Used Fuel Disposition Campaign

Fuel Cycle Technologies
Technical Basis for Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste in Salt

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What is a “Technical Basis”? 
- Achieved through iterative process:
  1. Understand Relevant Processes
  2. Develop Conceptual/Mathematical/Numerical Models
  3. Parameterize/Validate Models with Observations
  4. Quantify Limitations and Uncertainty in Models

Outline:
- Highlights of HLW-related testing in salt
- What has been learned?
- What remains?
Heated Salt In Situ Testing Timeline

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Asse

WIPP

MCC potash

Salt Vault

Avery Island

Kuhlman & Sevougian (2013)
**NAS panel**
- disposal of liquid reprocessing waste in salt domes (Hess et al., 1957)

**U Texas Austin performed early lab testing**
- Uniaxial creep ($\leq 410^\circ C$)
- Cavity closure
- Salt permeability ($k$) testing
  - $He$, brine, and kerosene flow
  - Crystals are impermeable
- Closure observations Grand Saline Mine (Dallas, TX)

**Learned:**
- Early geomechanical tests validated thermo-mechanical theory
ORNL Pre Salt Vault: Hutchinson, KS

**Heated liquid PUREX waste in salt**
- Lab test in 2’ salt blocks (1/10 scale) for 2 months (1959)
- Field test in pits in mine floor (1/5 scale) for 2.5 months (1960)
- Full-scale test in mine floor for 13 months (1961)

**Monitored waste/salt behavior**
- Room + cavity creep closure
- Solids precipitation/deposition
- Corrosion of materials
- Gas generation

**Learned:**
- Direct liquid disposal infeasible due to gas generation & cavity stability
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**ORNL Project Salt Vault: Lyons, KS**

- Lyons AEC solid waste demo
- Hot borehole (July ‘62)
  - Two 5-kW heaters
  - Salt to >350°C (major decrepitation)
- 3 heater test sites (‘65 – ’67)
  - 7 boreholes per site (10.5 kW)
  - Change out radioactive sources
- Heated Pillar Creep (’66 – ’67)
  - Driven by 22 heaters (33 kW)
- Learned:
  - Significant brine from non-salt layers
  - Decrepitation can be issue
  - Brine inclusion migration to heaters
  - Without numerical simulations

布拉德肖 & 麦克莱恩 (1971)
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**OWL/ONWI (RESPEC) Avery Island, LA**

- **Site C heater test ('78 – ’83)**
  - Central + 8 guard heaters (5.6 kW)
  - Heater power constant for 5 years
  - Salt $k$ testing using gas flow
  - Thermal conductivity ($\alpha$) salt/backfill

- **Learned:***
  - $Salt \ k \approx 10^4$ decrease with heating (healing DRZ) due to creep + thermal expansion

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**Figure:**
- Waldman & Stickney (1984)

**Diagram:**
- Personal photo by Wes Deyonge

**Graph:**
- Stickney & Van Sambeek (1984)
- **Brine migration test (’79 – ’80)**
  - Unheated/heated boreholes
  - Tracer test (Deuterium)
- **Gas permeability tests**
  - $k \approx 10^5$ increase during cool down
- **Learned:**
  - Brine inclusion flow not significant (salt is porous medium)
  - $k$ increase @ cooling allows brine flow
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**SNL Lab Test: Salt Block II (‘78 – ’79)**

- 1 m salt cylinder (1700 kg)
- Axially heated/cooled in steps
- High-frequency monitoring
  - Brine inflow to heater borehole
  - Temperature distribution
- Learned:
  - Thermal response simple, brine flow requires new conceptual model

±Temperature changes lead to spikes in brine inflow

Largest spike in brine inflow @ first cool-down step
**SNL Lab Test: Salt Cracker (‘80)**

- **Two 1.6-kg salt cylinders**
- **Heated to 200 & 300 °C**
- **Brine Release Events**
  - Decrepitation (inclusions)
  - Cool down (increase in $k$ and porosity ($n$))
  - Increase in heater power (differential thermal expansion)
- **Learned:**
  - Acoustic emissions reveal salt microfracturing
  - Brine release @ cooling, even after decrepitation

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**Decrepitation**

**Cool-down**

[Hohlfelder et al. (1982)]
SNL Pre-WIPP Potash Mine Tests ('80 – ’81)

- Tests conducted in Miss. Chem. Company Potash Mine before 1st WIPP shaft
- Waste package material testing
- Heater/brine inflow testing
- Instrumentation “dry run” for WIPP
- Learned:
  - Difficulties of working underground

Shefelbine (1982)
Molecke & Torres (1983)
3 Primary SNL DHLW Test Programs
- for future Deaf Smith site

Thermal/Structural Interactions (TSI)
- Rooms A1-A3 (18 W/m² DHLW mockup)
- Room B (DHLW overtest)
- Room H (Heated axisymmetric pillar)
- Room D (Isothermal Room B)

Waste Package Performance (WPP)
- DHLW materials tests in Rooms A1/B
  - Waste Package materials tests
  - Borehole backfill materials tests

Plugging and Sealing Program (PSP)
- Brine release in Rooms A1/B

Many Non-DHLW programs
- TRU tests Rooms J & T, brine flow in Q, etc.

* Tyler et al. (1988) is comprehensive summary of DHLW testing at WIPP

** Jensen et al. (1993) **
**SNL WIPP DHLW: Rooms A/B**

- **A Rooms:** “design” DHLW thermal load (470 W heaters)
- **Room B:** “overtest” conditions (1800 W heaters)
- **4 brine migration boreholes**
- **18 Waste Package Performance tests (7 retrieved)**

**Room B**
- 17 @ 1.8 kW
- 4 @ 4.0 kW
- 8 @ 1.5 kW

**58.6 kW total**

**Rooms A1-A3**
- 34 @ 0.47 kW
- 34 @ 1.41 kW

**63.9 kW total**
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**SNL WIPP DHLW: Rooms A/B/D**

- **Rooms A/B:**
  - Temperature, differential creep, oriented stress (pressure), brine inflow, room closure, heat flux, and heater power.

- **Room D:**
  - Room B geometry w/ room closure obs.

- **Learned:**
  - Roof failure in rooms preceded by rapid closure increase
  - Ti alloy $\rightarrow$ corrosion-resistant canisters

<table>
<thead>
<tr>
<th>Room</th>
<th>Mining</th>
<th>Heat on</th>
<th>Heat off</th>
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<tbody>
<tr>
<td>D</td>
<td>Mar-Apr 1984</td>
<td></td>
<td></td>
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<tr>
<td>B</td>
<td>May-June 1984</td>
<td>Apr 1985</td>
<td>Jan 1989</td>
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Kuhlman et al. (2012)
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SNL WIPP DHLW: Room A2 (‘85–’90)
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**SNL WIPP DHLW: Room B (‘85‐’89)**

Typical WPP DHLW canister in Room B at installation and removal. Creep closure and salt crust deposition required overcoring to remove.

Schuh et al. (2013)
**Brine release:**
- Quantified before and during heating.
- Room B produced $\approx 8 \times$ more brine from same geology @ $\approx 3 \times T$
- Significant brine inflow at Clay F

**Learned:**
- Vapor transport of brine in intact salt is insignificant
- Observed brine inflow consistent with salt rind observed @ heater retrieval.
- Thermo-poro-elasticitic model (McTigue, 1990) consistent with observed heated and isothermal flow (didn’t consider brine inclusions)
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**ANDRA Amélie Tests* (‘87 – ‘94)**

- **Heated borehole consolidation of crushed salt (‘87–’88)**
  - 5-boreholes: different grain-size distributions
    - 1.6 & 2.2-kW heaters

- **Borehole heater test (CPPS) (‘91–’93)**
  - 4-kW heater in 7-m borehole
  - Reached 200°C max T at heater
  - 7 months of heating

- **Gas/brine permeability tests (‘94)**

**Learned:**
- No backfill complicated heat transfer, while crushed salt simplified it
- Viscoplasticity model needed to explain brine flow under some conditions

* Kazan & Ghoreychi (1997) and Ghoreychi et al., (1992) are English-language summaries of this work.
Asse II Mine

**Borehole heater tests 1–6 (‘68 – ’85)**
- Early tests to
  - *Determine in situ thermal properties of halite / crushed salt*
  - *Demonstrate heater, thermocouple, and brine collection systems*
  - *Demonstrate geophysical methods to interrogate heated salt (Kessels et al., 1986)*

**Heated deep borehole closure (‘79 – ’82)**
- Closure data (calipers) inside borehole during heating (Doeven et al., 1983)

**Heated Brine Migration test (‘83 – ’85)**

**High Activity Waste (HAW) heater test (‘88 – ’94)**

**Crushed Salt Reconsolidation**
- Heated drift backfilled with crushed salt: TSDE (‘90 – ’04)
- Heated vertical boreholes: DEBORA-1/2 (‘97 – ’98)
Heated 4 borehole sets (‘83 – ’85):
- 2 with $^{60}$Co sources
- 2 sealed (vs. 1 atm)

Measured
- Closure, Temperature
- Brine inflow
- Borehole gas content
- Acoustic emissions

90% of brine collected during cooling

Learned:
- Mechanical similar to bedded, brine flow $\ll$ bedded
- Radiation had minimal effect
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- Abandoned 8-borehole High Activity Waste demonstration
- 2 electrically heated boreholes
  - A1 & B1 heated '88 – '92
- Excavated B1 for corrosion study

Bechthold et al. (1995)
**Asse Borehole Salt Reconsolidation**

- **Measured**
  - Corrosion,
  - Temperature, pressure,
  - Borehole convergence,
  - Crushed salt $k$ & $n$

- **DEBORA-1 (’97 – ’98)**
  - 9-kW heater *in* 15-m borehole

- **DEBORA-2 (’97 – ’98)**
  - 15-kW heaters *around* 15-m borehole

- **Learned:**
  - Crushed salt reconsolidated significantly in months in boreholes

**DEBORA-1**
- $n$: 38% → 9%
- $k$: $5 \times 10^{-12}$ → $7 \times 10^{-14}$ m²

**DEBORA-2**
- $n$: 37% → 12%
- $k$: $1 \times 10^{-10}$ → $4 \times 10^{-13}$ m²

Bechthold et al. (1999)
Asse In-Drift Salt Reconsolidation

- **Thermal Simulation of Drift Emplacement (TSDE)**
- **Six Pollux casks**
  - 1.5 m × 5 m
  - 6.4-kW heaters
- **Backfilled to roof**
- **Large thermal-mechanical time series collected**
- **Post-test excavation data**
- **Learned:**
  - Crushed salt reconsolidation less than in boreholes
  - Extensive in situ validation dataset

BAMBUS (Bechthold et al., 1999)
BAMBUS II (Bechthold et al., 2004)
**Heater T decreased (at constant power)**
- Backfill $\alpha$ increasing with decreasing porosity
- Non-linear thermal conductivity: $\alpha(T) \approx \alpha_0(T-T_0)^{-1.1}$

**Steady-state T reached near heaters (but not at roof)**
Technical Basis for HLW in Salt Disposition

- **Salt Vault presented 1st safety case for HLW in salt (1971)**
  - Culmination of 10+ years of laboratory and field testing
  - Bradshaw & McClain (1971) summarized technical basis
  - AEC proposed Lyons, KS as pilot-scale site for heat-generating waste

- **NRC Summary**
  - Geoscience database for nuclear waste repositories (salt, granite, clay) (Isherwood, 1981)

- **Deaf Smith Site Characterization Plan (DOE, 1988; 10 vol.)**
  - Regional site description
  - Salt properties determined from core & other sites
  - Site Investigation Plan (very detailed)

- **Gorleben safety case: ISIBEL project (2006—2010)**
  - Site characterization
  - Disposal system design
  - Weber et al. (2011) summarized safety case.

- **Recent UFD/SNL historical testing and technical basis summaries**
  - Kuhlman et al. (2012), Kuhlman & Malama (2013), Kuhlman & Sevougian (2013)
**Technical Basis for HLW in Salt**

**Technical basis for heat-generating waste in salt is not new**

**Thermal-mechanical behavior is well known**

**Modern numerical models**
- Allow non-linear and coupled processes
- Must be benchmarked against data
- Not technical basis, but important tools

**Long-term viability of salt repository:**
- Salt deposit provides long-term containment
- Shaft seals ensure containment uncompromised
  - Seal emplacement
  - Reconsolidation of backfill
- Other repository features of secondary safety case importance
  - Waste forms/waste packages
  - Brine migration into and through excavation

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<thead>
<tr>
<th>Test Locale</th>
<th>Bedded vs. Domal</th>
<th>Crushed vs. Intact</th>
<th>Borehole vs. In-Drift</th>
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</thead>
<tbody>
<tr>
<td>Salt Vault</td>
<td>B</td>
<td>I</td>
<td>B</td>
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<tr>
<td>Avery Island</td>
<td>D</td>
<td>I</td>
<td>B</td>
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<tr>
<td>WIPP DHLW</td>
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<td>Amélie</td>
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<td>?</td>
<td>B</td>
<td>C</td>
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References


Hohlfelder, J.J. Salt Block II: Description and results. SAND79-2226, Sandia National Laboratories, 1980.


