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

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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)
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**

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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

- Low porosity ($\phi \leq 0.1 \text{ vol-\%}$) and permeability ($k \leq 10^{-22} \text{ m}^2$)
- High thermal conductivity ($\geq 5 \text{ W/m \cdot K}$)
- High peak temperature ($T_{\text{max}} \approx 200 \text{ °C}$)
- Openings creep closed ($> 10^0 - 10^2 \text{ yr}$)
- Run-of-mine salt heals to intact salt
- No flowing groundwater ($\leq 5 \text{ wt-\% water}$)
- Chlorine ($\geq 190 \text{ g/L}$) $\rightarrow$ reduces criticality concerns
- Hypersaline $\rightarrow$ reduces colloid mobility
- Low water activity ($< 0.75$) $\rightarrow$ biologically simple

Near-field, Short-term Complexities

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

Borns & Stormont (1988)
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$_2$Ca$_2$Mg(SO$_4$)$_4$·2H$_2$O; < 5 vol-%)
4. Intergranular brine (<< 1 vol-%)

Each responds differently to heat & pressure
Intro: General Post-Closure Safety Strategy

- **Release to Biosphere Requires**
  - Solvent (water)
  - Method & driving force
    - Advection: $\Delta$ pressure (closure + gas pressure)
    - Diffusion: $\Delta$ 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 $\rightarrow \Delta$ pressure)
  - Diffusive transport up shaft seals (slow)
  - Human intrusion (by law)
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 $\rightarrow$ intact salt
  - EDZ $\rightarrow$ intact salt
  - EdZ shrinks significantly
Gaps: Understanding Fundamental Processes

- Safety Assessment Relies on Far-field Properties
  - Material properties (porosity, permeability)
  - State variables (pore pressure, saturation, stress)

- Steep Gradients across EDZ/EdZ
  - Mechanical / thermal / hydrological perturbation
  - Heat pipe in granular salt?
  - Thermal expansion → permeability change
  - Two-phase fracture flow
  - Operations (e.g., ventilation)

- Early-time Non-linear Predictions
  - Dissolution / precipitation modifies
    - Transport properties ($k$, $\phi$, 2-phase flow)
    - Mechanical properties (strength, creep)

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Beauheim & Roberts (2002)
Salt heat pipe conceptual model (Kuhlman, 2019)
Avery Island permeability data (Stickney & Van Sambeek, 1984)
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
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

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 $\gg$ conduction, $\downarrow T_{\text{max}}$)
- Quantify when backfill & EDZ $\rightarrow$ intact salt

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 \( k, \phi \)
    - Cannot measure \( k, \phi \) from surface (500 – 1000 m away)
    - Need underground access (i.e., URL)
  - Oil/gas exploration methods ineffective
    - Low permeability + creep = difficult testing
    - Flowing brine \( \rightarrow \) 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
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 \( \rightarrow \) 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
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

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LaForce et al., 2020

Hu & Rutqvist (2020)

Jordan et al., (2015)

http://vorocrust.sandia.gov
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)

*Safety assessment relies on geology, bolstered by EDZ understanding.*
### Acronyms and Initialisms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>BATS</td>
<td>brine availability test in salt</td>
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<tr>
<td>CT</td>
<td>computed tomography</td>
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<tr>
<td>DECOVALEX</td>
<td>Development of Coupled models and their Validation against Experiments</td>
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<tr>
<td>DOE-EM</td>
<td>DOE Office of Environmental Management</td>
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<tr>
<td>DOE-NE</td>
<td>DOE Office of Nuclear Energy</td>
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<tr>
<td>DPC</td>
<td>dual-purpose canisters</td>
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<tr>
<td>EBS</td>
<td>engineered barrier system</td>
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<tr>
<td>EDZ</td>
<td>excavation damaged zone</td>
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<tr>
<td>EdZ</td>
<td>excavation disturbed zone</td>
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<tr>
<td>FEHM</td>
<td>LANL porous media flow and transport simulator</td>
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<tr>
<td>FLAC</td>
<td>Itasca geomechanical simulator</td>
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<tr>
<td>FY</td>
<td>fiscal year (Oct-Sept)</td>
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<tr>
<td>GDSA</td>
<td>geologic disposal safety assessment</td>
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<td>HLW</td>
<td>high-level waste</td>
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<td>KOMPASS</td>
<td>Joint Project on the Compaction of Crushed Salt for Safe Containment</td>
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<td>LaGriT</td>
<td>Los Alamos grid toolbox</td>
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<td>LANL</td>
<td>Los Alamos National Laboratory</td>
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<td>LBNL</td>
<td>Lawrence Berkeley National Laboratory</td>
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<tr>
<td>PA</td>
<td>performance assessment</td>
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<td>PFLOTRAN</td>
<td>Open-source massively parallel GDSA reactive flow and transport simulator</td>
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<td>RANGERS</td>
<td>Design and Integrity Guideline for Engineered Barrier Systems for a HLW Repository in Salt</td>
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<tr>
<td>R&amp;D</td>
<td>research and development</td>
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<td>SA</td>
<td>safety assessment</td>
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<tr>
<td>SFWST</td>
<td>Spent Fuel &amp; Waste Science &amp; Technology</td>
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<tr>
<td>TH</td>
<td>thermal-hydrological</td>
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<tr>
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<td>TOUGH</td>
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<td>VoroCrust</td>
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<td>WIPP</td>
<td>Waste Isolation Pilot Plant (DOE-EM site)</td>
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