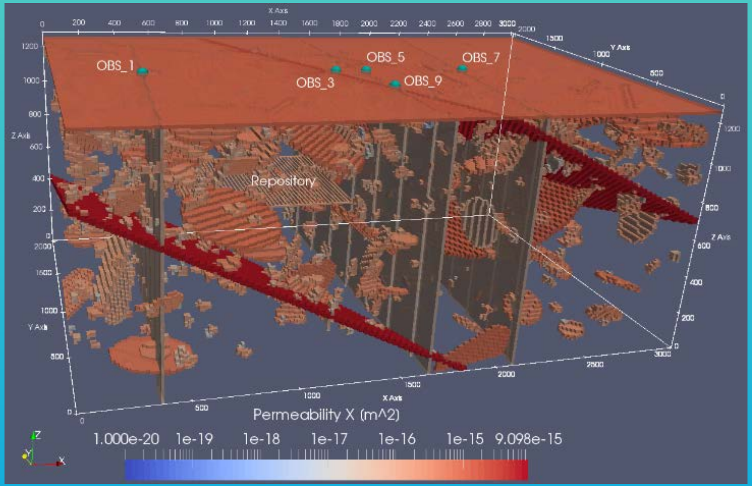

Salt Host Rock Generic Disposal Research R&D

Nuclear Waste Technical Review Board

Fall 2020 Fact-Finding Meeting (Nov 4-5, 2020)

Generic Disposal Research & Development Program Priorities

Kristopher L. Kuhlman
Sandia National Laboratories

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Overview

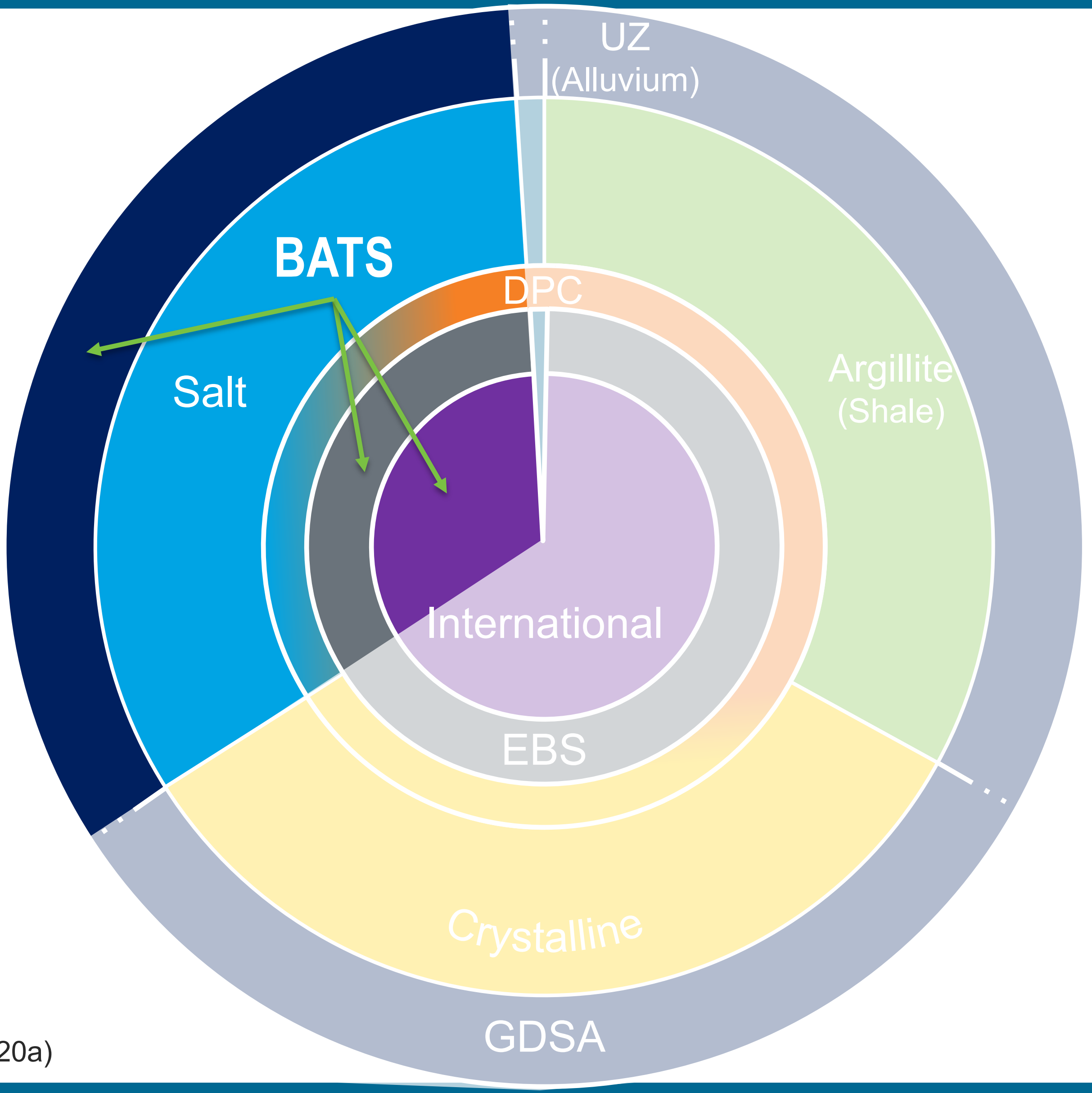
1. Introduction
   - Characteristics
   - General safety strategy
2. Possible Gaps in Understanding
   - Fundamental processes
   - State of technology
   - Research needs
3. DOE-NE Research Addressing Gaps
   - Brine Availability Test in Salt (BATS)
   - Engineered barrier systems (EBS)
   - Model development (including GDSA)

WIPP salt in Map-Unit 3 at BATS

Continuous miner at WIPP

Intro: Salt R&D Priorities Context

- Brine Availability Test in Salt (BATS)
  - Focus of program
  - EBS, International & GDSA aspects
- No foreign salt URL
- Mature collaborations*
  - Germany, UK, Netherlands
  - US/German workshop (11 years)
  - DECOVALEX 2023 Task E
- DPC not focused on salt



DECOVALEX = Development of Coupled models and their Validation against Experiments
UZ = unsaturated sone
DPC = dual purpose canisters
EBS = engineered barrier system
GDSA = Geologic Disposal Safety Assessment
URL = underground research laboratory
WIPP = Waste Isolation Pilot Plant

*Kuhlman et al., (2020a)

Intro: Unique Salt 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 ($T_{\mathrm{max}} \approx 200\ ℃$)
- Openings creep closed ($> 10^0 - 10^2$ yr)
- Run-of-mine salt heals to intact salt

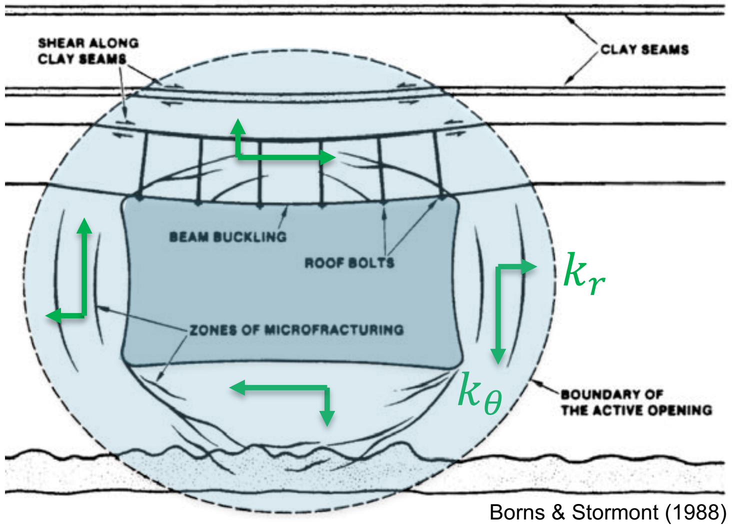
Brine
- No flowing groundwater (≤ 5 wt-% water)
- Chlorine (≥ 190 g/L) → reduces criticality concerns
- Hypersaline → reduces colloid mobility
- Low water activity (< 0.75) → biologically simple

Near-field, Short-term Complexities

EDZ
- ϕ and k higher near drift
- Near drift fractured, highly anisotropic ($k_r < k_\theta$)

Alpine miner at WIPP

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

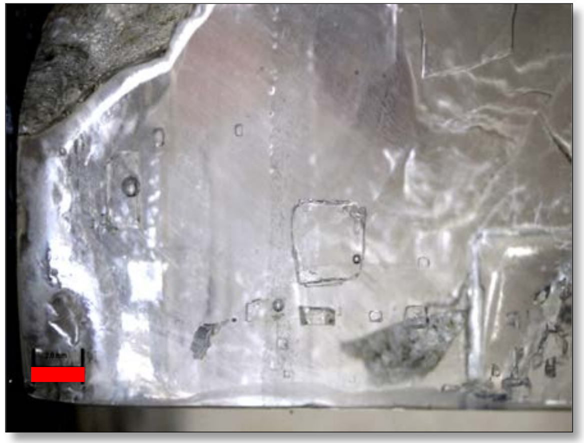


Borns & Stormont (1988)

Intro: Unique Properties: Brine in Bedded Salt

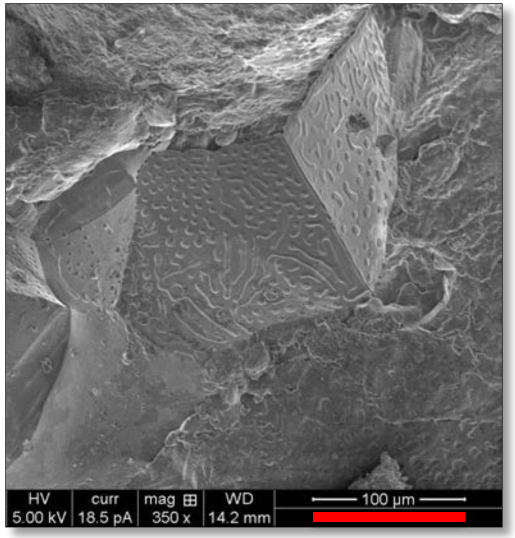
Water in Bedded Salt

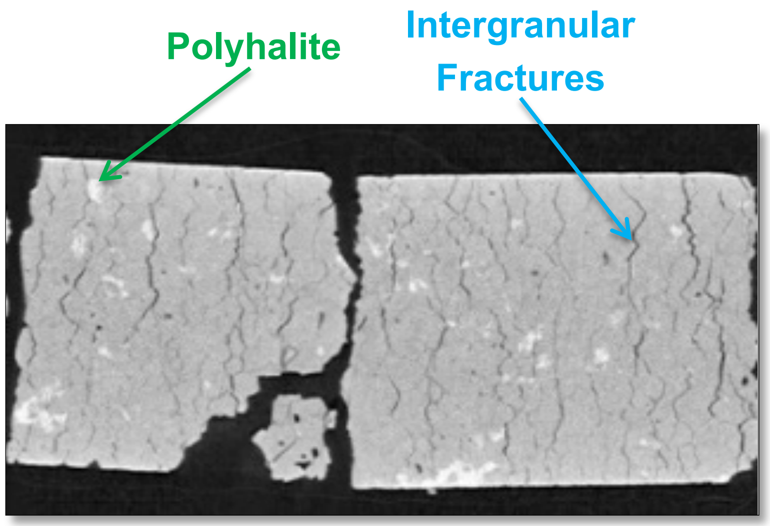
1. Disseminated clay (< 5 vol-%; ~ 25 vol-% brine)
2. Intragranular fluid inclusions ($1 - 2$ vol-%)
3. Hydrous minerals (e.g., $K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$; < 5 vol-%)
4. Intergranular brine ($<< 1$ vol-%)

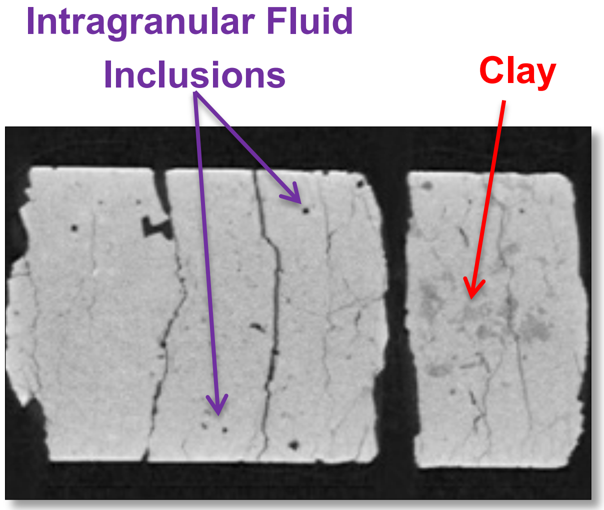


WIPP Fluid inclusions
2 mm scale bar
(Caporuscio et al., 2013)

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



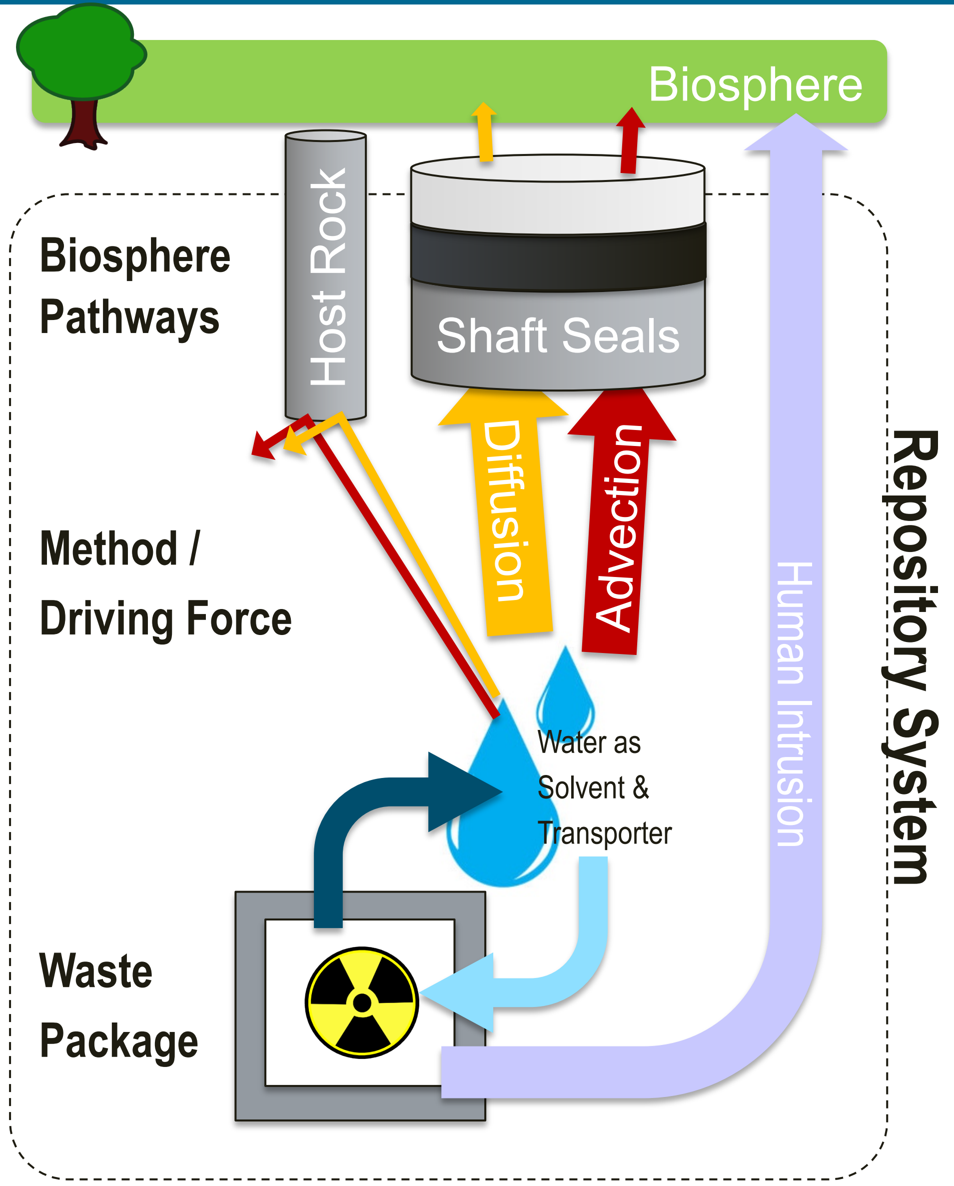




10.1 cm diameter core X-ray CT data from BATS (Betters et al., 2020)

Each responds differently to heat & pressure

Intro: General Post-Closure Safety Strategy

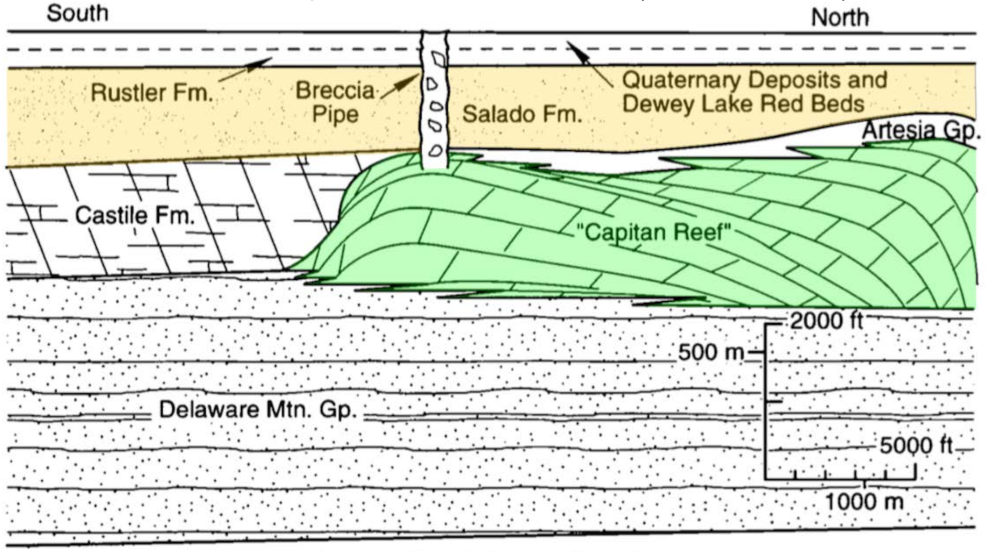


- Release to Biosphere Requires
  - Solvent (water)
  - Method & driving force
    - Advection: Δ pressure (closure + gas pressure)
    - Diffusion: Δ concentration
  - Pathway to biosphere
    - Shaft seals
    - Host rock
- Salt Disposal Benefits from
  - Minimal free water
  - Impermeable host rock
- Shaft Seals main Pathway to Biosphere
  - Designed to reduce/eliminate advection
  - Shaft seal *multi-barrier* concept
  - *RANGERS US/DE collaboration*: drift/shaft seals

Intro: Salt Repository Susceptibility to Climate Change

- Fresh Water Impacts?
  - Density-limited impact of overlying fresh water
    - Stable arrangement
  - High-pressure fresh water from below repository
    - Unstable arrangement
    - Could erode salt as “breccia pipe”
    - *Avoided in siting process*
- No Direct Impacts of
  - Increased precipitation / temperature
  - Glaciation / Deglaciation
- Main Release Drivers
  - Advection up shaft (creep + corrosion + microbes → Δ pressure)
  - Diffusive transport up shaft seals (*slow*)
  - Human intrusion (by law)

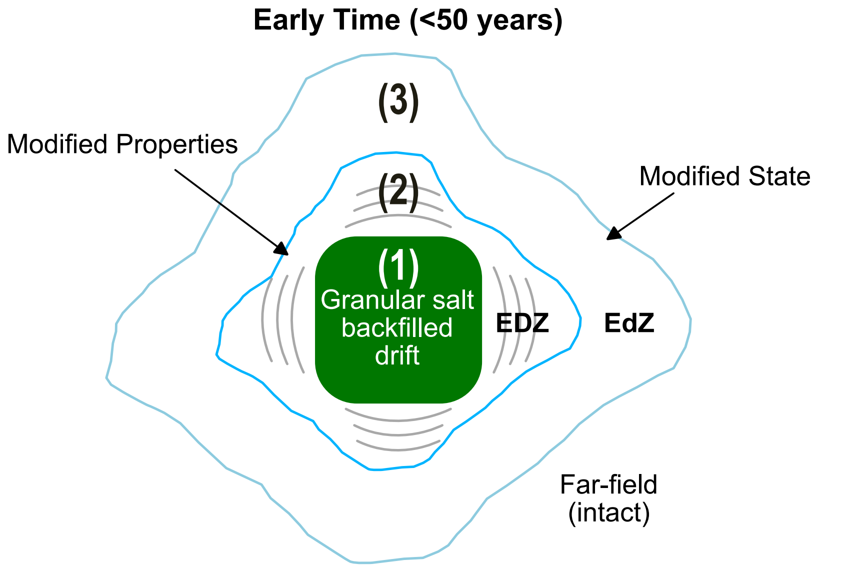
Breccia Pipes in Delaware Basin (Powers, 1996)

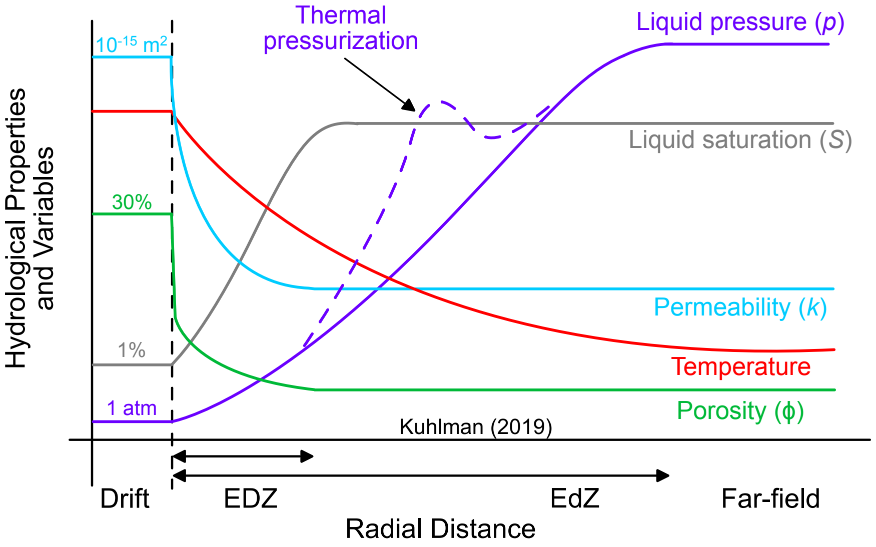


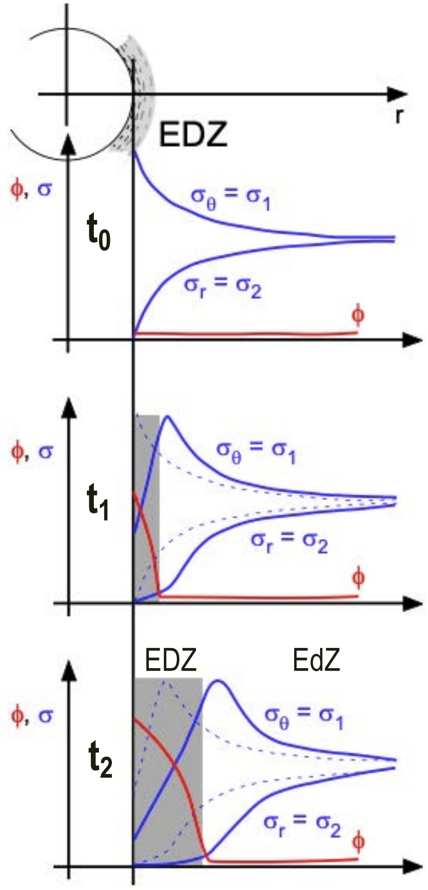
Generalized Cross Section

Gaps: Fundamental Processes in Salt / Definitions

- Salt Repository Regions
  1. Backfilled drift
  2. Excavation Damaged Zone (EDZ)
     - Properties change
     - 1 – 1.5 radii
  3. Excavation disturbed Zone (EdZ)
     - System state change
     - 2 – 5 radii
- Early Time
  - $\Delta\sigma \rightarrow$ EDZ $\rightarrow \Delta k$ and $\Delta\phi$
- Later Time (10 – 1000 yrs)
  - Backfill → intact salt
  - EDZ → intact salt
  - EdZ shrinks significantly



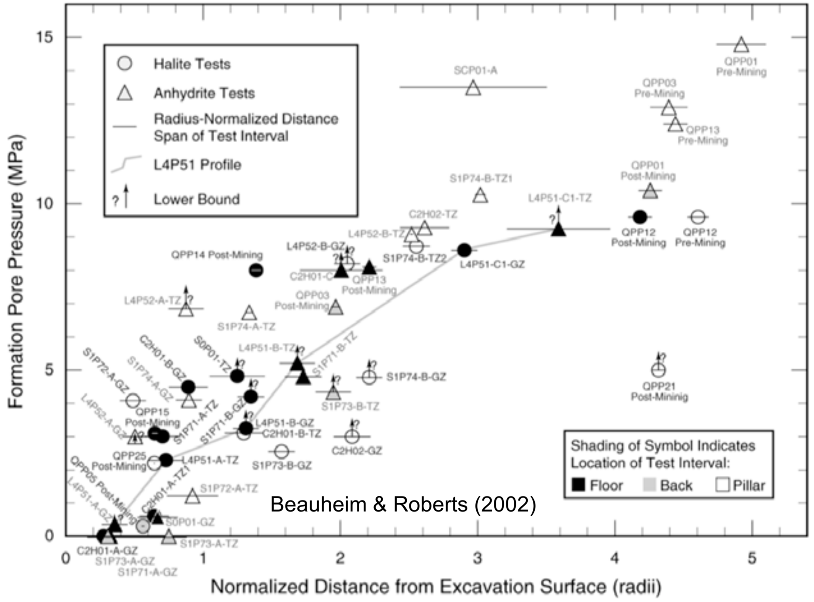




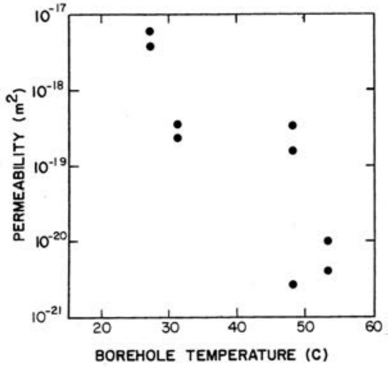
Popp (2019)

Gaps: Understanding Fundamental Processes

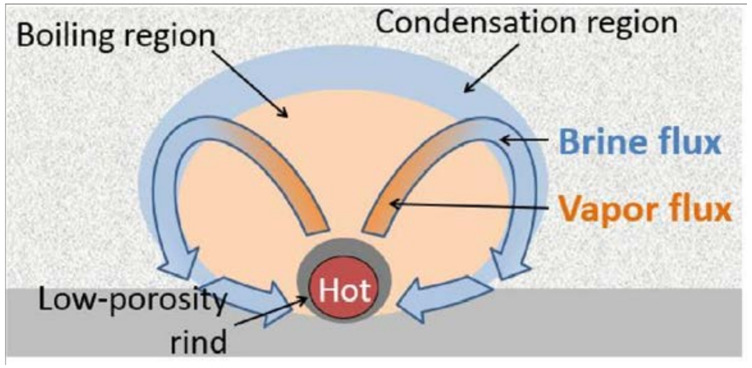
- Safety Assessment Relies on Far-field Properties
- Steep Gradients across EDZ/EdZ
  - Material properties (porosity, permeability)
  - State variables (pore pressure, saturation, stress)
- Early-time Non-linear Predictions
  - Mechanical / thermal / hydrological perturbation
  - Heat pipe in granular salt?
  - Thermal expansion → permeability change
  - Two-phase fracture flow
  - Operations (e.g., ventilation)
  - Dissolution / precipitation modifies
    - Transport properties (k, ϕ, 2-phase flow)
    - Mechanical properties (strength, creep)



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



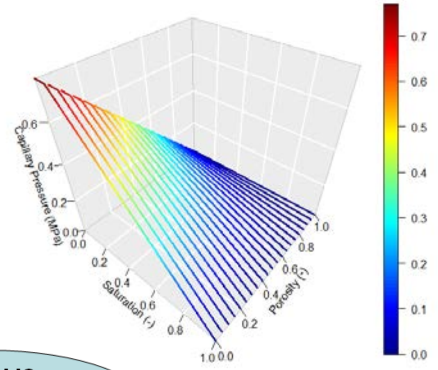
Salt heat pipe conceptual model (Kuhlman, 2019)



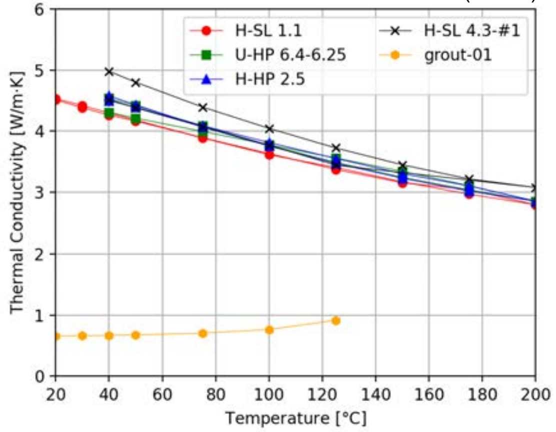
Gaps: State of Conceptual/Numerical Models

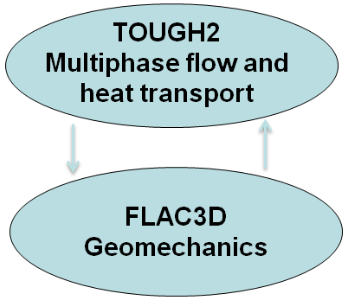
- Far-field Modeling
  - GDSA model (PFLOTRAN)
  - Single-phase flow
  - Minor system perturbation (~linear)
- Non-linear EDZ/EdZ Process Modeling
  - THMC models (TOUGH/FLAC)
  - Appropriate simplifications?
    - Single-phase flow
    - Fractured salt is porous medium
    - Uncouple fast / slow processes
    - Use TH/THC models (PFLOTRAN, FEHM, TOUGH)
  - More work on
    - Constitutive laws *(WEIMOS US/DE collaboration)*
    - Model parameterization (*DECOVALEX 2023*)
    - Complex chemistry and C-M coupling

Johnson et al. (2018)

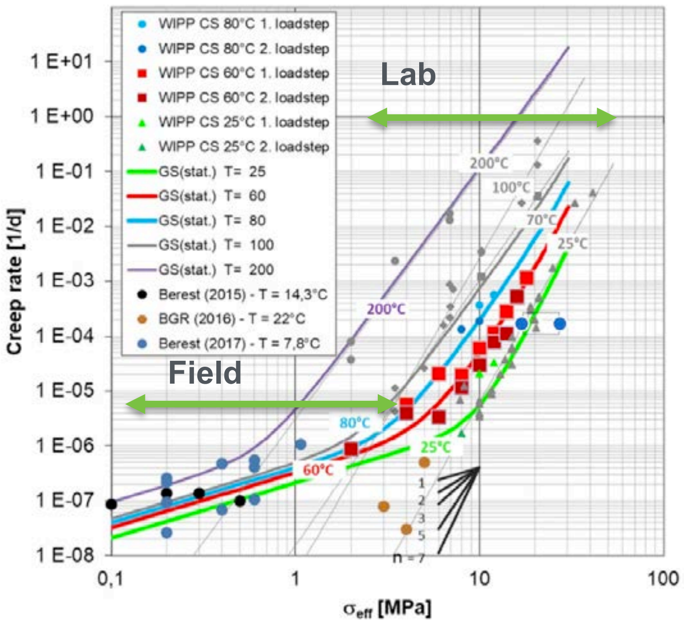


Kuhlman et al. (2020b)





Bérest et al. (2019)



Gaps: Strategy for Safety Assessment in Salt

Q: Does Safety Assessment *Require* Accurate EDZ Predictions?

Option 1: Rely entirely on geological isolation

- 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 EDZ/brine processes

- Heat dries out waste (limits corrosion & transport)
- Heat reduces EDZ porosity/permeability
- Few halophilic microbes (less driving force)
- Heat pipes in granular salt (convection ≫ conduction, ↓ $T_{\max}$)
- Quantify when backfill & EDZ → intact salt

} Understanding EDZ/Brine Processes

Option 3: Fall back on geology, investigate EDZ processes

Gaps: State of Monitoring/Characterization

- Only Open/flowing Fractures in EDZ
- 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
    - Low permeability + creep = difficult testing
    - Flowing brine → changes salt (precipitation / dissolution)
    - Helium “leak testing” methods required
  - Brine corrosive to instrumentation

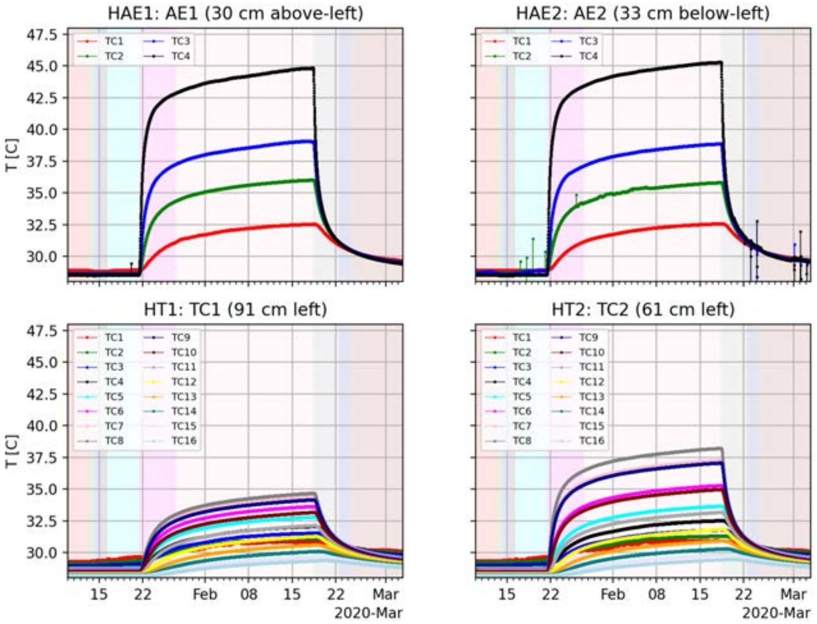
Discrete fractures in BATS near-drift EDZ

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

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
  - In-drift spectroscopy
- Cement Seals Study
  - Cement + Salt + Brine interactions
- Geophysics Mapping
  - “4D” Electrical resistivity tomography
  - Acoustic emissions
- BATS Phases
  - 1a: Jan-Mar 2020 (done)
  - 1b-1c: early 2021 (tracer tests)
  - 2.0: New Boreholes in late 2021
- DECOVALEX 2023 Task E
- 2019 NWTRB Presentation

BATS in WIPP Drift N940 December 2019



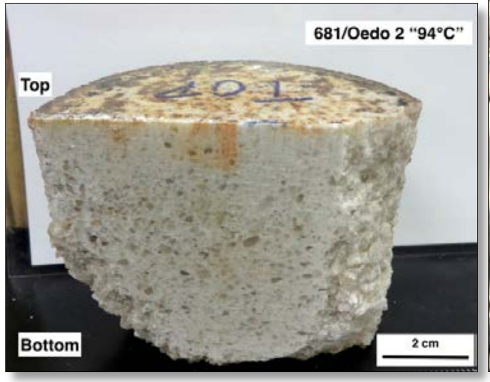
BATS 1a temperature data (Kuhlman et al., 2020b)

BATS team SNL, et al., 2020)

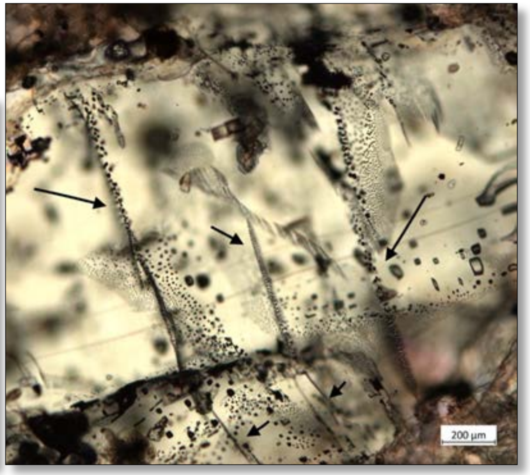
Current R&D: Engineered Barriers Systems

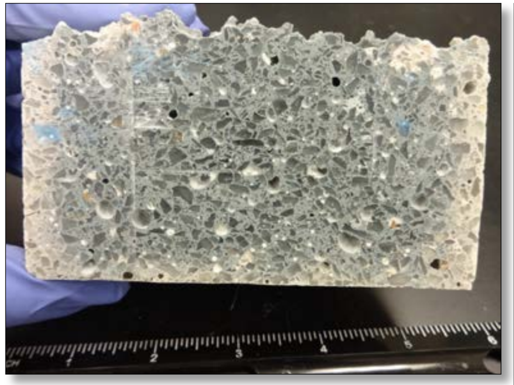
- *RANGERS US/DE Collaboration*: Drift/Shaft Seals
- Run-of-Mine Salt Seals
  - *KOMPASS US/DE collaboration*: granular salt
  - Granular salt reconsolidation: $f(T, \sigma, \text{moisture}, \ldots)$
    - Standardize testing methods
    - Increase reconsolidation rate
  - Time to evolve granular → intact salt
    - Field conditions: $10^1 - 10^3$ 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 salt sample

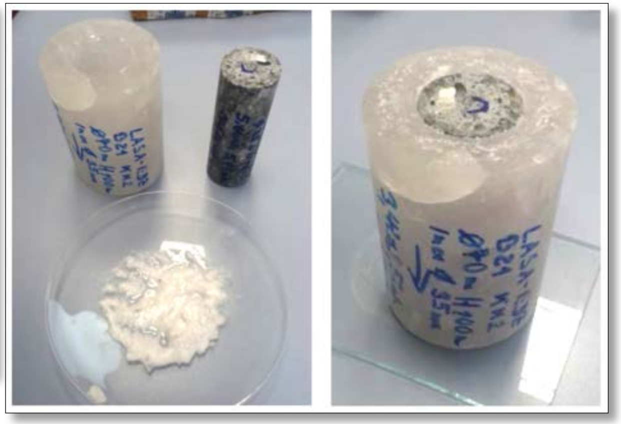


Photomicrographs of KOMPASS Samples (Kuhlman et al., 2020a)





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

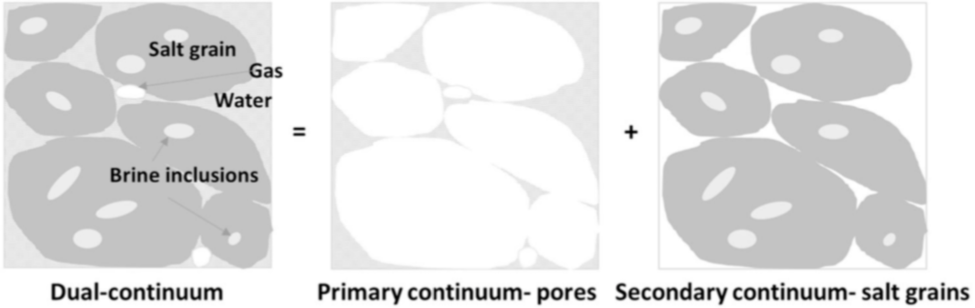


Czaikowski et al. (2016)

Current R&D: Model Development

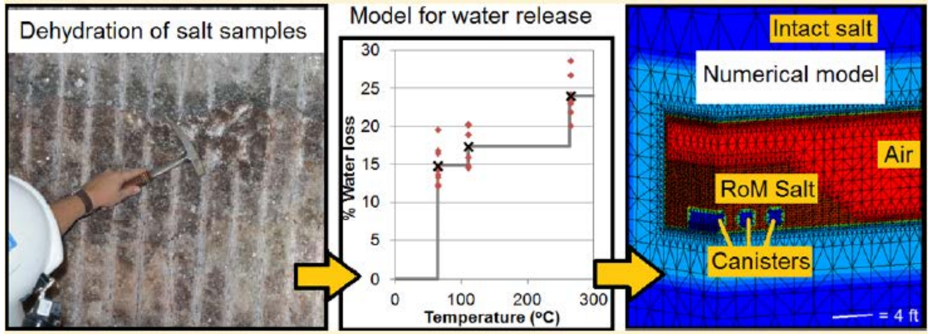
- Improved Processes and Non-linear Coupling in PFLOTRAN (GDSA)
  - Temperature-dependent thermal conductivity (LaForce et al., 2020)
  - Include and improve geomechanical models
- International Benchmarking / Validating Models
  - *DECOVALEX Task E*: BATS heater/brine test
  - *WEIMOS*: mechanical constitutive models
  - *KOMPASS*: granular salt reconsolidation
- Improving Process Models (TOUGH/FEHM)
  - Multicontinuum fluid inclusions
  - Salt dehydration & porosity evolution
  - Two-phase flow (brine + air) in salt
  - Cutting-edge meshing tools
    - LaGriT & VoroCrust

Hu & Rutqvist (2020)



http://vorocrust.sandia.gov

Jordan et al., (2015)

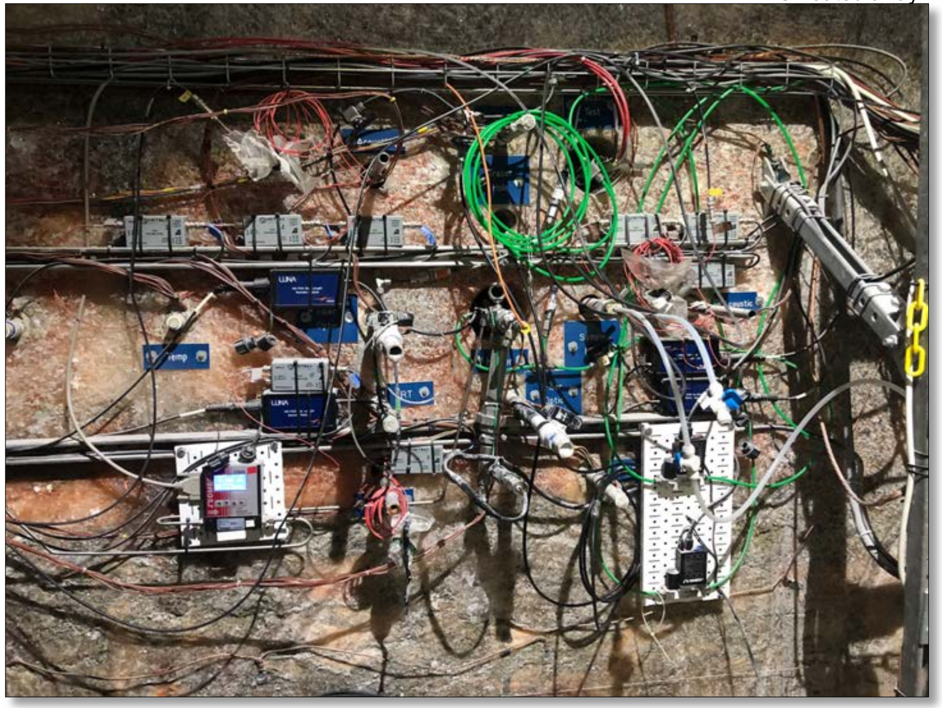


Summary: Prioritization of Salt R&D

Where does work have the greatest impact?

- Lower Priority
  - Far-field salt behavior
  - Large/hot waste packages
- Higher Priority (next 5 years)
  - Drift/shaft seal (RANGERS, KOMPASS)
    - Multi-barrier design
    - Timing of return to far-field conditions
  - Investigating coupled EDZ processes
  - BATS field test at WIPP (DECOVALEX)

BATS heated array



Safety assessment relies on geology, bolstered by EDZ understanding.

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Acronyms and Initialisms

BATS	brine availability test in salt
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 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
PA	performance assessment
PFLOTRAN	Open-source massively parallel GDSA reactive flow and transport simulator
RANGERS	Design and Integrity Guideline for Engineered Barrier Systems for a HLW Repository in Salt
R&D	research and development
SA	safety assessment
SFWST	Spent Fuel & Waste Science & Technology
SNL	Sandia National Laboratories
TH	thermal-hydrological
THC	thermal-hydrological-chemical
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)