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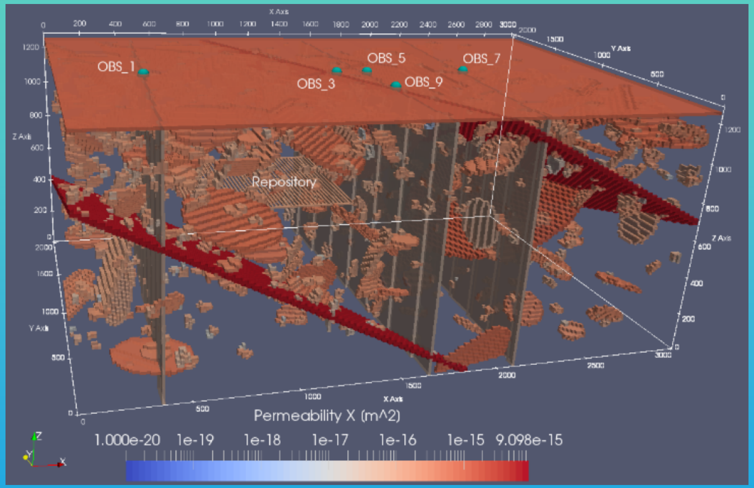
Spent Fuel and Waste Science and Technology (SFWST)

SAND2020-13128PE



Salt Host Rock: Disposal Concepts and Research & Development Activities

U.S. Nuclear Waste Technical Review Board
Fall 2020 Board Meeting
December 02-03, 2020
Virtual Meeting

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Sandia National Laboratories

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Overview

1. Introduction
   - Salt characteristics
   - Safety strategy
   - Climate change susceptibility
2. Possible Knowledge Gaps
   - Monitoring and characterization
   - Fundamental processes
   - Conceptual and numerical models
3. DOE-NE Research Addressing Gaps
   - Brine Availability Test in Salt (BATS)
   - Engineered barrier systems (EBS)
   - Model development

WIPP salt in Map-Unit 3 at BATS

Continuous miner at WIPP

Intro: Salt R&D Priorities Context

BATS heated array at WIPP

- Brine Availability Test in Salt (BATS)^
  - Field test at Waste Isolation Pilot Plant (WIPP)
  - Focus of Salt R&D program
  - Lab / modeling work supports BATS

- Mature International Collaborations*

US/German workshop + NEA Salt Club	11th yr	SNL/LANL/LBNL / DE/NL/UK
WEIMOS: TM constitutive laws	8+ yr	SNL/DE
BenVaSim: THM model validation	3rd yr	LBNL/DE
KOMPASS: granular salt reconsolidation	2nd yr	SNL/DE
RANGERS: salt engineered barriers	1st yr	SNL/DE
DECOVALEX 2023: Task E BATS	1st yr	SNL/LANL/LBNL / DE/NL/UK

*Kuhlman et al. (2020a), ^Kuhlman et al. (2020b)

DE: Germany, NL: Netherlands, UK: United Kingdom, NEA: Nuclear Energy Agency

Intro: Salt Host Rock Characteristics

Salt Long-term Benefits at km-scale

Salt
- Low porosity ($\phi \leq 0.1$ vol-%) and permeability ($k \leq 10^{-22}\ \mathrm{m}^2$)
- High thermal conductivity ($\geq 5\ \mathrm{W/m \cdot K}$)
- High peak temperature ($T_{\max} \approx 200$ °C)
- Openings creep closed ($> 10^0 - 10^2$ yr)
- Run-of-mine salt heals to intact salt

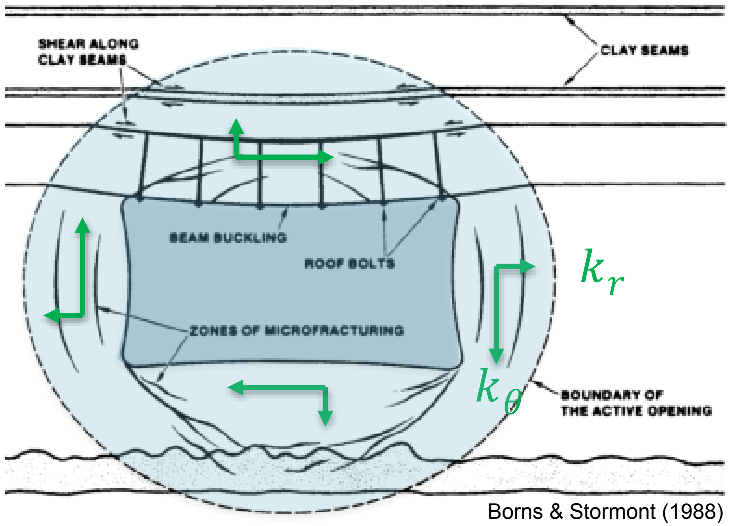
Brine
- No flowing groundwater (≤ 5 wt-% water)
- Chlorine (≥ 190 g/L) → reduces criticality concerns
- Hypersaline → reduces colloid mobility
- Low water activity (< 0.75) → biologically simple

Near-field, Short-term Complexities

EDZ
- ϕ and k higher near drift
- Damage is highly anisotropic ($k_r < k_\theta$)

Alpine miner at WIPP

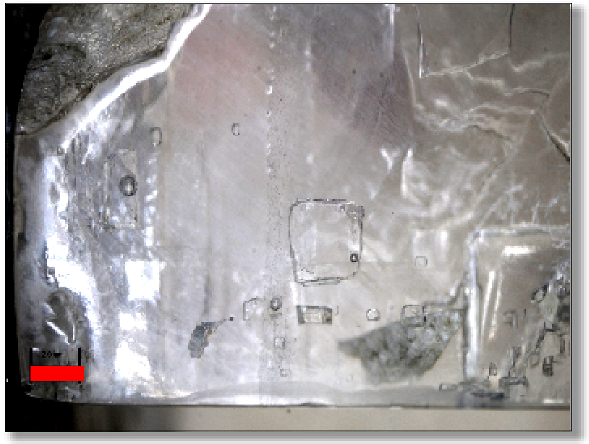
Cross-section view of Excavation Damaged Zone (EDZ) around drifts



Borns & Stormont (1988)

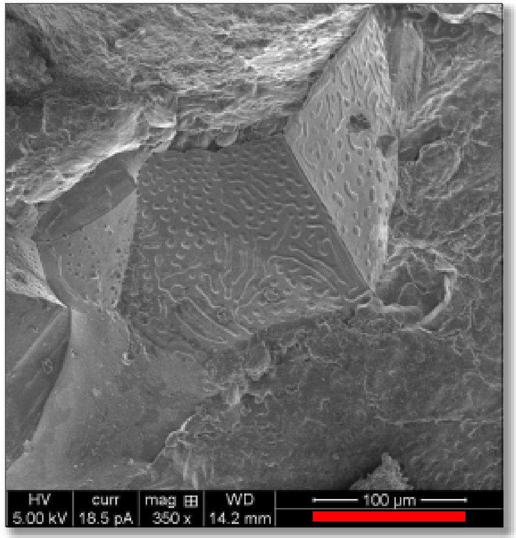
Intro: Salt Host Rock Characteristics - Brine

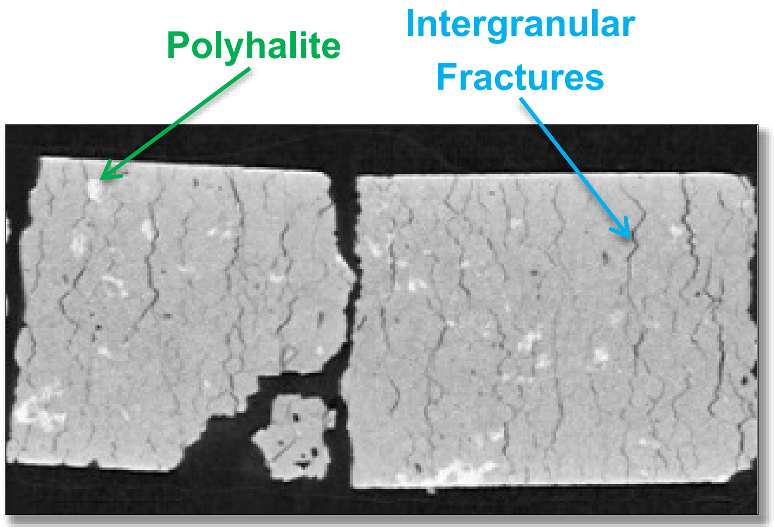
- Water in Bedded Salt from Permian Deposition*
  1. Disseminated clay (< 5 vol-%; ~25 vol-% brine)
  2. Intragranular fluid inclusions (1 – 2 vol-%)
  3. Hydrous minerals (e.g., $K_2Ca_2Mg(SO_4)_4{\cdot}2H_2O$; < 5 vol-%)
  4. Intergranular brine (<< 1 vol-%)

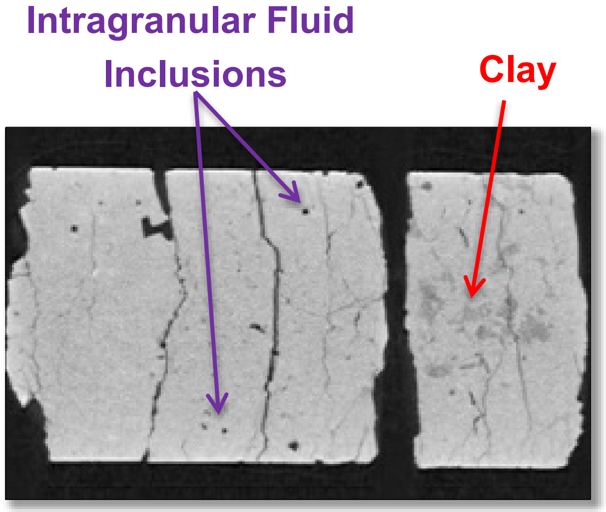


WIPP Fluid inclusions
2 mm scale bar
(Caporuscio et al., 2013)

Intergranular fluid inclusions
in reconsolidated granular salt
100 μm scale bar
(Mills et al. 2018)





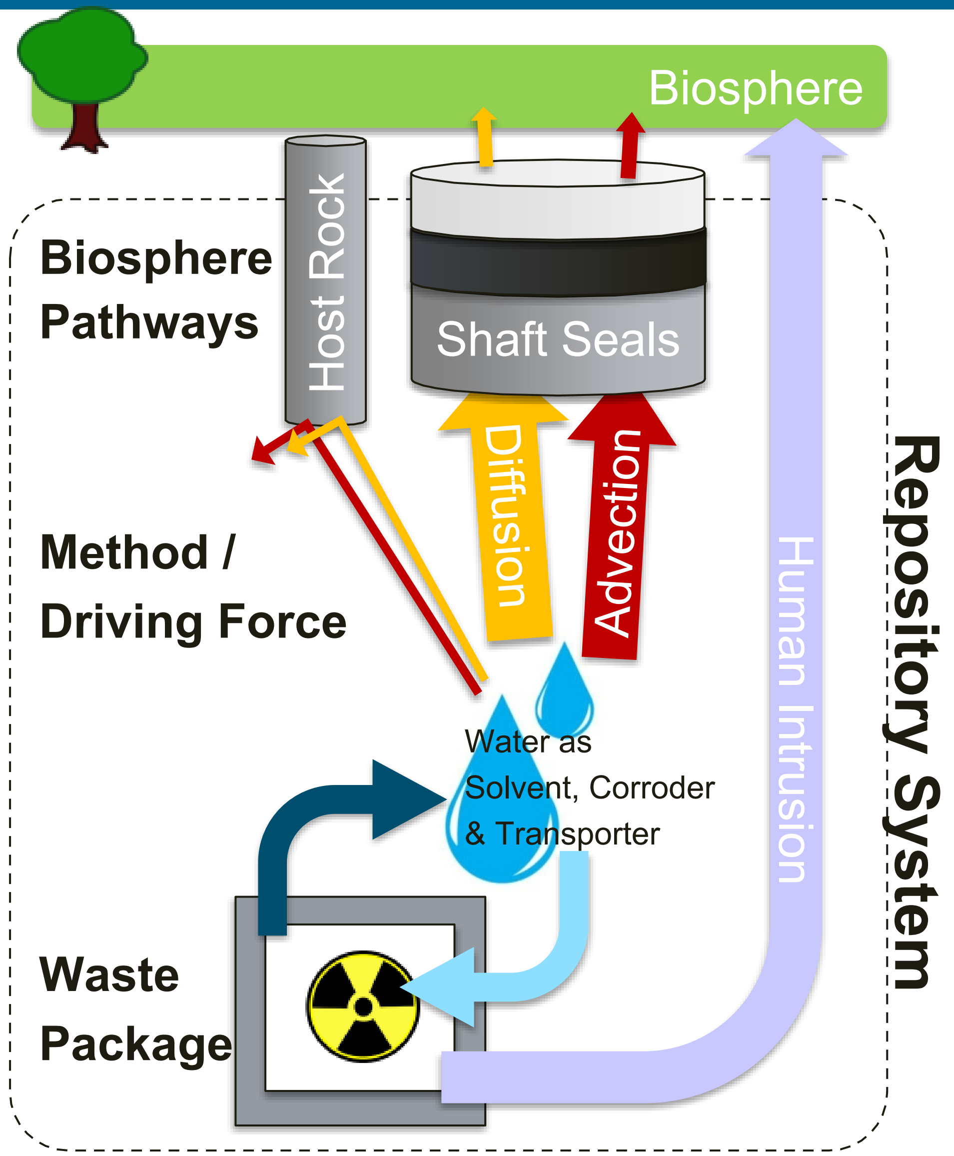


10.1 cm diameter core X-ray CT data from BATS (Betters et al., 2020)

- Each Responds Differently to Heat & Pressure

* Krumhansl (2000); Permian geologic period was 252 – 299 million years ago

Intro: Salt Post-Closure Safety Strategy

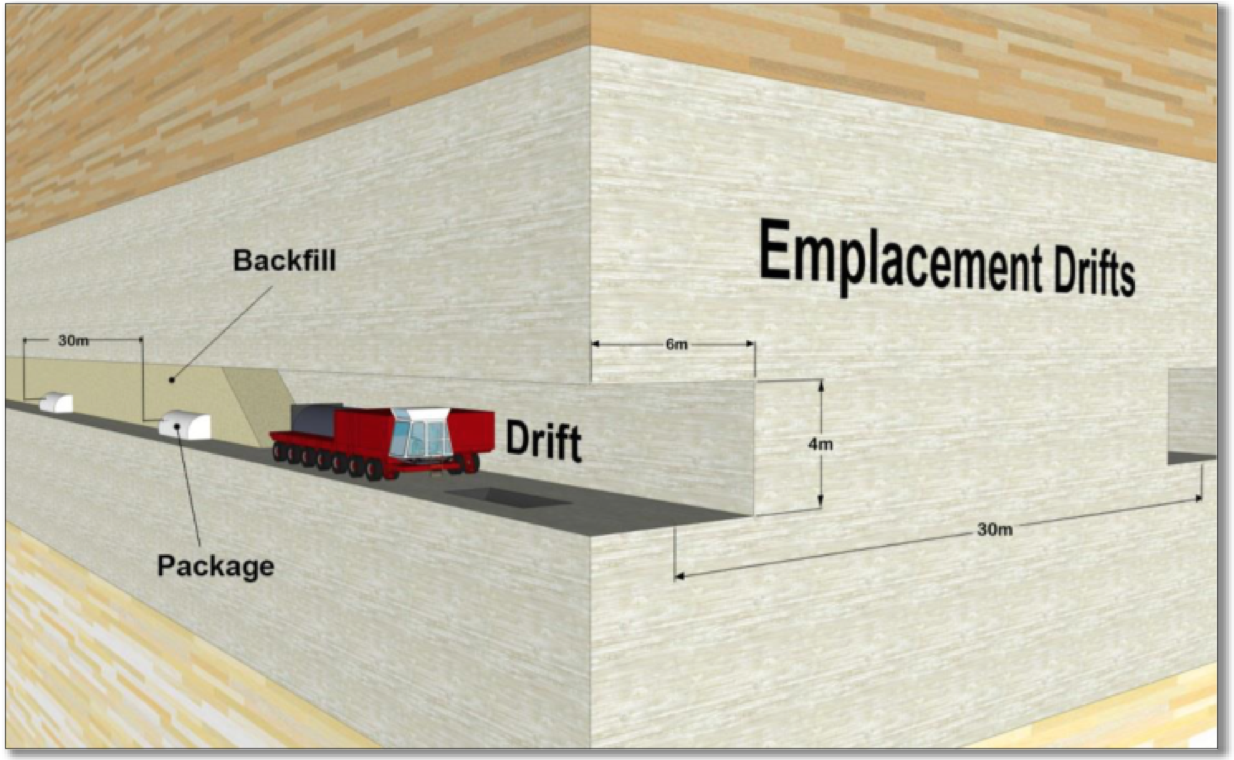


- Containment
  - Minimal reliance on waste package
  - Salt is the container
    - Self-healing
    - Impermeable
- Limited Transport
  - Minimal free water
  - Impermeable host rock
  - Effectively zero diffusion
  - Shaft Seals Main Pathway to Biosphere
    - Designed to reduce / eliminate advection
    - Shaft seal *multi-barrier* concept
    - *RANGERS US/DE collaboration*: drift/shaft seals

Intro: Waste Form and Engineered Barrier in Salt

- Glass High-Level Waste
  - Logs emplaced across drift floor
  - Run-of-mine salt backfill

- Commercial Spent Nuclear Fuel (SNF)
  - 12-, 21-, 24- and 37-PWR
  - In-drift axial emplacement (notches)
  - Run-of-mine salt backfill
  - 10 kW per package max power
  - High-burnup SNF only requires 50 years storage



In-drift axial emplacement of large, heavy waste packages showing shielded emplacement transporter, and notches in the drift floor (SNL, 2019).

PWR = pressurized water reactor assembly

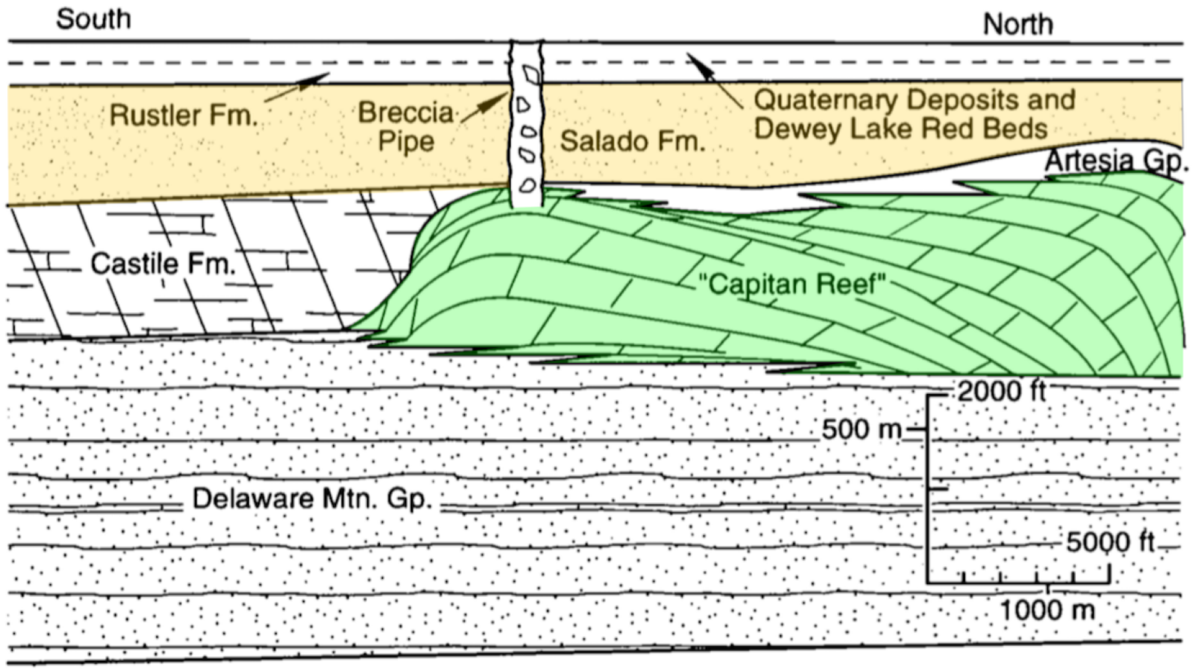
Mariner et al. (2015); Sevougian et al. (2016); SNL (2019)

Intro: Salt Repository Susceptibility to Climate Change

- Fresh Water Impacts?
  - Salt very soluble in fresh water
  - Fresh water from above
    - Stable arrangement
    - Density-limited impacts
  - High-pressure fresh water from below
    - Unstable arrangement
    - Could erode “breccia pipe”
    - *Avoided in siting process*

- No Direct Impacts of
  - Increased precipitation / temperature
  - Glaciation / deglaciation

Breccia Pipes in Delaware Basin (Powers, 1996)

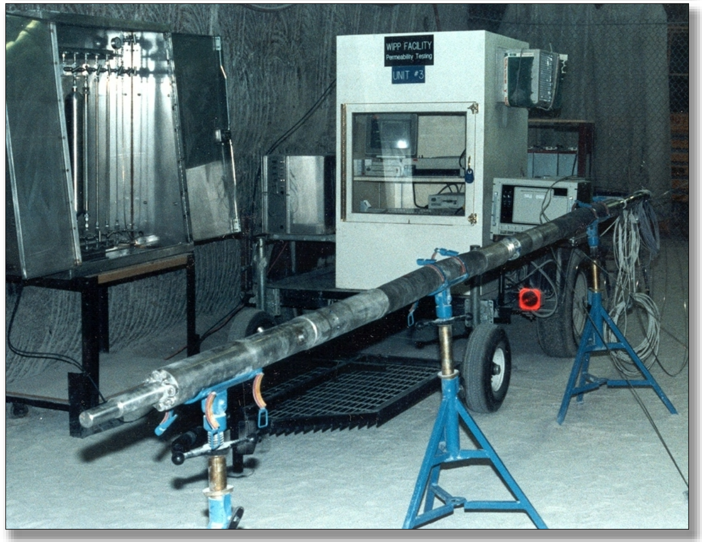


Generalized Cross Section

Gaps: State of Monitoring / Characterization

- Only Open Fractures in EDZ
  - No mapping of far-field fractures / faults
- Siting to Avoid “Fatal Flaws”:
  - Deep high-pressure fresh water (breccia pipes)
  - Human impacts (boreholes / solution mining)
- Difficult Monitoring / Exploration
  - Far-field salt has “immeasurably” low k, ϕ
    - Cannot measure k, ϕ from surface (500 – 1000 m away)
    - Need underground access (i.e., URL)
  - Oil / gas exploration methods ineffective
  - Precipitation / dissolution makes lab testing difficult
  - Brine corrosive to instrumentation

Discrete fractures in BATS near-drift EDZ



(Roberts et al., 1999; Beauheim & Roberts, 2002)
WIPP brine permeability testing

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

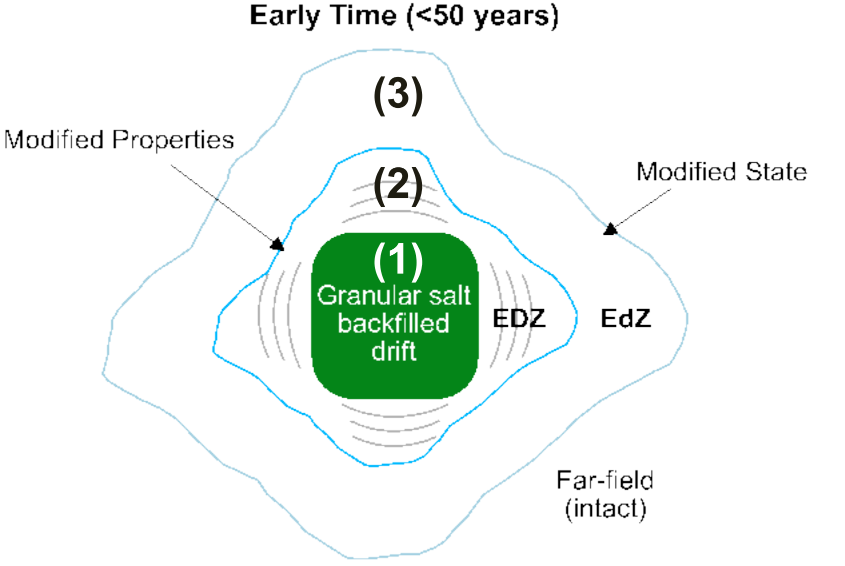
High Priority R&D Activities	
I-04	Experiment of bentonite EBS under high temperature, HotBENT
I-06	Mont Terri FS Fault Slip Experiment
I-08	DECOVALEX-2019 Task A: Advective gas flow in bentonite
I-12	TH and THM Processes in Salt: German-US Collaborations (WEIMOS)
I-13	TH and THM Processes in Salt: German-US 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

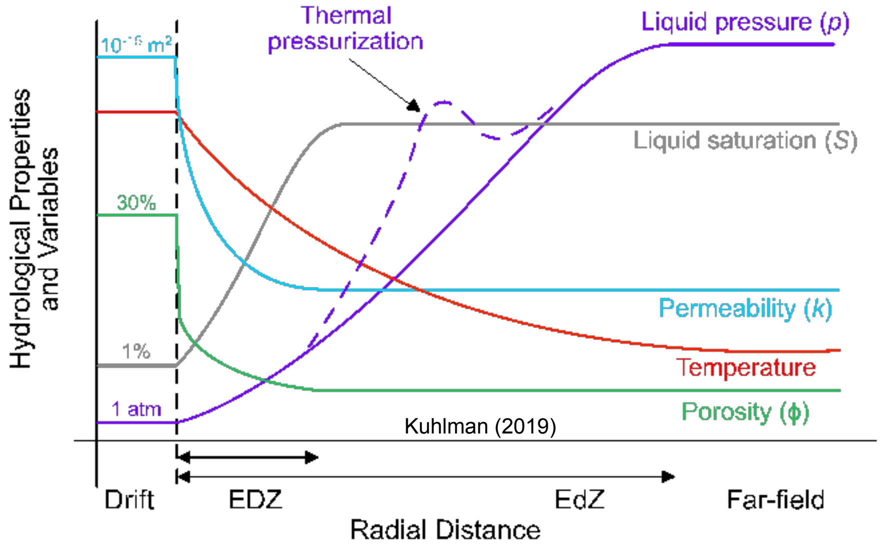
Legend

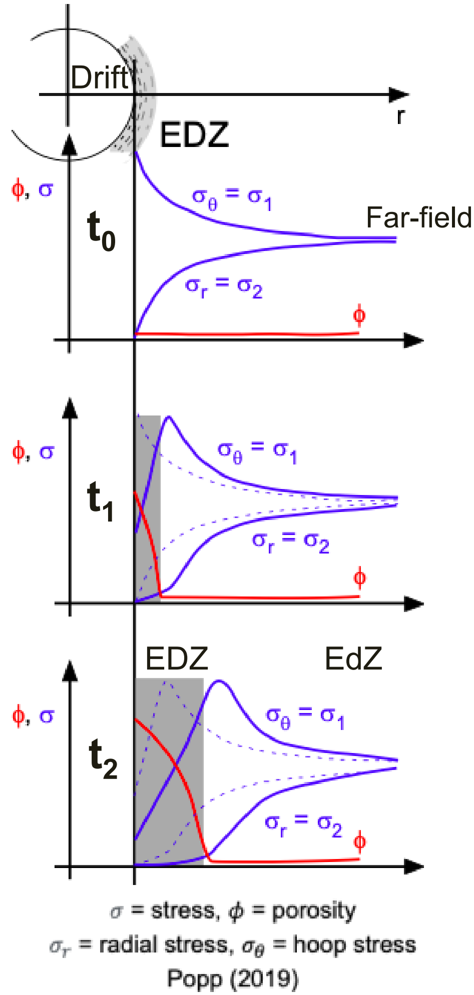
A	Argillite
C	Crystalline
D	Dual Purpose Canisters
E	Engineered Barrier System
I	International
P	Performance Assessment
S	Salt
*	Gap Activity

Gaps: Definitions of Fundamental Processes

- Salt Repository Regions*
  1. Backfilled drift
  2. Excavation Damaged Zone (EDZ)
  3. Excavation disturbed Zone (EdZ)
- Open-Drift and Early Time
  - $\Delta\sigma \rightarrow$ EDZ $\rightarrow \Delta\phi$ and Δk
- Later Time (>10 – 1,000 years)
  - Backfill → intact salt
  - EDZ → intact salt
  - EdZ shrinks significantly



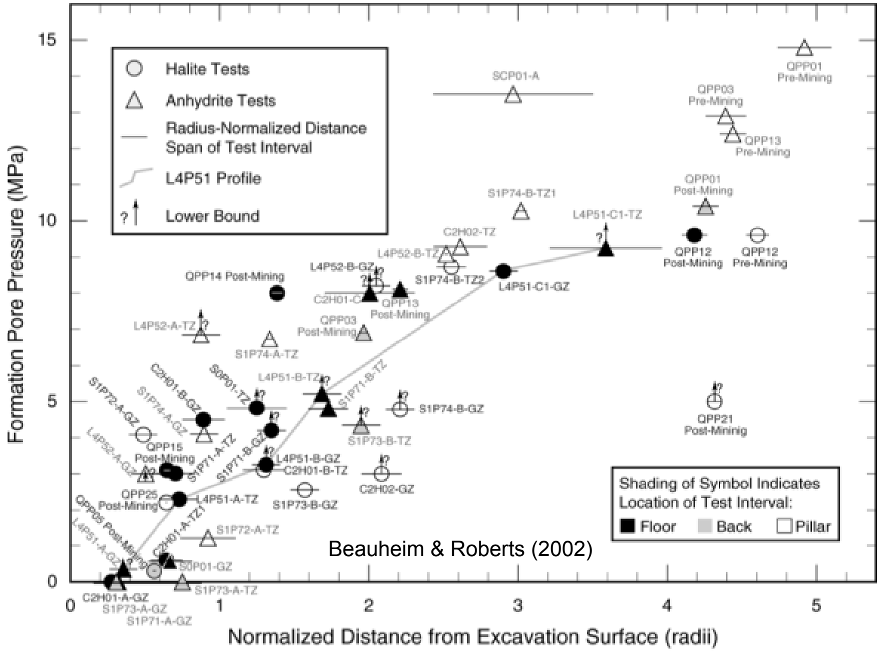




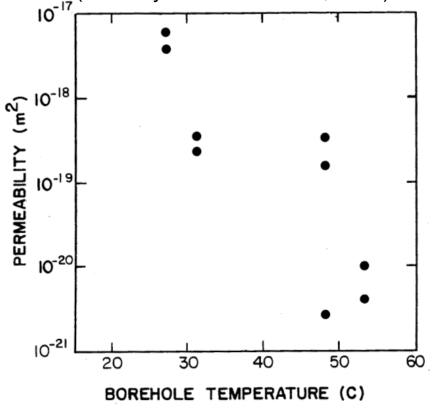
*Davies & Bernier (2005)

Gaps: Understanding Fundamental Processes

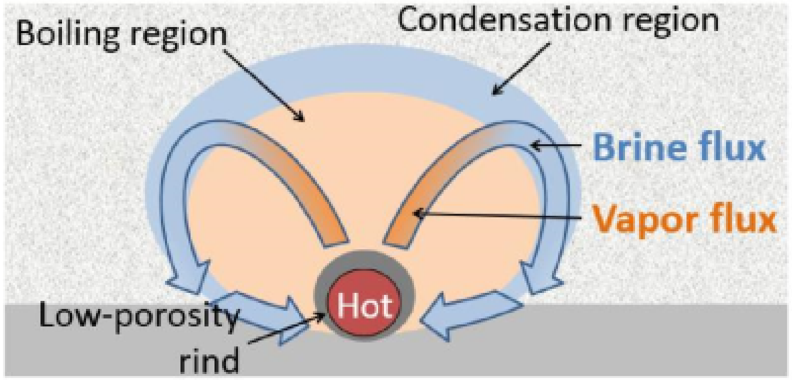
- Steep Gradients Across EDZ / EdZ
  - Material properties (k, ϕ)
  - State variables (p, brine saturation, σ)
- Early-time Non-linear Effects
  - Mechanical / thermal / hydrological perturbation
  - Two-phase (air / brine) fracture flow
  - Ventilation dry-out
  - Dissolution / precipitation
    - Transport properties (k, ϕ, 2-phase flow)
    - Mechanical properties (strength, creep)
  - Heat pipe in granular salt?
  - Thermal expansion → permeability change



Avery Island permeability data (Stickney & Van Sambeek, 1984)

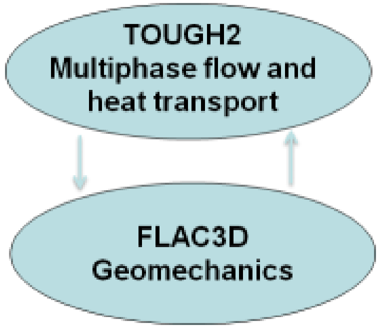


Salt heat pipe conceptual model (Kuhlman, 2019)

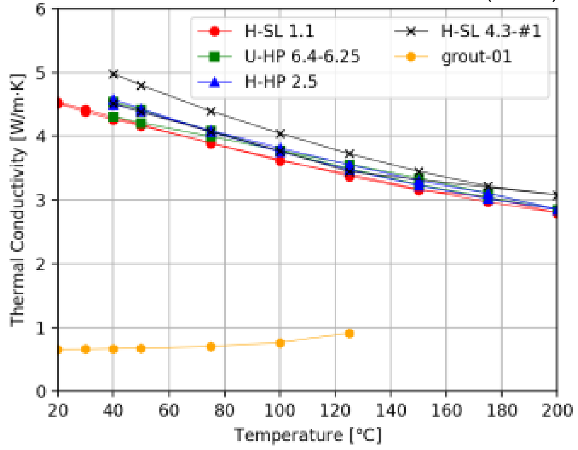


Gaps: State of Conceptual/Numerical Models

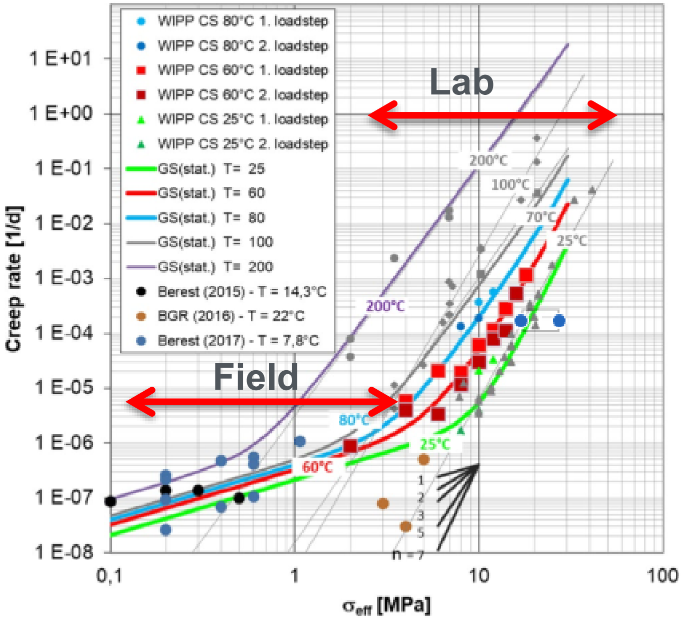
- Far-field GDSA Modeling
  - Larger distances, longer times
- Near-field EDZ / EdZ Process Modeling
  - Shorter distances, shorter times
  - THMC models (TOUGH-FLAC)
  - Appropriate simplifications?
    - Single-phase flow
    - Fractured salt is porous medium
    - Uncouple fast / slow processes
    - Simpler TH / THC models (PFLOTRAN, FEHM, TOUGH)
  - Need more work on:
    - Constitutive laws *(WEIMOS US/DE collaboration)*
    - Modeling approach / parameterization (*DECOVALEX 2023*)
    - Complex chemistry and CM coupling



Kuhlman et al. (2020b)



Bérest et al. (2019)



Gaps: Strategy for Safety Assessment in Salt

Q: Do We *Need* Accurate EDZ Predictions?

Option 1: Rely entirely on geology, avoid complex processes

- Enough brine for fast corrosion
- Enough brine to dissolve radionuclides
- Microbial & corrosion gas generation (more driving force)
- Heat conduction only

Conservative Simplifications

Option 2: Account for complex processes

- Heat dries out waste (limits corrosion & transport)
- Thermal expansion in EDZ reduces k & ϕ
- Few halophilic microbes (less driving force)
- Granular heat pipes (convection $\gg$ conduction, $\downarrow T_{\max}$)
- Timing of backfill & EDZ return to intact salt

Understanding EDZ / Brine Processes

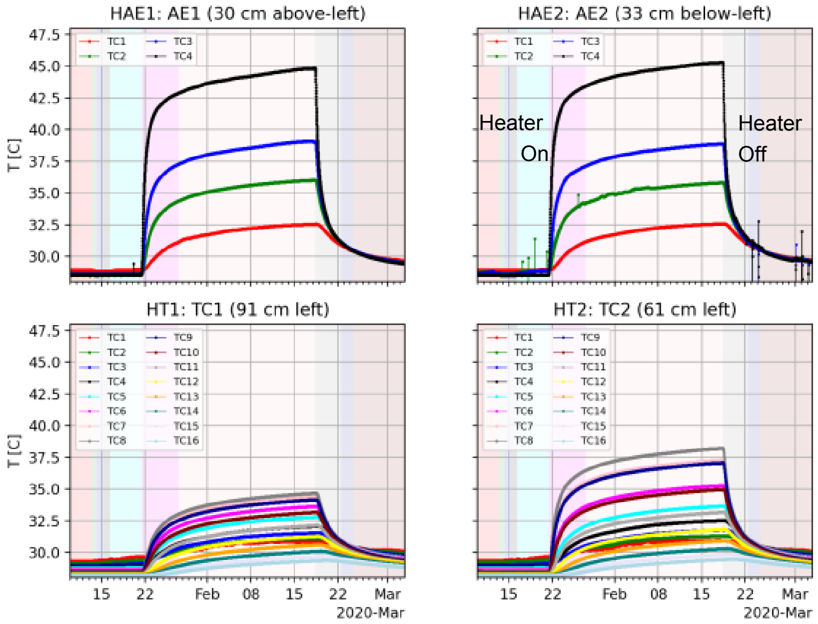
Option 3: Fall back on geology, investigate EDZ processes

Current R&D: Brine Availability Test in Salt (BATS) at WIPP

- Two Arrays: Heated / Unheated
- Central Packer (heater 2.75 m deep)
  - Borehole closure
  - Water production and isotopic composition
- Cement Seals Study
  - Cement + Salt + Brine interactions
- Geophysics Mapping
  - “4D” electrical resistivity tomography
  - Acoustic emissions from cracking

- BATS Phases
  - 1a: Jan-Mar 2020 (complete)
  - 1b–1c: early 2021 (tracer tests)
  - 2: New Boreholes in late 2021
- DECOVALEX 2023 Task E

BATS in WIPP Drift N940 December 2019



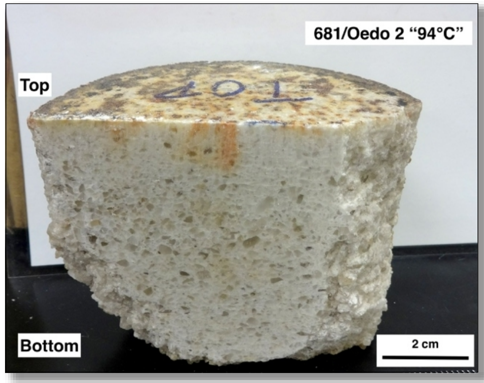
BATS 1a temperature observations at thermocouples (TC); Kuhlman et al., (2020b)

BATS team: SNL et al. (2020)

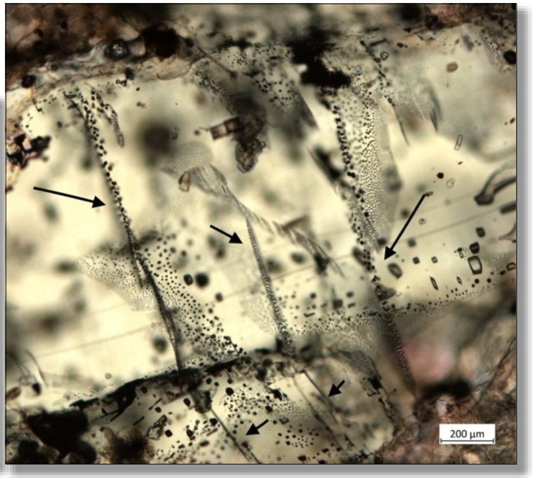
Current R&D: Salt Engineered Barriers Systems

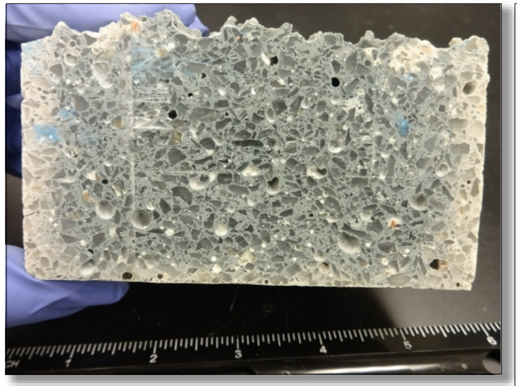
- *RANGERS US/DE Collaboration*: Drift/Shaft Seals
- Run-of-Mine Salt Seals
  - *KOMPASS US/DE collaboration*: granular salt
  - Granular salt reconsolidation: $f(T, \sigma, \text{moisture}, \ldots)$
  - Time to evolve granular → intact salt
    - Field: $10^1 - 10^3$ years
    - How to speed up in laboratory?
- Cementitious Seals
  - Sorel cement ($MgO + MgCl_2$ brine)
  - Salt concrete (Furnace slag + NaCl brine)
  - BATS: demo salt/seals with/without heating
  - *DECOVALEX US/DE collaboration*: lab seals

KOMPASS reconsolidated granular salt (Kuhlman et al., 2020a)

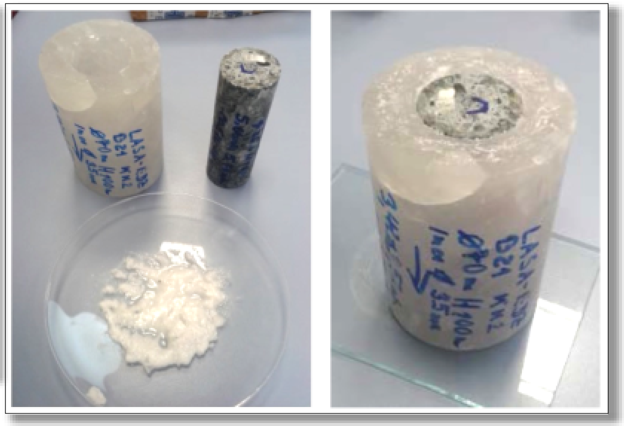


Photomicrographs of KOMPASS Samples (Kuhlman et al., 2020a)





BATS salt concrete sample (Kuhlman et al., 2020b)



Lab seals experiment (Czaikowski et al., 2016)

Current R&D: Model Development

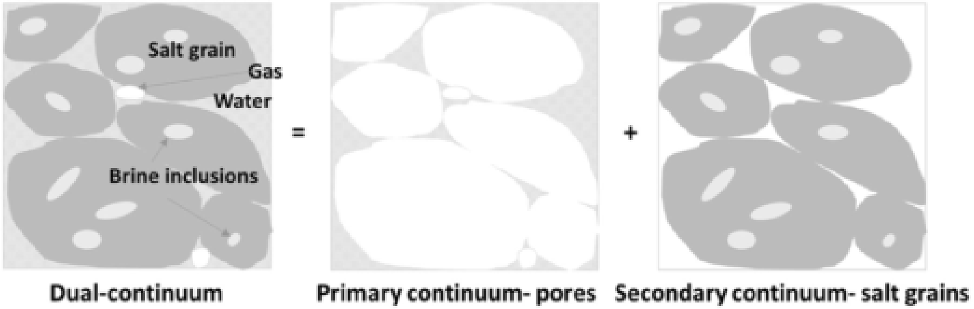
- Improving GDSA Framework (PFLOTRAN)
  - T-dependent thermal conductivity (LaForce et al., 2020)
  - Meshing tools: LaGriT & VoroCrust

- Improving Process Models (TOUGH / FEHM)
  - Multicontinuum fluid inclusions
  - Salt dehydration & porosity evolution
  - Two-phase flow (brine + air) in salt

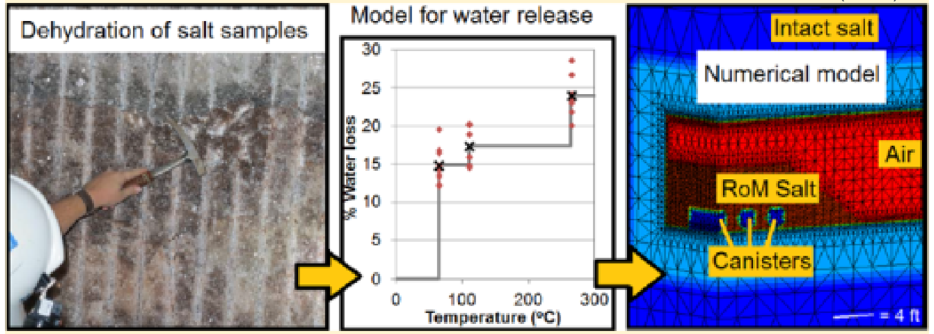
- International Benchmarking Activities
  - *DECOVALEX Task E*: BATS heater test
  - *WEIMOS*: TM constitutive models
  - *KOMPASS*: granular salt reconsolidation
  - *BenVaSim*: THM model validation

http://vorocrust.sandia.gov

Hu & Rutqvist (2020)



Jordan et al. (2015)

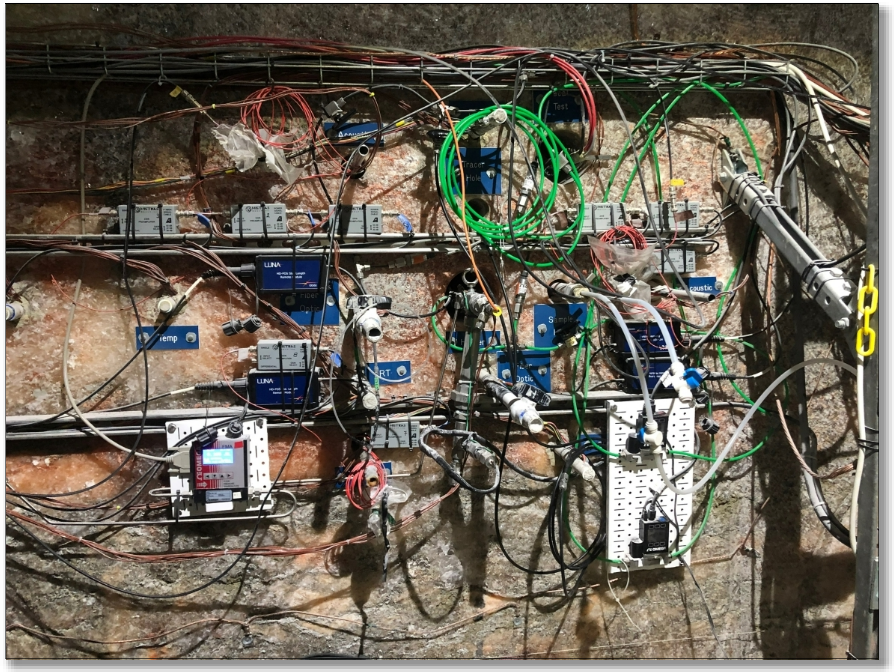


GDSA = geologic disposal safety assessment

Summary: Prioritization of R&D

Where does our work have the greatest impact?

BATS heated array



- Lower Priority
  - Far-field salt behavior
  - Large / hot waste packages
- Higher Priority (next 5 years)
  - Drift / shaft seal (RANGERS, KOMPASS) (E-9,17)
    - Timing of return to far-field conditions
    - Modeling salt / EBS evolution and interactions
  - Investigating coupled EDZ processes (S-1,3,4; I-12,13)
  - BATS field test at WIPP (DECOVALEX) (S-5; I-16)

Safety assessment relies on salt geology, bolstered by EDZ understanding.

Salt R&D Multi-Lab Team

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Lawrence Berkeley National Laboratory (LBNL)

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Acronyms and Initialisms

BATS	Brine Availability Test in Salt
BenVaSim	Benchmarking for Validation and Verification of THM Simulators with Special Regard to Fluid Dynamic Processes in Repository Systems
CM	chemical-mechanical
CT	computed tomography
DECOVALEX	Development of Coupled Models and their Validation Against Experiments
DOE-EM	DOE Office of Environmental Management
DOE-NE	DOE Office of Nuclear Energy
DPC	dual-purpose canisters
EBS	engineered barrier system
EDZ	excavation damaged zone
EdZ	excavation disturbed zone
FEHM	LANL porous media flow and transport simulator
FLAC	Itasca commercial geomechanical simulator
FY	fiscal year (Oct-Sept)
GDSA	geologic disposal safety assessment
HLW	high-level waste
KOMPASS	Joint Project on the Compaction of Crushed Salt for Safe Containment
LaGriT	Los Alamos grid toolbox
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
NEA	Nuclear Energy Agency
PA	performance assessment
PFLOTRAN	Open-source massively parallel GDSA reactive flow and transport simulator
RANGERS a	Design and Integrity Guideline for Engineered Barrier Systems for HLW Repository in Salt
R&D	research and development
SA	safety assessment
SFWST	Spent Fuel & Waste Science & Technology
SNL	Sandia National Laboratories
TC	thermal-chemical
TH	thermal-hydrological
THC	thermal-hydrological-chemical
THM	thermal-hydrological-mechanical
THMC	thermal-hydrological-mechanical-chemical
TOUGH	LBNL porous media flow and transport simulator
URL	underground research laboratory
VoroCrust	Sandia Voronoi meshing toolbox
WEIMOS	Further Development and Qualification of the Rock Mechanical Modeling for the Final HLW Disposal in Rock Salt
WIPP	Waste Isolation Pilot Plant (DOE-EM site)