FCRD-UFD-2014-000335, SAND2013-10592P. U.S. Department of Energy, Office of Nuclear Energy, Used Fuel Disposition Campaign, Washington, D.C.

Hokr, M., Slovak, J. (2011) *Bedrichov Tunnel Test Case Proposal for DECOVALEX 2015*, Presentation given at 7th DECOVALEX 2011 Workshop, April 2011, Helsinki, Finland.

Hokr, M., Balvín, A., Škarydová, I., Rálek, P. (2014) *Tunnel inflow in granite - fitting the field observations with hybrid model of discrete fractures and continuum*, in (Sharp and Troeger, eds) Groundwater in Fractured Rocks, 13 pages, to appear 2014

Hunt, C.W., Worthington, M.H. (2000) *Borehole electrokinetic responses in fracture dominated hydraulically conductive zones*. Geophysical Research Letters, 27(9), 1315-1318.

Hyman, J., Gable, C.W., Painter, S.L., Makedonska, N. (2014) *Conforming Delaunay Triangulation of Stochastically Generated Three Dimensional Discrete Fracture Networks: A Feature Rejection Algorithm for Meshing Strategy*. SIAM Journal on Scientific Computing, 36(4), A1871-A1894.

ITASCA (2009) *FLAC3D V4.0, Fast Lagrangian Analysis of Continua in 3 Dimensions, User's Guide*, Itasca Consulting Group, Minneapolis, Minnesota.

Jing, L., Hudson, J.A. (2011) *Technical Descriptions of the Three Tasks Proposed for the Next Phase of the DECOVALEX Project (2012–2015)*, Internal DECOVALEX Report, December 15, 2011.

Jove-Colon, C.F., Caporuscio, F.A., Levy, S.S., Xu, H., Blink, J.A., Halsey, W.G., Buscheck, T., Sutton, M., Serrano de Caro, M.A., Wolery, T.J., Liu, H.-H., Birkholzer, J.T., Steefel, C.I., Rutqvist, J., Tsang, C.-F., Sonnenthal, E. (2010) *Disposal Systems Evaluations and Tool Development - Engineered Barrier System (EBS) Evaluation*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, Used Fuel Disposition Campaign.

KAERI (2011) *KURT – KAERI Underground Research Tunnel*, Brochure, Korea Atomic Energy Research Institute, Division of Radioactive Waste Technology Development.

Kawai, T. (1978). *New Discrete Models and their Application to Seismic Response Analysis of Structures.* Nuclear Engineering and Design, 48, 207-229.

Kersting, A., Zavarin, M., Zhao, P., Dai, Z. Carroll, S., Wang, Y., Miller, A., James, S., Reimus, P., Zheng, L., Li, L., Rutqvist, J., Liu, H.-H., Birkholzer, J. (2012) *Radionuclide Interaction and Transport in Representative Geologic Media*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-UFD-2012-000154, Sandia National Laboratories.

Kersting, A.B., Efurd, D.W., Finnegan, D.L., Rokop, D.J., Smith, D.K., Thompson, J.L. (1999) *Migration of plutonium in ground water at the Nevada Test Site*. Nature, 397, 56-59.

Lanyon, W. et al. (2013) *Review of the FEBEX in situ experiment and the mock-up after 15 years of operation and monitoring*. NAGRA NAB 13-096.

Lanyon, G.W., Marschall, P., Trick, T., de La Vaissière, R., Shao, H. and Leung, H. (2009). *Hydromechanical Evolution and Self-Sealing of Damage Zones around a Microtunnel in a*

Claystone Formation of the Swiss Jura Mountains. American Rock Mechanics Association, ARMA 09-333.

Lebon, P. (2011) *Large-scale Experiment at Bure*, Presentation given at the HADES Workshop, “30 Years of Underground Research Laboratory,” May 23-25, 2011, Antwerp, Belgium.

Leroy, P., Revil, A., Coelho, D. (2006) *Diffusion of Ionic Species in Bentonite*, J. Colloid Interface Sci. 296 (1), 248–255.

Li, X. (2011) *Design and Status of the PRACLAY Seal and Heater Test*, Presentation given at the HADES Workshop, “30 Years of Underground Research Laboratory,” May 23-25, 2011, Antwerp, Belgium.

Liu, H.-H., Houseworth, J., Rutqvist, J., Zheng, L., Asahina, D., Li, L., Vilarrasa, V., Chen, F., Nakagawa, S., Finsterle, S., Doughty, C., Kneafsey, T., Birkholzer, J.T. (2013) *Report on THMC Modeling of the Near Field Evolution of a Generic Clay Repository: Model Validation and Demonstration*, Prepared for U.S. Department of Energy Used Fuel Disposition, FCRD-UFD-2013-000244, Lawrence Berkeley National Laboratory.

Liu, H.-H., Rutqvist J., Berryman J.C. (2009) *On the Relationship Between Stress and Elastic Strain for Porous and Fractured Rock*, International Journal of Rock Mechanics & Mining Sciences 46, 289–296.

Liu, H.-H., Houseworth, J., Rutqvist, J., Li, L., Asahina, D., Chen, F., Birkholzer, J. (2012) *Report on Modeling Coupled Processes in the Near Field of a Clay Repository*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-UFD-2012-000223, Lawrence Berkeley National Laboratory.

Los Alamos Grid Toolbox, LaGriT (2011) Los Alamos National Laboratory, <http://lagrit.lanl.gov>.

McMahon, K. (2014) *Report on the Status of the UFD Campaign International Activities in Disposal Research at SNL*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-UFD-2014-000510, Sandia National Laboratories.

Maes, N., Weetjens, E., Aertsen, M., Govaerts, J., Van Ravestyn, L. (2011) *Added Value and Lessons Learned from In Situ Experiments – Radionuclide Migration*, Presentation given at the HADES Workshop, “30 Years of Underground Research Laboratory,” May 23-25, 2011, Antwerp, Belgium.

Marschall, P. and several others (2012) *Gaspath Through Host Rock and Along Seal Sections (HG-A)*, Presentation given at the Mont Terri Technical Meeting TM-30, February 8 and 9, 2012, Saint Ursanne, Switzerland.

Marschall, P., Distinguin, M., Shao, H., Bossart, P., Enachescu, C. Trick, T. (2006) *Creation and Evolution of Damage Zones Around a Microtunnel in a Claystone Formation of the Swiss Jura Mountains*. Society of Petroleum Engineers, SPE-98537-PP.

Millard, A., Barnichon, J.D. (2014) *Task A – Step 2: Modelling of the SEALEX WT-1 test*, Presentation given at 5th DECOVALEX 2015 Workshop, April 2014, Avignon, France.

NAGRA (2010) *Grimsel Test Site – Research on Safe Geologic Disposal of Radioactive Waste*, Brochure in Recognition of 25 Years of Research at Grimsel Test Site, NAGRA, July 2010.

NAGRA (2014) *FEBEX-DP Kick-Off Meeting*, Presentation given at the kick-off meeting for the FEBEX-DP project, Thun, Switzerland, June 2014.

Nater, P. (2012) *Mont Terri / FE-Experiment Geomechanische Modellierung des Vortriebs*. NAGRA Report, AN 12-184.

Nutt, M. (2010) *Used Fuel Disposition Campaign International Activities Implementation Plan*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-USED-2011-000016 REV 0, Argonne National Laboratory.

Nutt, M. (2011) *Used Fuel Disposition Campaign Disposal Research and Development Roadmap,* Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-USED-2011-000065 REV0, Argonne National Laboratory.

Painter, S., Gable, C., Makedonska, N., Hyman, J., Hsieh, T.-L. Bui, Q., Liu, H.H., Birkholzer, J. (2012) *Fluid Flow Model Development for Representative Geologic Media*. Los Alamos National Laboratory. LAUR-12-26878. FCRD-UFD-2013-000058.

Polak, A., Elsworth, D., Yasuhara, H., Grader, A.S., Halleck, P.M. (2003) *Permeability Reduction of a Natural Fracture Under Net Dissolution by Hydrothermal Fluids*, Geophys. Res. Lett., 30(20), 2020.

Posiva (2011) *Olkiluoto Site Description 2011*, Posiva Oy, Report POSIVA 2011.

Reimus, P.W., Pohll, G., Mihevc, T., Chapman, J., Papelis, L., Lyles, B., Kosinski, S., Niswonger, R., Sanders, P. (2003) *Testing and Parameterizing a Conceptual Model for Radionuclide Transport in a Fractured Granite Using Multiple Tracers in a Forced-Gradient Test*, Water Resour. Res., 39(12), p. 1350, doi:10.1029/2002WR001597.

Reimus, P. (2012) *Preliminary Interpretation of a Radionuclide and Colloid Tracer Test in a Granodiorite Shear Zone at the Grimsel Test Site, Switzerland*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign.

Rejeb A., Cabrera J. (2006) *Time-dependent evolution of the excavation damaged zone in the argillaceous Tournemire Site (France)*, Proceedings “GeoProc 2006,” Invited lecture in the 2nd International Conference on Coupled THMC Processes in Geosystems and Engineering, May 22-25 2006, Nanjing, China, pp. 65-74.

Rutqvist, J., Wu, Y.-S., Tsang, C.-F., Bodvarsson, G. (2002) *A Modeling Approach for Analysis of Coupled Multiphase Fluid Flow, Heat Transfer, and Deformation in Fractured Porous Rock*, Int. J. of Rock Mechanics & Mining Sciences, 39, 429–442.

Rutqvist, J., Blanco Martin, L., Mukhopadhyay, S., Houseworth, J., Birkholzer, J. (2014b) *Modeling Coupled THMC Processes and Brine Migration in Salt at High Temperatures*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-UFD-2014-000341, Lawrence Berkeley National Laboratory.

Rutqvist, J.R., Steefel, C., Chen, F., Houseworth, J., Vilarrasa, V., Liu, H.-H., Birkholzer, J.T. (2013) *THM and Reactive Transport Model Development and Evaluation: International Activities*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-UFD-2013-000372, Lawrence Berkeley National Laboratory.

Rutqvist, J. (2011) *Status of the TOUGH-FLAC simulator and recent applications related to coupled fluid flow and crustal deformations*. Computers & Geosciences, 37, 739–750.

Rutqvist, J., Zheng, L., Chen, F, Liu, H.-H, Birkholzer, J.T. (2014a) *Modeling of Coupled Thermo-Hydro-Mechanical Processes with Links to Geochemistry Associated with Bentonite-Backfilled Repository Tunnels in Clay Formations*. Rock Mechanics and Rock Engineering, 47, 167–186.

SKB (2011a), *Äspö Hard Rock Laboratory Annual Report 2010*, SKB Technical Report TR-11-10, February 2011.

SKB (2011b), *Äspö Hard Rock Laboratory Planning Report for 2011*, SKB International Progress Report IPR-10-19, February 2011.

Sugita, Y., Nakama, S. (2012) *Task B: EBS Horonobe Experiment*, Presentation given at 1st DECOVALEX 2015 Workshop, April 2012, Berkeley, CA.

Suski, B., Lander, F., Baron, L., Vuataz, F.-D., Philippossian, F., Holliger, K. (2008) *Detection and characterization of hydraulically active fractures in a carbonate aquifer: results from self-potential, temperature and fluid electrical conductivity logging in the Combioula hydrothermal system in the southwestern Swiss Alps*. Hydrogeology Journal, 16, pp. 1319-1328.

Tsang, C.-F., Stephansson, O., Jing, L., Kautsky, F. (2009) *DECOVALEX Project: from 1992 to 2007*, Environmental Geology, 57, 1221–1237, 2009.

Tsang, C.-F., Barnichon, J.D., Birkholzer, J.T., Li, X.L., Liu, H.-H., Sillen, X., Vietor, T. (2011) *A Review of Coupled Thermo-Hydro-Mechanical Processes in the Near-field of a High-Level Radioactive Waste Repository in a Clay Formation*, International Journal of Rock Mechanics and Mining Sciences, 49, pp. 31-44.

UFD (2012) *Office of Used Nuclear Fuel Disposition International Program – Strategic Plan*, April 2012, U.S. Department of Energy.

Van Marcke, P., Bastiaens, W. (2010) *Construction of the PRACLAY Experimental Gallery at the Hades URF*, Clay in Natural and Engineered Barriers for Radioactive Waste Confinement, 4th International Meeting, March, 2010, Nantes, France.

Vietor, T., Polster, M., Garitte, B., Martin, D. (2011) *Mine-by Test in the Mont Terri Rock Laboratory – MB Experiment*, Presentation given at 7th DECOVALEX 2011 Workshop, April 2011, Helsinki, Finland.

Wang, Y. (editor) (2010) *Natural System Evaluation and Tool Development – FY10 Progress Report*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, August 2010, Sandia National Laboratories.

Wang, Y., Gardner, P., Kuhlman, K.L., Kim, G.-Y., Ji, S.-H. (2014) *International Collaborations on Fluid Flow in Fractured Crystalline Rocks: FY14 Progress Report*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-UFD-2014-000499, Sandia National Laboratories.

Wersin, P., Van Loon, L.R., Soler, J.M., Yllera, A., Eikenberg, J., Gimmi, Th., Hernán, P., Boisson, J.-Y. (2004) *Long-term Diffusion Experiment at Mont Terri: First Results from Field and Laboratory Data*, Applied Clay Science, 26, 123-135.

Wersin, P., Soler, J.M., Van Loon, L., Eikenberg, J., Baeyens, B., Grolimund, D., Gimmi, T., Dewonck, S. (2008) *Diffusion of HTO, Br^-, I^-, Cs^+, $^{85}Sr^{2+}$ and $^{60}Co^{2+}$ in a Clay Formation: Results and Modeling from an In Situ Experiment in Opalinus Clay*, Applied Geochemistry, 23, 678-691.

Wileveau, Y. (2005) *THM Behavior of Host Rock (HE-D Experiment): Progress Report September 2003 – October 2004*, Mont Terri Technical Report TR2005-03.

Wishart, D.N., Slater, L.D., Gates, A.E. (2006) *Self-potential improves characterization of hydraulically-active fractures from azimuthal geoelectrical measurement*. Geophysical Research Letters, 33, 17314, doi: 10.1029/2006GL02792.

Yasuhara, H., Elsworth, D., Polak, A. (2004) *The Evolution of Permeability in a Natural Fracture: Significant Role of Pressure Solution*, J. Geophys. Res., 109(B3).

Yasuhara, H., Polak, A., Mitani, Y., Grader, A., Halleck, P., Elsworth, D. (2006) *Evolution of Fracture Permeability Through Fluid-Rock Reaction Under Hydrothermal Conditions*, Earth Planet. Sci. Lett. 244: 186–200.

Yasuhara, H., Kinoshita, N., Ohfuji, H., Lee, D.S., Nakashima, S., Kishida, K. (2011) *Temporal Alteration of Fracture Permeability in Granite Under Hydrothermal Conditions and its Interpretation by Coupled Chemo-Mechanical Model*, Appl. Geochem. 26, 2074–2088.

Zavarin, M., Benedicto, A., Kersting, A.B., Sutton, M. (2014) *Thermodynamic Evaluations Progress Report*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, M4FT-14LL0806039, Lawrence Livermore National Laboratory.

Zheng, L., Rutqvist, J., Steefel, C., Kim, K., Chen, F., Vilarrasa, V., Nakagawa, S., Houseworth, J., Birkholzer, J.T. (2014) *Investigation of Coupled Processes and Impact of High Temperature Limits in Argillite Rock*, Prepared for U.S. Department of Energy Used Fuel Disposition Campaign, FCRD-UFD-2014-000493, Lawrence Berkeley National Laboratory.

Zuidema, P. (2007) *Advancements in Deep Geological Disposal of Radioactive Waste through International Cooperation: The Role of Underground Laboratories – Mont Terri Project*, Proceedings of the 10 Year Anniversary Workshop, pp 69-71, Rep. Swiss Geol. Surv. 2.