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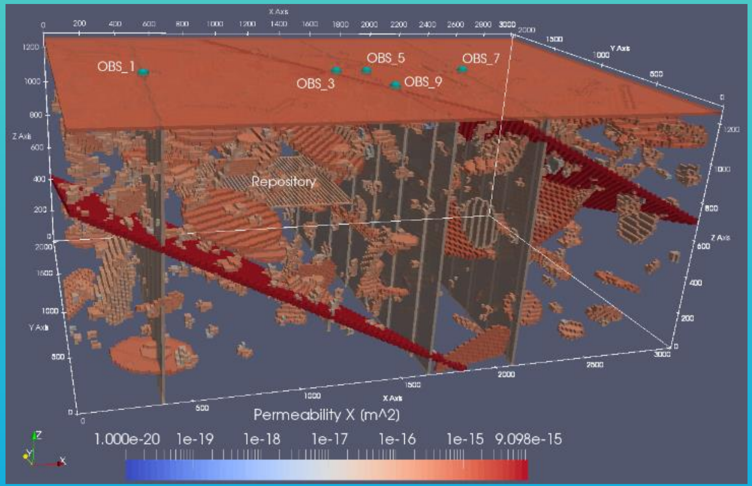

Crystalline Host Rock: Disposal Concepts and Research & Development Activities

US Nuclear Waste Technical Review Board
Fall meeting
December 2-3, 2020
Online virtual meeting

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Outline

- Host rock characteristics
- Disposal concepts
- Technical gaps and priorities
- Process model development and integration
- Future work

Characteristics of host rocks

Attributes	Salt	Shale	Granite (crystalline rock)	Deep boreholes
Thermal conductivity	High	Low	Medium	Medium
Permeability	Low	Low	Low (unfractured) to permeable (fractured)	Low
Mechanical strength	Low	Low	High	High
Deformation behavior	Visco-plastic	Plastic to brittle	Brittle	Brittle
Stability of cavity	Low	Low	High	Medium to high
Dissolution behavior	High	Very low	Very low	Very low
Chemical condition	Reducing; high ionic strength; relatively simple chemical system	Reducing; complex chemical system	Reducing; relatively simple chemical system	Reducing; relatively simple chemical system; moderate to high ionic strength
Radionuclide retention	Very low	High	Medium to high	Medium to high
Thermal limit	Relatively high	Relatively low (?)	No limit	No limit
Available geology	Wide	Wide	Wide	Wide
Geologic stability	High	High	High	High
Engineered barrier system	Minimal; waste package damage by room closure	Minimal; waste package damage by room closure	Needed. Able to fully take credit for the engineered barrier system	Borehole seal needed
Human intrusion/resource exploration	Relatively high	Relatively high	Low	Low
Retrievability of waste	Feasible	Feasible	Easily retrievable	Difficult

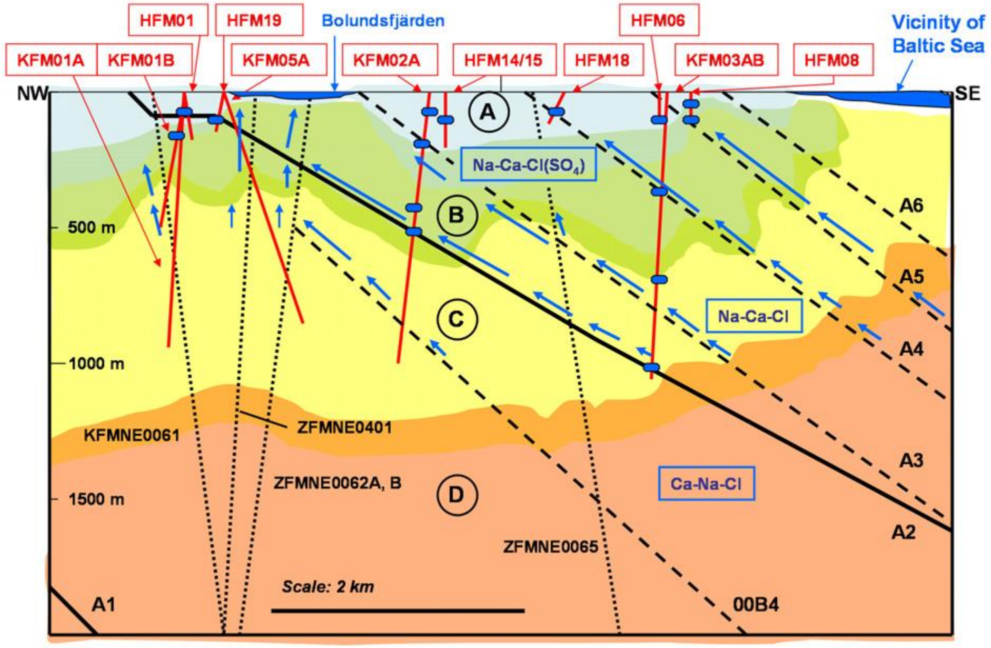
World-nuclear-news.org

- High mechanical strength and thermal limit
    - Suitable for disposal of large and hot waste canisters
- Fractured nature
    - Engineered barrier system equally important as the nature barrier

Geochemical characteristics of groundwater

Water type A: Dilute 0.5-2 g/L TDS; $\delta^{18}O$ = -11.7 to -9.5 ‰ SMOW; $Na\text{-}HCO_3$; mainly Meteoric
Main reactions: Weathering, ion exchange, dissolution of calcite, redox reactions, microbial reactions
Redox conditions: Oxidising - reducing

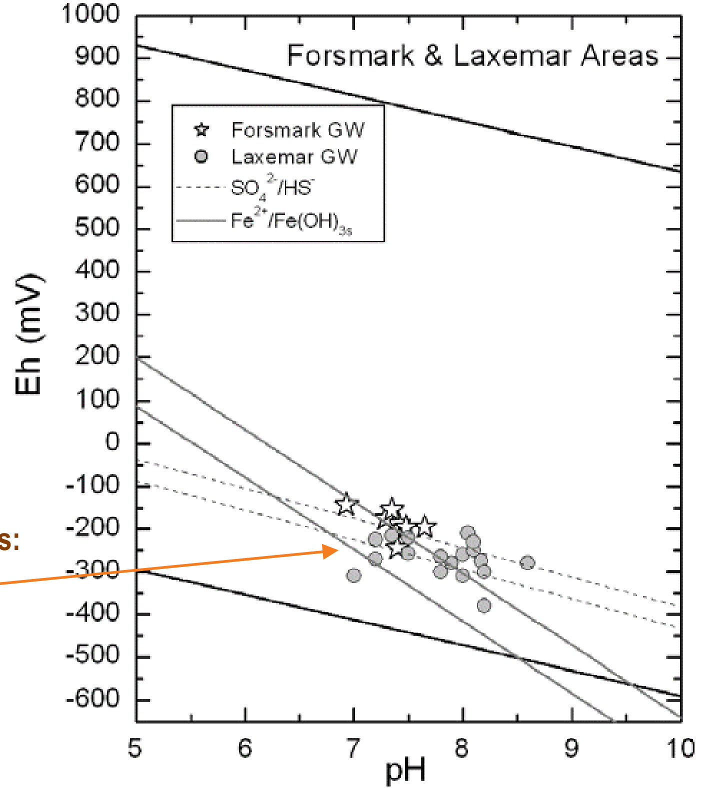
Water type B: Brackish 5-10 g/L TDS; $\delta^{18}O$ = -11.5 to -8.5 ‰ SMOW; $Na(Ca,Mg)\text{-}Cl(SO_4)$ to $Ca\text{-}Na(Mg)\text{-}Cl(SO_4)$; Marine (Strong Littorina Sea component) ±Meteoric; Glacial ± Deeper Saline component.
Main reactions: Ion exchange, pptn. of calcite, redox and microbial reactions
Redox conditions: Reducing



Water type C: Saline 10-15 g/L TDS; $\delta^{18}O$ = ~-11.6 to -13.6‰ SMOW (only 3 samples); Na-Ca-Cl to Ca-Na-Cl; Glacial - Deeper Saline mixture
Main reactions: Ion exchange, microbial reactions
Redox conditions: Reducing

Water type D: Strongly saline > 20 g/L TDS; Ca-Na-Cl; Deep saline origin (Field observations)
Main reactions: Long term water rock interactions
Redox conditions: Reducing

https://www.wsj.com/articles/a-100-000-year-tomb-for-finlands-nuclear-waste-1485253831



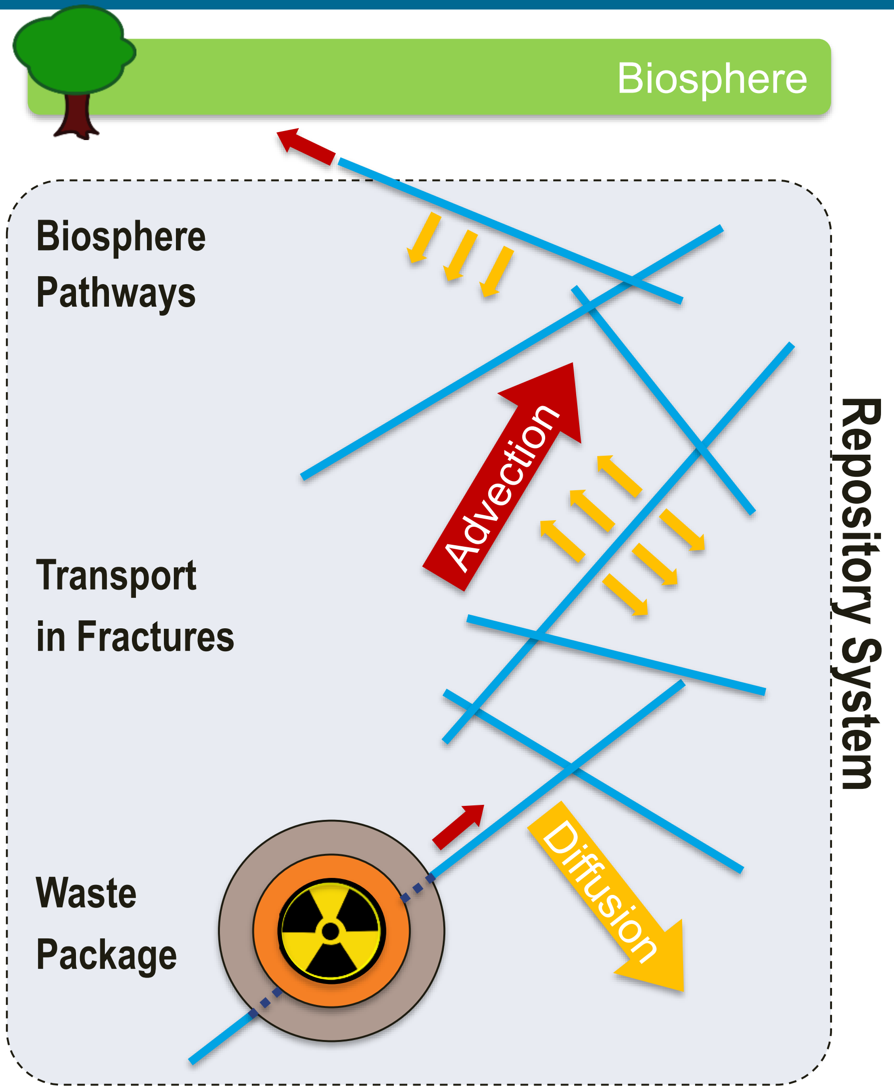
Reducing conditions: Iron and sulfate reduction

Laaksoharju et al. (2008)

Post-closure safety strategy

- Containment
  - Waste package is isolated by depth, and protected by buffer/backfill and reducing conditions
  - Canister integrity is maintained for a significant portion of the regulatory time period.
- Limited Release
  - Slow fuel dissolution in anoxic repository
  - Low permeability of host rock (especially in rock matrix)
  - Retardation along fracture paths due to
    - Fracture-matrix diffusion
    - Adsorption in fractures and matrix

R&D objective: Advance understanding of long-term disposal of used fuel in crystalline rocks (granitic or metamorphic rocks) and develop experimental and computational capabilities to evaluate various disposal concepts in such media.



Disposal concept

- Glass High-Level Waste
  - 5 logs per waste package
  - In-drift axial emplacement
  - Bentonite buffer
- Spent nuclear fuel (SNF) in 4-PWR waste package
  - Vertical deposition holes in floor of drift (KBS-3V disposal concept)
  - Compacted blocks of bentonite buffer
  - To be implemented for DECOVALEX-2023 performance assessment comparison task
- SNF in 12-PWR waste package
  - In-drift axial emplacement
  - Bentonite buffer with or without additives

4-PWR

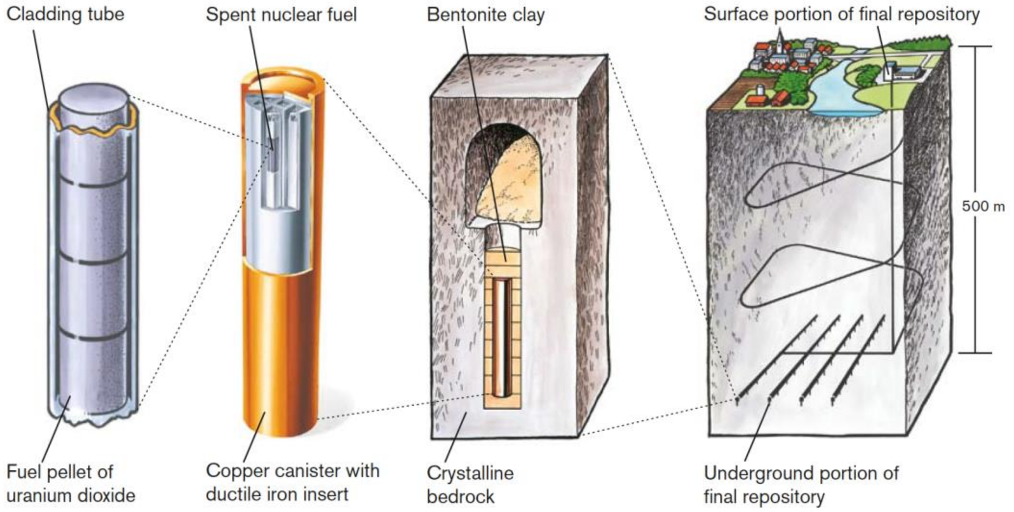
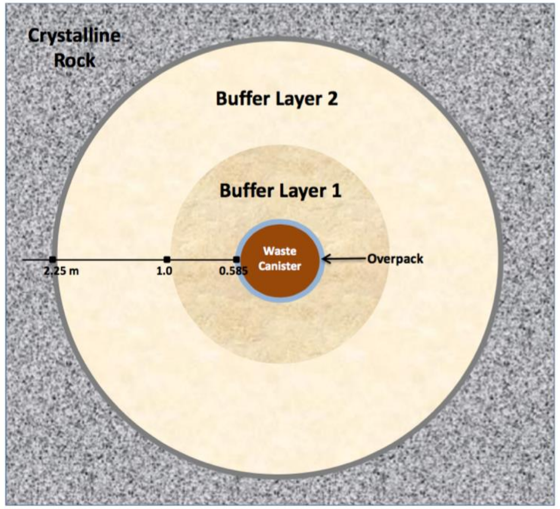


Figure S-1. The KBS-3 concept for disposal of spent nuclear fuel.

12-PWR



Schematic cross-section of a double-layer buffer in a disposal drift of a crystalline repository (Wang et al. 2014).

2019 Roadmap Update: High-Priority R&D Activities

High Priority R&D Activities	
A-08	Evaluation of ordinary Portland cement (OPC)
C-15*	Design improved backfill and seal materials
C-16*	Development of new waste package concepts and models for evaluation of waste package performance for long-term disposal
D-01	Probabilistic post-closure DPC criticality consequence analyses Task 1 - Scoping Phase Task 2 - Preliminary Analysis Phase Task 3 - Development Phase
D-03	DPC filler and neutron absorber degradation testing and analysis
D-04	Coupled multi-physics simulation of DPC postclosure (chemical, mechanical, thermal-hydraulic) including processes external to the waste package.
D-05	Source term development with and without criticality
E-09	Cement plug/liner degradation
E-11	EBS High Temp experimental data collection- To evaluate high temperature mineralogy /geochemistry changes.
E-14*	In-Package Chemistry
E-17*	Buffer Material by Design

High Priority R&D Activities	
I-04	Experiment of bentonite EBS under high temperature, HotBENT
I-06	Mont Terri FS Fault Slip Experiment
I-08	DECOVALEX-2019 Task A: Advective gas flow in bentonite
I-12	TH and THM Processes in Salt: German-US Collaborations (WEIMOS)
I-13	TH and THM Processes in Salt: German-US Collaborations (BENVASIM)
I-16*	New Activity: DECOVALEX Task on Salt Heater Test and Coupled Modeling
I-18*	New Activity: Other potential DECOVALEX Tasks of Interest: Large-Scale Gas Transport
P-12	WP Degradation Model Framework
S-01	Salt Coupled THM processes, hydraulic properties from mechanical behavior (geomechanical)
S-03	Coupled THC advection and diffusion processes in Salt, multi-phase flow processes and material properties in Salt
S-04	Coupled THC processes in Salt, Dissolution and precipitation of salt near heat sources (heat pipes)
S-05	Borehole-based Field Testing in Salt

Activity Designator Legend:

A – Argillite

C – Crystalline

S – Salt

D – Dual Purpose Canisters

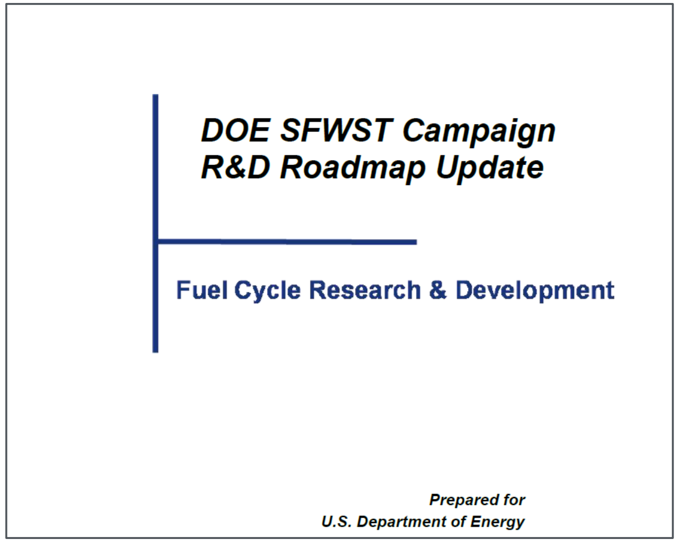
E – Engineered Barrier System

I – International

O – Other

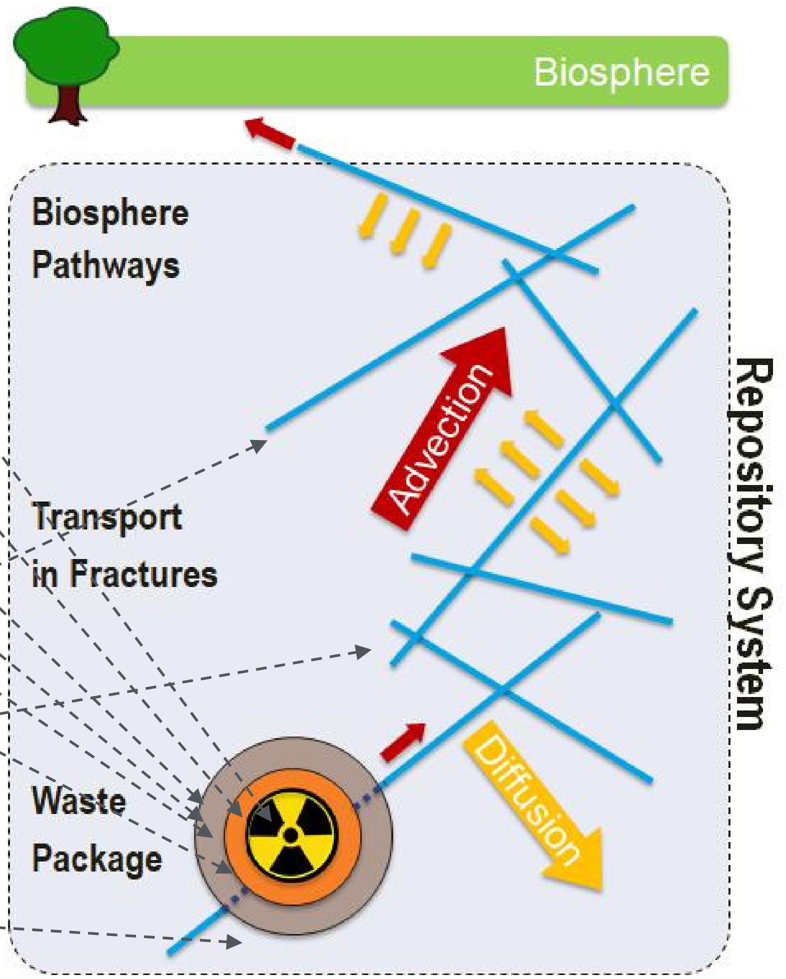
P – Performance Assessment

* – indicates Gap Activity



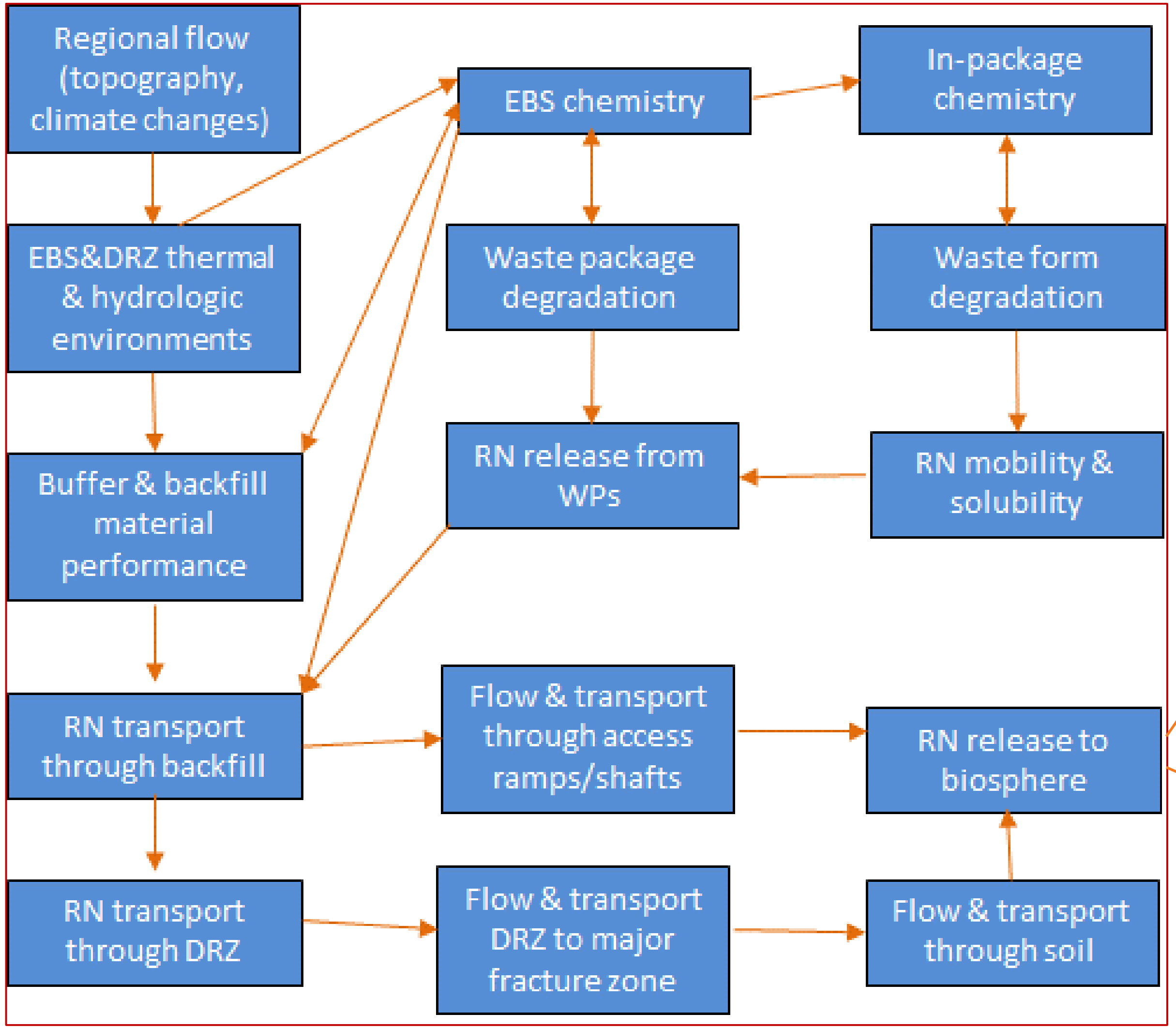
Current R&D activities and priorities mapped to R&D roadmap

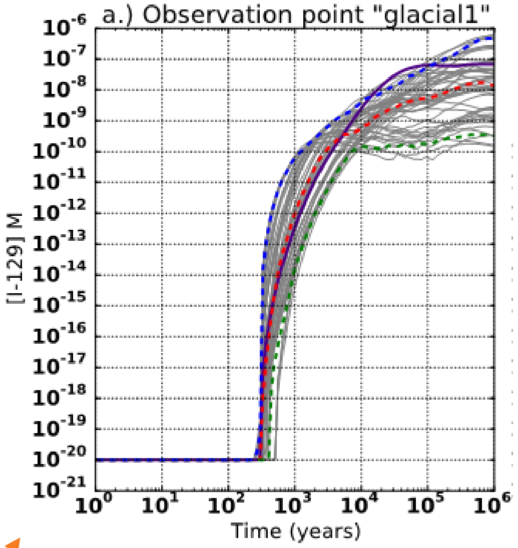
- Fuel matrix degradation model (FMDM). (ANL). (H: D-05, E-14)
- Radionuclide interactions with corrosion products (LLNL). (H: D-05, E-14)
- Bentonite erosion and colloid generation and transport (LANL). (H: C-15, M-H: E-20)
- Fluid flow in low-permeability media (SNL, LBNL). (H: I-08, M-H: C-11)
- Multiple scale core experiments on radionuclide-bentonite interactions (SNL, LBNL). (H: C-15, M: C-08)
- New-generation buffer materials/waste package materials; understanding thermal limits of buffer materials (SNL). (H: C-15, C-16, E-11, E-17)
- Discrete fracture network (DFN) model; especially a reduced order model for GDSA (LANL). (M-H: C-01, P-02)
- Workflow for field data synthesis and flow modeling in fractured media (SNL). (M-H: C-01, M-H: C-13, P-02)
- Geophysical and well-testing techniques for site characterization (LBNL). (M-H: E-03)

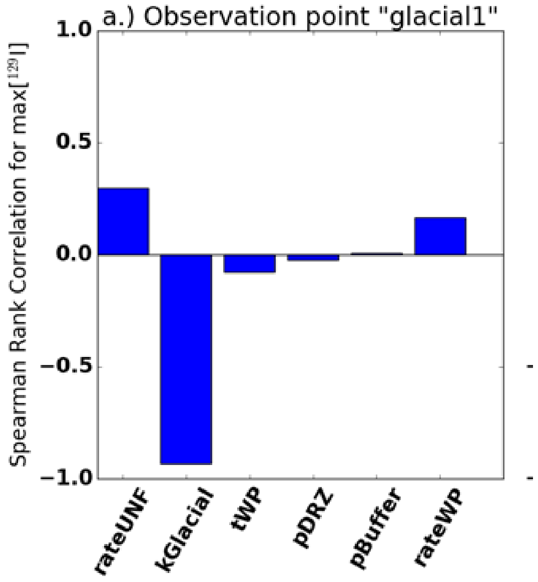


Current focuses: (1) better characterization and understanding of fractured media and fluid flow and transport in such media, and (2) designing effective engineered barrier systems (EBS) for waste isolation.

Process model development and integration

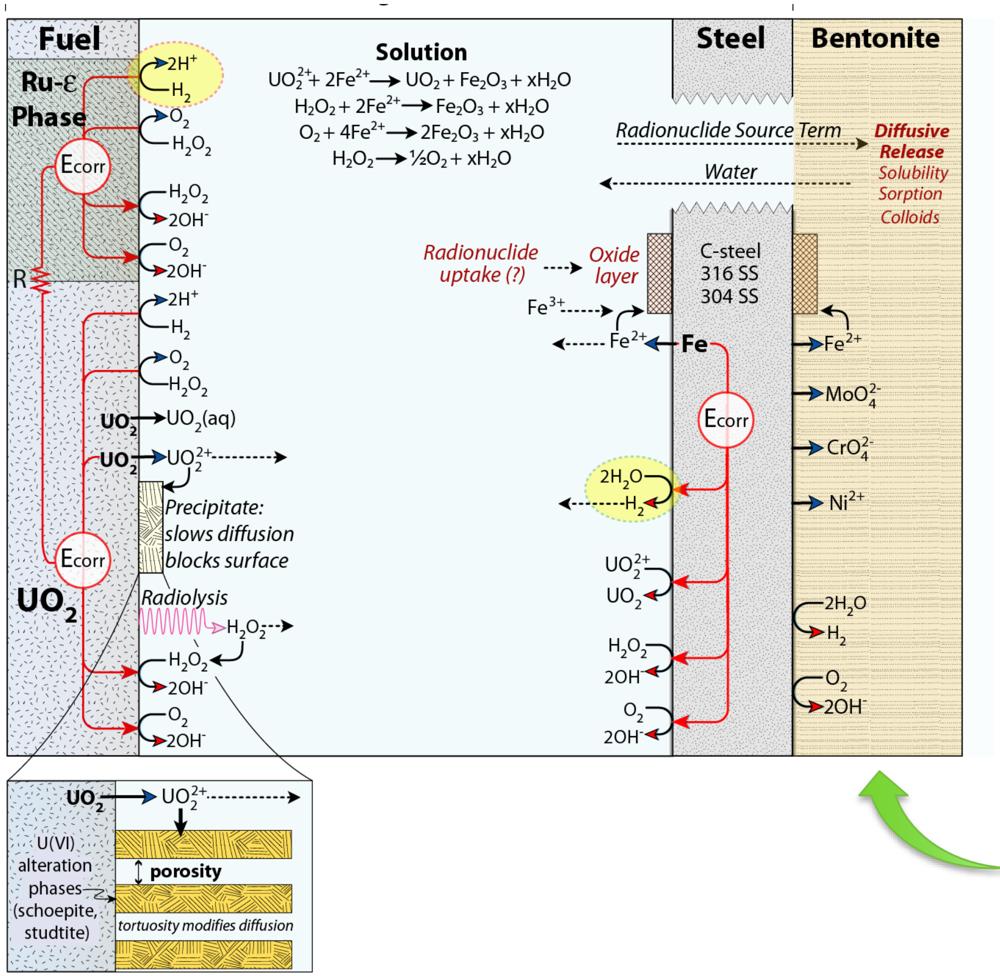




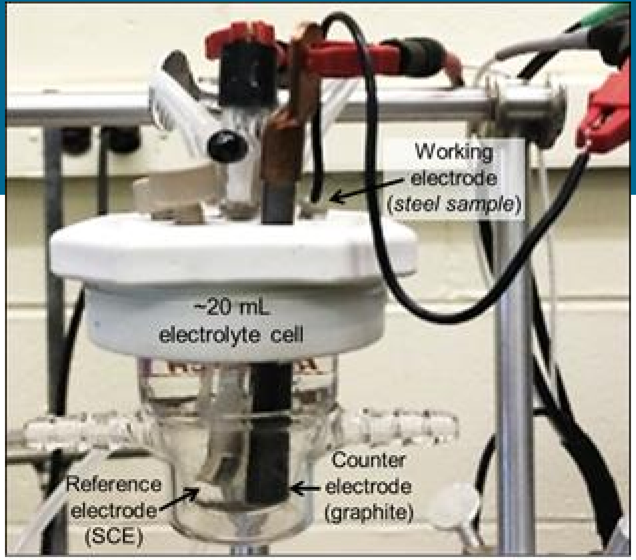


DRZ = Disturbed rock zone
RN = Radionuclide
THMC – Thermal-hydrologic-mechanical-chemical
WP = Waste package

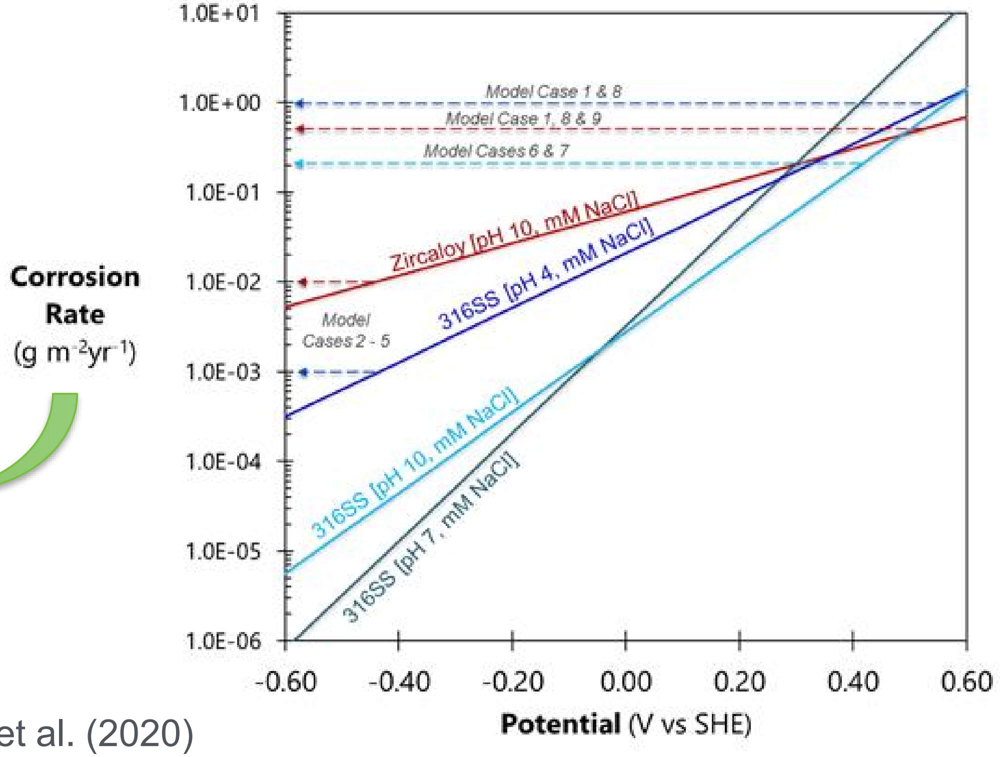
Waste form and engineered barrier



Fuel matrix degradation model accounts for effects of radiolysis and waste package degradation (e.g. H_2 generation).

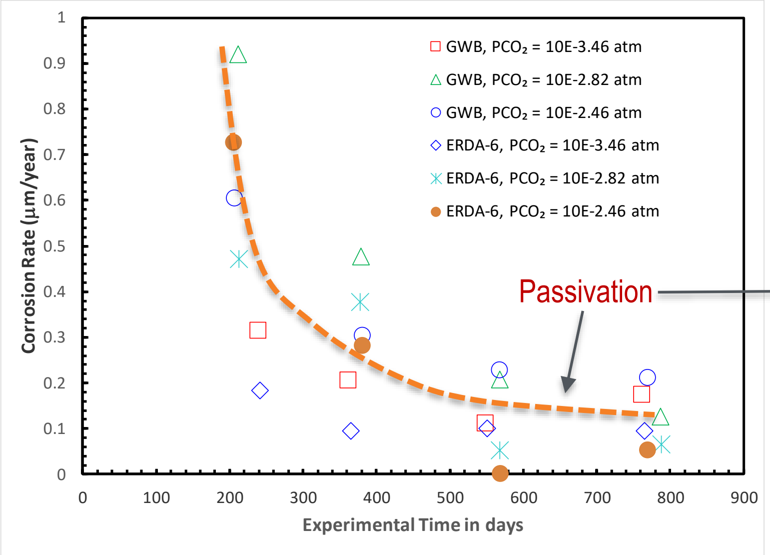


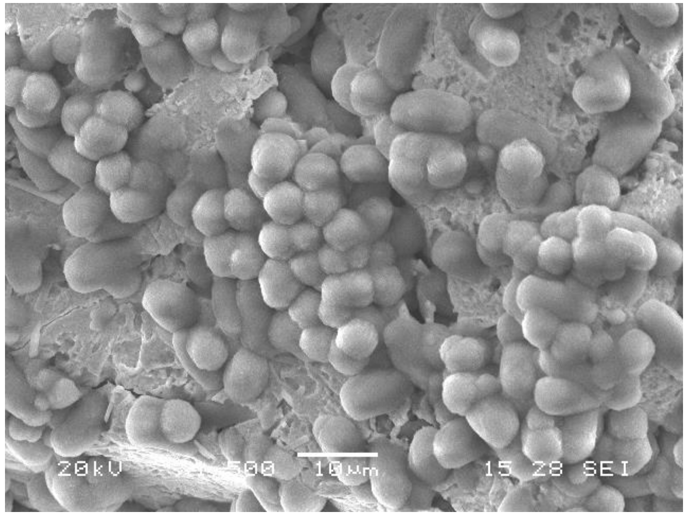
Three-electrode electrochemical cell

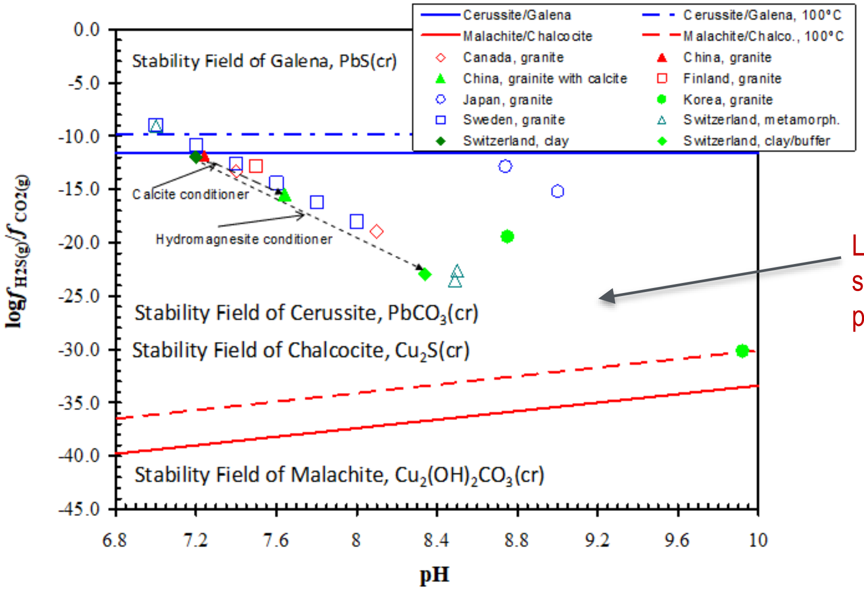


Wang et al. (2020)

Lead/lead-alloy as a corrosion-resistant outer layer packaging material



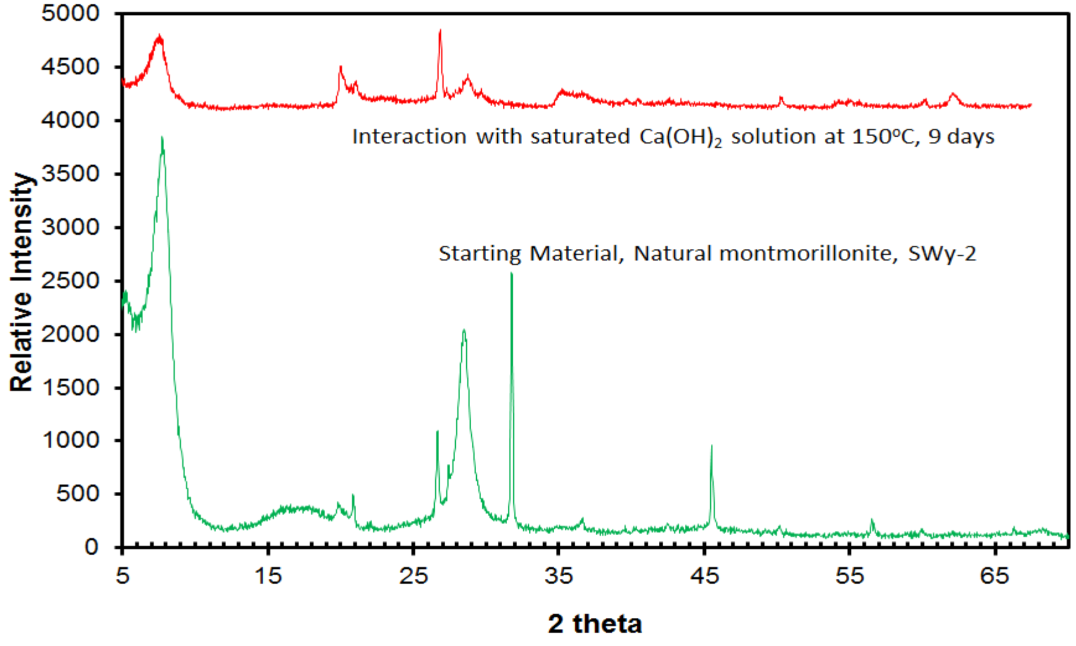




Lead/lead alloy is much more stable than copper in the presence of H2S.

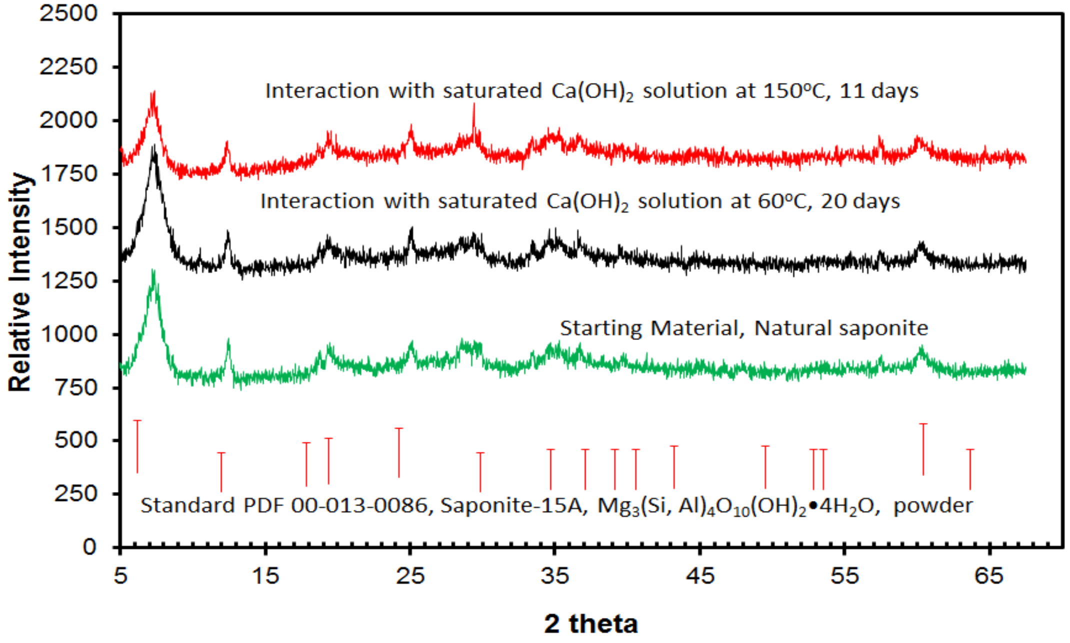
- Requirements
  - Longevity: >1000 years ✓
  - Avoid any detrimental impacts on other EBS materials. ✓
  - Retrievability ✓
  - Radiation shielding ✓
  - Reasonable structural strength (tensile stentgh 70 MPa for alloy) ✓
  - Availability ✓
- Lead
  - Good resistance in sulfide environments
  - \$0.87/lb
  - RCRA: Already present as fission product

Development of next-generation buffer materials for harsh environments



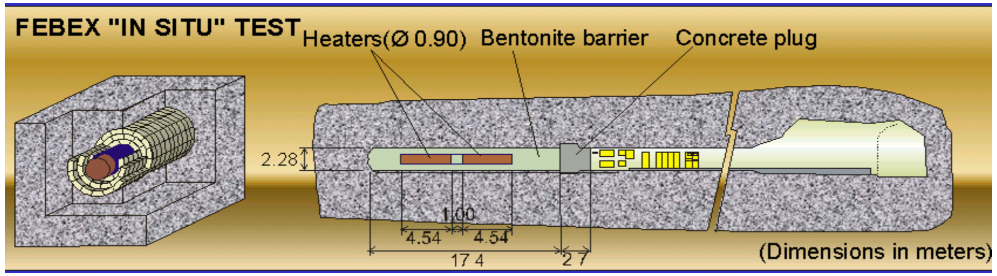
Leverage materials science and engineering for engineered material development.

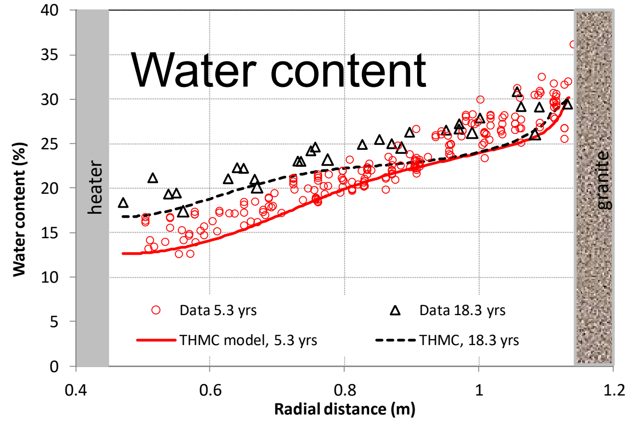
Saponite is more stable than Na-montmorillonite in alkaline and high temperature environments.



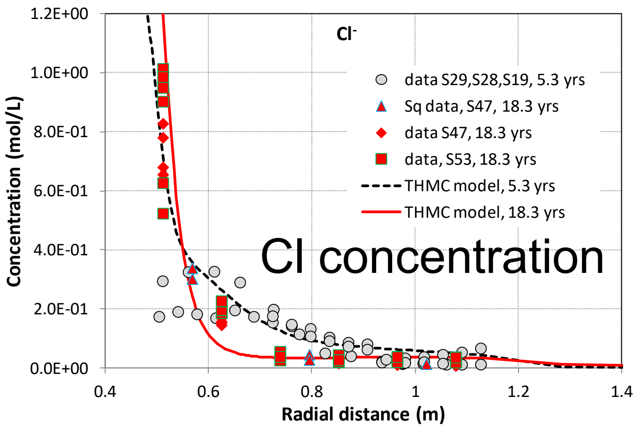
Coupled thermal-hydrological-mechanical-chemical (THMC) model buffer materials

- The full-scale *in situ* test is located in Grimsel, Switzerland, heating started in 1997 at 100 °C, as part of FEBEX (Full-scale Engineered Barrier Experiment).
- Extensive laboratory tests were carried out to characterize THMC properties of bentonite, concrete, steel liner and granite after two dismantling events (2002 and 2015).
- Coupled THMC models were developed to understand the processes in the bentonite and granite.



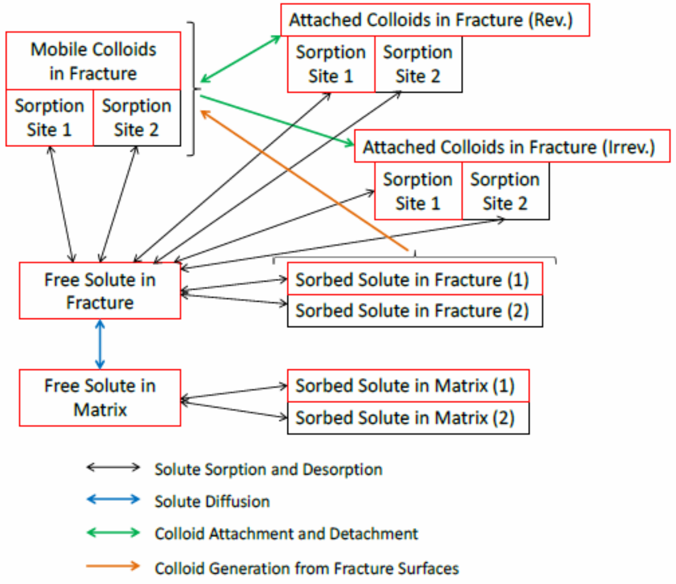


In 2015, Dismantling of Heater #2



Colloid-facilitated transport model and buffer material erosion

Multiple site sorption model



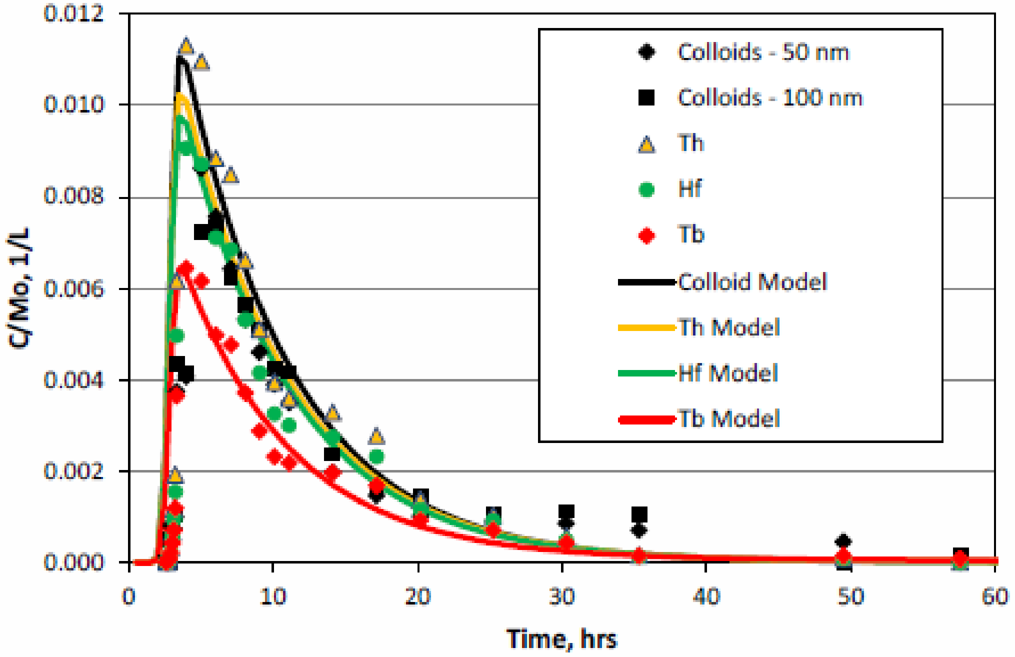
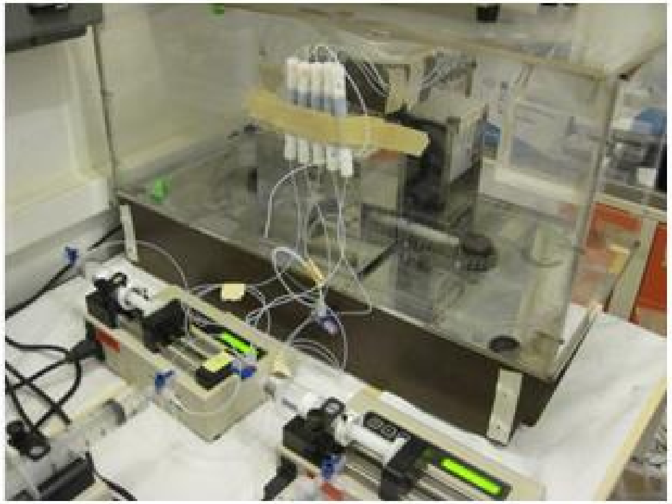


Figure 2-11. Model matches to the extraction breakthrough curves of test 08-01.

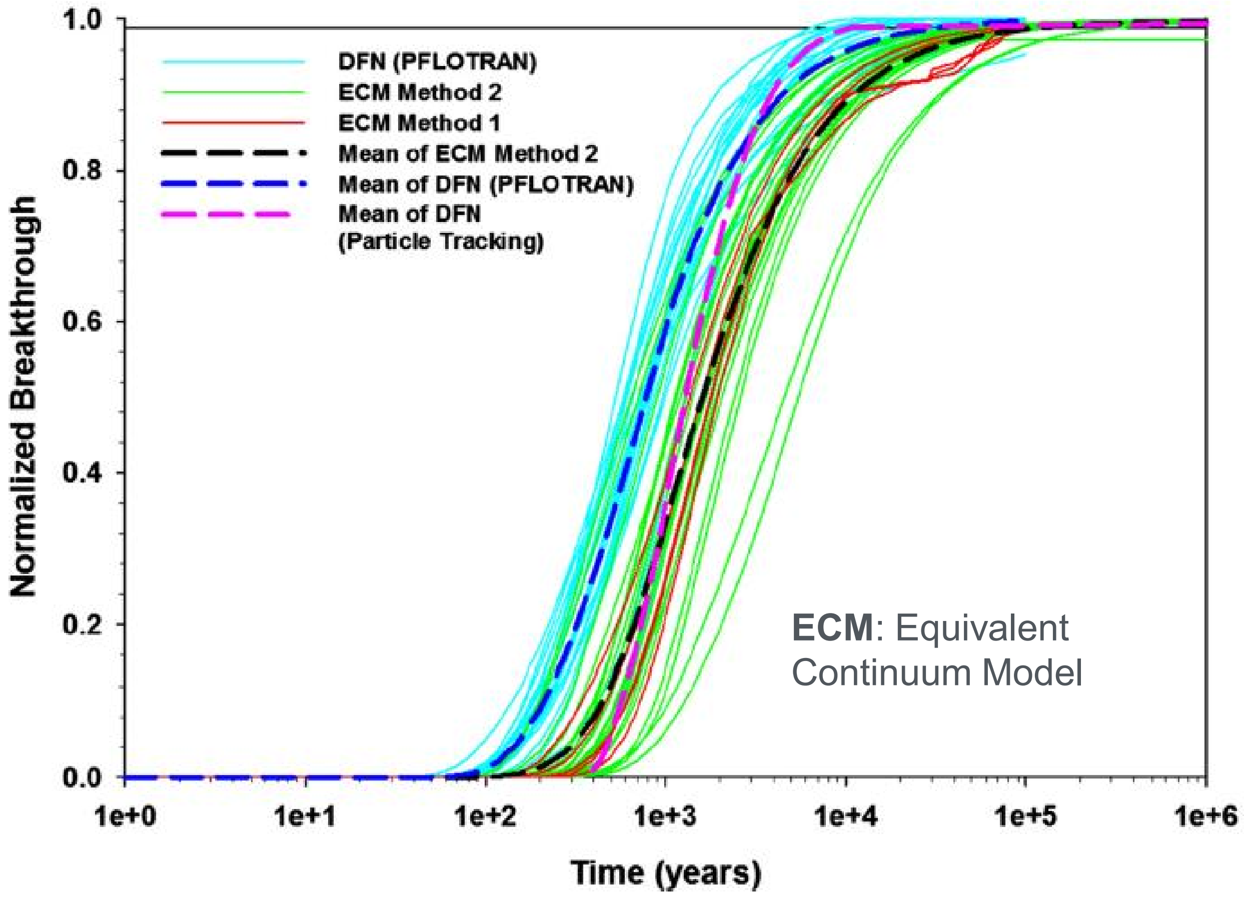
Multiple column experiments for interrogating radionuclide sorption parameters

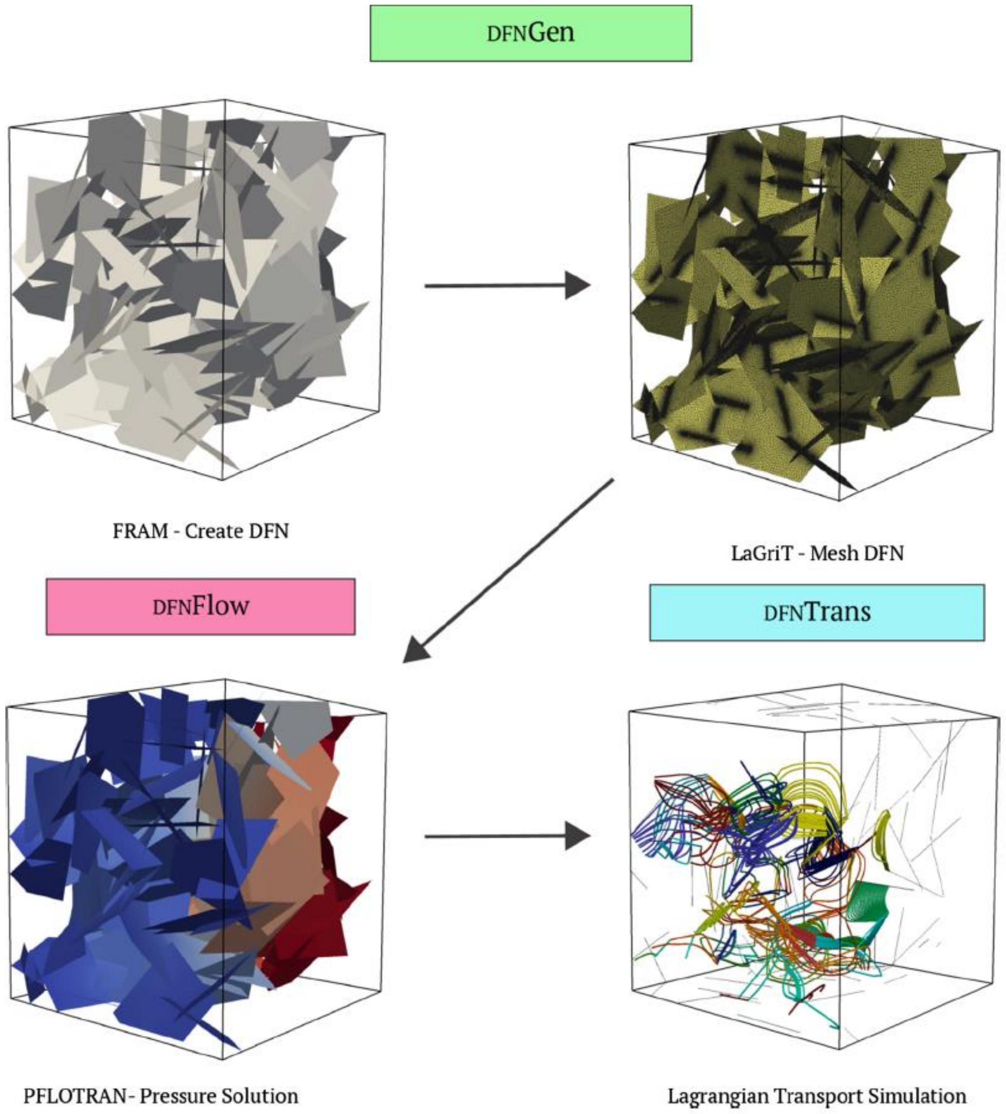


The model is ready available to be incorporated into Generic Disposal Safety Analysis (GDSA)

Reimus et al. (2017)

Development of discrete fracture network (DFN) model





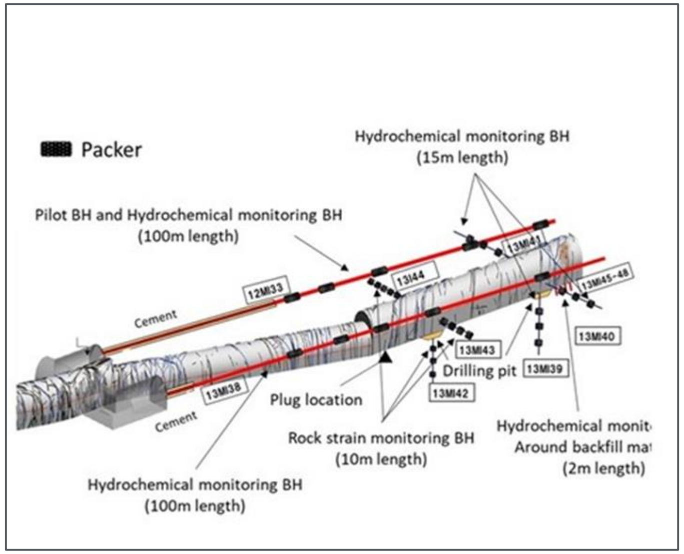
Comparison of different modeling approaches: The results show that DFN and ECM are comparable in the prediction of fluid flow and transport.

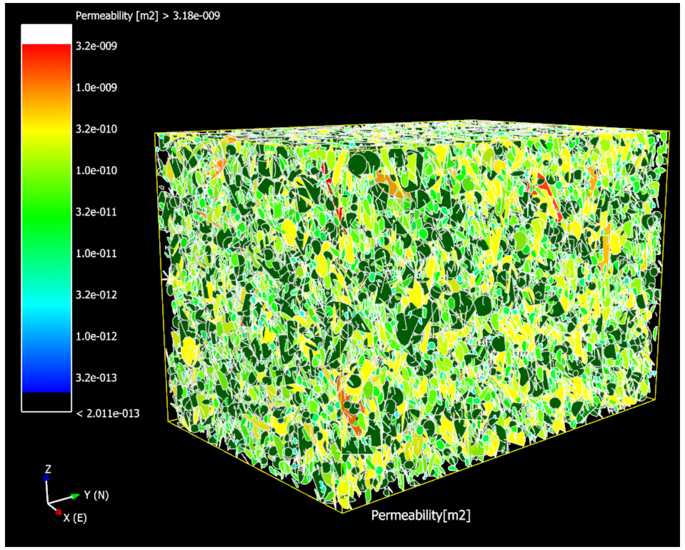
DFN toolkit for meshing discrete fractures and simulating flow and transport in fracture networks.

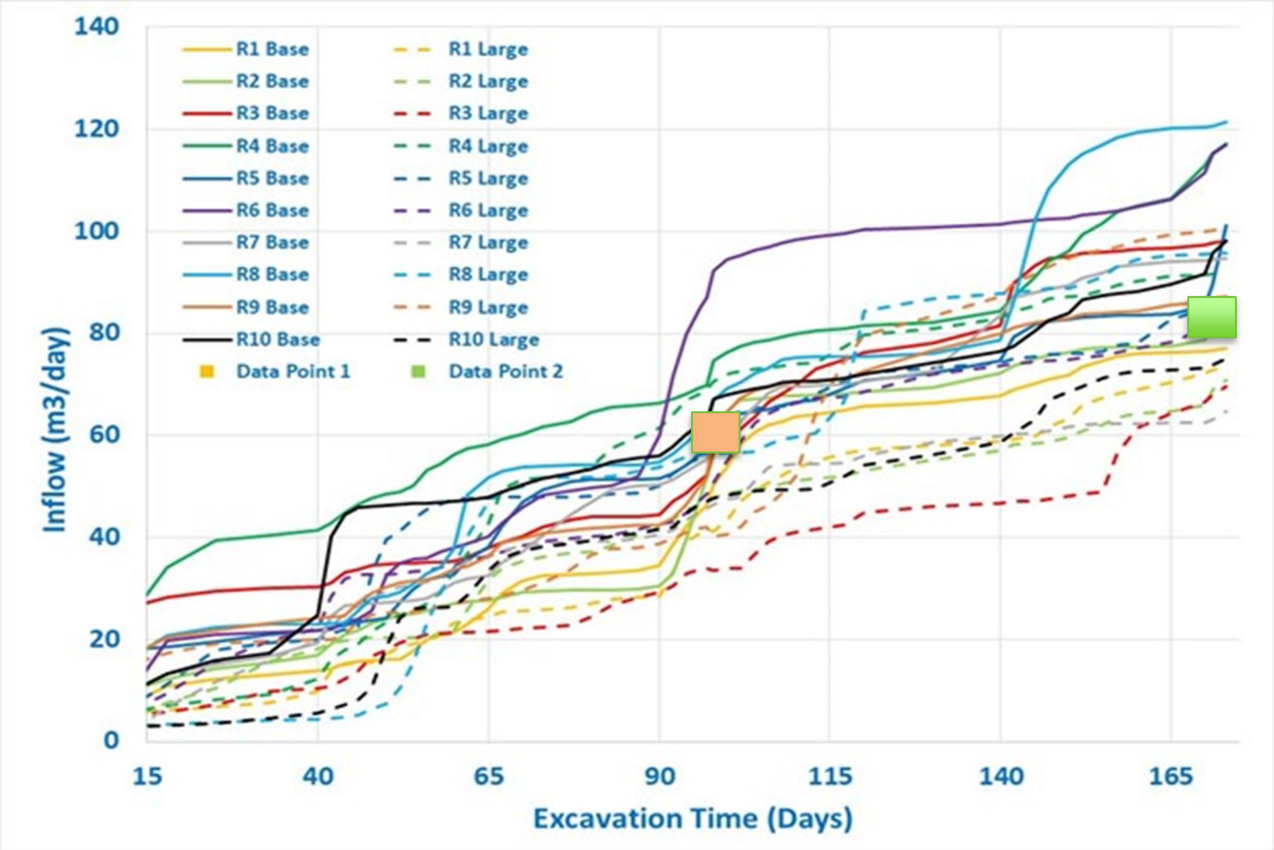
Hadgu et al. (2017)

Discrete fracture model: Field data synthesis and validation

Mizunami Underground Research Lab, Japan







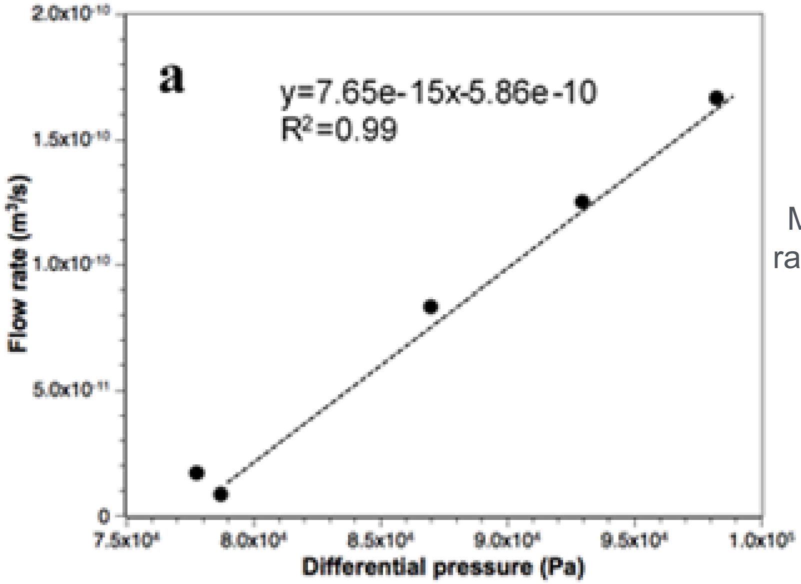
Wang et al. (2020)

- It is important to condition fracture network generation on actual fracture distribution (location, size) in tunnel and borehole.
- Statistical stability of fracture networks?

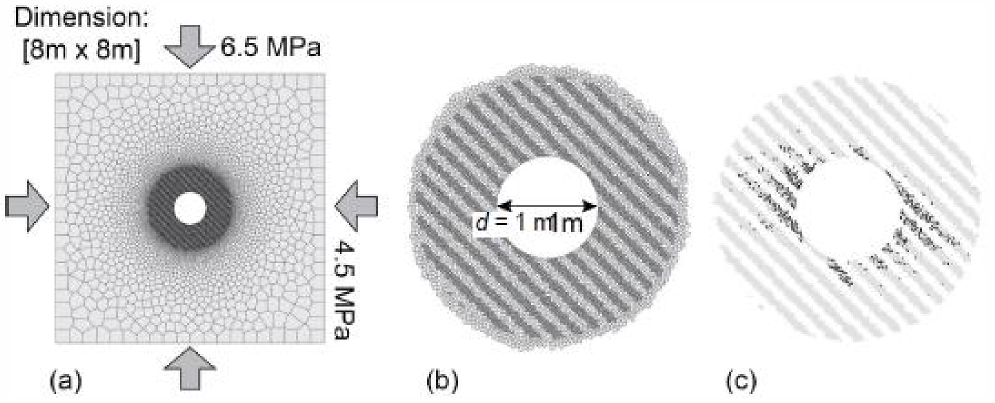
Technology for site characterization and monitoring: Disturbed rock zone (DRZ) characterization

Dual-sample triaxial rock testing system

Granite core samples from Grimsel, Switzerland

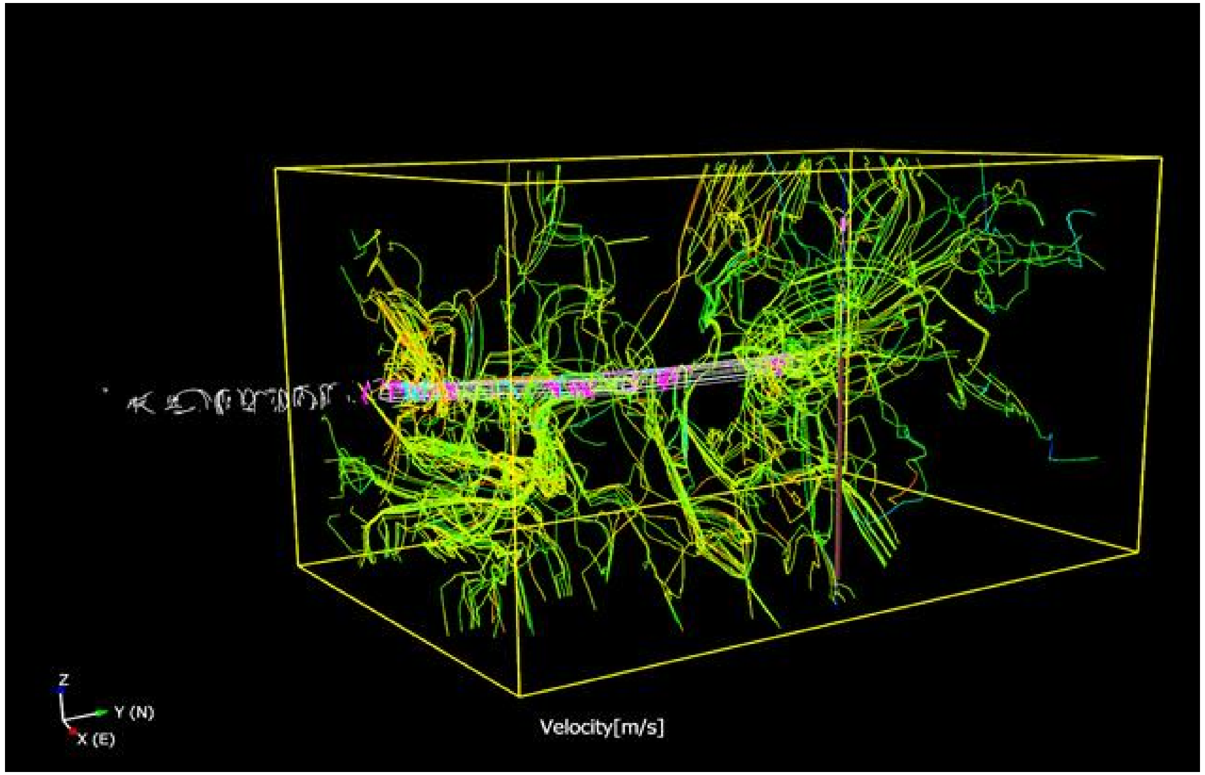


Measurements of flow rate of a rock sample as a function of stress

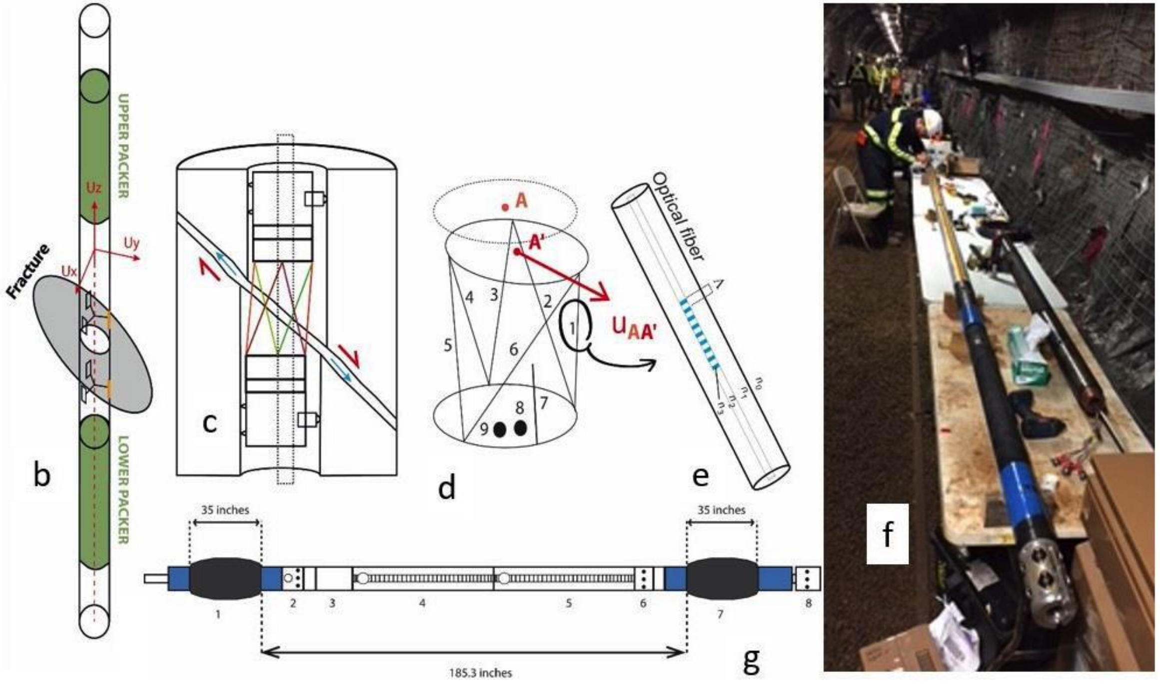


Rigid-body-spring network model for simulating fracture patterns

Fracture characterization and field monitoring



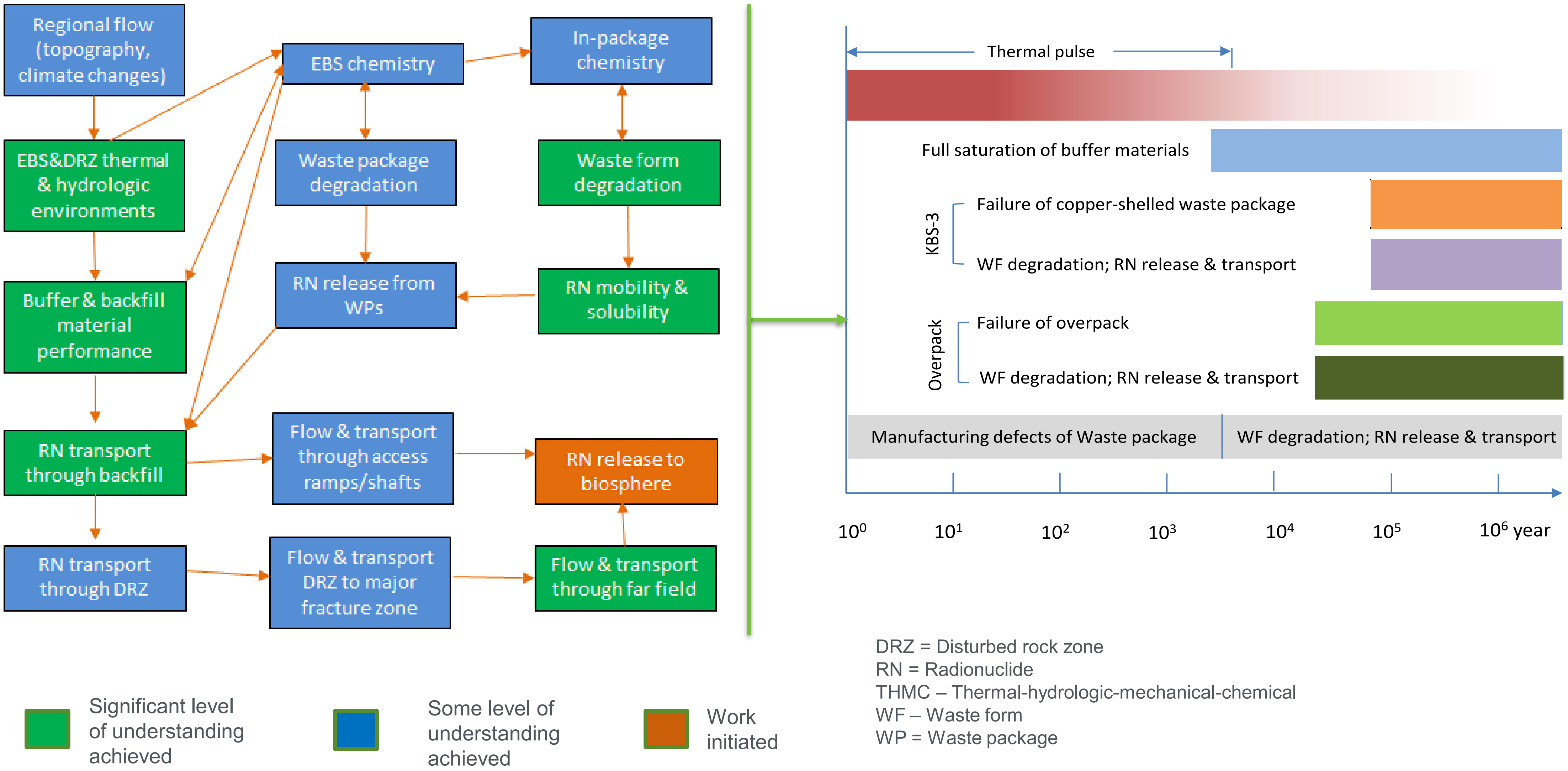
500 particles evenly distributed within the tunnel at time 0.



Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) system

- Challenge: Design a monitoring system to capture sufficient number of particles.
- Key capabilities: High-resolution geophysical techniques for fracture characterization

Current status of process models and total system integration

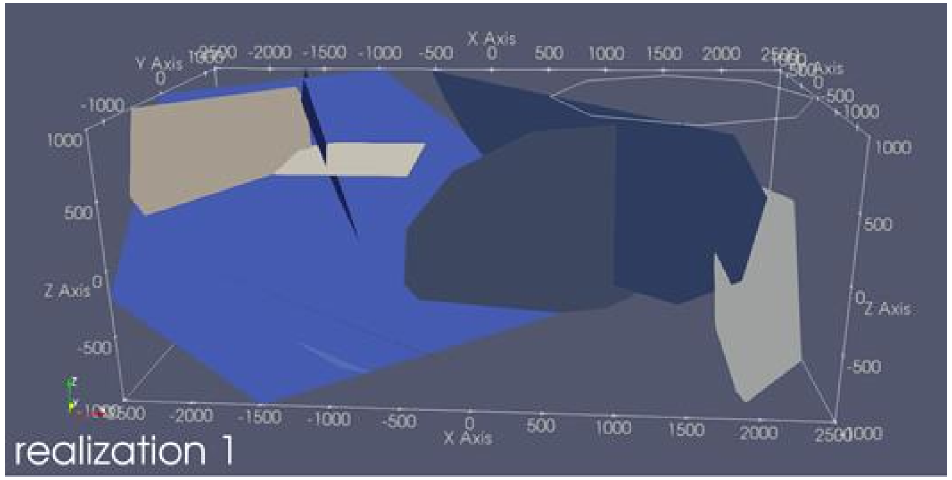


DRZ = Disturbed rock zone
RN = Radionuclide
THMC – Thermal-hydrologic-mechanical-chemical
WF – Waste form
WP = Waste package

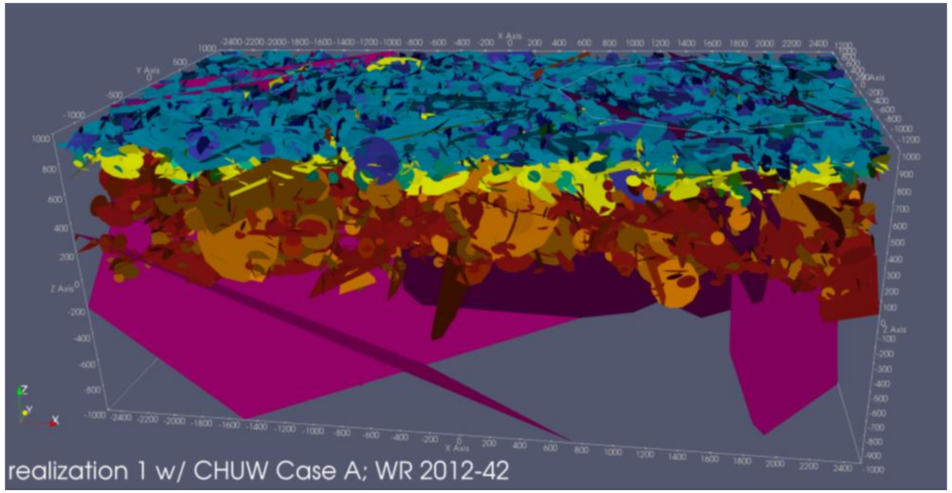
Next steps

- Develop a sensible GDSA model for sensitivity analyses.
  - Provide a minimum set of process models to GDSA
- Move model development more towards model validation with real data.
- Develop reduced order models for incorporation into the GDSA model.
- Continue with buffer material development.
- Develop and refine engineered barrier system (EBS) models, especially waste package (WP) degradation models.

Towards a more realistic representation of fluid flows in crystalline rocks: Crystalline rocks are generally quite impermeable.



Deterministic fracture zones



Stochastic fractures

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- Wang et al. (2020) Process Model Development and Experimental Investigation for Spent Fuel Disposal in Crystalline Rocks: FY20 Report. SAND2020-11539 R.

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Questions?