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, Fact Finding Meeting
February 26, 2019
Las Vegas, NV

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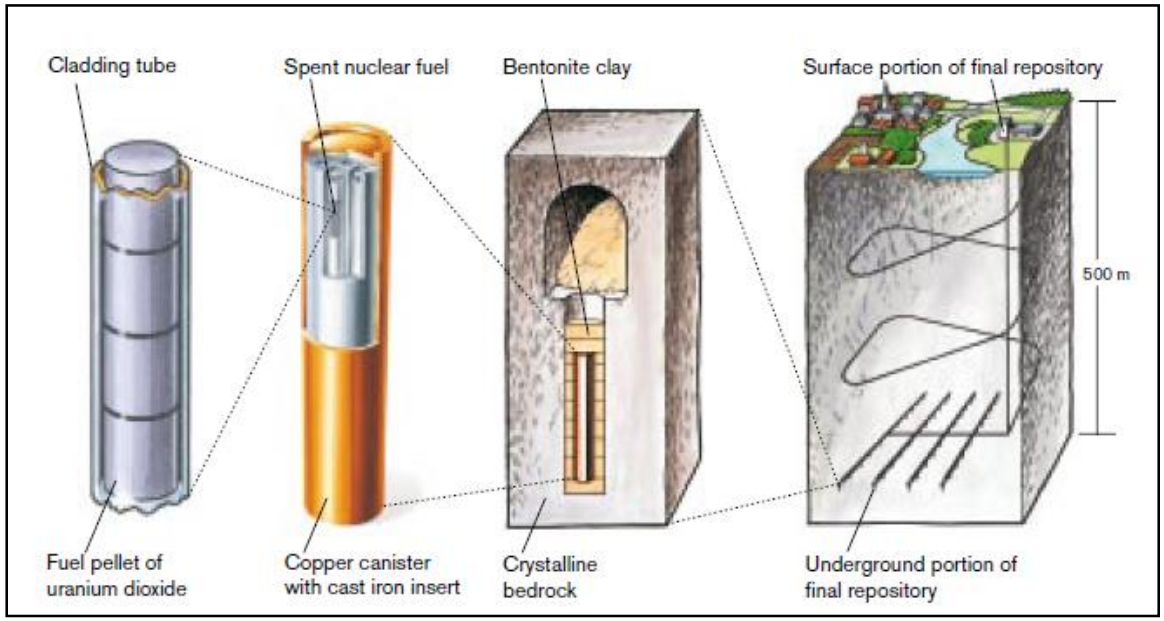
Outline

- **Background and Motivation**
- International Disposal Activities: Principles and Portfolio
- Opportunities for International URL Collaborations
- Priorities and Selection Process
- Overview of DOE's International Activities
- Integration with Generic Research Program
- Successes and Concerns

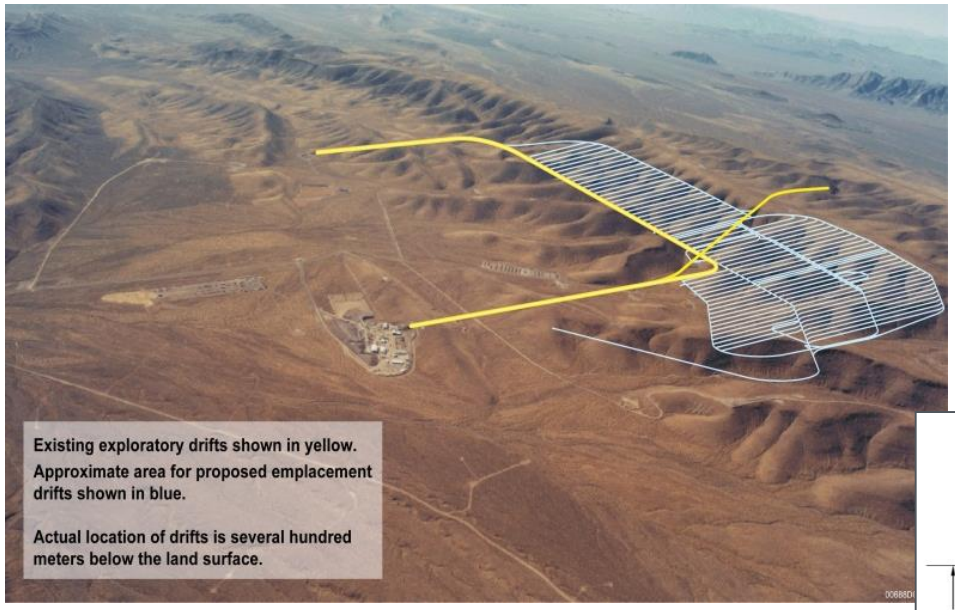
DOE's Disposal Research: Current Focus

- 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

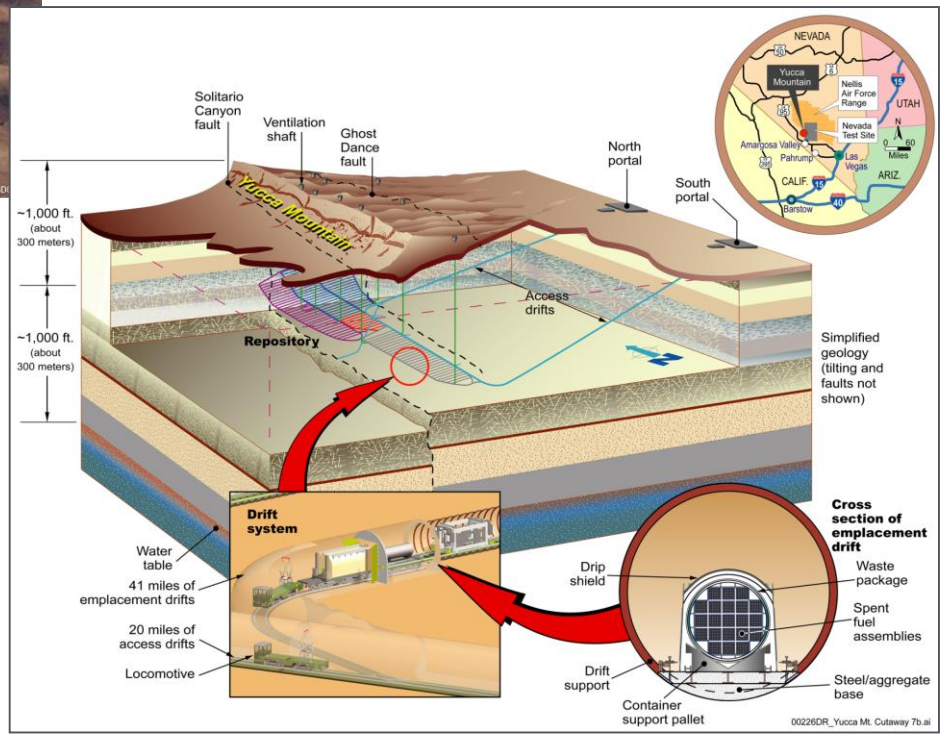


Dual Purpose Canisters: From NAC International Website March 31 2012

DOE's Disposal Research: Until 2010



Yucca Mountain



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

From Yucca Mountain to Alternative Host Rocks

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

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

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

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

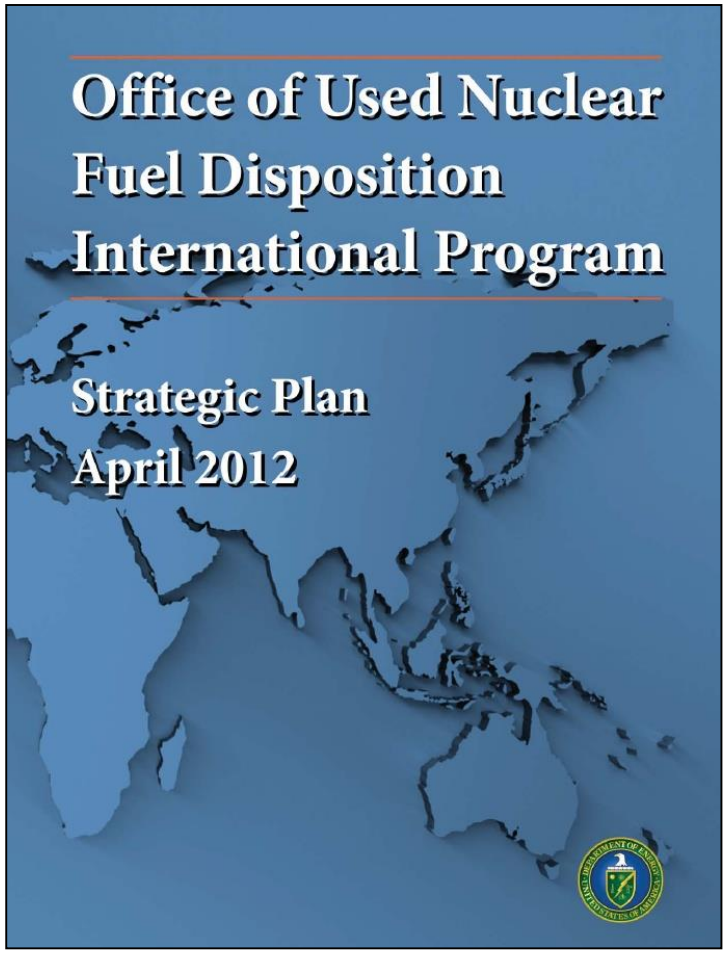
Disposal Research – International Activities

Strategic Plan for Increased International Collaboration in Disposal Research

The DOE Office of Nuclear Energy has four strategic goals for the International Program

- **Leverage global knowledge to meet domestic goals**
- **Increase global deployment of advanced technology**
- **Build a foundation for collaboration, trust, and joint action**
- **Accelerate global learning and innovation**

http://www.energy.gov/ne/downloads/office-unf-disposition-international-program-strategic-plan



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Principles of International Collaboration

- Focus on activities that complement ongoing disposal R&D within SFWST (e.g., testing advanced process modeling tools developed in SFWST in comparison with international experiments, improving characterization/monitoring methods)
- 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)
- Emphasize collaboration that provides access to and/or allows participation in field experiments conducted in operating underground research laboratories (URLs) not currently available in the U.S.
- Select collaborative R&D activities based on technical merit, relevance to safety case, and cost/benefit, and strive for balance in terms:
  - Host rock focus (clay, crystalline, salt)
  - Repository design (mined repository, high-temperature)
  - Key R&D issues (natural barrier perturbation, engineered barrier integrity, flow and transport, integrated system behavior)

SFWST's International Portfolio with URL Focus

Status 2019

Multinational Initiatives

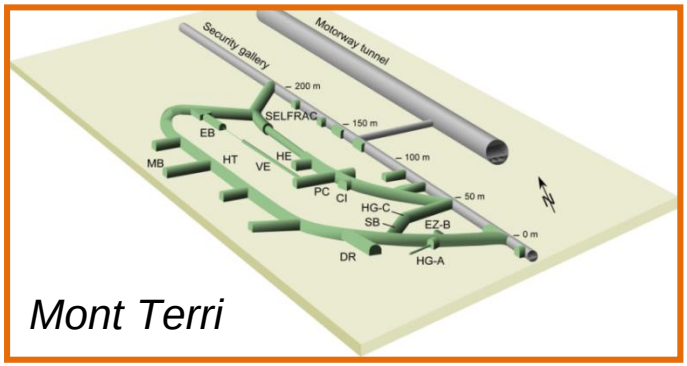
- **Mont Terri Project**
  - *Participate in experiments at Mont Terri argillite URL in Switzerland*
- **DECOVALEX Project**
  - *Participate in model comparison initiative for several URL-related tasks in different host rocks*
- **Colloid Formation and Migration Project**
  - *Participate in colloid research at Grimsel crystalline rock URL in Switzerland (participation ended in 2015)*
- **FEBEX DP**
  - *Participate in FEBEX dismantling project, which evaluates bentonite-rock behavior after 18 years of heating*
- **SKB Task Forces**
  - *Participate in crystalline rock research centered around Äspö HRL in Sweden*
- **HotBENT (starting soon)**
  - *Conduct a high-temperature heater test to evaluate feasibility of 200°C waste disposal*

Bilateral Research Collaborations

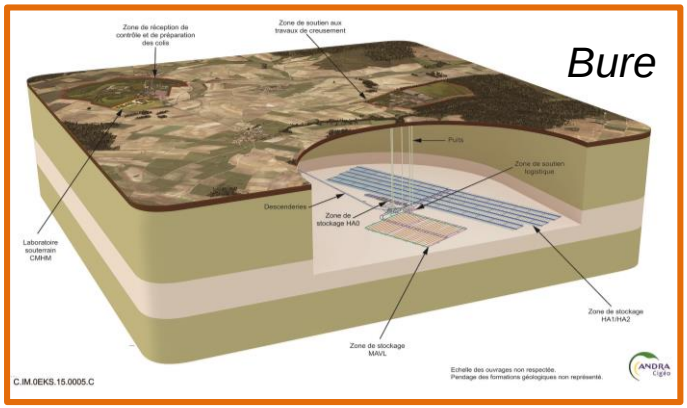
- **US-Republic of Korea (ROK)**
  - *Participate in KAERI Underground Research Tunnel (KURT) experiments in crystalline rock*
- **US-Germany Salt Collaboration**
  - *Participate in testing and modeling studies for thermal-mechanical and hydrological behavior of domal and bedded salt*
- **US-Sweden COSC Collaboration**
  - *Participate in testing hydrogeological characterization methods*
- **Other Potential Opportunities**
  - *Explore use of existing Memorandum of Understanding (MoU) between DOE and Spain (ENRESA), France (ANDRA), Japan (JNEAP) and Belgium*
  - *Observe developments and plans for new URLs in China and Korea*

There are several other international collaboration activities not focused on URL access and participation, e.g., the Thermodynamic Database Project, or NEA's Clay, Salt and Crystalline Clubs.

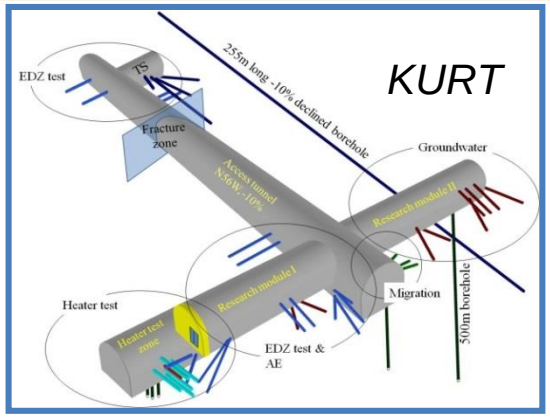
International URLs with U.S. Participation



Mont Terri

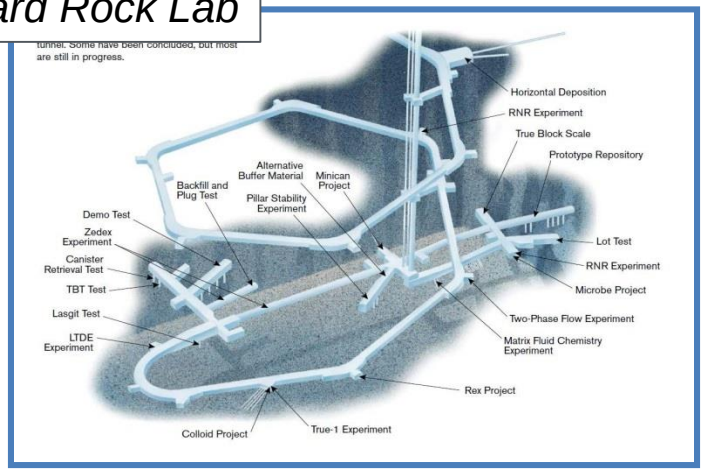


Bure

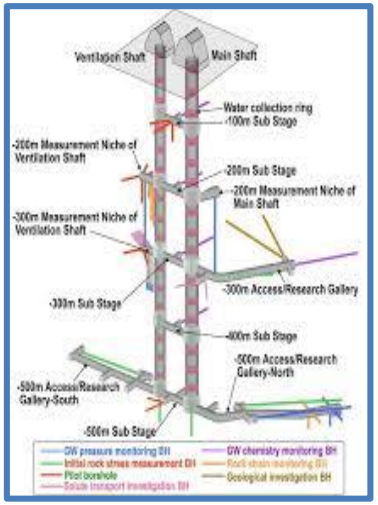


KURT

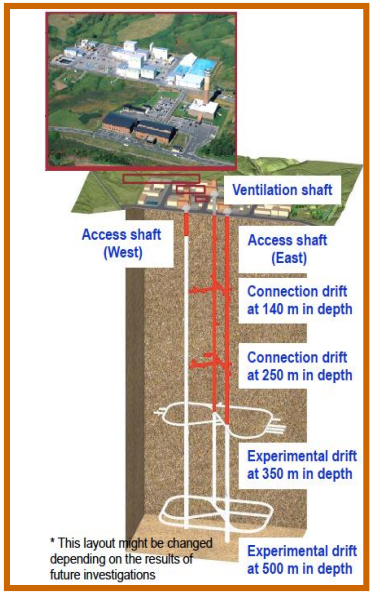
Äspö Hard Rock Lab



Mizunami URL

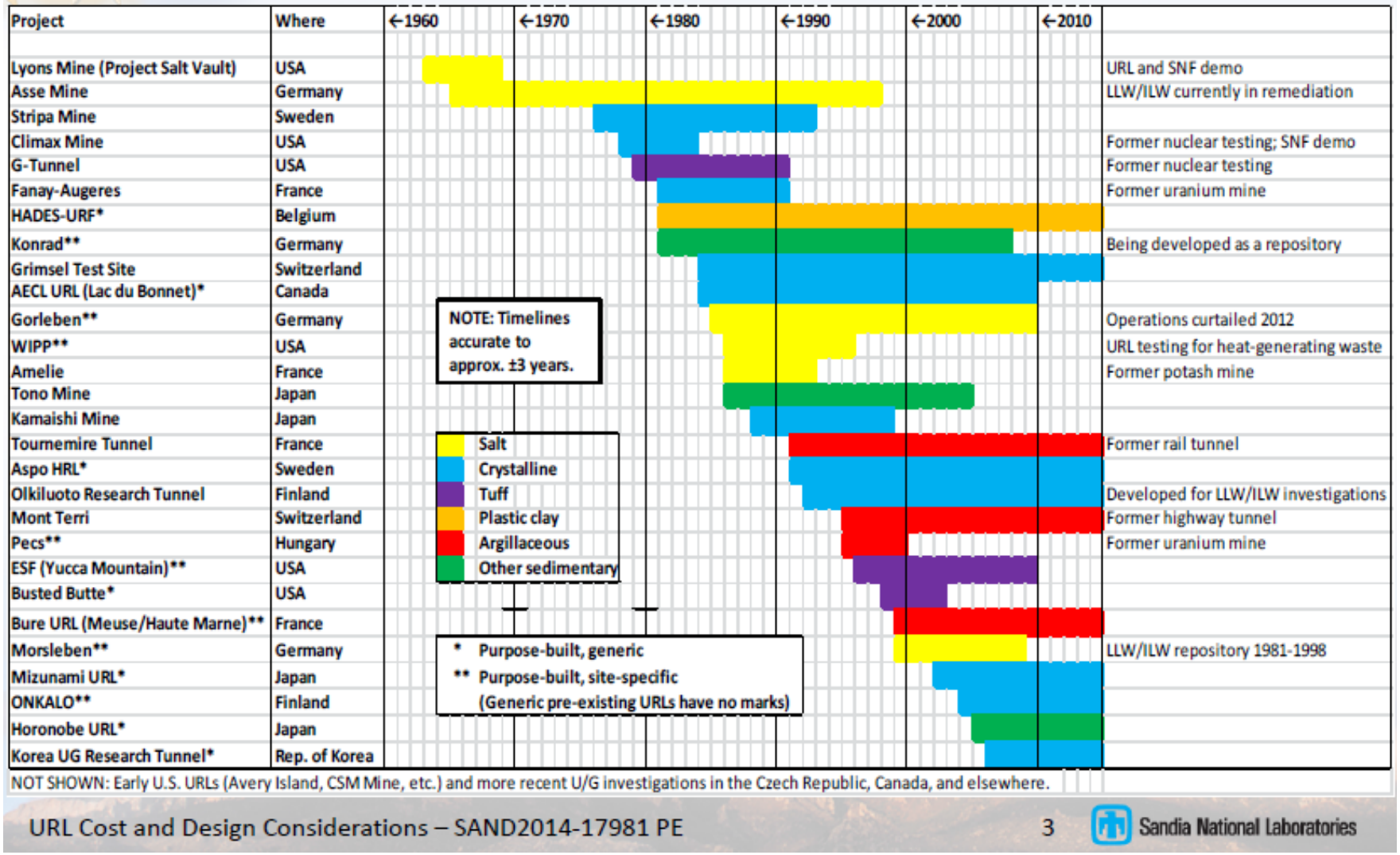


Grimsel Test Site



Horonobe URL

URLs in Nuclear Waste Disposal – A Long History



Note: URLs have a long history in radioactive waste disposal field, yet there has been a growing list of dedicated underground research test sites for other subsurface applications (SURF mine in South Dakota, oil & gas shale test sites, Mont Terri experiments that are not waste disposal related)

Research in URLs– Why?

Characteristics:

Dedicated facilities for observation and controlled experiments, located in representative lithologies

Testing at true spatial scale, under in situ conditions, in complex and heterogeneous subsurface environments

Comprehensive characterization and monitoring

Ability to manipulate the subsurface & perform destructive testing

Community facilities with partnership between various stakeholders; open access to data and results

Scientific Objectives:

Improve process understanding

Prototype advanced imaging/monitoring methods

Test simulation capabilities and validate predictive models

Advance new approaches through testing and demonstration to adoption

Multinational Initiatives

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

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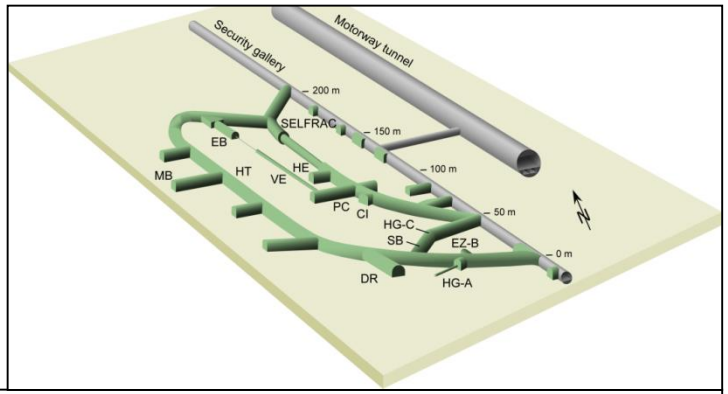
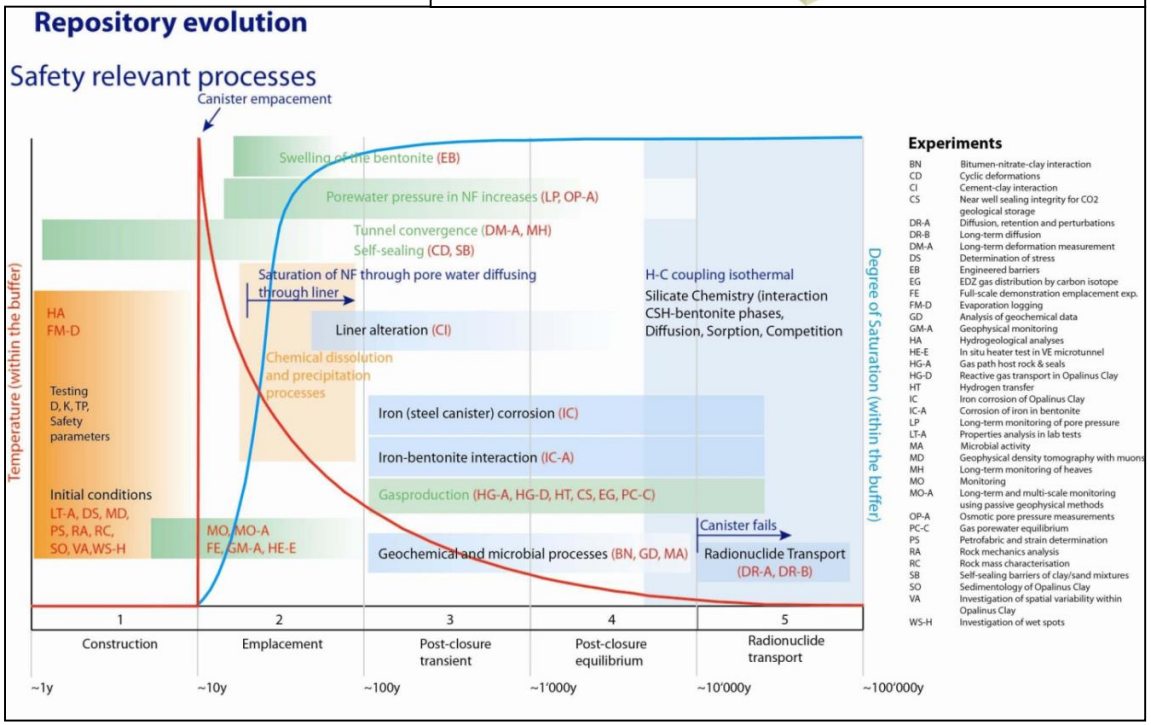
Mont Terri Project

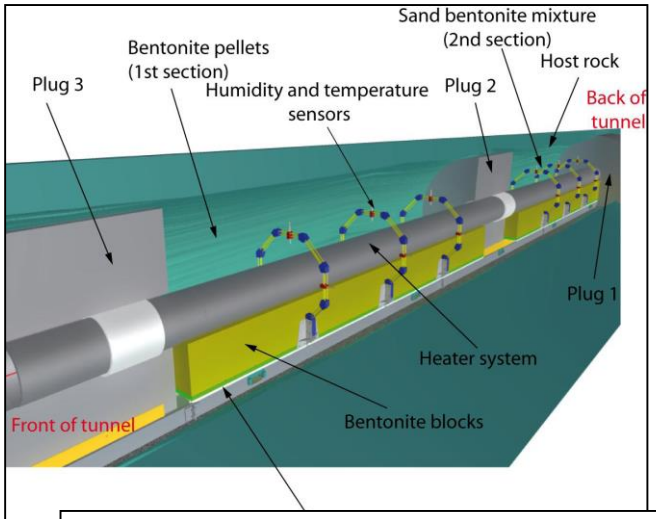
Multi-Purpose, Argillite URL

- **International research project for hydrogeological, geochemical, and geotechnical studies in an argillite formation**
- **URL is situated near the town of St Ursanne in Northwestern Switzerland**
- **Access to experimental data with many past, ongoing and future experiments addressing various relevant R&D issues**
- **Opportunity to participate directly in international research groups that conduct, analyze, and model experiments**
- **Opportunity for conducting own experiments**
- **DOE formally joined Project Phase 18 starting July 2012**
- **SFWST researchers have since been involved in several key experiments at Mont Terri**



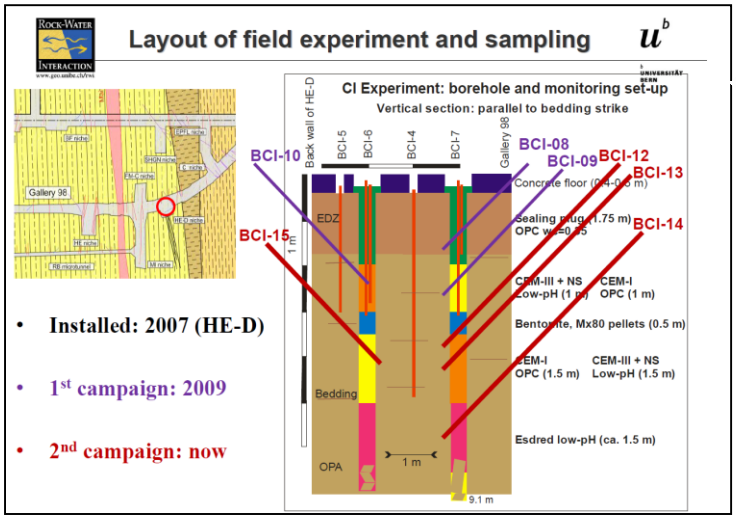


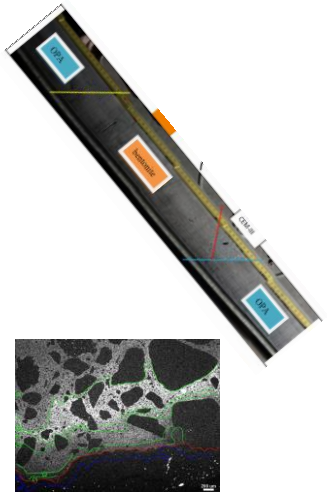
Mont Terri Project: Selected Experiments

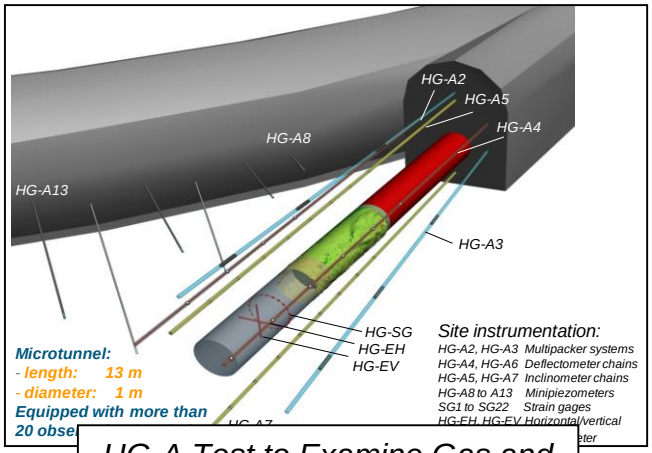


HE-E and FE Heater Tests

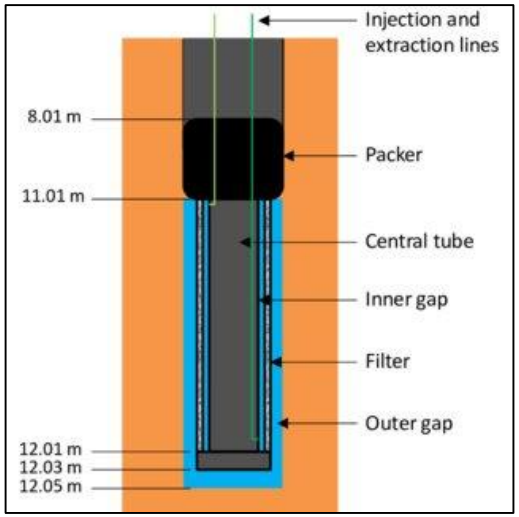
Cement-Clay Interaction (CI) Experiment







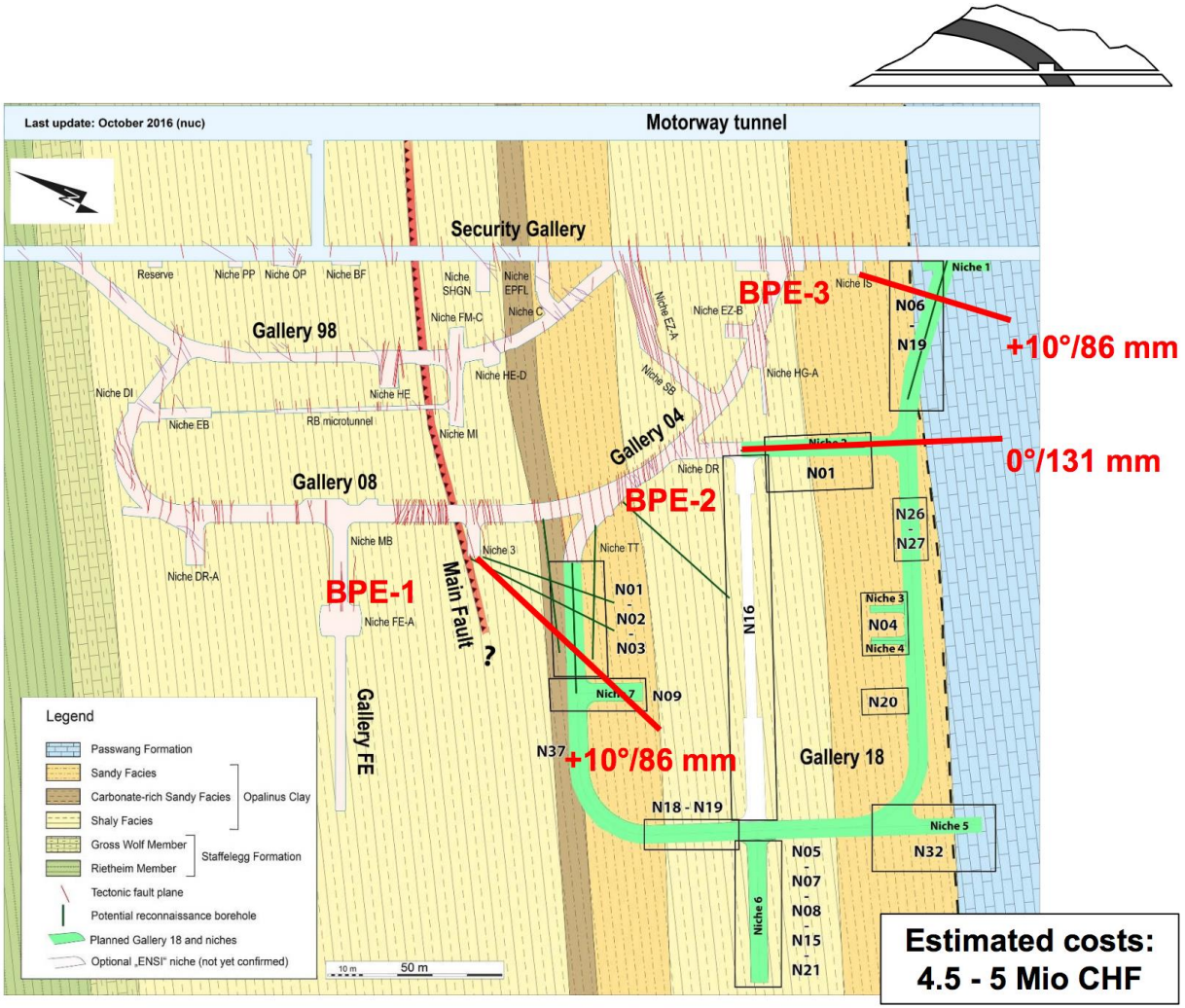
HG-A Test to Examine Gas and Water Flow in the EDZ



DR-A Diffusion Test to Characterize Ion Migration Through the Opalinus Clay

Mont Terri Extension Underway

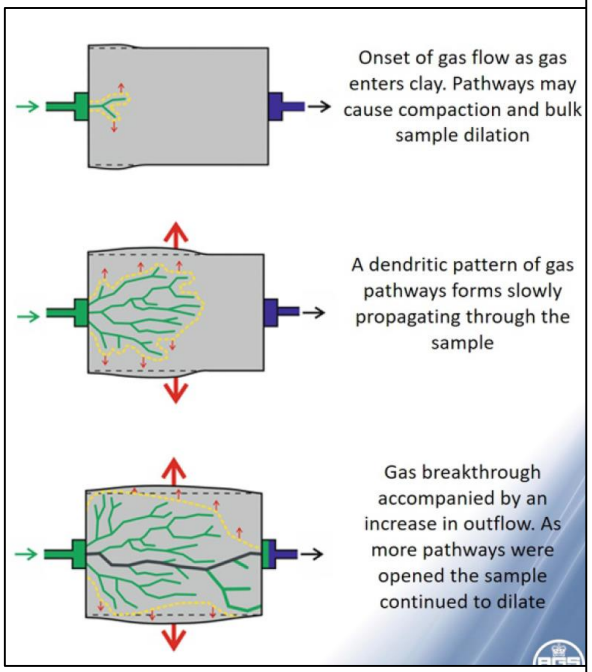
- **Significant addition for new experiments**
- **Most of the construction cost covered by Swiss partners**
- **New research program:**
  - 45 proposals
  - 60% are nuclear waste related
  - 10 proposals in detailed planning stages

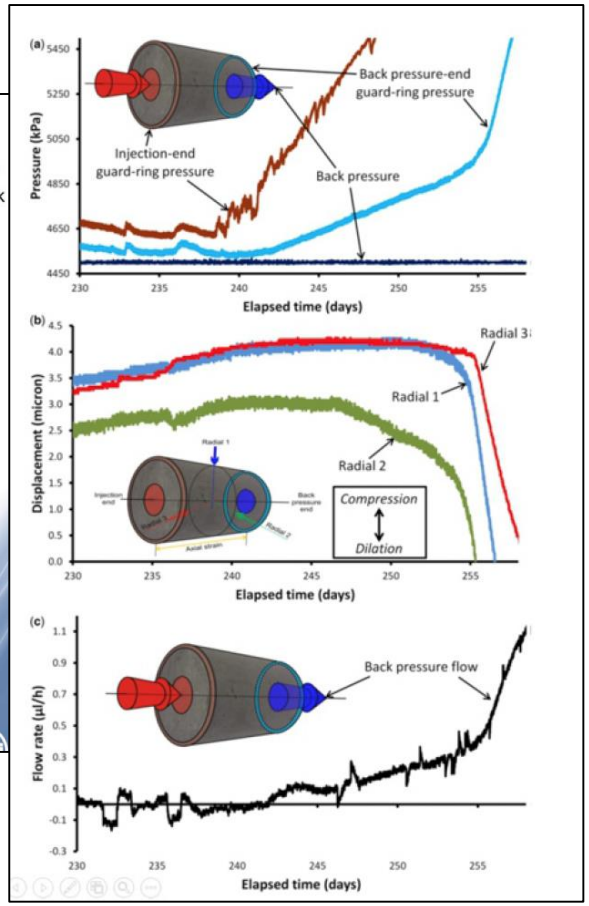


Example of Planned New Experiment

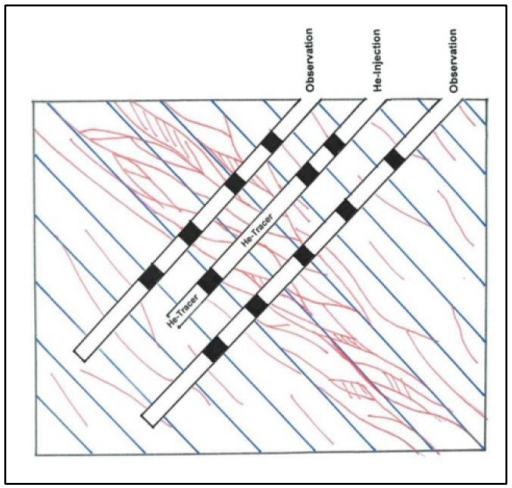
GT Experiment: Evaluation of gas transport models and of the behavior of clay rocks under gas pressure

Lab Studies 2018 to 2020





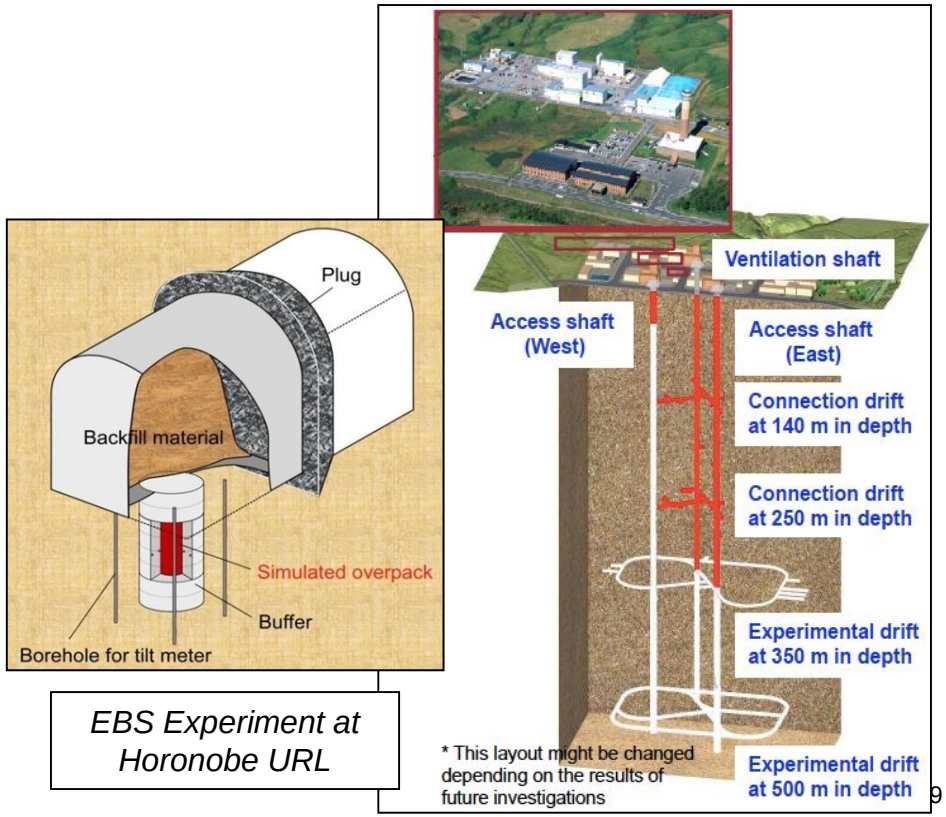
Field Studies 2019 to 2021



DECOVALEX Project

Multi-Purpose, Multiple Host Rocks

- **DECOVALEX was established in 1992, and has been active since, in several project stages**
  - DECOVALEX stands for “Development of Coupled Models and Their Validation Against Experiments”
  - The objective is to achieve a better understanding and improved modeling of the effects of coupled (T-H-M-C) processes in radioactive waste repositories
  - DECOVALEX participation involves joint analysis and modeling of selected sets of experimental data from different URLs and host rocks
- **DOE formally joined DECOVALEX-2015 project phase in 2012, focusing on three tasks**
  - Sealing experiment at Tournemire URL (clay)
  - Heater tests at Mont Terri URL and Horonobe URL (clay)
  - Bedrichov Tunnel Experiment on fracture flow and transport patterns (crystalline)
- **DECOVALEX 2019, now chaired by Jens Birkholzer at LBNL, has seven tasks tackling a variety of relevant R&D issues**
- **Plans for new project phase, referred to as DECOVALEX 2023, are underway**



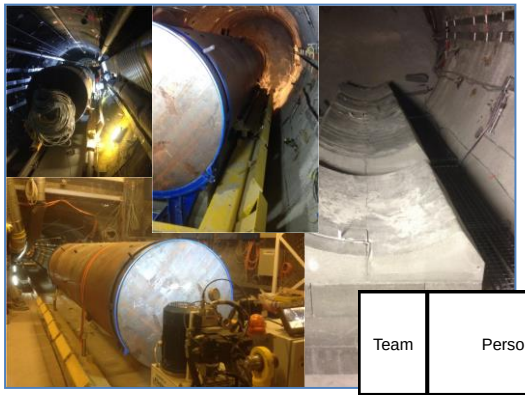
EBS Experiment at Horonobe URL

www.decovalex.org

DECOVALEX: Philosophy and Working Mode

- In-depth and regular discussions among national agencies and research teams with different views
- Multiple approaches, conceptual models, and simplifications applied to the same problem
- Consideration of a broad set of challenges, designs, host rocks, processes
- Emphasis on comparative analyses
- Tasks closely reflecting interests of funding organizations
- Excellent publication records, training standard of PhD students, and international visibility and reputation
- A successful long-term platform of information and knowledge exchange

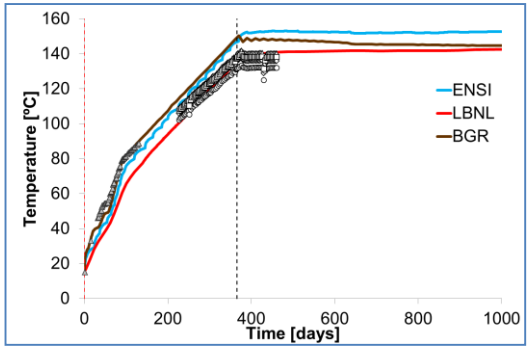
Advanced experiments



Multiple research teams

Team	Person	F.O.	Country	Code
BGR	Wang Xuerui	BGR	Germany	OpenGeoSys
CAS	Pengzhi Pan	CAS	China	EPCA3D
LBNL	Jonny Rutqvist	DOE	USA	TOUGH-FLAC
ENSI	Bastian Graupner	ENSI	Switzerland	OpenGeoSys
CNSC	Son T. Nguyen	IRSN	Canada/France	COMSOL
JAEA	Keisuke Maekawa	JAEA	Japan	THAMES
KAERI	Changsoo Lee	KAERI	South Korea	FLAC
CNWRA	Chandrika Manepally	NRC	USA	FLAC-xFlo

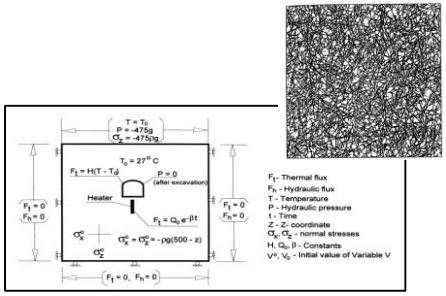
HE-E Heater Test

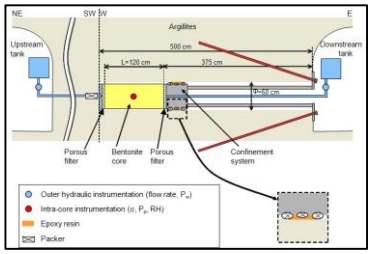


In-depth comparison and discussion

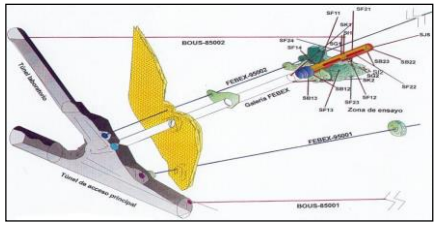
DECOVALEX: 25 Year History

Initial focus: Coupled HM and THM Processes in Fractured Hard Rock

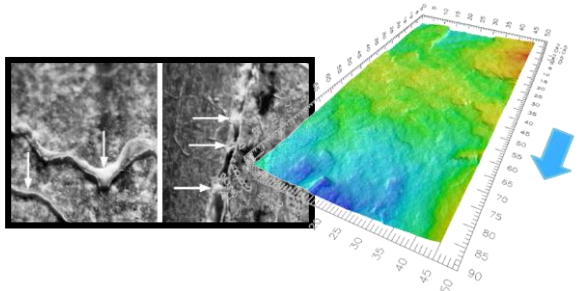




Increasing Emphasis on Argillites and Other Clay- or Mudstones in Addition to Crystalline Rock



First Full-Scale THM Experiments in URLs



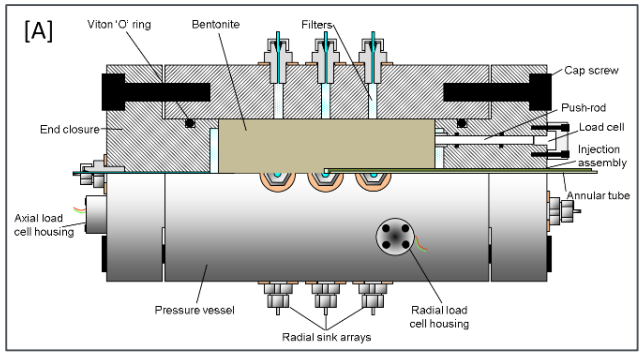
Adding Chemistry to THM

DECOVALEX I 1994
DECOVALEX II 1999
DECOVALEX III 2003
DECOVALEX-THMC 2007
DECOVALEX-2011 2011
DECOVALEX-2015 2015
DECOVALEX-2019

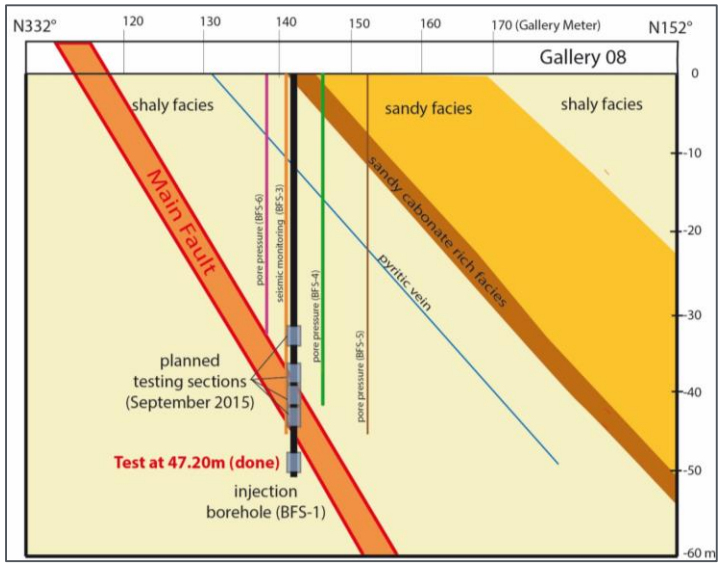
1992 — 2017

DECOVALEX 2019: Tasks

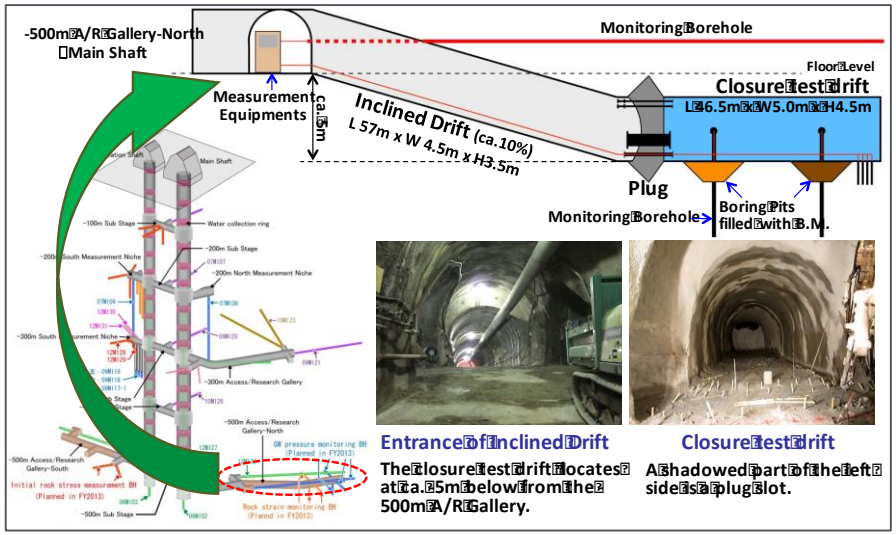
Task A: Gas Transport in Bentonite



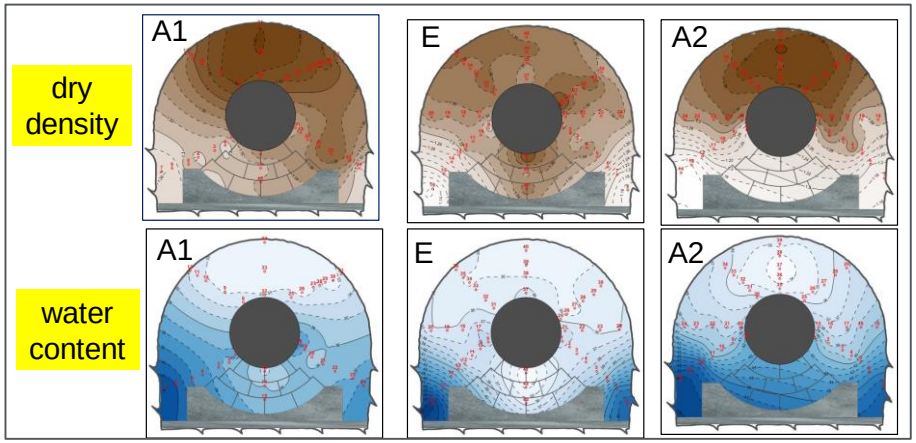
Task B: Fault Slip



Task C: GREET (Groundwater Recovery)



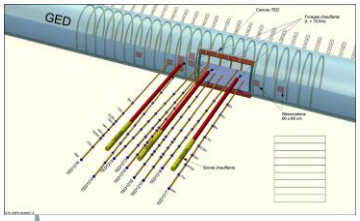
Task D: Bentonite Homogenization



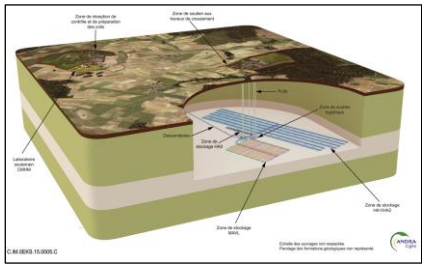
DECOVALEX 2019: Tasks

Task E: Heater Test Upscaling

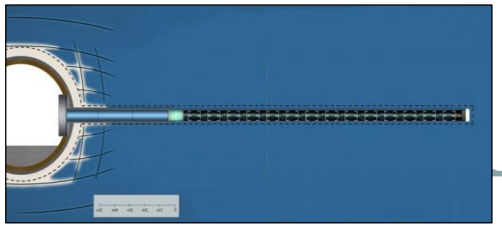
Small-scale TED Experiment



Repository Scale

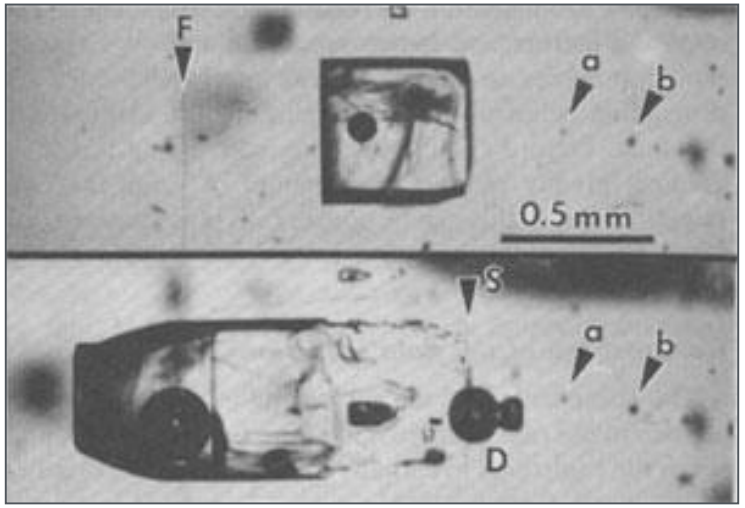


Full-scale ALC Experiment

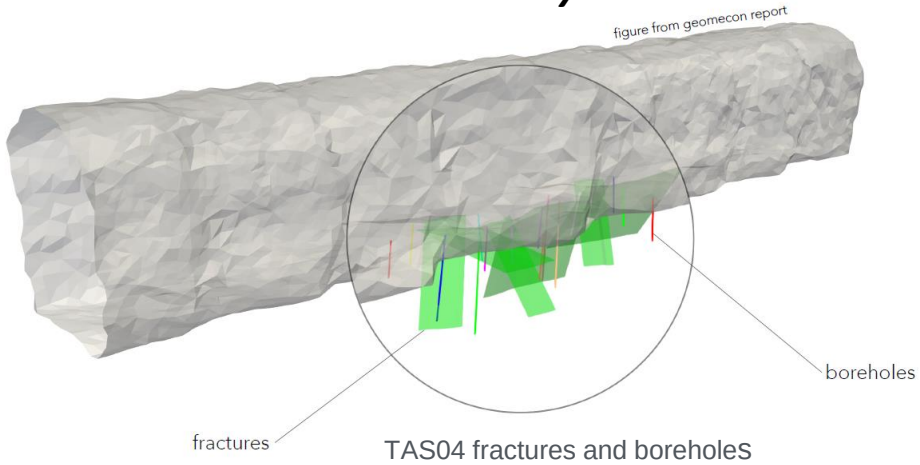


Tests at Bure URL, led by ANDRA

Task F: Fluid Inclusions



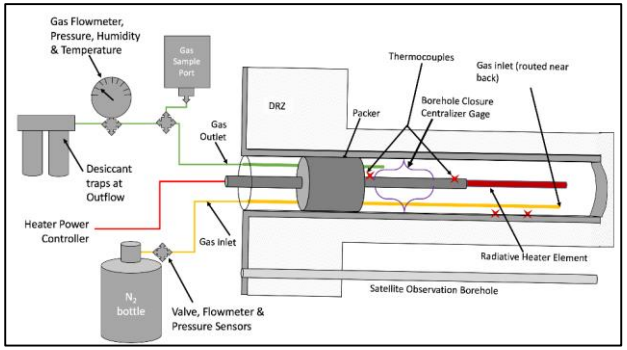
Task G: EDZ Evolution in Crystalline Rock



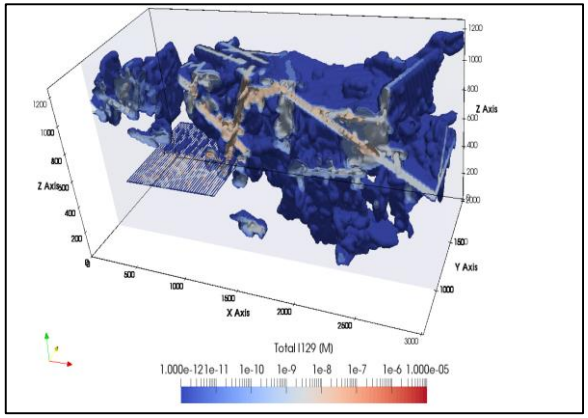
TAS04 fractures and boreholes

DECOVALEX 2023: Potential Tasks

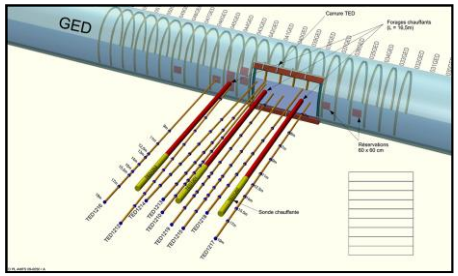
Salt Heater and Brine Migration Test



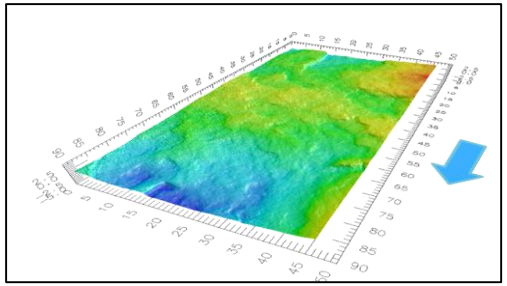
PA and UQ



Thermal Fracturing Experiment

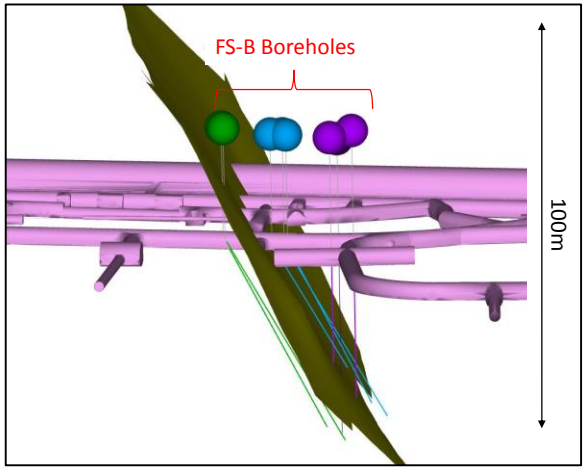


Single Fracture THMC

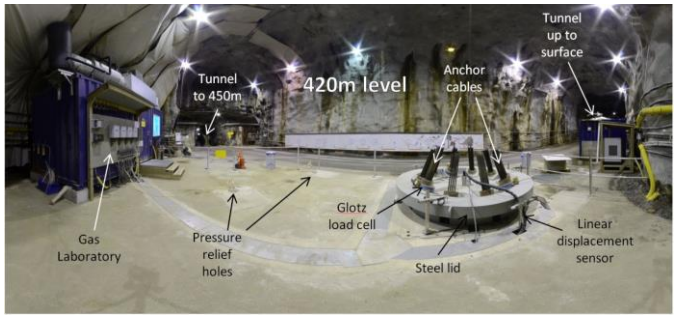


In-DEBS EBS Experiment

FS-B Experiment



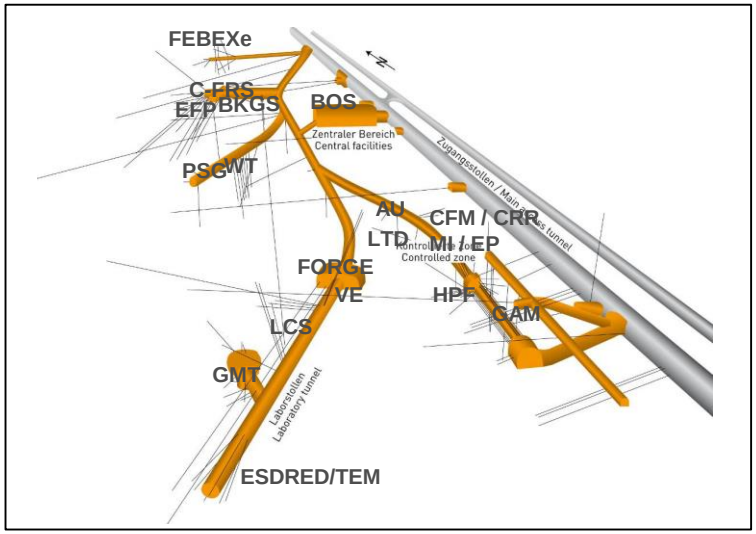
Gas Transport Field Experiments (LASGIT)



Grimsel Test Site (GTS)

Several Single-Purpose Projects, Crystalline URL

- **International research project for hydrogeological, geochemical, and radionuclide transport studies in crystalline rock**
- **URL is situated in in the Swiss Alps**
- **Participation in URL experiments requires individual contracts and buy-in**
- **Membership provides access to experimental data from individual experimental projects**
- **Opportunity to participate directly in international research groups that conduct, analyze, and model individual experiments**
- **Opportunity for conducting own experiments**

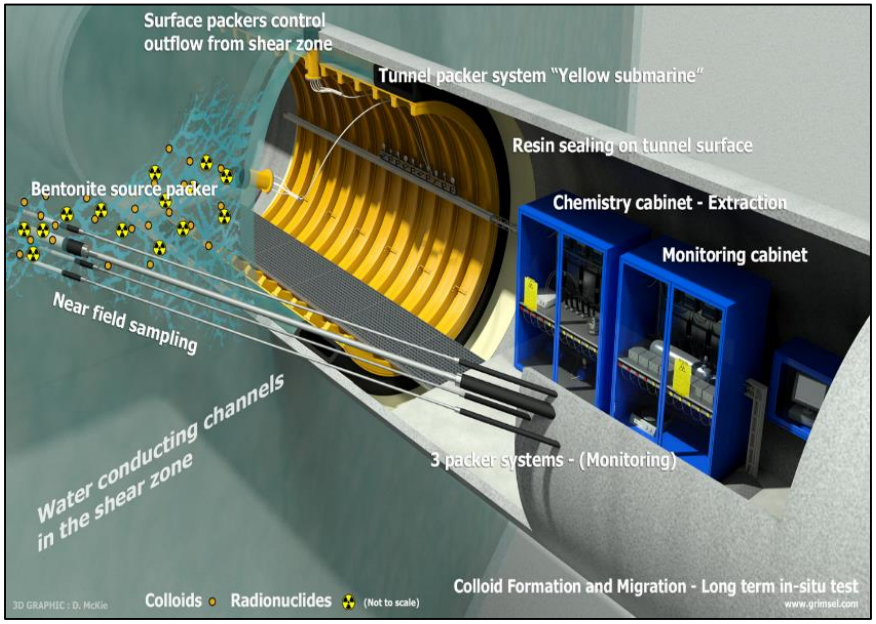


Colloid Formation and Migration project (CFM)

Membership from 2012 to 2015

Investigation of colloid formation/bentonite erosion, colloid migration, and colloid-associated radionuclide transport

- Long-term project with several experimental phases and dozens of transport experiments
- Current phase focuses on colloid transport originating from radionuclide-doped bentonite plugs emplaced in a flowing shear zone (Long-term In-Situ Test, LIT, since 2015)

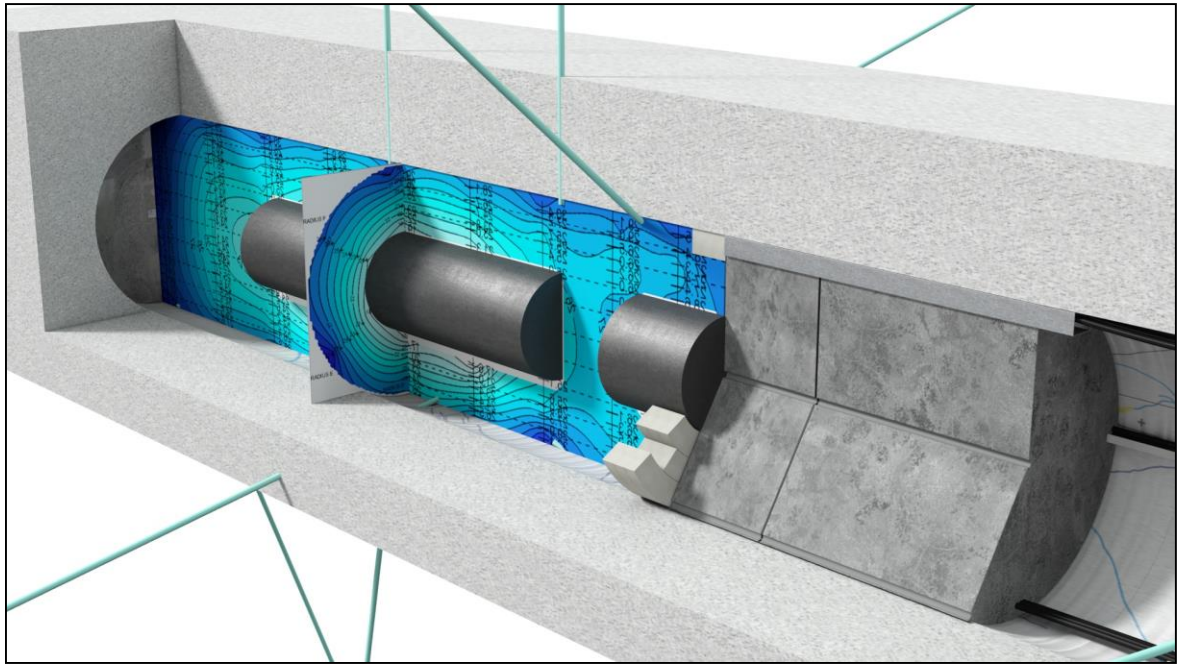


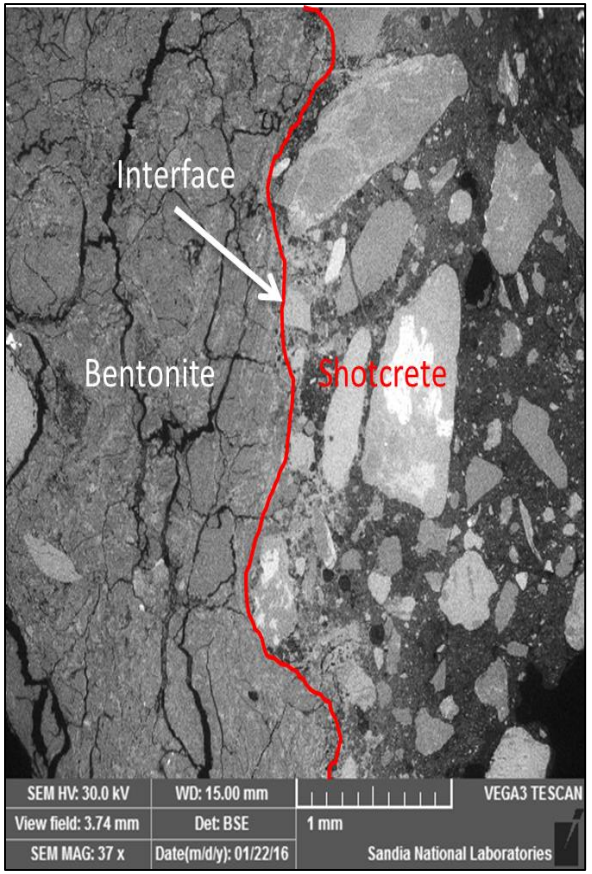
FEBEX Dismantling Project (FEBEX-DP)

Membership from 2015 to 2018 (project end)

What are the bentonite buffer capabilities after 18 years of hydration and thermal alteration? Will bentonite buffer homogenize?

- Dismantling and characterization of EBS after 18 years of continuous heating
- Bentonite and canister characterization
- Mineralogical interfaces imaging
- THMC modeling compared to post-mortem data



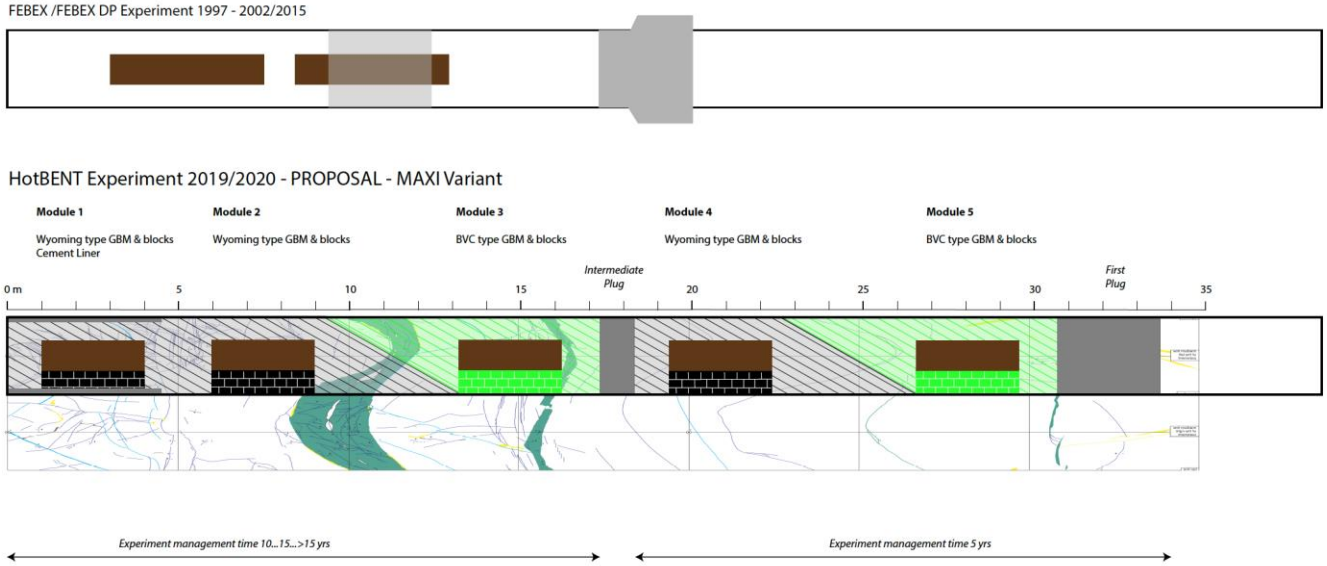


HotBENT: High-Temperature Bentonite Test

Membership from 2019 to ????

Can waste package and bentonite buffer temperature safely be raised to 200ºC, without causing performance relevant alteration and damage in barrier behavior?

- Potential impacts due to high temperature:
  - Cementation possibly affecting mechanical properties
  - Illitization (certain conditions, e.g. high potassium concentrations) affecting swelling and transport properties
- Potential impacts due to strong thermal gradients:
  - Thermal pressurization and complex moisture transport process, including convection of vapor
  - Delayed saturation and heterogeneous, time-dependent density distribution (differential swelling)

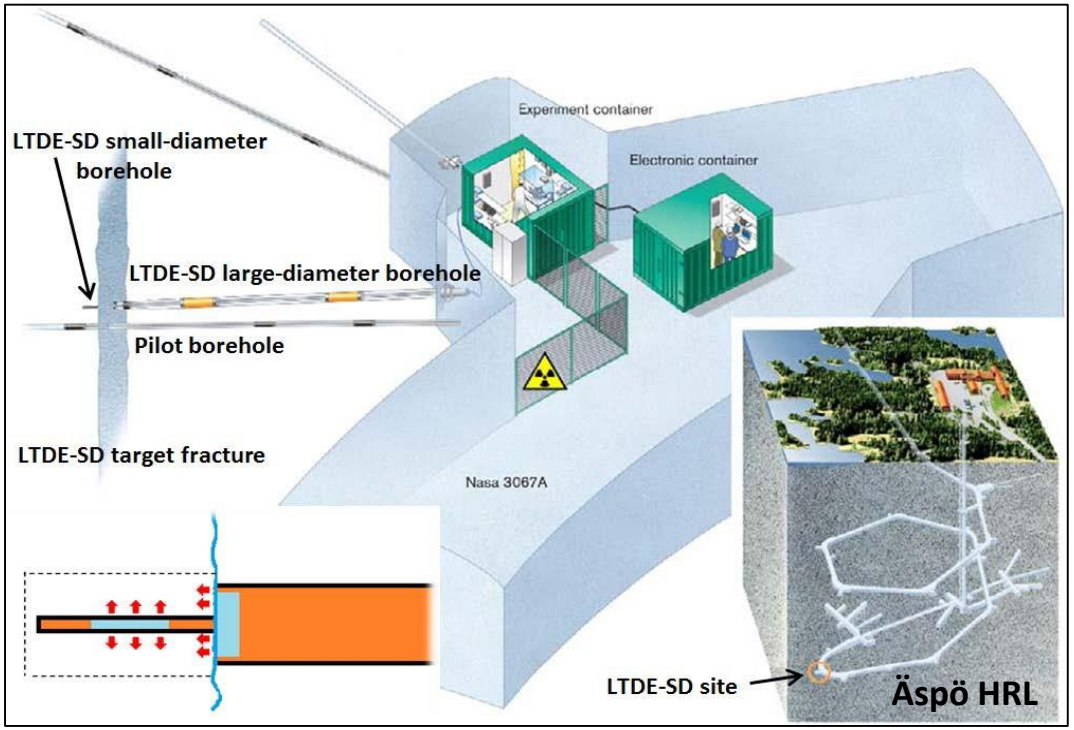


SKB Task Forces

Multi-Purpose, Crystalline URL

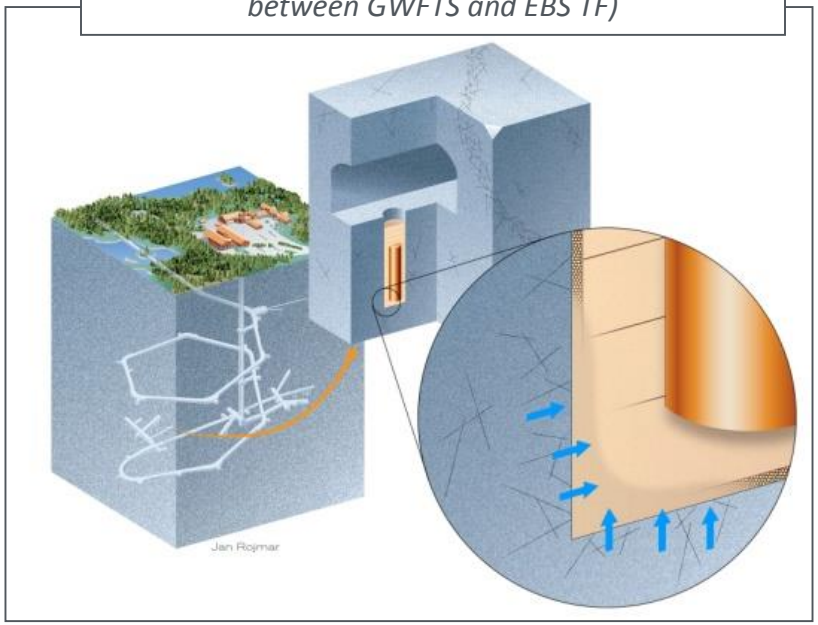
- **SKB has two task forces for Groundwater Flow and Transport of Solutes (GWFTS, since 1992) and Engineered Barrier Systems (EBS, since 2004)**
- **Different modeling tasks, often involving experiments carried out at the Äspö HRL in Sweden, are addressed collaboratively**
- **GWFTS Task Force: To develop and apply appropriate methods for flow and transport in fractured crystalline rock**
- **EBS Task Force: To develop and apply tools for the advanced coupled THM and THC analysis of buffer and backfill materials**
- **DOE joined both task forces in 2014, and SFWST researchers have since been involved in a number of experiments**

LTDE – Long-term Diffusion Experiment (GWFTS)



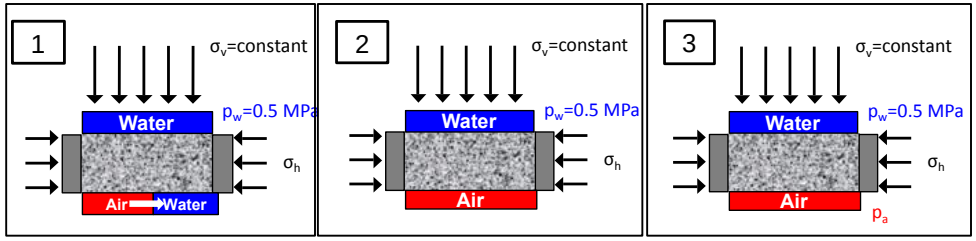
SKB Task Forces: Selected Tasks

BRIE experiment: Improved understanding of water exchange at bentonite-rock interface (shared task between GWFTS and EBS TF)



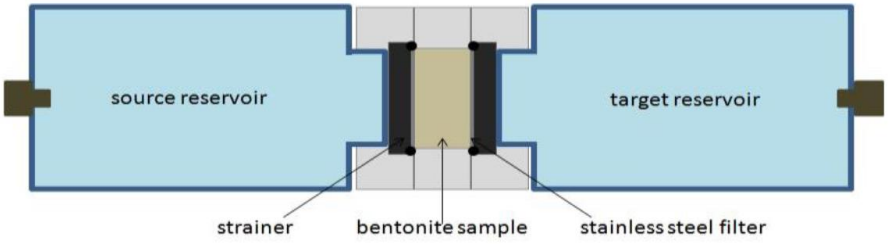
Prototype Repository: Improved prediction of final state of the buffer as affected by fractured rock inflow (EBS TF)

Hydro-Mechanical Processes associated with Gas Transport in MX-80 Bentonite (EBS THM TF)



Oedometer Tests Done at UPC

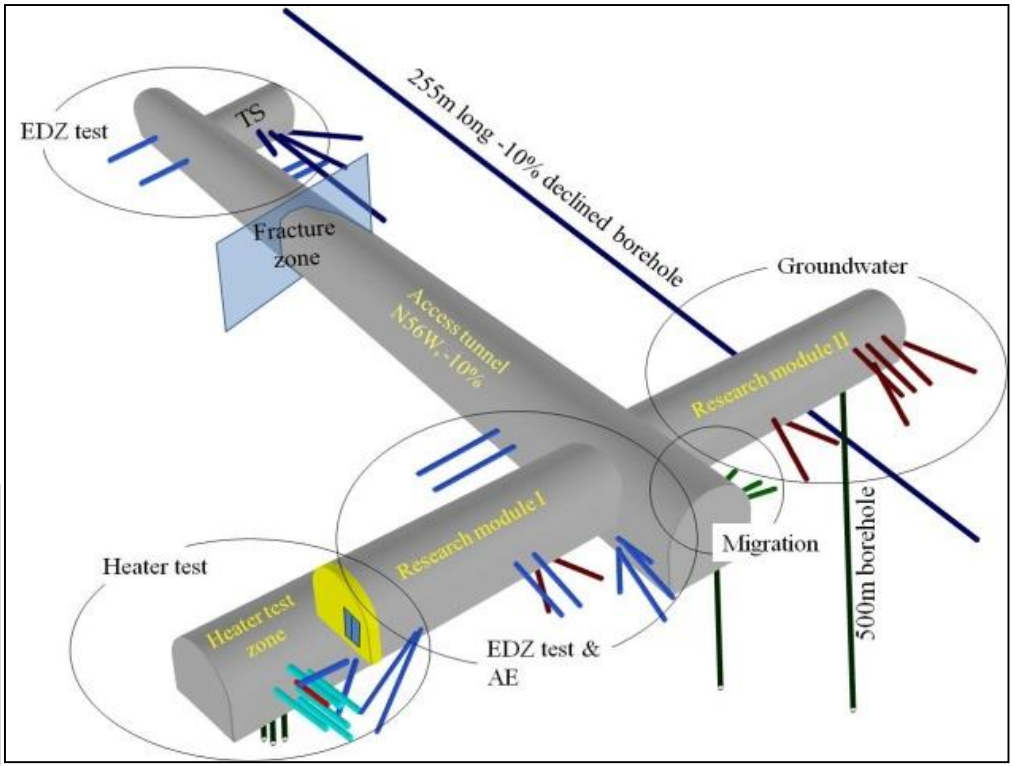
Diffusion of anions (Cl, Se, I) through compacted bentonite (EBS THC TF)

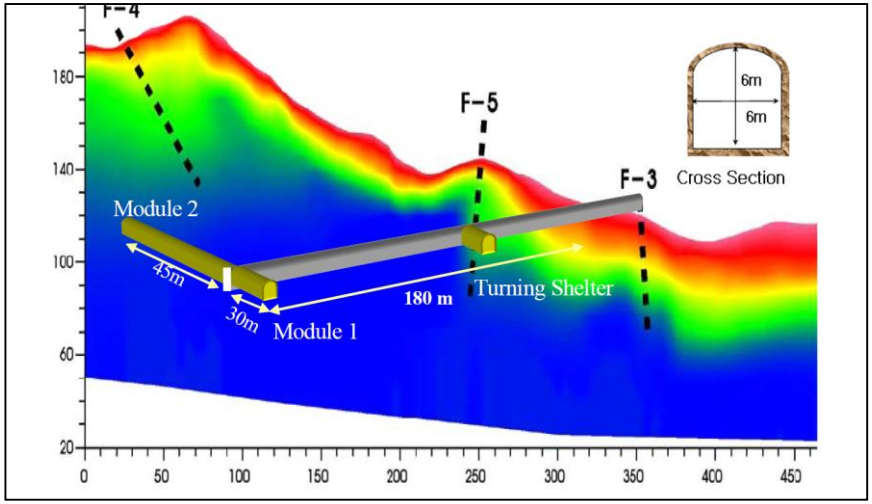


Selected Bilateral Collaborations: KURT

KAERI Underground Research Tunnel

- **Multi-year bilateral agreement with the Republic of Korea, with KURT URL as central central element**
- **Focus is on joint field testing and modeling to support the study of high-level nuclear waste disposal in crystalline media**
- **Technical scope includes developing improved techniques for in situ borehole characterization and new methods for measuring fracture flow/transport**

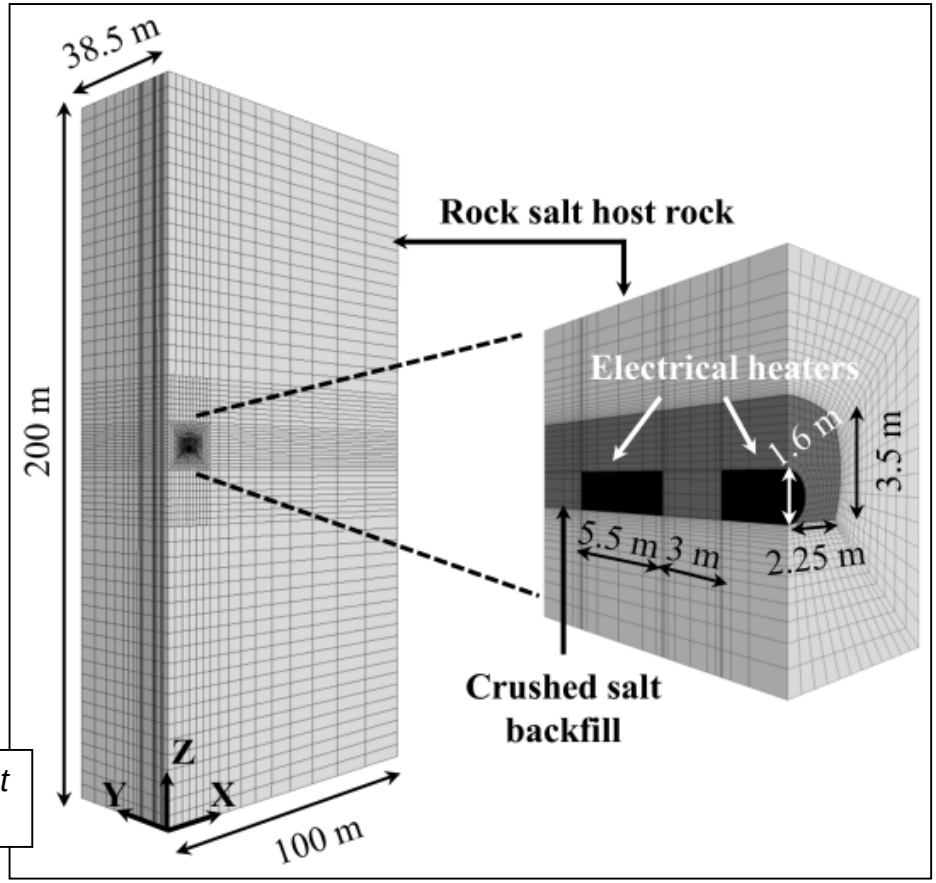




Selected Bilateral Collaborations: Germany on Salt

US-Germany Collaborative Studies for Salt THM Behavior

- **A Memorandum of Understanding, signed by the US DOE and BMWi (German Federal Ministry of Education and Research) in 2012, allows US and German researchers to advance the basis for salt disposal**
- **Building the scientific basis for salt disposal combines the extensive knowledge from Germany on domal salt structures (Gorleben, Asse Mine) with that from the US on bedded salt formations (WIPP)**
- **Ongoing collaborations between German and US scientists include laboratory testing, advanced thermal-mechanical-hydrological modeling and benchmarking, and seal system performance studies**

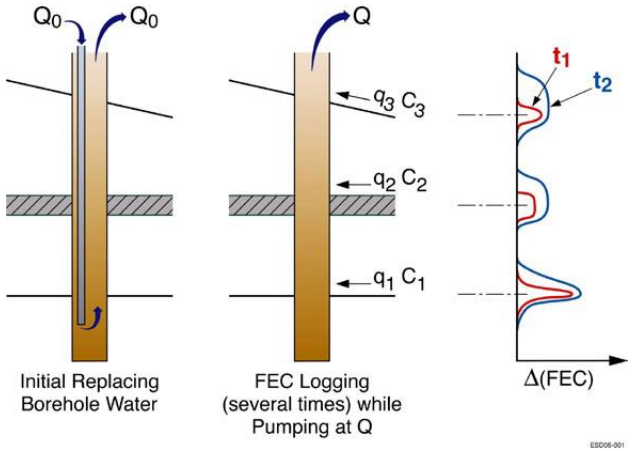


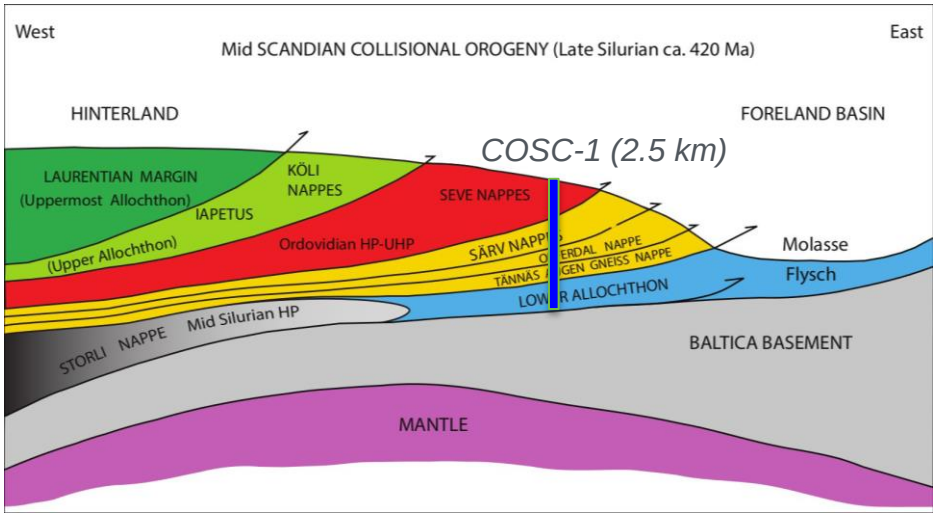
Modeling of TDSE heater test at Asse Mine in Germany

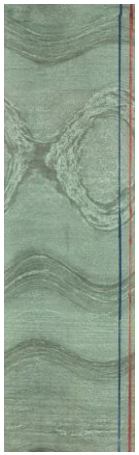
Selected Bilateral Collaborations: COSC

US-Sweden Collaboration on Fractured Rock Characterization

- **COSC provides access to a deep drilling project in crystalline rock**
- **SFWST researchers explored several site characterization techniques in cooperation with Swedish science team**
  - Flowing fluid electric conductivity (FFEC) logging of well to detect flowing fractures
  - Sampling and analysis of water compositions and microbial communities associated with fracture zones
  - Correlation of fractured core samples with field evidence of flowing fracture zones







COSC: Collisional Orogeny in the Scandinavian Caledonides

Outline

- Background and Motivation
- International Disposal Activities: Principles and Portfolio
- Opportunities for International URL Collaborations
- **Priorities and Selection Process**
- Overview of DOE's International Activities
- Integration with Generic Research Program
- Successes and Concerns

Planning Related to International Disposal R&D

- June and September 2010: R&D Roadmap Workshops to identify high-priority FEPs for SFWST campaign
- April 2012: International collaboration workshop to discuss priority 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)
- Re-evaluate international portfolio
- Ensure full integration with generic R&D activities

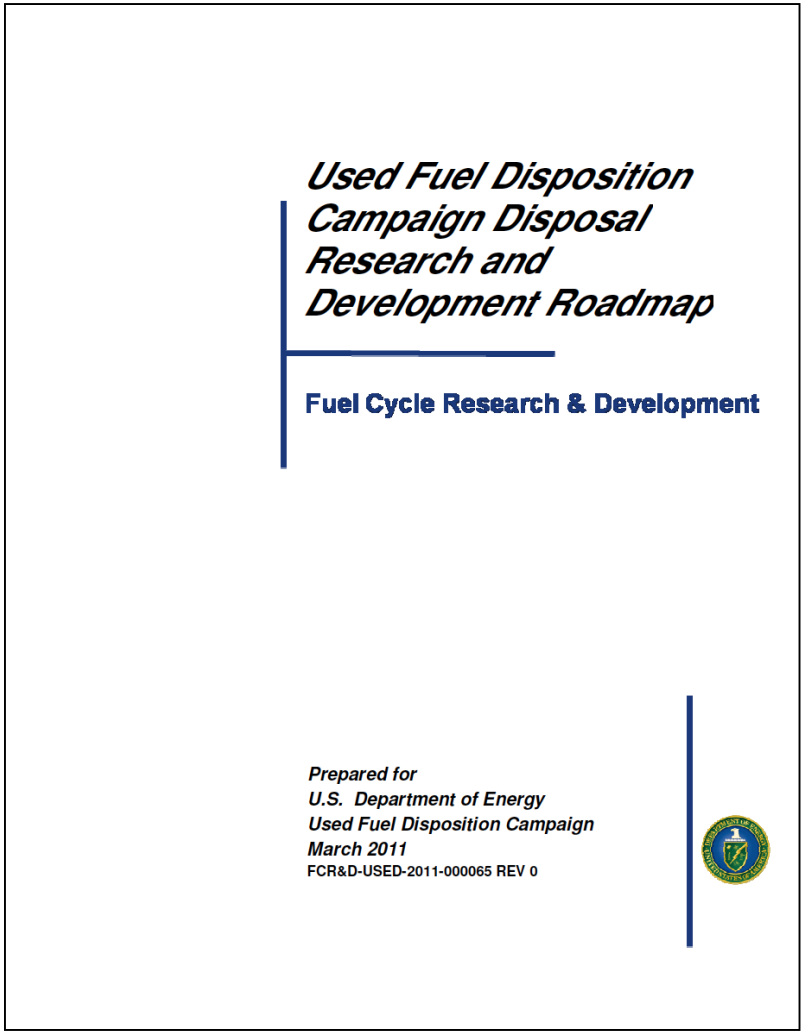
- January 2019: R&D Update Roadmap to review and revise existing R&D activities, assess priority levels, and brainstorm gaps (full integration of generic and international R&D activities)

R&D Roadmap Workshops June & September 2010

Systematic FEP-Based Prioritization (professional judgment)

Priority FEPs in Natural System*

- Excavation disturbed zone for shale media
- Flow and transport pathways in crystalline media
- Chemical processes for shale media
- Thermal processes for shale media
- Hydrologic processes for salt media



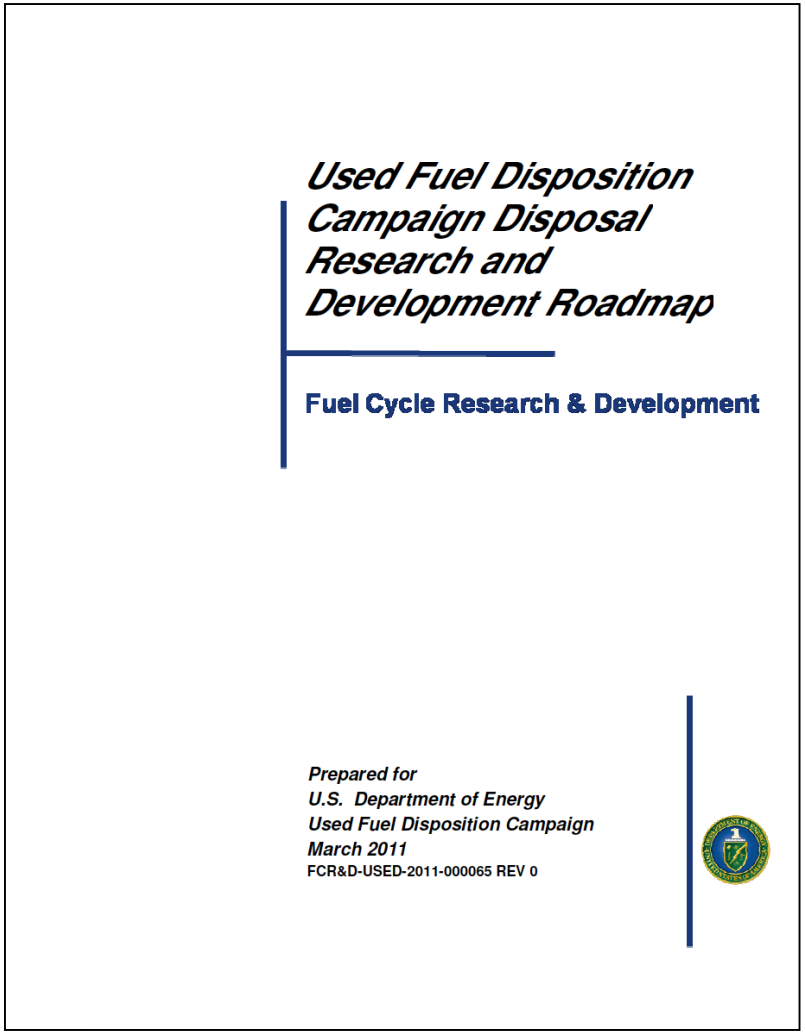
*See also Nutt presentation at Nuclear Waste Technical Review Board Fall 2011 Board Meeting

R&D Roadmap Workshops June & September 2010

Systematic FEB-Based Prioritization (professional judgment)

Priority FEPs in EBS*

- Buffer and Backfill Materials: Issues related to chemical, mechanical and thermal processes generally ranked high
- Overall, chemical processes in the considered EBS components ranked higher than others but these are strongly coupled to thermal, hydrological, and even mechanical processes within the EBS



*See also Nutt presentation at Nuclear Waste Technical Review Board Fall 2011 Board Meeting

International Priorities Workshop in 2012

Planning Workshop April 2012: Selection Criteria for International Collaboration Portfolio:

- **Technical merit, key research gaps addressed, relevance to safety case, access to URLs or related data**
- **Program balance in terms of host rock focus and performance period**
- **Cost/benefit**

Spreadsheet developed and discussed in 2012 workshop: Started with a selected list of international URL experiments

Relevant Ongoing or Planned Experiments (Selected)	URL	Cooperation Possible?	Participation?	Host Rock	Main Focus	FEPs Ranking	Test Period
FE: Full-scale heater test demonstration experiment	Mont Terri, Switzerland (Opalinus Clay)	Via Mont Terri Project	Yes, LBNL	Opalinus Clay	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 preparation and design phase; heating to start in 2014
HE-H: Half-scale heater test in VE test section	Mont Terri, Switzerland	Via DECOVALEX or Mont Terri Project	Yes, LBNL	Opalinus Clay	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 2014
MB: Mine-by Test for full-scale HM validation	Mont Terri, Switzerland	Via Mont Terri Project	No	Opalinus Clay	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
SB: Self-sealing barries of clay/sand mixtures	Mont Terri, Switzerland	Via Mont Terri Project	No	Opalinus Clay	EBS Test performance of different clay/sand mixtures for backfill and seals allowing for gas pressure release while very low permeability to water	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	Experiment has ended and post-test analysis is ongoing
CI: Cement clay interaction	Mont Terri, Switzerland	Via Mont Terri Project	Maybe, SNL	Opalinus Clay	Mostly EBS Investigation of interaction between cement, bentonite and opalinus clay. Chemical processes at interfaces are evaluated.	Engineered System FEPS: Buffer/Backfill materials 2.1.04.01: Buffer/Backfill >> High 2.1.09.01, .04, .07, .09, .13: Chemical Processes - Chemistry >> Medium Engineered System FEPS: Seal/liner materials 2.1.05.01: Seals >> Medium 2.1.09.01, .04, .07, .09, .13: Chemical Processes - Chemistry >> Medium	Sampling and modeling is ongoing.

Frequent Re-evaluation of International Portfolio

Example Slide from International Mini-Workshop at 2017 Working Group Meeting

Spent Fuel and Waste Science and Technology

Discussion

- **Taking stock of current and future activities:**
  - Do we have the right portfolio/balance of projects and tasks?
  - Are there valuable opportunities we missed? Why?
  - What is the benefit to the program?
  - How do we evaluate benefit to the program?
  - What are the lessons learned from ongoing projects?
- **Going forward**
  - Revisit, change, and add to current portfolio?
  - Are there too many opportunities with too little support?
  - Is it time for DOE to be more active than reactive in international settings? Plan own experiments? Organize and lead own modeling tasks?

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R&D Roadmap Workshop January 2019

Systematic Activity-Based Prioritization (professional judgment)

Review Draft - INTERNAL USE ONLY - 01/11/2019 -- Progr				Review Draft - INTERNAL USE ONLY - 01/11/2019		
R&D Task #	**R&D Task (or Activity) Name**	**Brief Task Description**	**2019 SAL *Numerical* Value** **(see current SAL table definitions)**	**Rationale for 2019 SAL (answer the Questions in the SAL Table)* *as a starting point you may consider the applicable state-of-the-art "DISCUSSION(s)" for the highest scoring related FEPs shown in the 202 UFD Roadmap App. A, last column)**	**2019 Importance to Safety Case (ISC) Descriptive Value (ISC = High, Medium, or Low; see ISC table definitions)**	**2019 ISC Numerical Value**
I-4	Experiment of bentonite EBS under high temperature, HotBENT	• Thermal limit of crystalline and argillite repository with bentonite EBS. • Hydrological, mechanical and chemical alteration of various types of bentonite that backfilled EBS under high temperature (200 °C) • Validation of coupled THMC model • Supply GDSA with the porosity, permeability, swelling pressure, vapor pressure evolution and clay mineral alteration under high temperature • LANL should have input from experimental work • Cross-fertilize with THC processes in EBS and thermodynamic DB development	5	HotBENT tackles a temperature regime of up to 200 degrees in a full-scale field heater test. This type of testing has never been done before; therefor SAL = 5.	ISC = High	5
I-5	Mont Terri FE (Full-scale Emplacement) Experiment	• Thermally driven THM evolution in both the EBS components and the host-rock behavior in argillaceous formations • Resaturation and swelling of the protective buffer around the waste package • Validation of coupled THM model of bentonite and clay host rocks • Supply GDSA with flow properties (e.g. porosity and permeability) evolution in the buffer, excavation disturbed zone and host rock • Inform GDSA related to local flow created by coupled THM processes.	3	The FE heat test is a full-scale long-term Demonstration experiment which will not produce new fundamental science findings but rathjer should demonstrate that the wste emplacementcan be engineered and predicted. As such, the experiment is mostly for improved defensibility.	ISC = High	5
I-6	Mont Terri FS Fault Slip Experiment	• Pressure-induced potentail for fault reactivation and development of pathways for RN transport • Driving force for pressure buildup coudl be thermal pressurization, long-term hydrogen generation, or distant earthquakes • Validation of coupled THM models for fault slip and permeability evolution • Could supply GDSA with transient flow properties for faults	5	This is about the possibility of transport pathways generated from seismic slip of fault going through repository. Not much is know about the relation between fault slip and permeability change.	ISC = High Group discussion as to why this is "High"--repository will not be sited on a fault; not transferable to other host rock environments	5

SAL = State of the Art Level (from 1 = Well Understood to 5 = Fundamental Gaps
ISC = Importance to Safety Case (from 1 = Low to 5 = High)

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Priority R&D Topics

Key R&D Issues	High-Level 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 predictive models for the THM behavior of elastoplastic & plastic geomaterials as affected by temperature and water content changes? Can thermal pressurization lead to long-term damage via fracturing or fault slip?
Engineered Barrier Integrity	What is the long-term stability and retention capability of backfills and seals when exposed to high temperatures? How relevant are interactions between engineered and natural barrier materials, such as metal-bentonite-cement interactions? Can gas pressure increase and gas migration become a concern for barrier integrity? In fractured granite, can bentonite be eroded when in contact with water from flowing fractures?
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 nano-pore materials such as compacted clays and bentonites best be described? What is the effect of high temperature on the diffusion 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 and is the planned construction/emplacement method feasible?

DOE's Activities Related to International URLs

Main Technical Area Addressed	International Experiment	URL	Main R&D Focus	SFWST International Activity and Status, Science Question Addressed
Near-Field Perturbation	HE-E Heater Test	Mont Terri, Switzerland	Bentonite/rock interaction to evaluate sealing and clay barrier performance at elevated temperature, micro-tunnel	THM modeling and interpretation of the heater test data to date and comparison of results with other international teams
Near-Field Perturbation	EBS Experiment	Horonobe, Japan	Studies of the thermo-hydro-mechanical-chemical (THMC) behavior of the EBS under heating conditions	THM modeling and interpretation of the heater test data to date and comparison of results with other international teams
Near-Field Perturbation	HG-A Test	Mont Terri, Switzerland	Evaluation of flow paths through the near-field damage zone and specifically along seals	Application of new discrete fracture damage model for rock strain and fracture damage
Near-Field Perturbation	Heater Experiments at Bure	Bure, France	Upscaling THM simulations from lab experiment to repository scale	Evaluation of experimental and modeling results across scales
Engineered Barrier Integrity	CI Experiment	Mont Terri, Switzerland	Chemical interaction between host rock and engineered barrier materials	Analysis of test samples (clay/cement interface) using small-angle neutron scattering
Engineered Barrier Integrity	BRIE (Bentonite-Rock Interaction experiment)	Äspö HRL, Sweden	Understand the impact of flowing fractures in crystalline rock on bentonite saturation, integrity and erosion	Discrete fracture modeling approach to interpret BRIE data
Engineered Barrier Integrity	FEBEX DP	Grimsel Test Site, Switzerland	Dismantling and sampling of long-term test evaluating the long-term integrity and performance of heated bentonite	Sample analysis and THMC modeling
Engineered Barrier Integrity	HotBENT	Grimsel Test Site, Switzerland	Complex THMC behavior of EBS materials up to 200 degrees C at the canister/bentonite interface.	Design planning and design simulations
Flow and Radionuclide Transport	Bedrichov Tunnel Experiment	Bedrichov, Czech Republic	Interpretation of water inflow patterns and tracer transport behavior in fractured granite	Simulation of transport of multiple environmental tracers to estimate fracture network properties
Flow and Radionuclide Transport	Streaming Potential Test	KURT, Korea	Site characterization techniques (in situ borehole characterization)	Streaming potential testing regarding correlation with groundwater flow in fractured granite
Flow and Radionuclide Transport	Colloid-facilitated RN Migration Test	Grimsel Test Site, Switzerland	Evaluate RN transport of bentonite colloids compared in a shear zone in fractured granite	Interpretation of breakthrough data via semi-analytical and numerical methods
Flow and Radionuclide Transport	Fault Slip Experiment	Mont Terri, Switzerland	Evaluation of pressure increase impacts on reactivation of faults and possibility of faults becoming migration pathways	Fault slip testing at Mont Terri, data analysis and modeling
Flow and Radionuclide Transport	GREET (Groundwater Recovery Experiment)	Mizunami, Japan	Evaluation of early resaturation behavior in crystalline rock looking at flow behavior and chemical-biological interactions upon resaturation	Modeling of near-field fracture flow and chemical interactions between natural and engineered materials
Flow and Radionuclide Transport	DR-A Experiment	Mont Terri, Switzerland	Ion diffusion through compacted clay where electro-chemical charges affect transport behavior	New continuum model development based on mean electrostatic potential
Flow and Radionuclide Transport	LTDE (Long-term Sorption Diffusion Experiment)	Äspö HRL, Sweden	Diffusion behavior in fractured crystalline rock	Application of new modeling capabilities (for discrete fracture network modeling) to LTDE data and comparison with international teams
Flow and Radionuclide Transport	COSC Deep Drilling Project	Borehole based, Sweden	Site characterization techniques (in situ borehole characterization)	Fluid logging methods for identification of flowing fractures
Demonstration of Integrated System Behavior	FE Heater Test	Mont Terri, Switzerland	Full-scale demonstration experiment, one of the largest and longest-duration heater tests. Testing overall performance of geologic disposal in Opalinus Clay.	Design phase predictions for better planning of test design and monitoring system. Model results are being compared between international teams.

DOE's Activities Related to International URLs

Main Technical Area Addressed	International Experiment	URL	Main R&D Focus	SFWST International Activity and Status, Science Question Addressed
Near-Field Perturbation	HE-E Heater Test	Mont Terri, Switzerland	Bentonite/rock interaction to evaluate sealing and clay barrier performance at elevated temperature, micro-tunnel	THM modeling and interpretation of the heater test data to date and comparison of results with other international teams
Near-Field Perturbation	EBS Experiment	Horonobe, Japan	Studies of the thermo-hydro-mechanical-chemical (THMC) behavior of the EBS under heating conditions	THM modeling and interpretation of the heater test data to date and comparison of results with other international teams
Near-Field Perturbation	HG-A Test	Mont Terri, Switzerland	Evaluation of flow paths through the near-field damage zone and specifically along seals	Application of new discrete fracture damage model for rock strain and fracture damage
Near-Field P				ing results
Engineered Ba				interface) ering
Engineered Ba				o interpret
Engineered Ba				eling
Engineered Ba				ations
Flow and Ra Trans				ironmental properties
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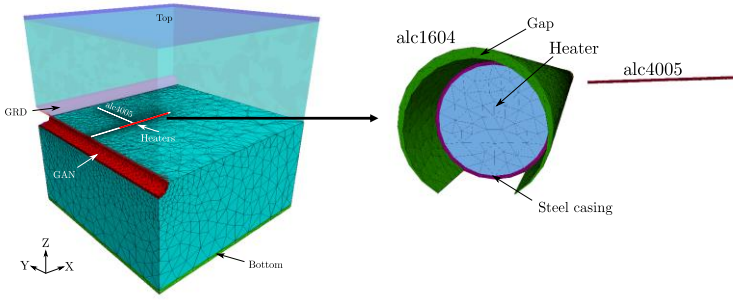
Significant variability in terms of level and duration of SFWST engagement

(from limited short-term participation such as imaging of CI samples to long-term engagement in planning and execution of major field experiments, such as HotBENT and FS-B)

Priority R&D Topics: THM Perturbations

THM Perturbations in Bentonite/Argillite Repositories: A Story Around the Heater Tests at Mont Terri and Bure, Jonny Rutqvist

Full-scale ALC Experiment at Bure



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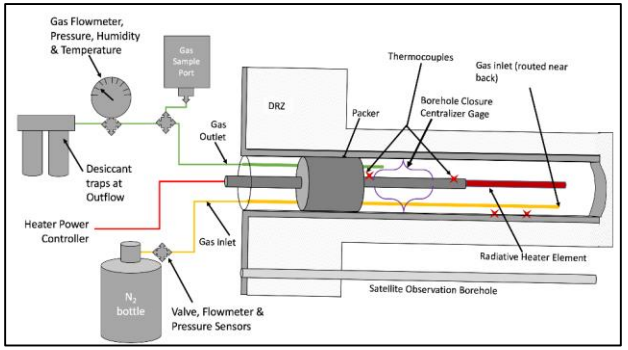
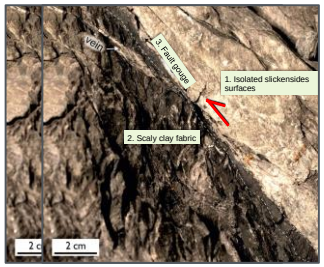
Understanding Heat-Driven Brine Migration in Salt, Kris Kuhlman and Phil Stauffer

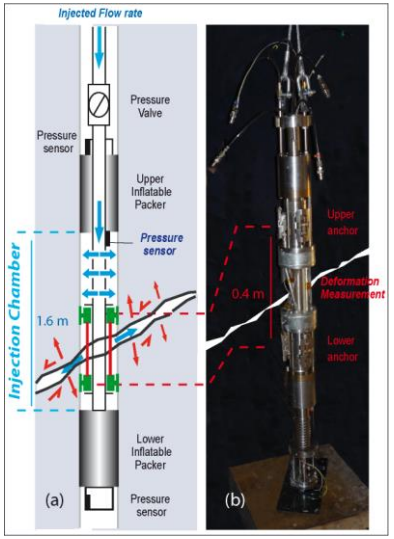


Salt Heater Test at WIPP

Priority R&D Topics: Thermally-Induced Fault Slip

Monitor, Understand and Predict Impact of Fault Slip on Potential for Creation of Permeable Pathways (not presented)





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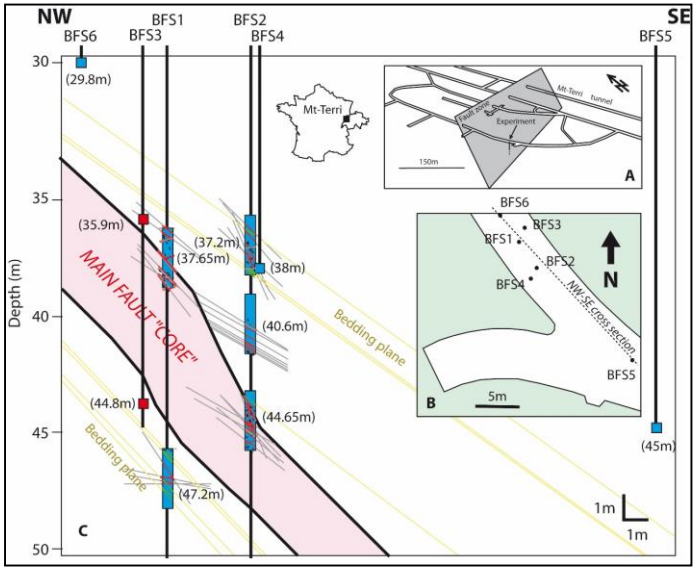
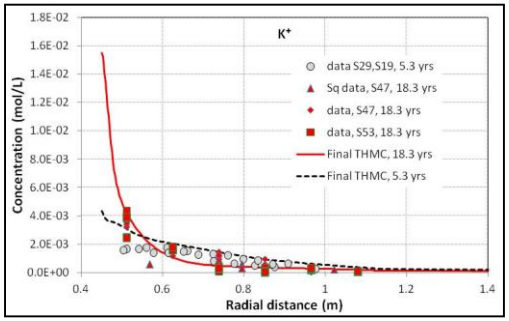


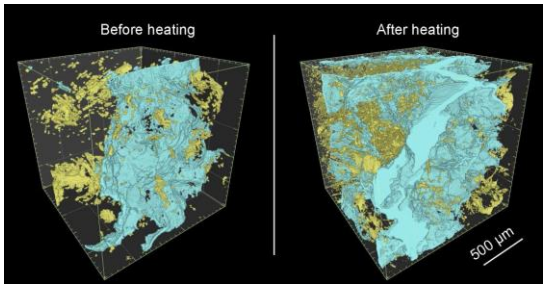
FS Experiment at Mont Terri

Priority R&D Topics: EBS THMC Processes

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



THMC Modeling of Calcium Conc.



X-Ray Micro-CT Analysis of FEBEX Samples

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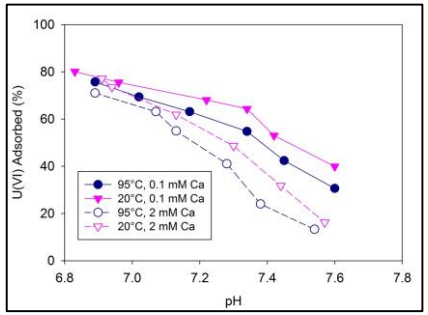


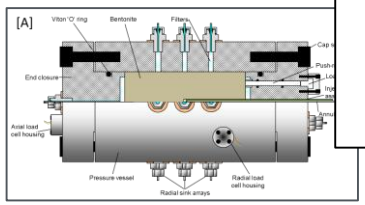
Adsorption Tests on FEBEX Samples

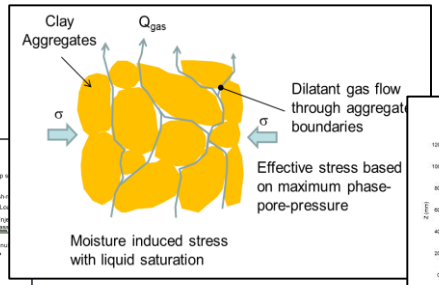
Thermal Implications on Transport in Bentonite: Using FEBEX-DP Samples for Lab Studies and Model Testing, Carlos Jove-Colon

Priority R&D Topics: Gas Transport

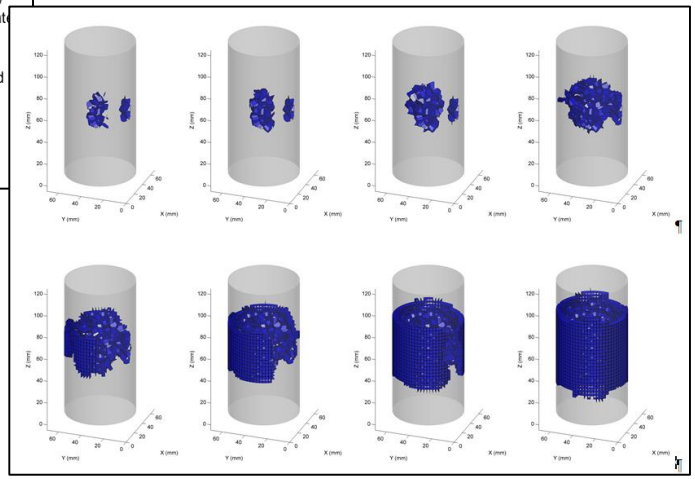
Gas Migration in Clay-Based Materials – International Collaboration Activities as Part of the DECOVALEX Project, Jonny Rutqvist

Only in fact-finding meeting





DFN Approach with Opening of Grain Boundaries for Dilatant Gas Migration



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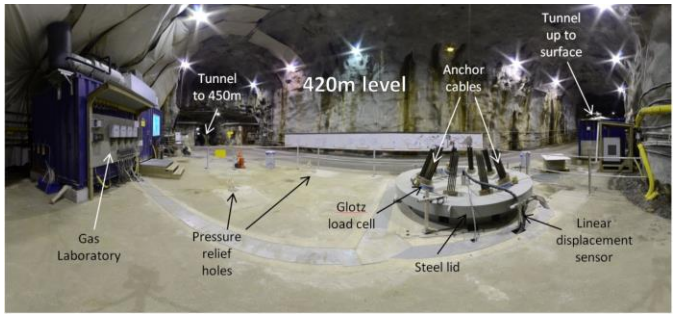
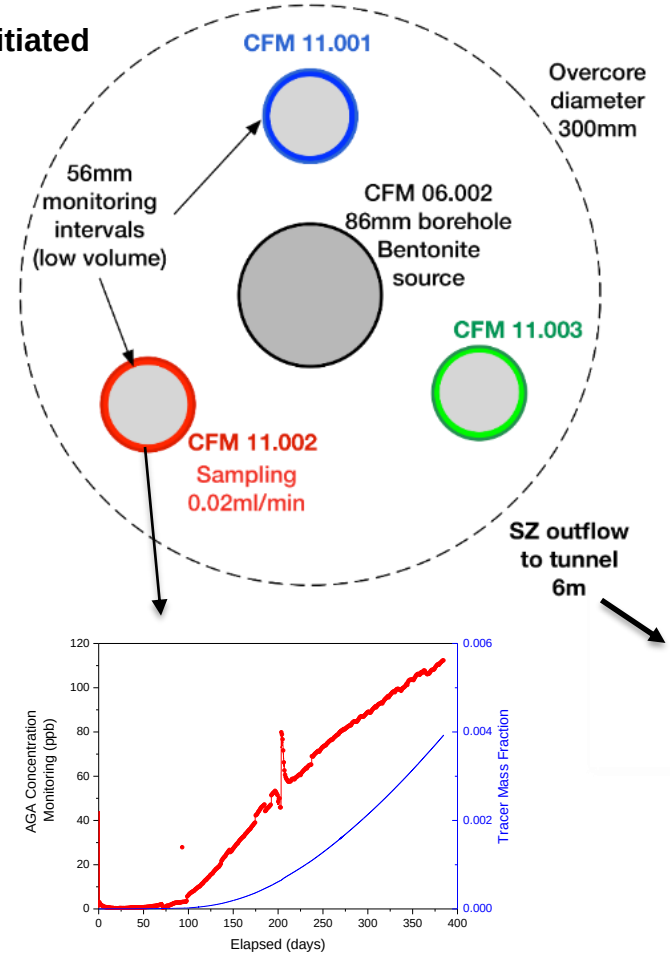
LASGIT in DECOVALEX 2023?



Priority R&D Topics: Colloid Formation & Migration

Colloid-Facilitated Transport – Studies Related to CFM Project at GTS, Hakim Boukhalfa

Overcoring (excavation) initiated in December 2018



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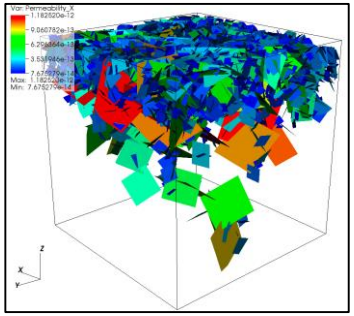
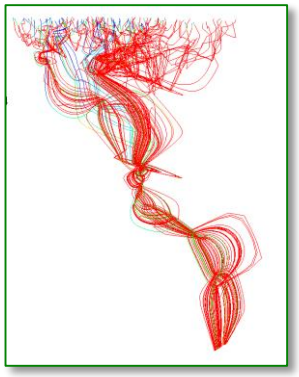
Priority R&D Topics: Discrete Fracture Studies

Flow and Transport in Fractured Granite: Modeling Studies Involving the BRIE, GREET and LTDE Experiments, Hari Viswanathan

LTDE Microfracture Flow and Transport Modeling



Discrete Microfracture Model with Lower Fracture Intensity at Matrix Core



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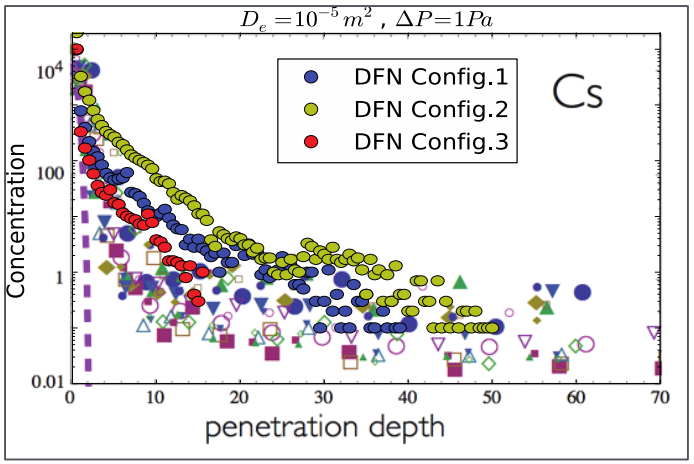
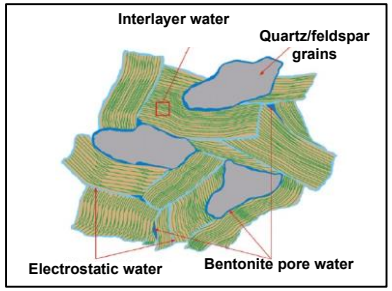
Cesium Concentrations for Different Microfracture Representations

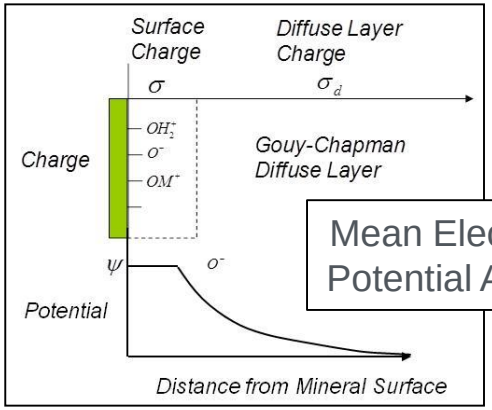


Priority R&D Topics: Bentonite Diffusion

Diffusion in Nanoporous Materials – Modeling Studies in Collaboration with International Scientists (not presented)



Improved Methods for Ion Transport Through Compacted Clay



Mean Electrostatic Potential Approach

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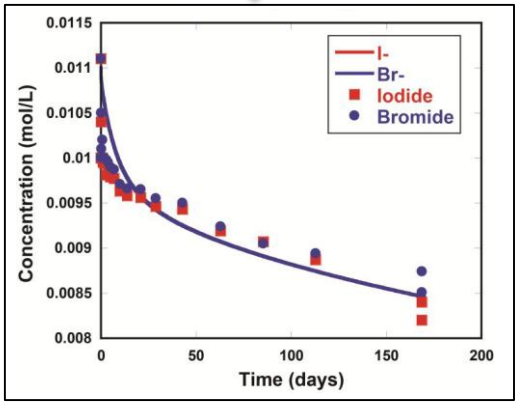
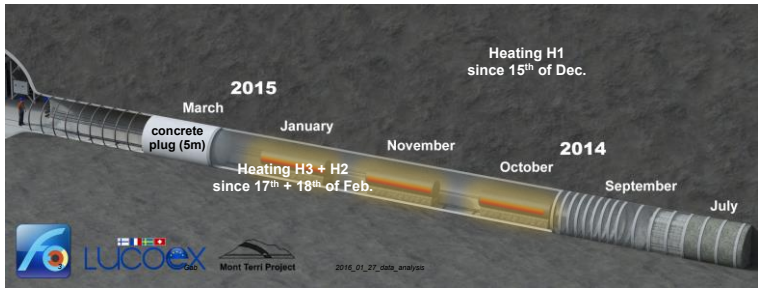
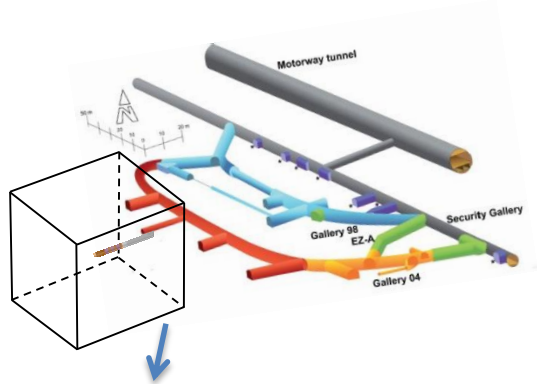


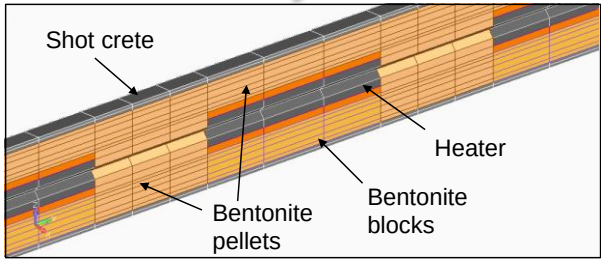
DR-A Test at Mont Terri

Priority R&D Topics: Demonstration Heater Test

The Full-Scale Heater Test at Mont Terri, Jonny Rutqvist







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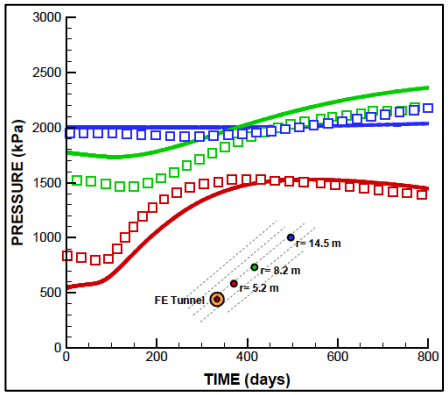
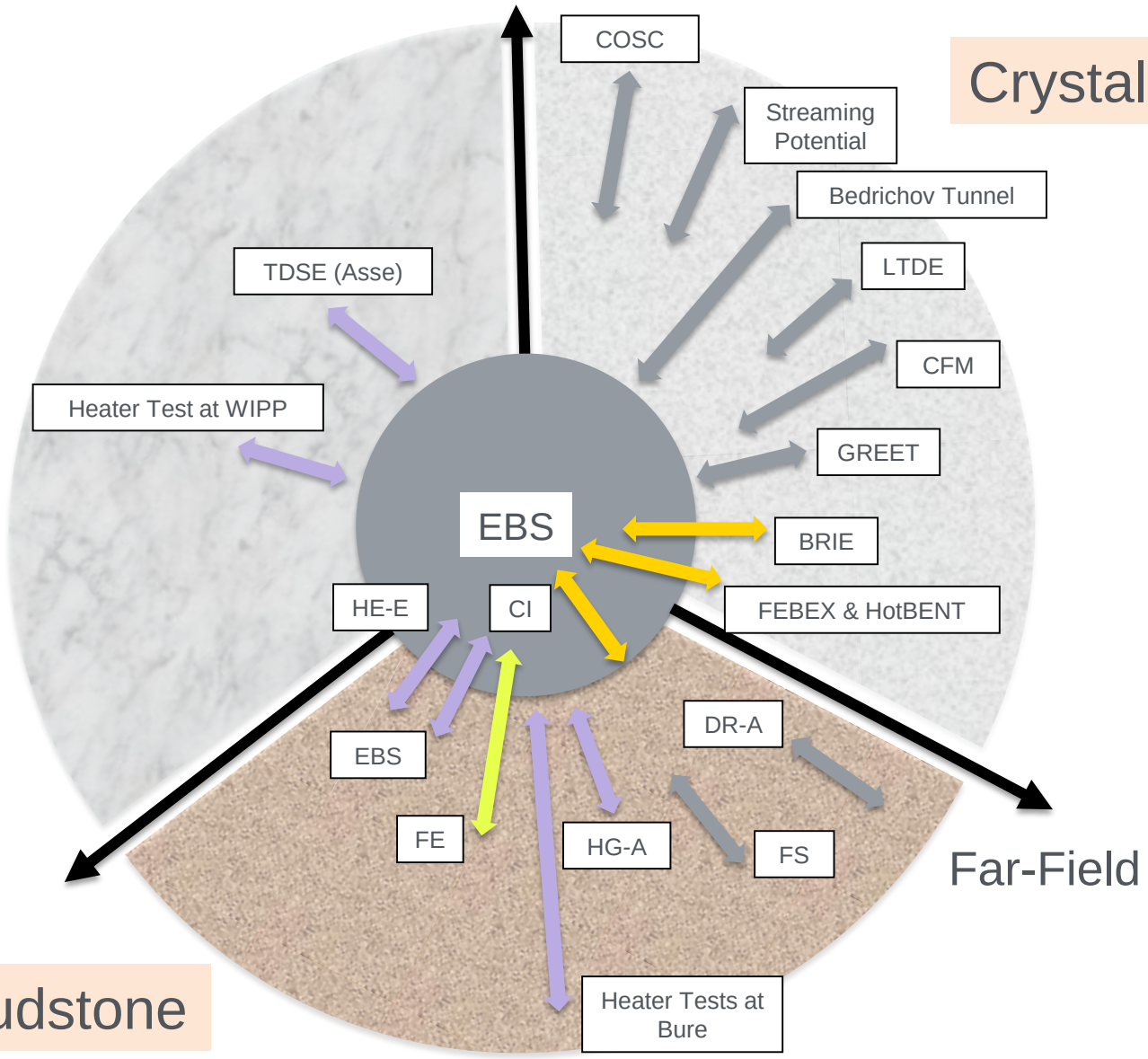


Thermal Pressurization in Host Rock Parallel to Bedding

International URL Portfolio in a Nutshell

Key R&D Issues

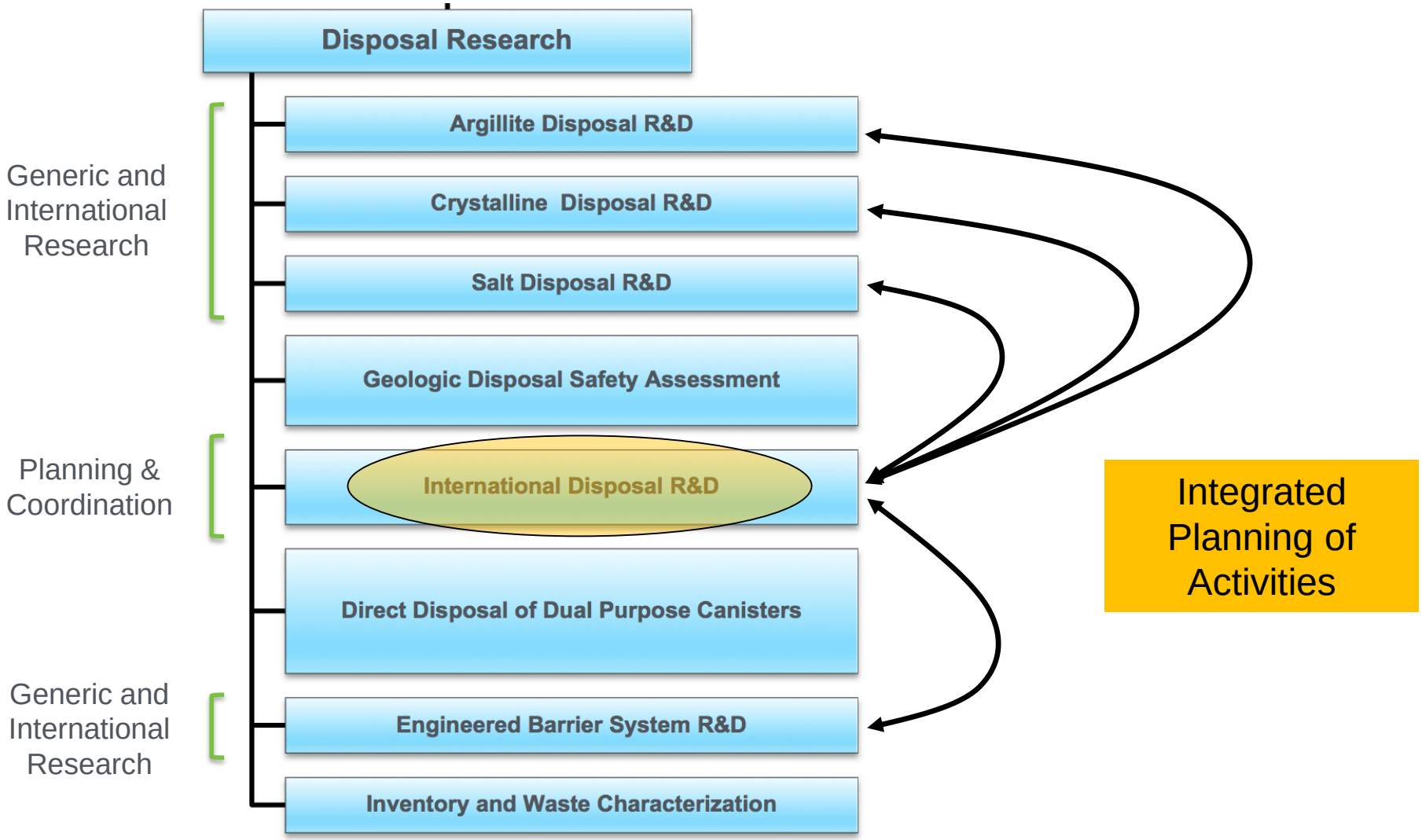
- Near-Field Perturbation
- Engineered Barrier Integrity
- Radionuclide Transport
- Demonstration of Integrated System Behavior



Outline

- Background and Motivation
- International Disposal Activities: Principles and Port**folio**
- Opportunities for International URL Collaborations
- Priorities and Selection Process
- Overview of DOE's International Activities
- **Integration with Generic Research Program**
- Successes and Concerns

FY18 SFWST Disposal Research Campaign



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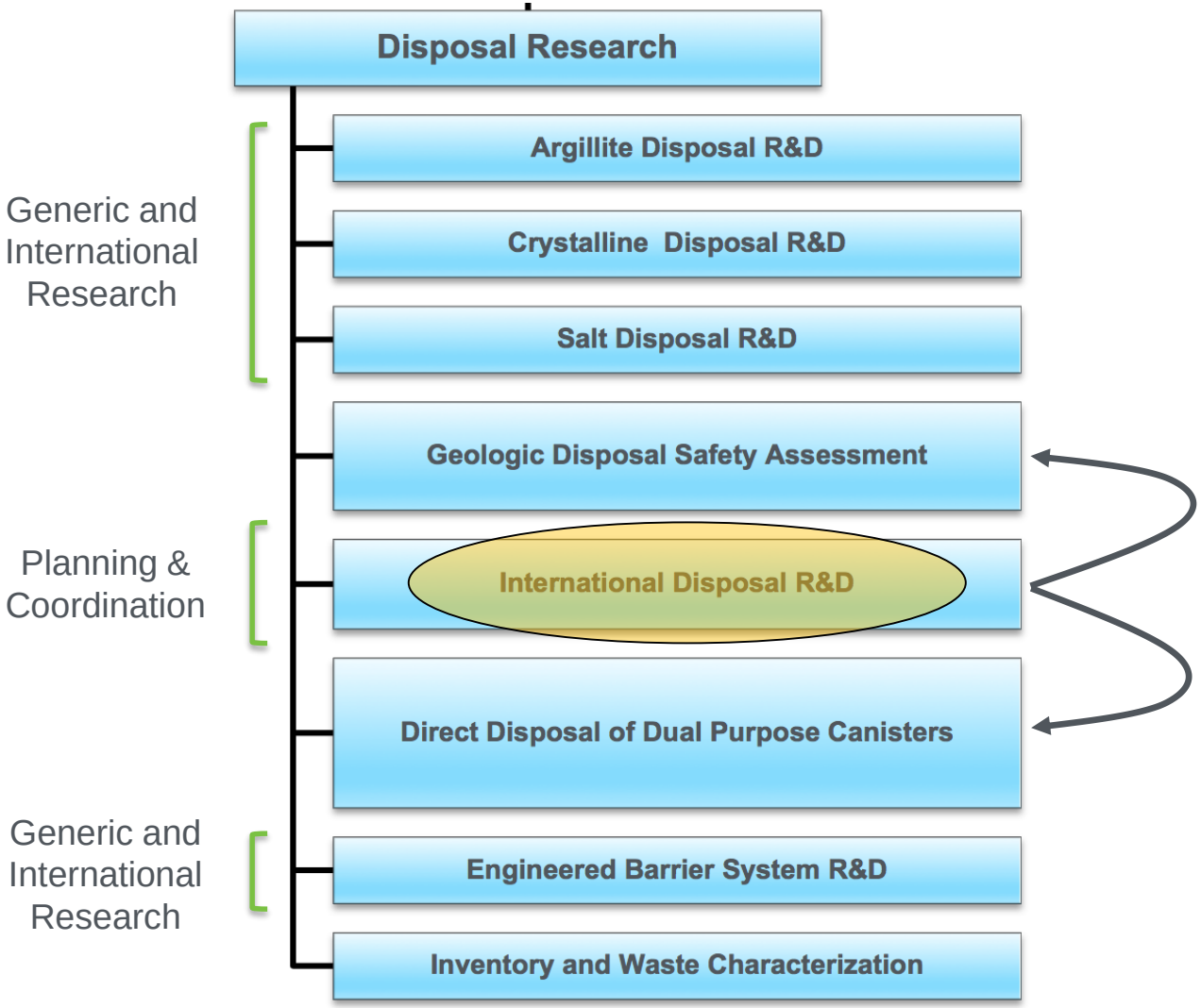
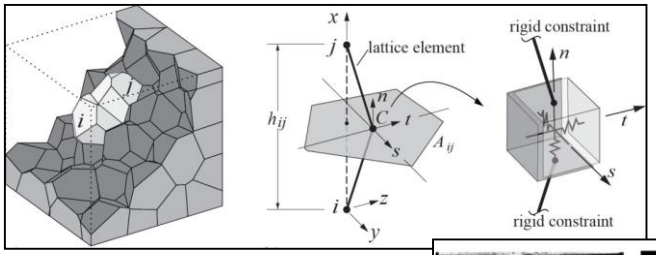


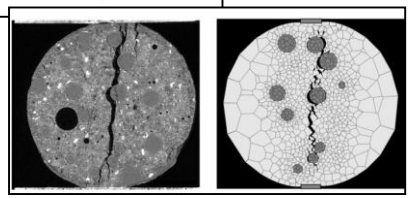
Improved Process Understanding and Tested Simulation Models

Example: EDZ Characteristics in Argillite Host Rock

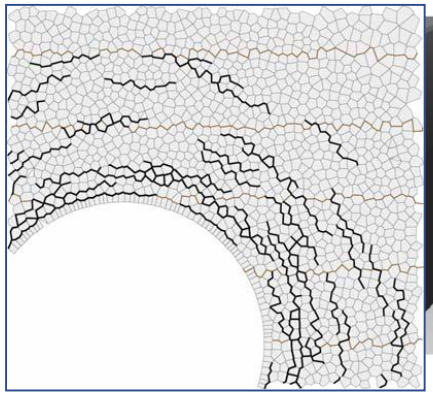
Tool Development

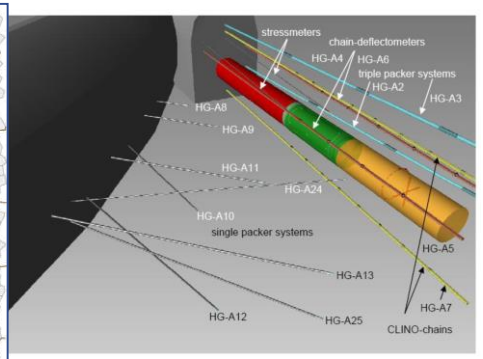


RBSN Dynamic Fracturing Simulator



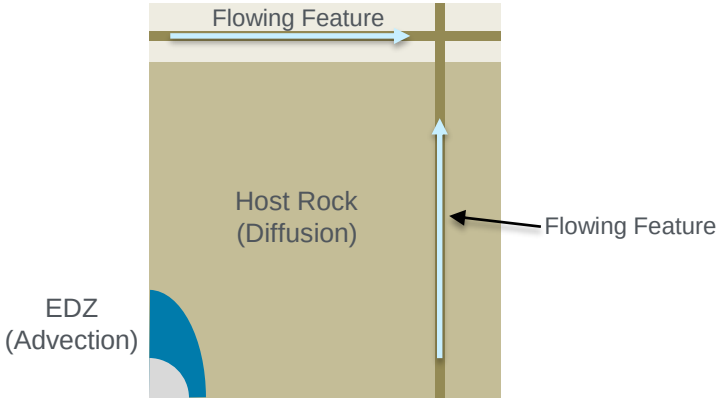
HG-A Modeling





UFD FEP ID No., Title, and Media	Overall Priority
2.2.01.01 - Evolution of EDZ - Clay/Shale	8.00
2.2.08.[illegible] - [illegible] Through the Host Rock - Salt	7.73
2.2.08.02 - Flow Through the Other Geologic Units - Confining units - Aquifers - Salt	7.73
2.2.08.06 - Flow Through EDZ - Salt	7.73
2.2.08.04 - Effects of Repository Excavation on Flow Through the Host Rock - Salt	7.10
2.2.08.07 - Mineralogic Dehydration - Salt	6.49
2.2.01.01 - Evolution of EDZ - Deep Boreholes	6.13
2.2.09.01 - Chemical Characteristics of Groundwater in Host Rock - Deep Boreholes	5.86
2.2.09.02 - Chemical Characteristics of Groundwater in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers - Deep Boreholes	5.86

Performance Assessment



Example: R&D for High Temperature Repositories

Clay and Bentonite Behavior at Temperature > 200 ºC

- **Alteration of physico-chemical properties:**
  - Laboratory testing of bentonite and host rock samples
  - Detailed THMC modeling of individual system components

→ Component behavior at given conditions (P,T,S,…)

- **EBS/NBS System Behavior:**
  - Laboratory and/or in-situ testing of disposal system components and interaction at high temperature
  - Validation of predictive process models for system behavior
  - 2D and 3D prediction of EBS and host rock perturbations
  - Component optimization studies (e.g., alternative backfills)

→ System perturbation and evolution

- **Reliable PA Models for DPC Disposal:**
  - Evaluate methods for including high temperature effects in PA models (e.g., abstractions)
  - Determine scenarios and parameters with significant influence on high-temperature repository performance
  - Conduct PA analysis for different thermal designs

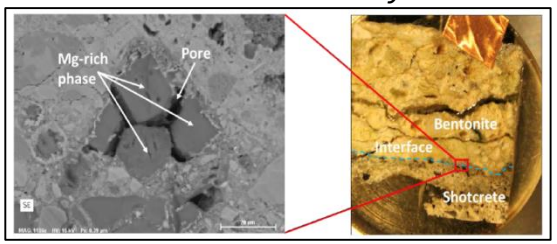
→ Performance assessment

From Micro-Structure to Field Tests to PA

Clay and Bentonite Behavior at Temperature > 200 ºC

- **Alteration of physico-chemical properties:**
  - Laboratory testing of bentonite and host rock samples
  - Detailed THMC modeling of individual system components

Micro-structural analysis



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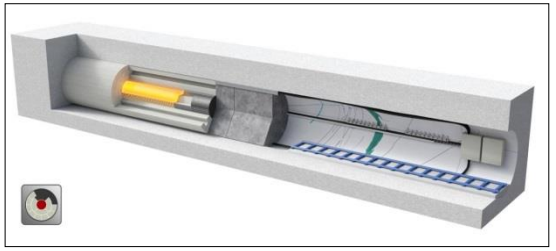
Field Experiments



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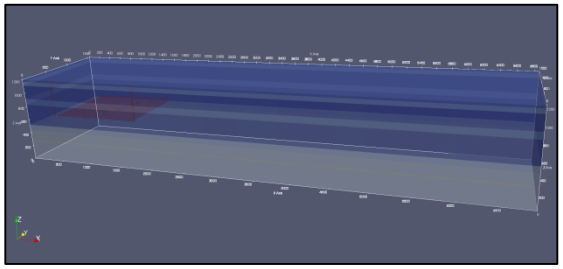
Generic PA Modeling



Outline

- Background and Motivation
- International Disposal Activities: Principles and Port**folio**
- Opportunities for International URL Collaborations
- Priorities and Selection Process
- Overview of DOE's International Activities
- Integration with Generic Research Program
- **Successes and Concerns**

International Collaboration: Accomplishments

- Active collaboration with international programs, initiatives, or projects is now a central element of DOE's disposal research program
- International disposal 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 tools, advanced monitoring methods, R&D priorities elsewhere
- Activities are balanced in terms of host rock, repository design and R&D issues
- HotBENT is first potential experiment that DOE is actively planning with partners; other activities have been mostly "participatory"

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
- Maintaining DOE's international leadership regarding the necessary expertise and tools to assess various disposal environments in the near-term and the long-term
- 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

Constraints for International Activities

- Our priorities and timing may not always align with international efforts and timing
- At least initially, we did not have a seat at the planning table for new international URL activities
- Disposal funding is relatively modest, spread across host rock options, and supports other (generic) R&D efforts in addition to international URL activities
- Disposal funding is uncertain and varies from year to year; this makes planning of long-term activities (like field experiments) difficult

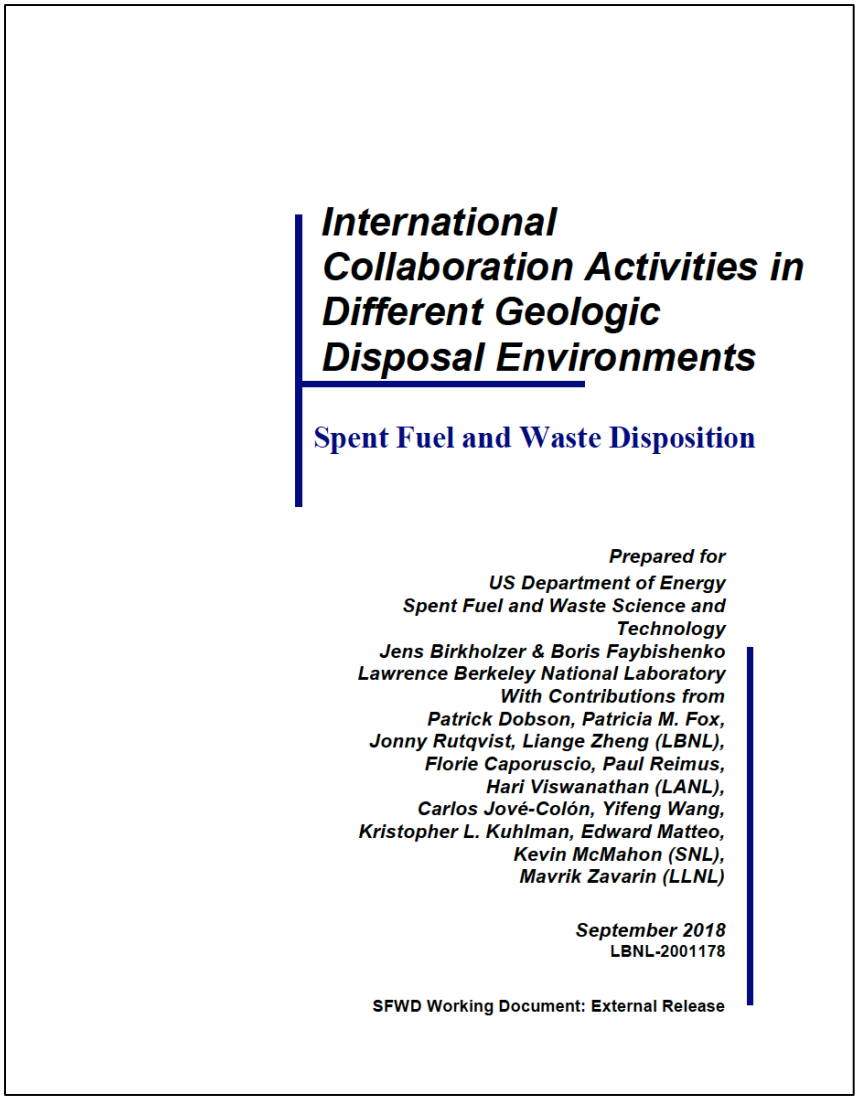
From Opportunistic Participation to Active Planning

- During the first few years of our international program, we selected to participate in R&D efforts that had been planned years earlier
- Since then, we moved more and more to active planning of new opportunities together with the international community, achieving more integration and exploring cross-cutting synergies:
- Examples:
  - Joint planning of HotBENT Project with NAGRA and other partners
  - Developing salt heater test at WIPP as an international modeling task in DECOVALEX
  - Providing input to planning of FEBEX-DP Project
  - Chairing the international DECOVALEX Project
  - Further integrating our modeling and lab testing activities with international URL efforts
  - Developing the new fault slip experiment (FS-B) at Mont Terri as a cross-cutting research project relevant to nuclear waste disposal and other subsurface engineering activities

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
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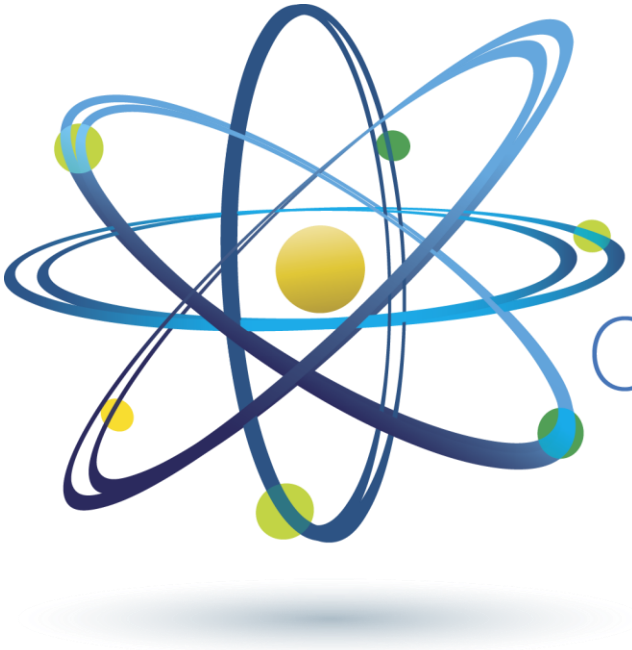
SFWD Working Document: External Release

Questions?



Clean. **Reliable. Nuclear.**