U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

Overview of DOE's International Collaboration and URL Activities

U.S. Nuclear Waste Technical Review Board, Workshop
April 24-25, 2019
Burlingame, CA

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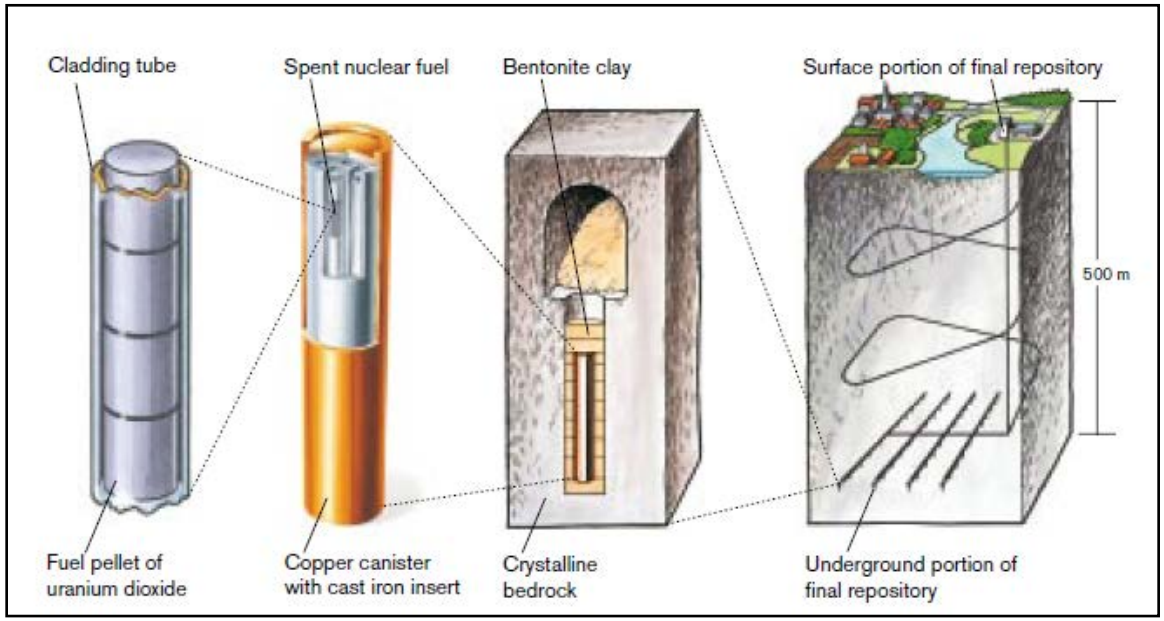
DOE's Disposal Research: Current Focus

- Provide a sound technical basis for multiple viable disposal options in the US
- Increase confidence in the robustness of generic disposal concepts
- Develop the science and engineering tools needed to support disposal concept implementation
- Conduct R&D on the direct disposal of existing dual purpose (storage and transportation) canisters
- **Leverage international collaboration**

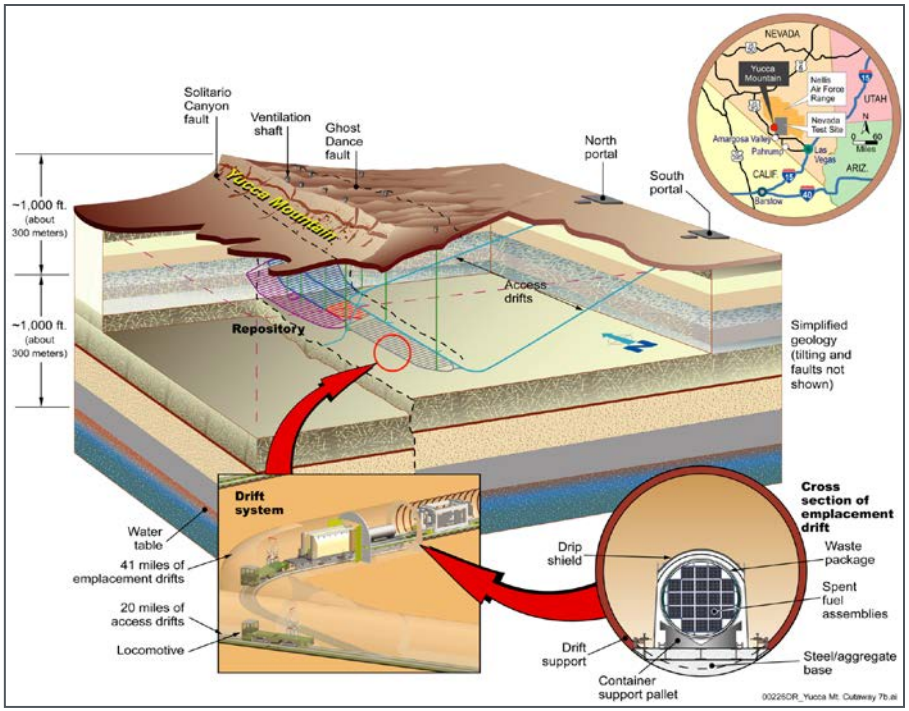


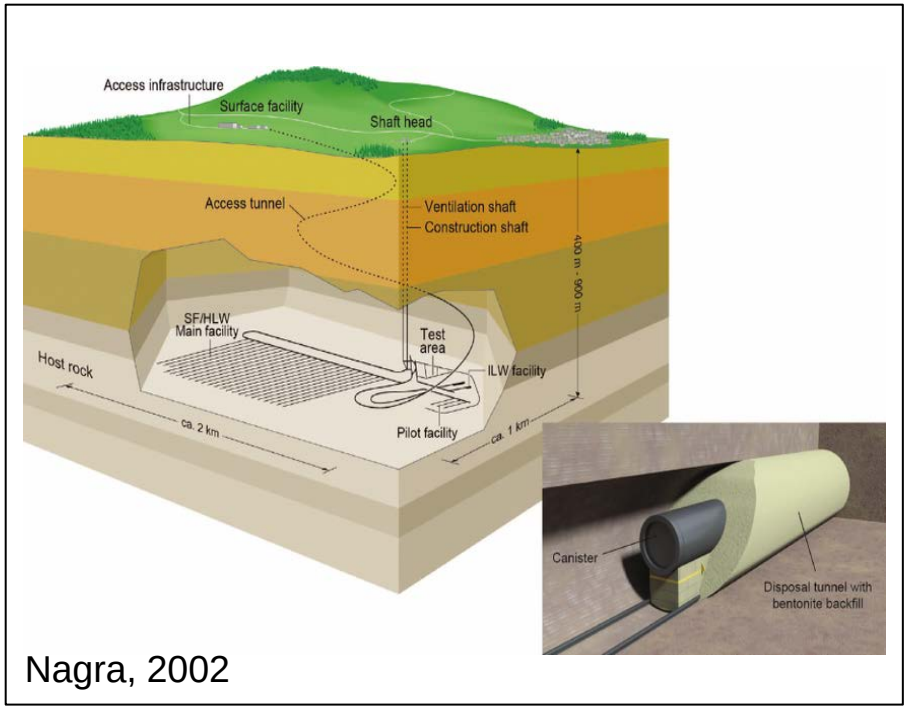
Dual Purpose Canisters: From NAC International Website March 31 2012

From Yucca Mountain to Alternative Disposal Concepts

- **Fractured volcanic tuff**
- **Unsaturated due to low precipitation**
- **Oxidizing conditions**
- **Open tunnel emplacement**

- **Low permeability host rock**
- **Saturated**
- **Reducing conditions**
- **Backfilled emplacement tunnels**





Nagra, 2002

Alternative Host Rocks and Engineered Barrier Backfill Materials

Crystalline, Granite

https://geology.com/rocks/granite.shtml

Clay, Argillite

From Steward et al., 2015

Bedded or Domal Salt

Courtesy of Kris Kuhlman

Bentonite Backfill

From Posiva

Crushed Salt Backfill

From Stauffer et al., 2013

Host Rock Focus by Country

Crystalline, Granite **Clay, Argillite** **Bedded or Domal Salt**

Nation	Host Rock	Status
Finland	Granitic Gneiss	Construction license granted 2015. Operations application to be submitted in 2020
Sweden	Granite	License application submitted 2011
France	Argillite	Disposal operations planned for 2025
Canada	Granite, sedimentary rock	Candidate sites being identified
China	Granite	Repository proposed in 2050
Russia	Granite, gneiss	Licensing planned for 2029
Germany	Salt, other	Uncertain
USA	Salt (transuranic waste at the Waste Isolation Pilot Plant) Volcanic Tuff (Yucca Mountain)	WIPP: operating Yucca Mountain: suspended
Others: Belgium (clay), Korea (granite), Japan (sedimentary rock, granite), UK (uncertain), Spain (uncertain), Switzerland (clay), Czech Republic (granitic rock), all nations with nuclear power.		

Source: Information from Faybishenko et al., 2016

International Collaboration

Benefits

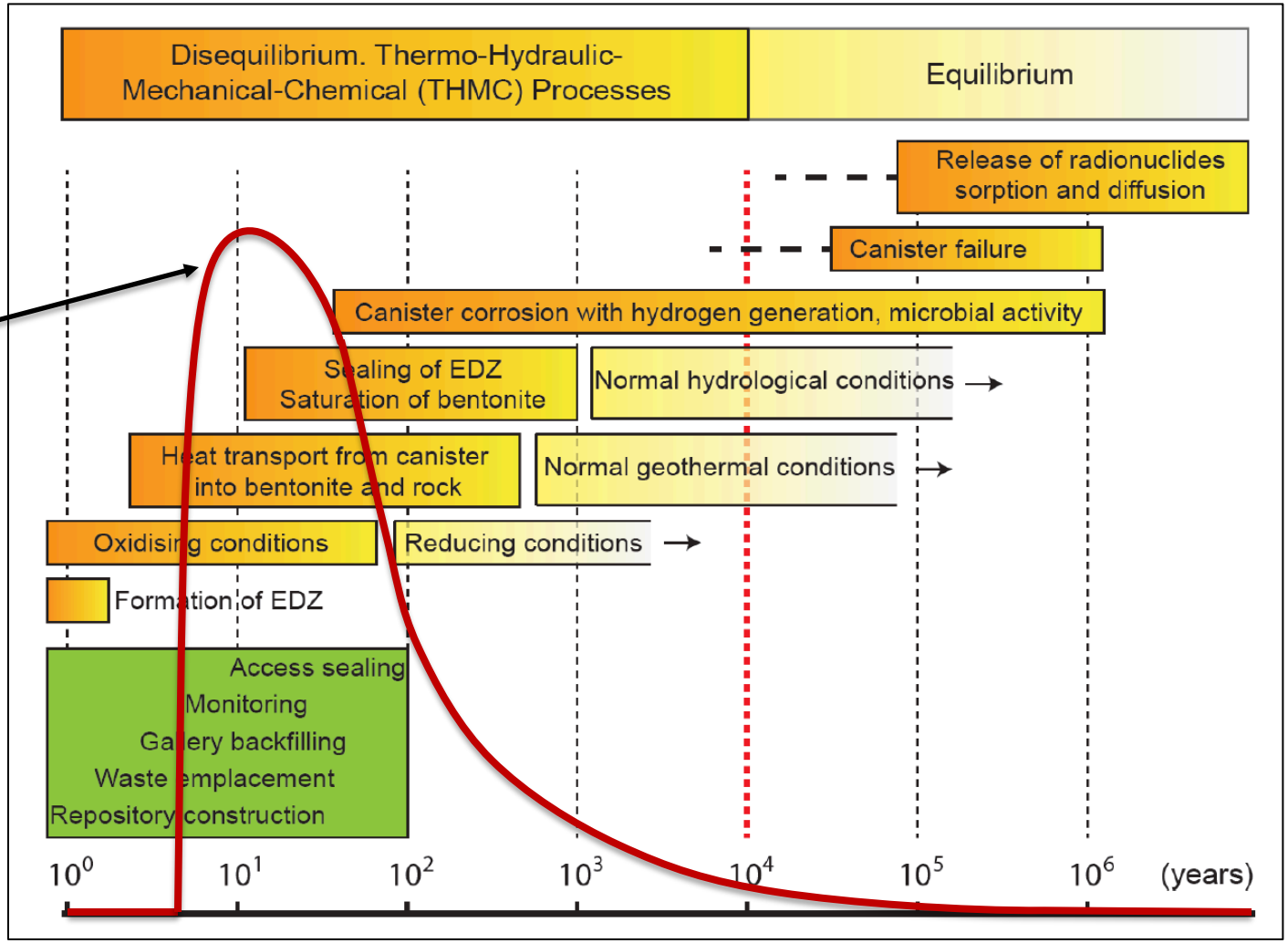
- Tap into global information and knowledge on alternative disposal concepts
- Gain access to international datasets, experiments and concepts
- Improve domestic science base, reduce uncertainties and build confidence
- Test and validate new advanced process-modeling and monitoring tools
- Share cost of science campaigns, in particular large experimental projects

Principles

- Focus on collaboration opportunities for active R&D participation
- Emphasize access to experiments in underground research laboratories (URLs)
- Select collaborative R&D activities based on technical merit, relevance to safety case, and cost/benefit
- Balance portfolio across host rocks, repository designs, and key R&D issues

SFWST R&D Planning Process (2010 – 2013)

Repository Phases and Relevant Processes in a Bentonite Backfilled Repository



Maximum Temperature

Bossart et al. (2017)

Many of these processes are not relevant in the safety case for Yucca Mountain, are less important, or have very different characteristics and research challenges

Cross-Cutting Priority R&D Topics

Key Topics	High-Level Research Questions
Near-Field Perturbation	• How important are thermal, mechanical, and other perturbations? • How effective is healing and sealing of damage zone in the long-term? • How reliable are existing predictive models for the strongly coupled thermal-hydrological-mechanical behavior of clays and salts?
Engineered Barrier Integrity	• What is the long-term stability and retention capability of buffer materials? • Can bentonite be eroded by contact with water from flowing fractures? • How relevant are interactions between engineered and natural barrier? • Is gas pressure increase and gas migration a concern for barrier integrity?
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Integrated System Behavior	• Can the early-time behavior of an entire repository system, including all engineered and natural barriers and their interaction, be demonstrated? • Can this integrated behavior be reliably predicted? • Is the planned construction/emplacement method feasible? • Which monitoring methods are suitable for performance confirmation?

SFWST's International Portfolio with URL Focus
Multinational Initiatives

Initiative	Host Rock	URL	Attributes
DECOVALEX DEvelopment of COupled models and their VALidation against Experiments Project	Multiple	Multiple	• Long-term international model comparison initiative • **Multiple modeling tasks** with validation against experiments
Mont Terri Project	Argillite	Mont Terri, Switzerland	• **Multiple experiments** are conducted and evaluated collaboratively • Access to data and results from past and ongoing experiments, joint experiments
SKB Task Forces SKB = Swedish Nuclear Fuel and Waste Management	Crystalline	Äspö Hard Rock Lab, Sweden	• Collaborative modeling of **multiple tasks** • Focus on flow and transport in fractured rock and engineered barrier system
Colloid Formation and Migration Project (CFM)	Crystalline	Grimsel Test Site (GTS), Switzerland	• Long-term project with several test phases • Investigation of colloid formation, colloid migration, and radionuclide transport
FEBEX-DP Full-Scale Engineered Barrier Experiment - Dismantling Proj.	Crystalline EBS Focus	GTS, Switzerland	• Dismantling and characterization of full-scale heater test after 18 years of heating • Collaborative analysis of data and samples
HotBENT (starting soon)	Crystalline EBS Focus	GTS, Switzerland	• Conduct a full-scale high-temperature heater test at 200ºC maximum temperature

Multinational Initiatives….Connecting the World

Nuclear Nation	Organizations	DECOVALEX	Mont Terri	Colloid Formation And Migration	FEBEX-DP	SKB Task Forces
Belgium	SCK/CEN FANC		x			
Canada	NWMO	x	x			x
	CNSC	x				
Czech Republic	SURAO	x			x	x
France	ANDRA		x		x	
	IRSN	x	x			
	Total		x			
Finland	POSIVA			x	x	x
Germany	BGR	x	x		x	x
	GRS		x			
	BMWi/KIT			x		x
	Helmholtz Ass.		x			
Great Britain	RWM	x	x	x	x	x
Japan	JAEA	x	x	x		x
	CRIEPI		x	x		x
	Obayashi		x		x	
Rep. of Korea	KAERI	x		x	x	x
Spain	ENRESA		x		x	
	CIEMAT				x	
Sweden	SKB			x	x	x
	SSM	x				
Switzerland	NAGRA		x	x	x	x
	ENSI	x	x			
	swisstopo		x			
Taiwan	TaiPower	x				
United States	DOE	x	x	x	x	x
	Chevron		x			

Status September 2018 (HotBENT not yet included)

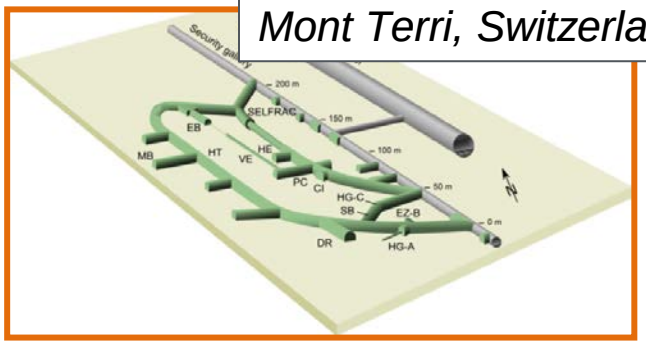
SFWST's International Portfolio with URL Focus Bilateral Collaborations

Organization(s)	Country	Host Rock	URL	Attributes
KAERI Korea Atomic Energy Institute	Republic of Korea	Crystalline	KURT (KAERI Underground Research Tunnel)	• Improved techniques for in situ borehole characterization • New methods for measuring fracture flow/transport
BMWi (German Federal Ministry of Education and Research)	Germany	Salt	Gorleben, Asse Mine, WIPP	• Lab testing and modeling of thermal-mechanical and hydrological behavior of domal and bedded salt
Andra French National Radioactive Waste Management Agency	France	Argillite	Bure URL	• Joint research on coupled processes in near-field host rock
JAEA Japan Atomic Energy Agency	Japan	• Crystalline • Mudstone	• Mizunami URL • Horonobe URL	• Joint research on coupled processes in near-field host rock

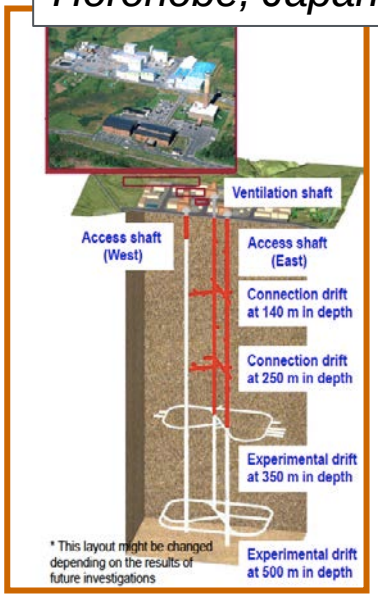
Note: DOE continues to explore the landscape for other bilateral URL opportunities, for example connecting with Belgium, Finland, and Czech Republic (existing URLs), or with China and Republic of Korea (plans for new URLs).

International URLs with U.S. Participation

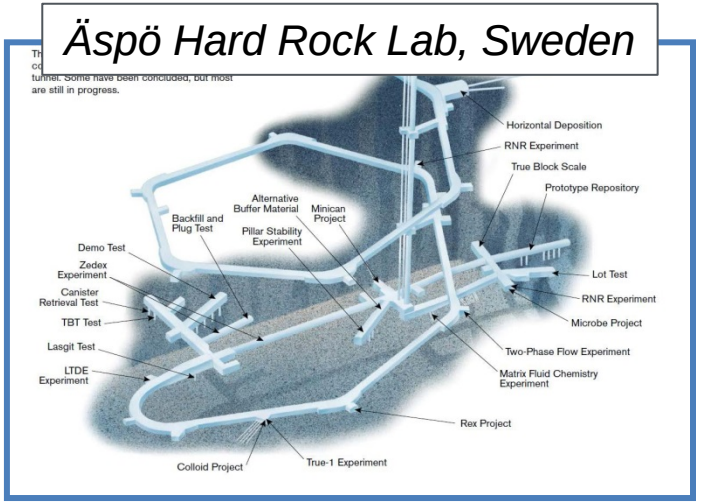
Mont Terri, Switzerland



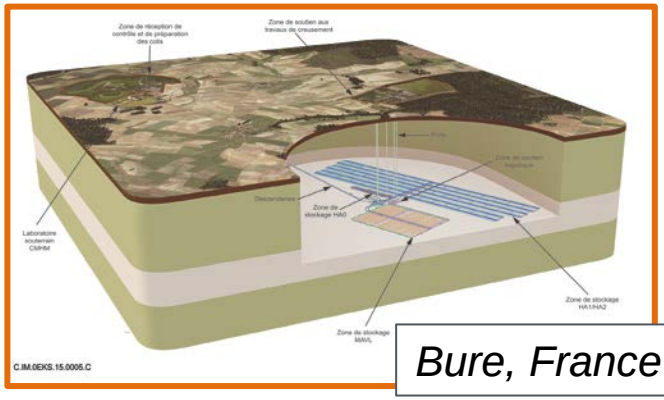
Horonobe, Japan



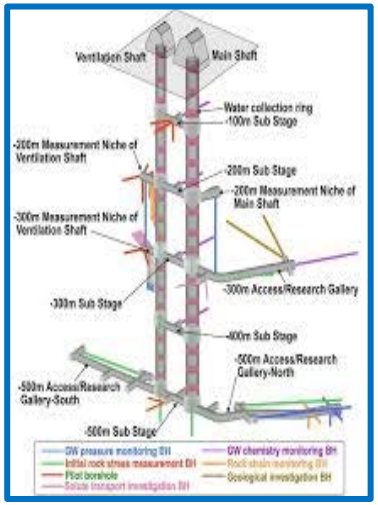
Äspö Hard Rock Lab, Sweden



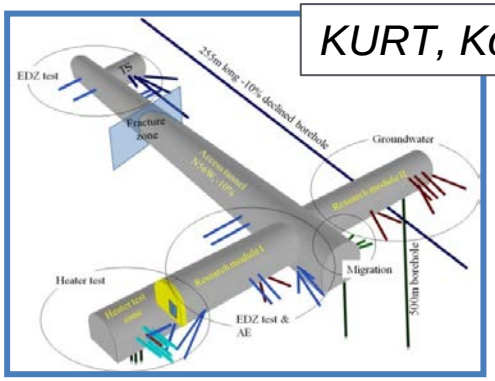
Bure, France



Mizunami, Japan



KURT, Korea



Grimsel Test Site, Switzerland

DOE's Activities Related to International URLs

Key Topics	International Experiment	URL	Main R&D Focus
Near-Field Perturbation	Heater Experiment E (HE-E)	Mont Terri, Switzerland	Bentonite/rock interaction to evaluate sealing and clay barrier performance at elevated temperature, micro-tunnel
	Thermal Experiment (TED) Full-scale Emplacement Test (ALC)	Bure, France	Upscaling THM simulations from lab tests to repository scale
	Gas Path Though Host Rock Experiment (HG-A)	Mont Terri, Switzerland	Evaluation of flow paths through the near-field damage zone and specifically along seals
	Thermal Simulation for Drift Emplacement (TSDE)	Asse Mine, Germany	Model benchmarking studies for thermal-hydrological-mechanical behavior salt heater test
	Brine Availability Test in Salt (BATS)	WIPP, USA	Monitoring brine distribution, inflow, and chemistry from heated salt using geophysical methods and direct liquid & gas sampling
Engineered Barrier Integrity	Cement Clay Interaction (CI) Experiment	Mont Terri, Switzerland	Chemical interaction between host rock and engineered barrier materials
	Bentonite-Rock Interaction Experiment (BRIE)	Äspö HRL, Sweden	Understand the impact of flowing fractures in crystalline rock on bentonite saturation, integrity and erosion
	Engineered Barrier System (EBS) Experiment	Horonobe, Japan	Studies of the thermo-hydro-mechanical-chemical (THMC) behavior of the EBS
	Full-Scale Engineered Barrier Experiment - Dismantling Project (FEBEX DP)	Grimsel Test Site, Switzerland	Dismantling and sampling of long-term test evaluating the long-term integrity and performance of heated bentonite
	HotBENT Experiment	Grimsel Test Site, Switzerland	Complex THMC behavior of EBS materials up to 200 degrees C at the canister/bentonite interface
	Gas Migration in Clay-Based Materials	NA	Laboratory tests and modeling studies to determine complex gas migration processes in bentonite and clays
Flow and Radionuclide Transport	Bedrichov Tunnel Experiment	Bedrichov, Czech Republic	Interpretation of water inflow patterns and tracer transport behavior in fractured granite
	Fault Slip (FS) Experiment	Mont Terri, Switzerland	Evaluation of pressure increase impacts on reactivation of faults
	GREET (Groundwater Recovery Experiment)	Mizunami, Japan	Evaluation of early resaturation behavior in crystalline rock looking at flow behavior and chemical-biological interactions upon resaturation
	Long-Term Sorption Diffusion Experiment (LTDE)	Äspö HRL, Sweden	Monitoring the diffusion behavior in fractured crystalline rock
	DR-A Experiment (Diffusion Retention and Perturbation Test)	Mont Terri, Switzerland	Ion diffusion through compacted clay where electro-chemical charges affect transport behavior
	Colloid-Facilitated Radionuclide Migration Test (CFM)	Grimsel Test Site, Switzerland	Evaluate RN transport of bentonite colloids compared in a shear zone in fractured granite
	Streaming Potential Test	KURT, Korea	Site characterization techniques (in situ borehole characterization)
Integrated System Behavior	Full-scale Emplacement Experiment (FE)	Mont Terri, Switzerland	Full-scale demonstration experiment, one of the largest and longest-duration heater tests

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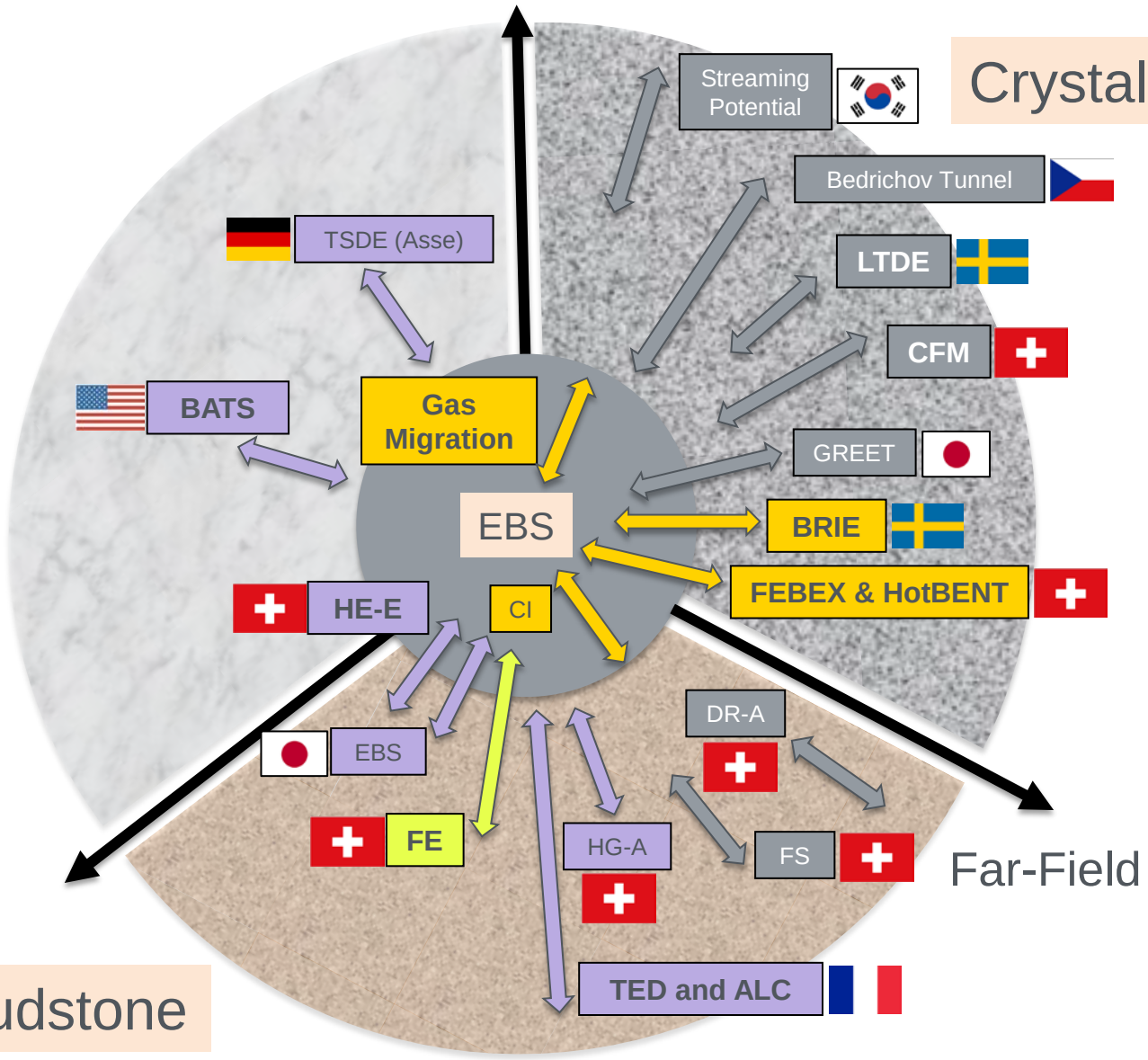
Significant variability in terms of level and duration of SFWST engagement

International URL Portfolio in a Nutshell

Key R&D Issues

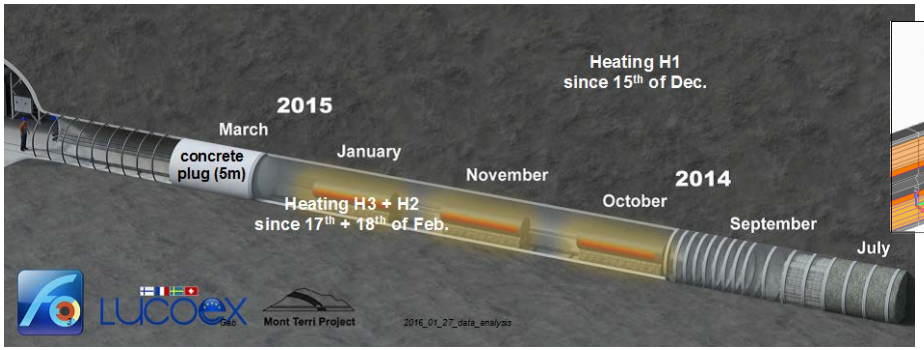
- Near-Field Perturbation
- Engineered Barrier Integrity
- Flow and Radionuclide Transport
- Demonstration of Integrated System Behavior

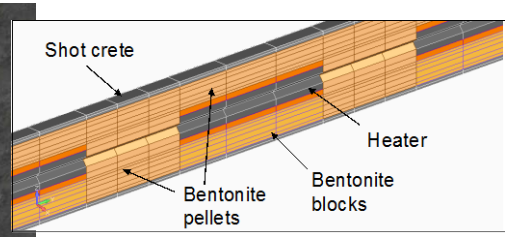


Priority R&D Topics: THM Perturbations

Thermo-Hydro-Mechanical (THM) Perturbations in Bentonite/Argillite Repositories: Heater Tests at Mont Terri and Bure, Jonny Rutqvist

Full-scale Emplacement Experiment (FE) at Mont Terri





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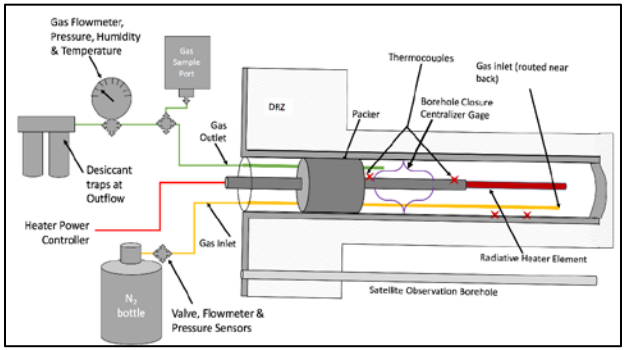
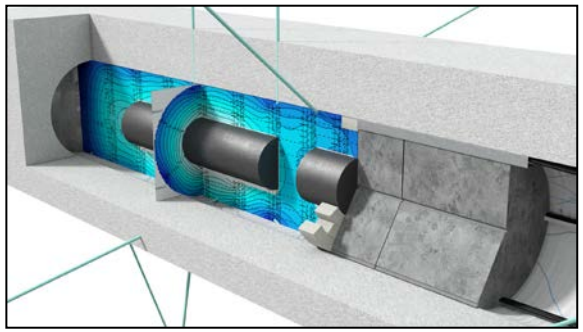
DOE Salt Research and WIPP Test, Kris Kuhlman and Phil Stauffer



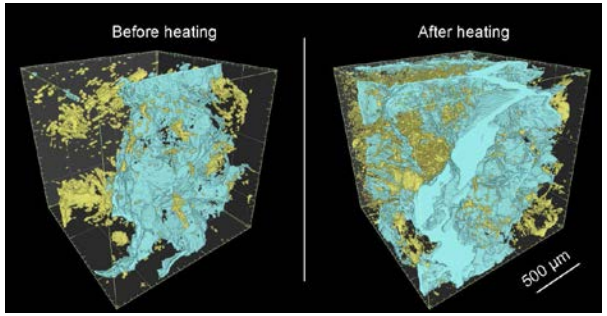
Salt Heater Test at Waste Isolation Pilot Plant (WIPP)

Priority R&D Topics: Engineered Barrier System THMC Processes

Understanding Engineered Barrier System Coupled Processes and Mineral Alterations at High Temperatures: From FEBEX-DP to HotBENT, Liange Zheng



Full-Scale Engineered Barrier Experiment-Dismantling Project (FEBEX-DP)



X-Ray Micro-CT Analysis of FEBEX Samples

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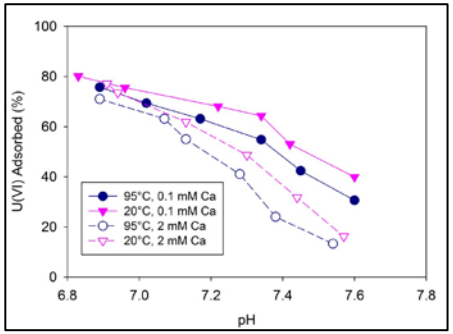
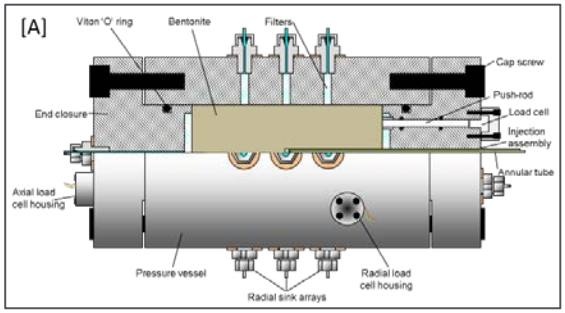


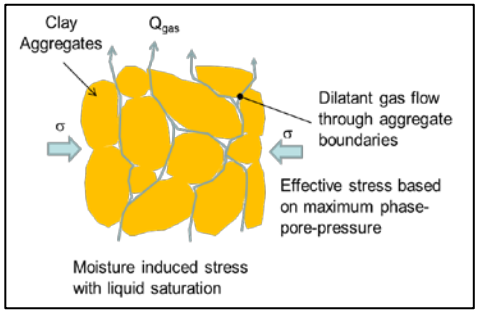
Adsorption Tests on FEBEX Samples

Thermal Implications on Transport in Bentonite: Lab Studies and Model Testing, Carlos Jove-Colon

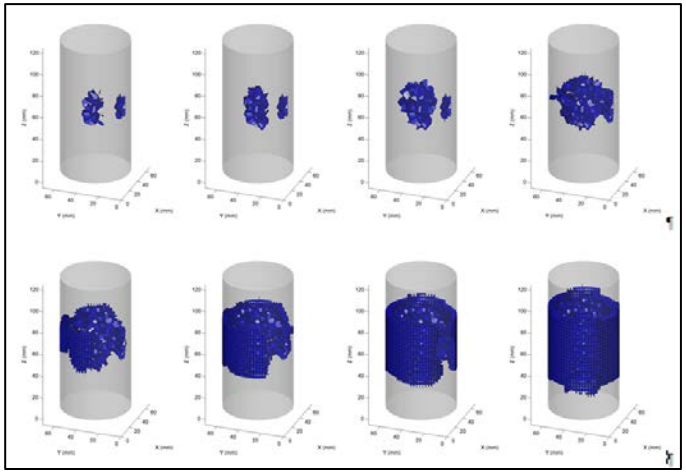
Priority R&D Topics: Gas Transport

Gas Migration in Clay-Based Materials – International Collaboration Activities as Part of the DECOVALEX Project, Jonny Rutqvist





Discrete Fracture Modeling Approach with Opening of Grain Boundaries for Dilatant Gas Migration



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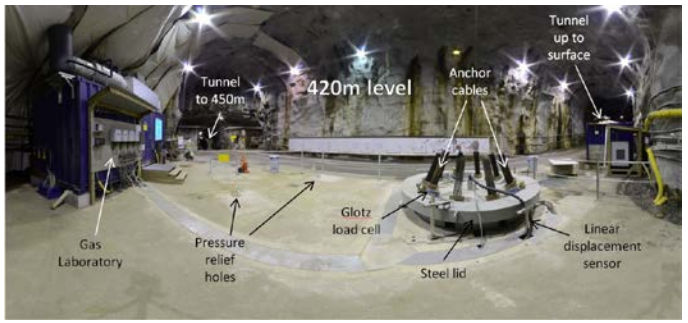
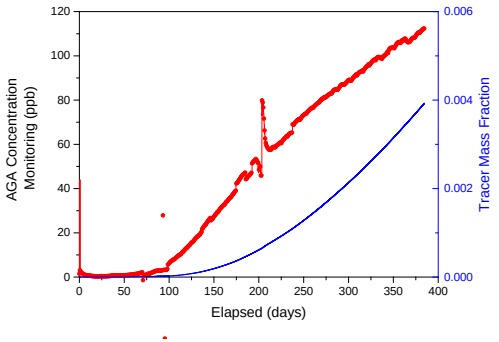
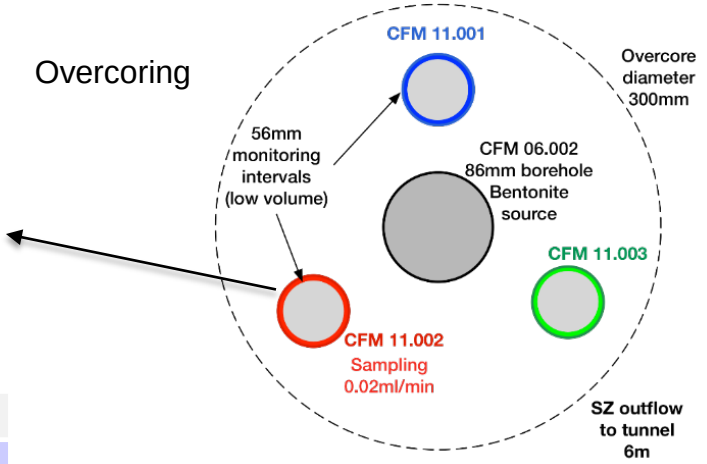
In-Situ Test LASGIT in DECOVALEX 2023?



Priority R&D Topics: Colloid Formation & Migration

Colloid-Facilitated Transport: Studies Related to Colloid Formation and Migration (CFM) Project at the Grimsel Test Site, Hakim Boukhalfa





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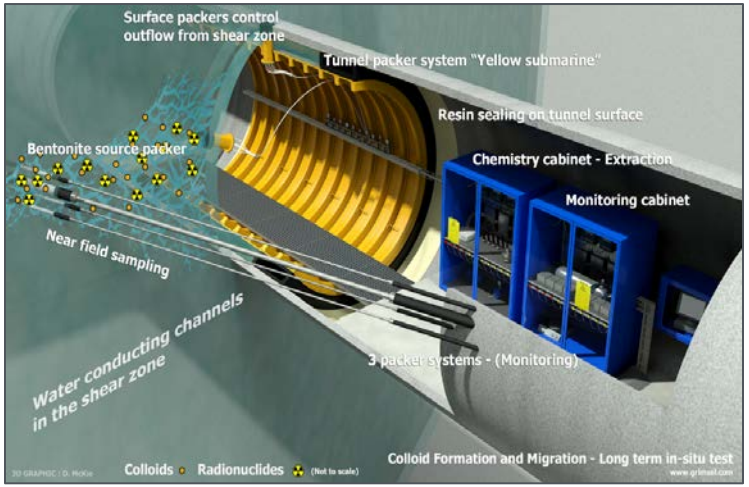
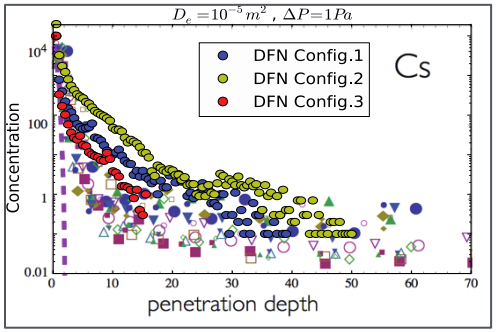
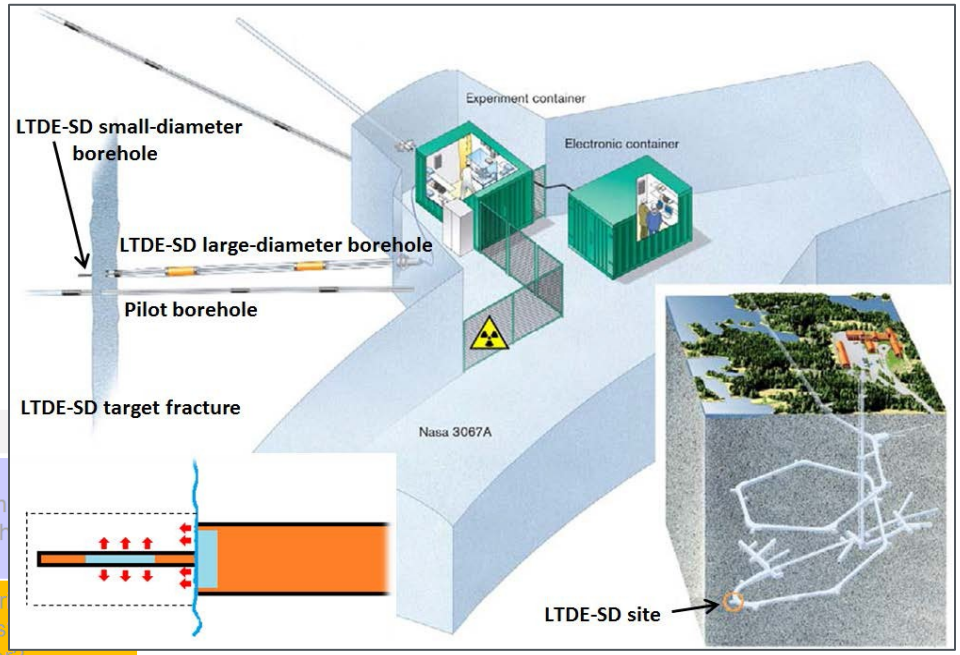


Priority R&D Topics: Discrete Fracture Studies

Flow and Transport in Fractured Granite: Modeling the Bentonite Rock Interaction Experiment (BRIE) and the Long Term Diffusion Experiment (LTDE), Hari Viswanathan

Simulated and Measured Concentrations





Key Topics	High-Level Research Questions
Near-Field Perturbation	• How important are thermal, mechanical, and other perturbations? • How effective is healing and sealing of damage zone in the long-term • How reliable are existing predictive models for the strongly coupled th hydrological-mechanical behavior of clays and salts?
Engineered Barrier Integrity	• What is the long-term stability and retention capability of buffer mater • Can bentonite be eroded by contact with water from flowing fractures • How relevant are interactions between engineered and natural barrier? • Is gas pressure increase and gas migration a concern for barrier integrity?
Flow and Radionuclide Transport	• What is the effect of high temperature on the diffusion and sorption characteristics of clays? • What is the potential for enhanced transport with colloids? • **Can transport in diffusion dominated (clays, bentonites) and advection dominated systems (fractured granites) be predicted with confidence?**
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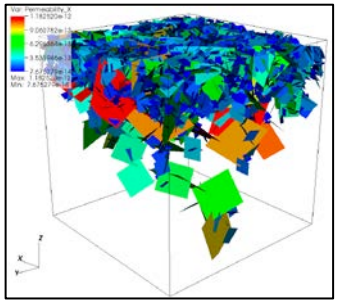
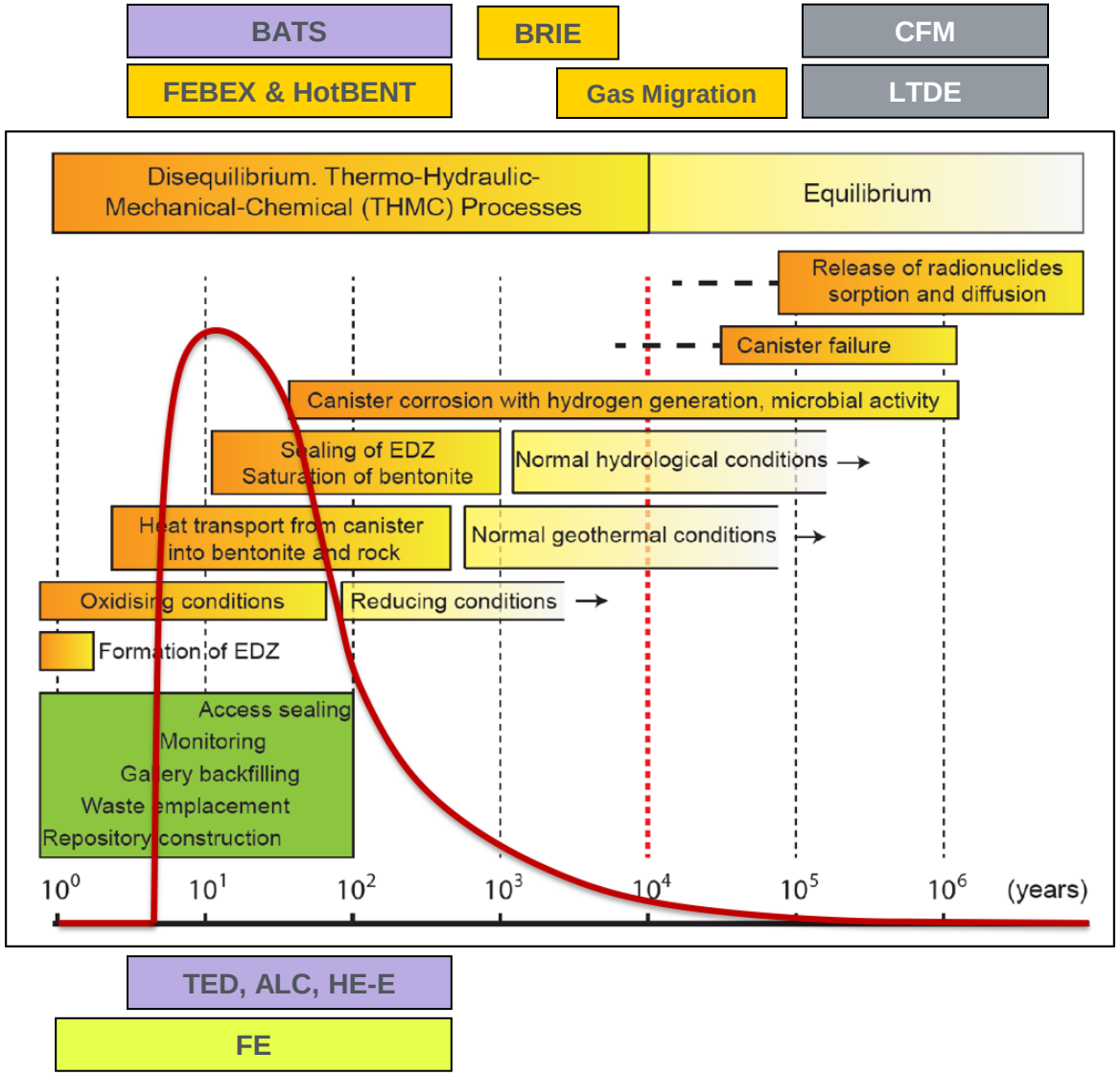


LTDE Microfracture Flow and Transport Modeling

Repository Phases and Relevant Processes

Key R&D Issues

- Near-Field Perturbation
- Engineered Barrier Integrity
- Flow and Radionuclide Transport
- Demonstration of Integrated System Behavior



Integrated Planning of Priority R&D Topics and International Collaboration Opportunities

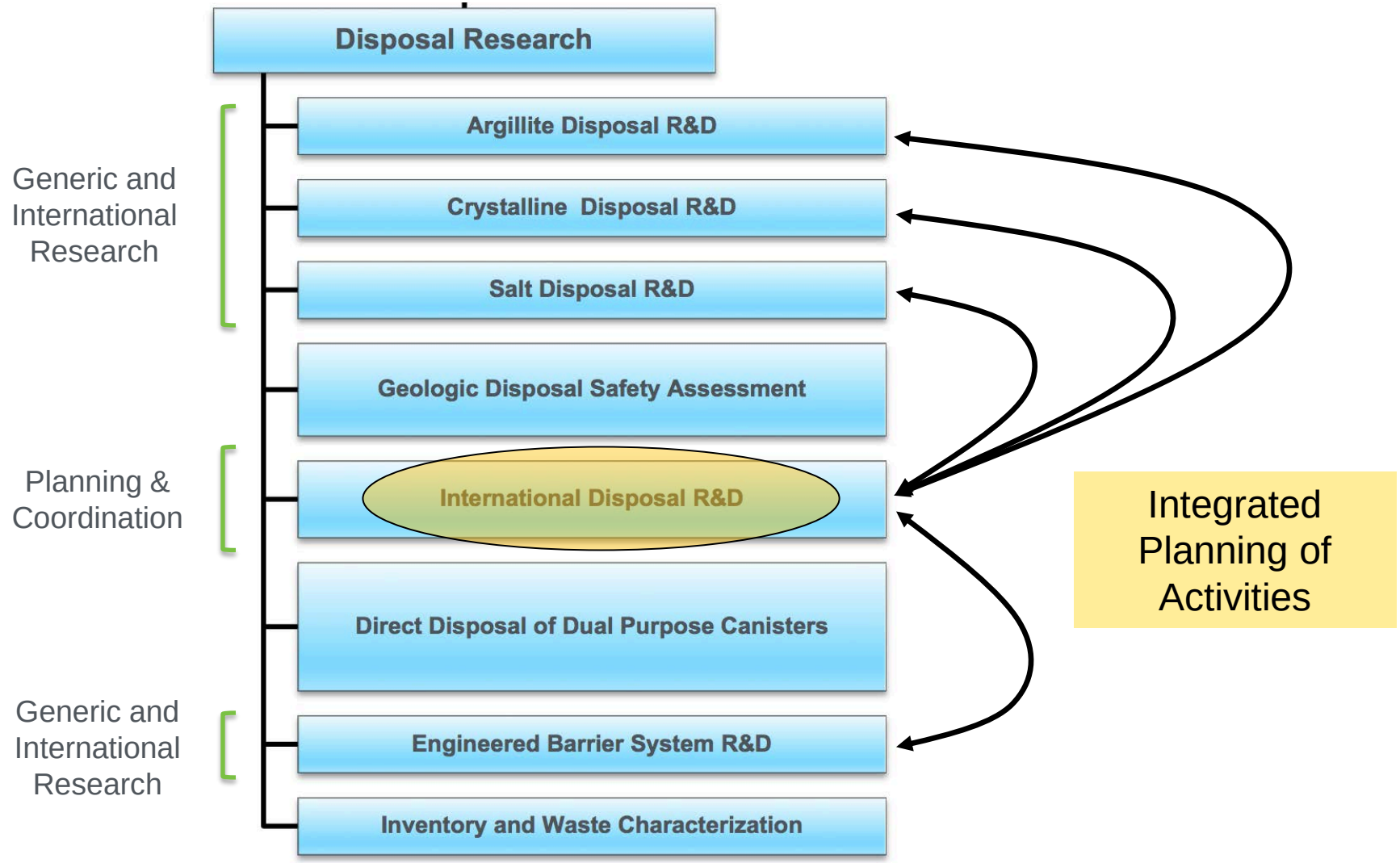
- **2010:** Roadmap Workshops to identify high-priority research needs for SFWST campaign
- **2012:** International collaboration workshop to discuss priority research activities related to international URLs

Annual SFWST Working Group Meetings:

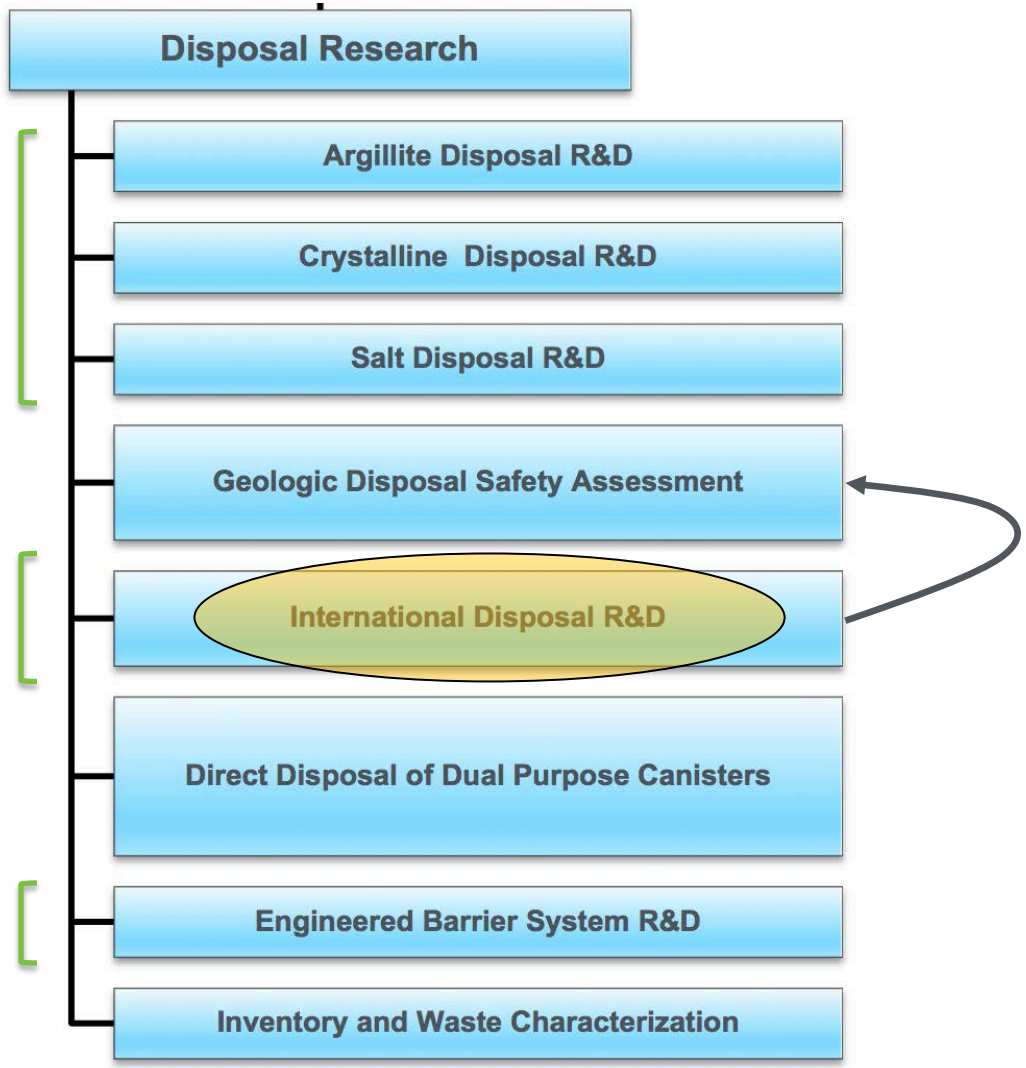
- Assess new international opportunities and R&D trends (e.g., gas pressure buildup)
- Consider changing or emerging SFWST priorities (e.g., dual purpose canisters, DPCs)
- Re-evaluate international portfolio

- **2019:** Roadmap workshop to review and revise existing R&D activities, assess priority levels, and brainstorm gaps

FY18 SFWST Disposal Research Campaign



FY18 SFWST Disposal Research Campaign



Benefit to GDSA

(Geologic Disposal Safety Assessment)

- International datasets and concepts
- Improved process understanding and tested simulation models
- Confidence enhancement

(Emily Stein)

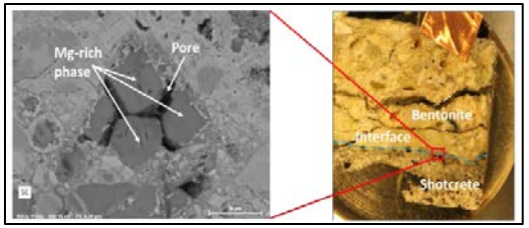
Example: R&D for High Temperature Repositories

Clay and Bentonite Behavior at Temperature > 200 ºC

Fundamentals of Physico-Chemical Alterations

- Laboratory testing/imaging of heated samples
- Detailed THMC modeling of individual components

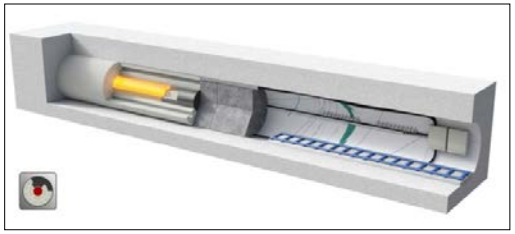
Micro-structural analysis



Barrier System Behavior

- Laboratory or *in situ* testing of barrier systems
- Validation of predictive process models for system behavior
- Predictions of engineered and natural barrier perturbations
- Optimization studies (e.g., alternative backfill materials)

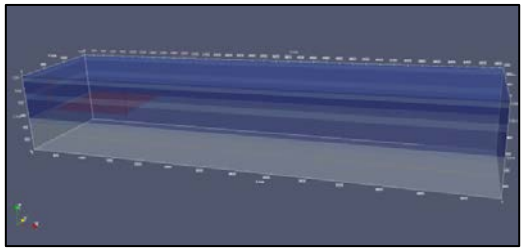
Field Experiments (HotBENT)



Performance Assessment Studies

- Develop methods for including high temperature effects in performance assessment models
- Determine scenarios and parameters with significant impact on high-temperature repository performance
- Conduct performance assessment for different thermal designs

Performance Assessment Modeling



From Opportunistic Participation to Active Planning

- During the first few years, DOE participated in international R&D efforts that had been planned years earlier
- Since then, DOE has been actively involved in planning of new projects together with the international community, achieving more integration and exploring cross-cutting synergies
- Examples:
  - Joint planning of HotBENT Project with NAGRA and other partners
  - Chairing the international DECOVALEX Project
  - Proposing salt heater test at WIPP as an international modeling task in DECOVALEX 2023
  - Proposing a performance assessment benchmarking exercise as an international modeling task in DECOVALEX 2023
  - Further integrating modeling and lab testing activities with international URL efforts

Constraints for International Activities

- DOE's research priorities and timing do not always align with international efforts and timing
- Disposal funding has been relatively modest, spread across host rock options, and has supported other (generic) R&D efforts in addition to international URL activities
- Disposal funding remains uncertain and varies from year to year; this makes planning of long-term activities (like field experiments) difficult

International Collaboration: Accomplishments

- Active collaboration with international programs is now a central element of DOE's disposal research program
- International research activities have been extremely beneficial to the SFWST Disposal Research Campaign:
  - Improving science base, reducing uncertainty, and building confidence in alternative geologic disposal options
  - Testing new advanced process-modeling and monitoring tools
  - Shared cost for large expensive experiments
  - Information and knowledge exchange in terms of best practices, state of the art simulation and monitoring methods, R&D priorities elsewhere
- Activities are balanced in terms of host rock, repository design and R&D issues

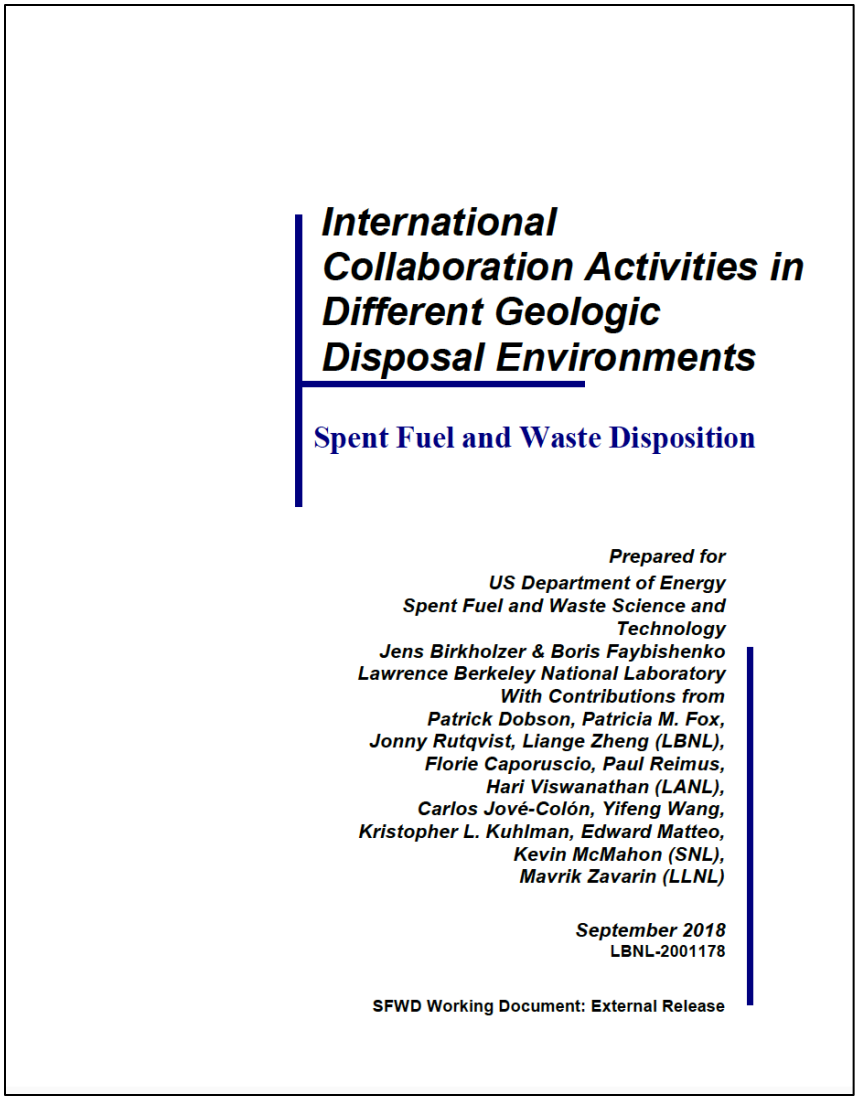
International Collaboration: Indirect Benefits

- Re-establishing the U.S. program as committed participants in international collaborative efforts
- Building valuable relationships of mutual respect and trust
- Sharing of knowledge and experience to stay abreast with new science advances
- Working towards a common set of disposal best practices and lessons learned
- Attracting and building a new generation of “waste disposal” scientists

References: International Collaboration Report

Content of Report (298 pages):

- **International Opportunities and Strategic Considerations**
- **Multinational Cooperative Initiatives**
- **Bilateral Collaboration Opportunities**
- **Selection of International Collaboration Activities**
- **Disposal Research Activities Associated with International Collaborations**



International Collaboration Activities in Different Geologic Disposal Environments

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology

Jens Birkholzer & Boris Faybishenko
Lawrence Berkeley National Laboratory
With Contributions from
Patrick Dobson, Patricia M. Fox, Jonny Rutqvist, Liange Zheng (LBNL), Florie Caporuscio, Paul Reimus, Hari Viswanathan (LANL), Carlos Jové-Colón, Yifeng Wang, Kristopher L. Kuhlman, Edward Matteo, Kevin McMahon (SNL), Mavrik Zavarin (LLNL)

September 2018
LBNL-2001178

SFWD Working Document: External Release

Poster Presentations

Deeper Dive on Oral Presentation Topics

- Understanding the Alteration of Bentonite Backfill Using Coupled THMC Modeling for a Long Term Heater Test (Liange Zheng et al., LBNL)
- Effect of Long-Term Bentonite Heating on Uranium(VI) Adsorption (Patricia Fox et al., LBNL)
- Field-scale Experiment and Simulations of Heat Generating Nuclear Waste in Salt (Philip Stauffer et al., LANL)
- Geophysical Monitoring of Brine Migration in Rock Salt: Results from an In Situ Heater and Tracer Experiment at WIPP (Yuxin Wu et al., LBNL)

Two Additional International Field Experiments and Modeling Efforts

- DECOVALEX-2019 Task C: GREET (Groundwater Recovery Experiment in Tunnel) - Fracture Characterization, Modeling of Hydrology, Geochemistry and Reactive Transport at the Mizunami Underground Research Laboratory, Japan (Teklu Hadgu et al., SNL)
- Short to Long Term Hydromechanical Response of Faults and Excavation Damage Zone in Argillite Host Rock (Yves Guglielmi et al., LBNL)

International Collaboration without URL Connection

- DOE and International Efforts in Thermodynamics and Database Development for Nuclear Waste Repository Science (Mavrik Zavarin, LLNL)

Questions?

Clean. **Reliable. Nuclear.**

Acronyms and Abbreviations

ANDRA	National Radioactive Waste Management Agency, France
ALC	Full-scale Emplacement Experiment
BATS	Brine Availability Test in Salt
BGR	Federal Institute for Geosciences & Natural Resources, Germany
BMWi	Ministry for Economy and Labor, Germany
BRIE	Bentonite Rock Interaction Experiment
CFM	Colloid Formation and Migration Project
CI	Cement Clay Interaction Experiment
CIEMAT	Centro Investigaciones Energéticas Medioambientales y Tecnológicas, Spain
CNSC	Canadian Nuclear Safety Commission, Canada
CRIEPI	Central Research Institute of Electric Power Industry, Japan
DECOVALEX	DEvelopment of COupled Models and their VALidation Against EXperiments
DPC	Dual Purpose Canister
DOE	Department of Energy, USA
DR-A	Diffusion, Retention, and Perturbation Experiment
EB	Engineered Barrier
EBS	Engineered Barrier System
EDZ	Excavation Damage Zone (or Excavation Disturbed Zone)
ENRESA	National Radioactive Waste Corporation, Spain
ENSI	Swiss Federal Nuclear Safety Inspectorate, Switzerland
FANC	Federal Agency for Nuclear Control, Belgium
FE	Full-scale Emplacement Experiment

Acronyms and Abbreviations

FEBEX	Full-scale Engineered Barrier Experiment
FEBEX-DP	FEBEX Dismantling Project
FEPs	Features, Events, and Processes
FS	Faults Slip Hydro-Mechanical Characterization Experiment
GAST	Gas-Permeable Seal Test
GDSA	Geologic Disposal Safety Assessment
GREET	Groundwater REcovery Experiment in a Tunnel
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit, Germany
GTS	Grimsel Test Site, Switzerland
GWFTS	Groundwater Flow and Transport Task Force, Sweden
GREET	Groundwater Recovery Experiment
HE-E	*In Situ* Heater Experiment in Micro-tunnel
HG-A	Gas Path through Host Rock Experiment
HM	Hydro-mechanical
HMC	Hydro-mechanical-chemical
HRL	Hard Rock Laboratory
IRSN	Institut de Radioprotection et de Sûreté Nucléaire, France
JAEA	Japan Atomic Energy Agency, Japan
KAERI	Korea Atomic Energy Research Institute, Republic of Korea
KIT	Karlsruhe Institute of Technology, Karlsruhe, Germany
KURT	KAERI Underground Research Tunnel, Republic of Korea
LASGIT	Large-scale Gas Injection Test

Acronyms and Abbreviations

LTDE	Long-Term Sorption Diffusion Experiment
NAGRA	Swiss waste management organization
NBS	Natural Barrier System
NEA	Nuclear Energy Agency
NUMO	Nuclear Waste Management Organization of Japan
NWMO	Nuclear Waste Management Organization, Canada
PA	Performance Assessment
POSIVA	Nuclear Waste Management Organization, Finland
RWM	Radioactive Waste Management Limited, UK
SCK/CEN	Belgian Nuclear Research Centre, Belgium
SFWST	Spent Fuel and Waste Science & Technology
SKB	Swedish Nuclear Fuel and Waste Management, Sweden
SSM	Swedish Nuclear Waste Regulator
SURAO	Radioactive Waste Repository Authority, Czech Republic
swisstopo	Federal Office of Topography, Switzerland
TSDE	Thermal Simulation for Drift Experiment
TED	Thermal Experiment
THC	Thermo-hydro-chemical
THM	Thermo-hydro-mechanical
THMC	Thermo-hydro-mechanical-chemical
URL	Underground Research Laboratory
WIPP	Waste Isolation Pilot Plant, New Mexico, USA