Used Fuel Disposition Campaign

Fuel Cycle Technologies

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

Kristopher L. Kuhlman
Sandia National Laboratories

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Technical Basis for HLW in Salt

- ***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?*

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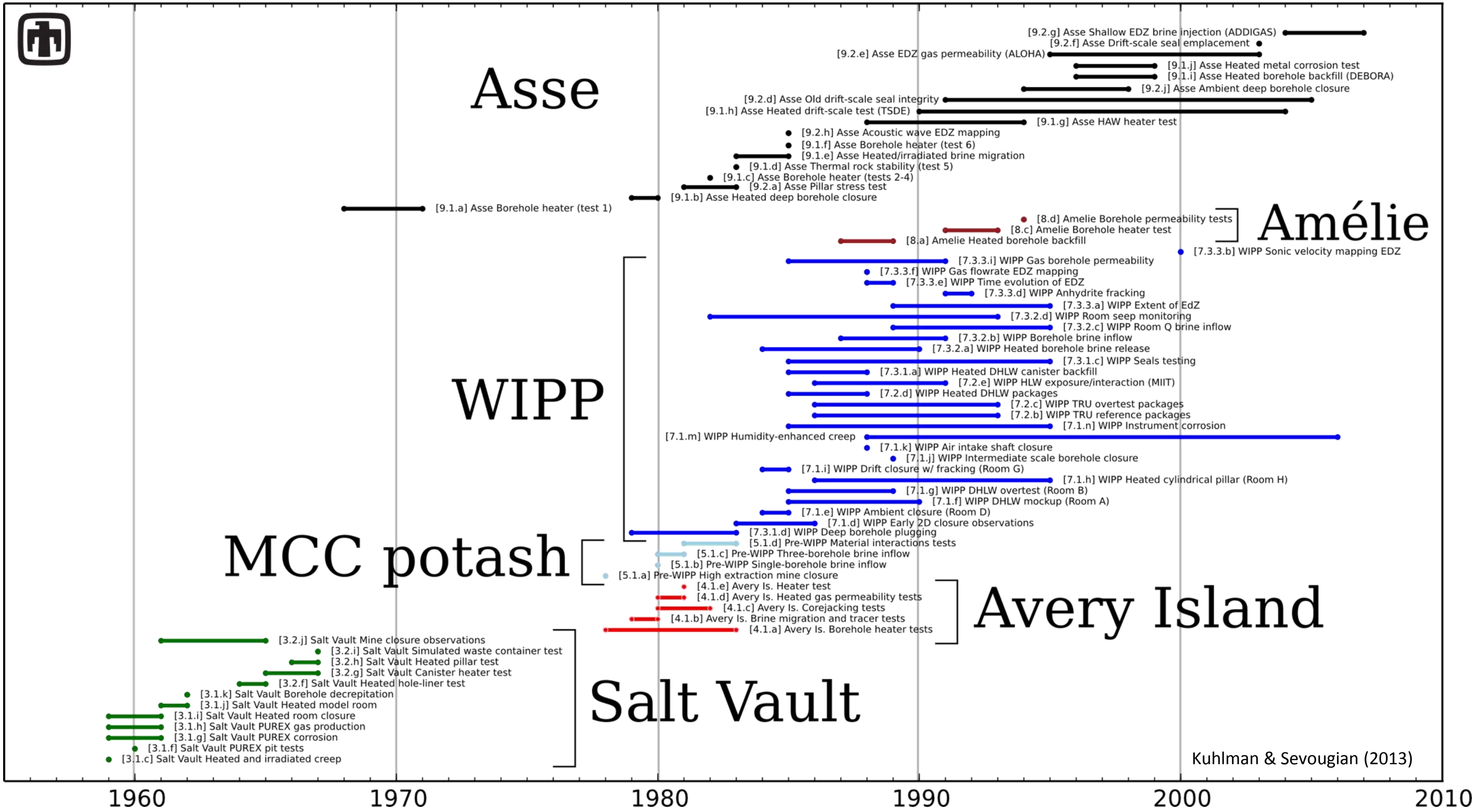
Heated Salt In Situ Testing Timeline



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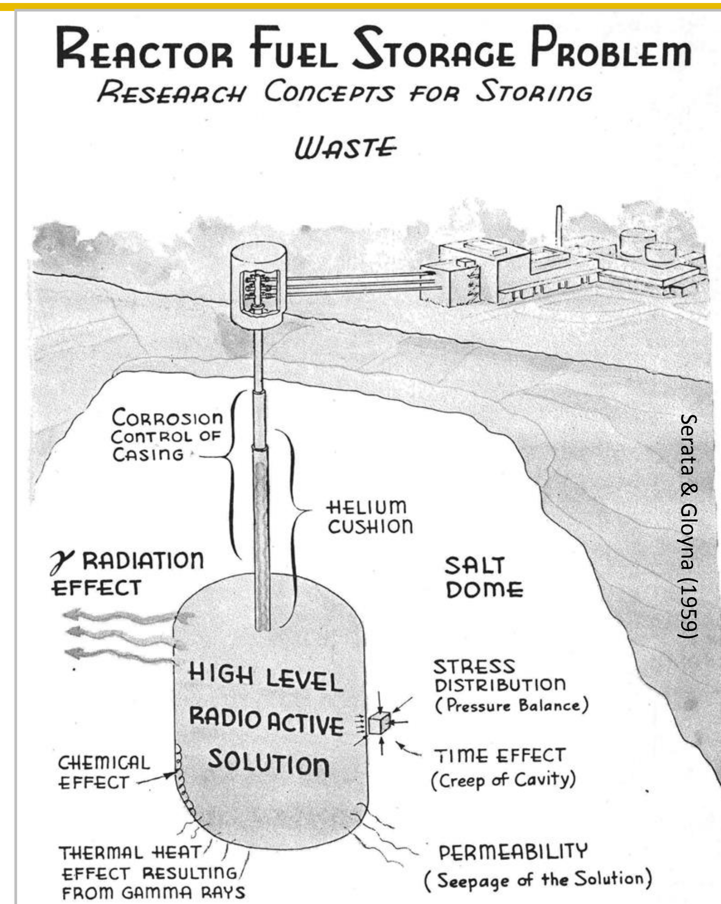
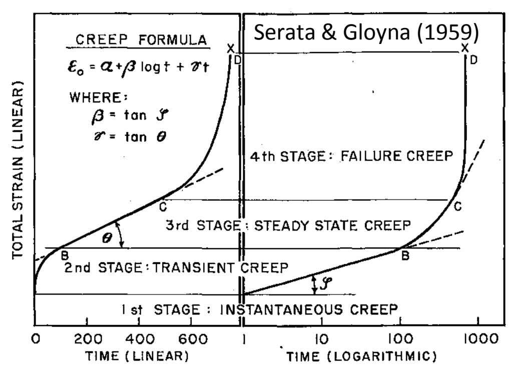
U Texas Lab Testing

- **_NAS panel_**
  - disposal of liquid reprocessing waste in salt domes (Hess et al., 1957)
- **_U Texas Austin performed early lab testing_**
  - Uniaxial creep (≤ 410° 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*





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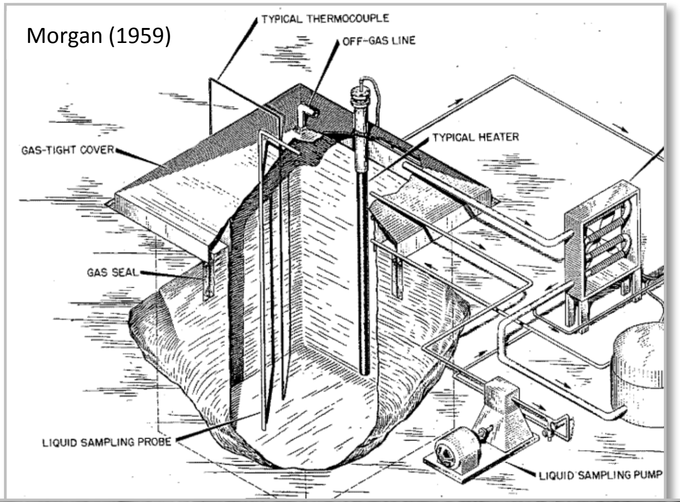
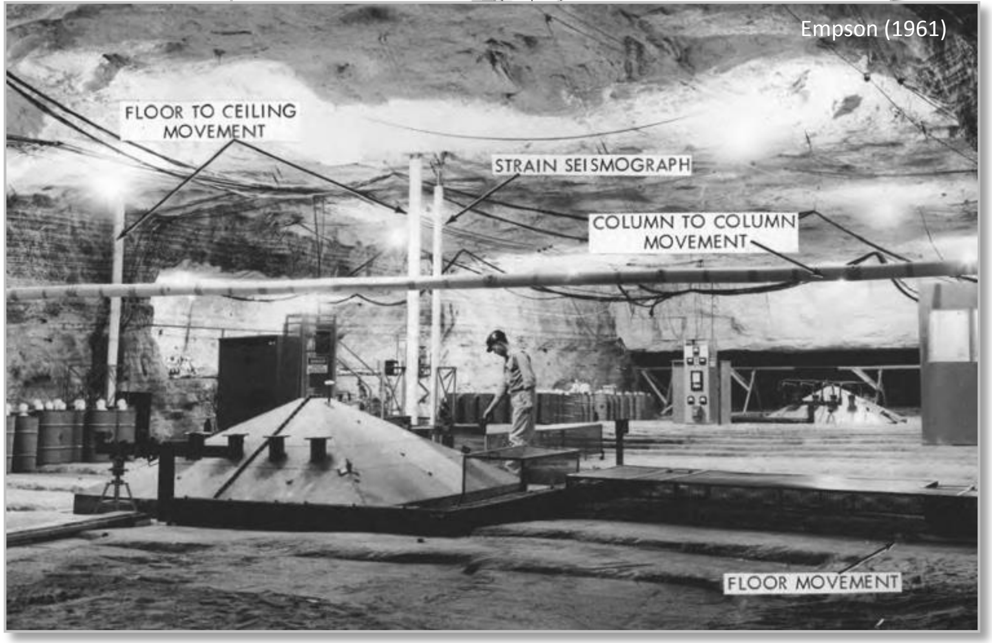
ORNL Pre Salt Vault: Hutchinson, KS

- ***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*

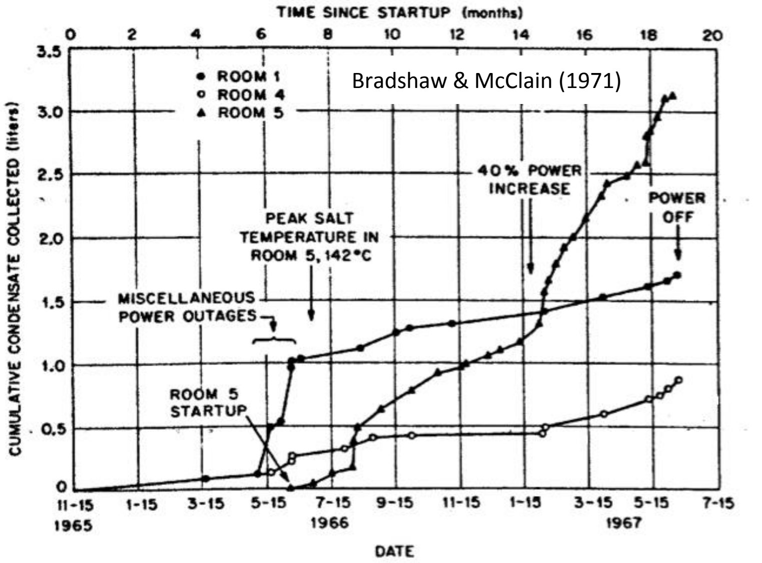




ORNL Project Salt Vault: Lyons, KS

- ***Lyons AEC solid waste demo***
- ***Hot borehole (July '62)***
  - *Two 5-kW heaters*
  - *Salt to >350^o 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*


Bradshaw & McClain (1971)



Bradshaw & McClain (1971)

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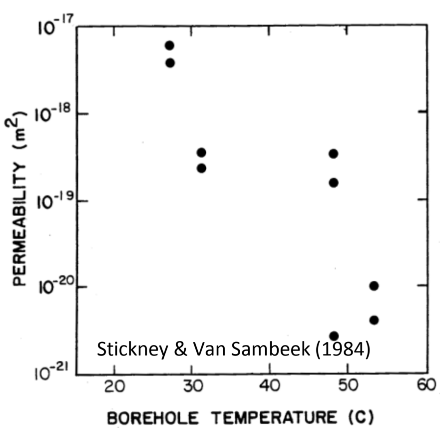
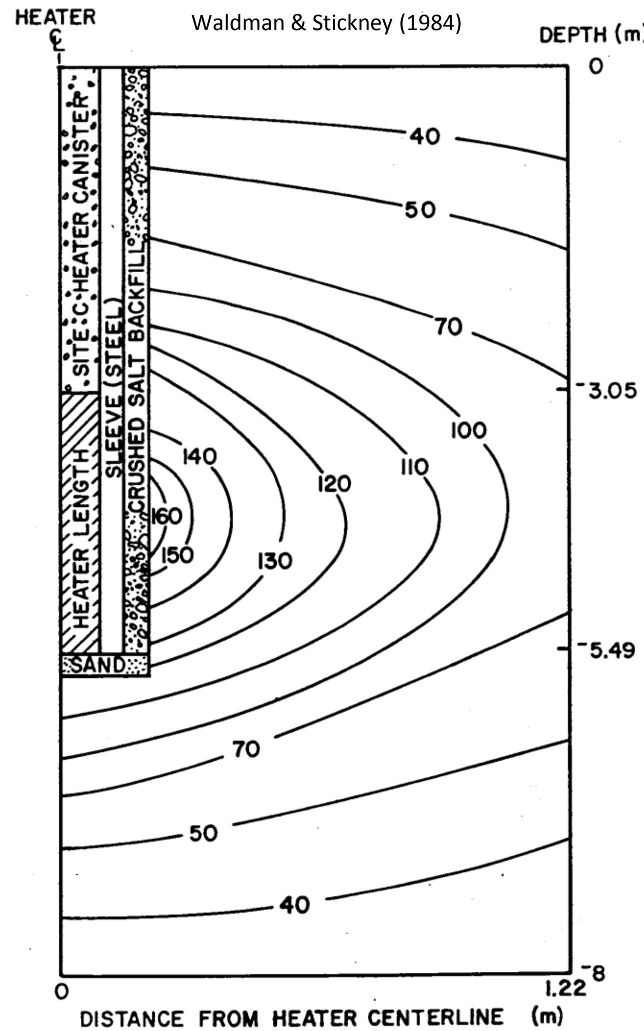
OWI/ONWI (RESPEC) Avery Island, LA

- ***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 (*α*) salt/backfill
- ***Learned:***
  - *Salt k ≈10^4 decrease with heating (healing DRZ) due to creep + thermal expansion*



Stickney & Van Sambeek (1984)

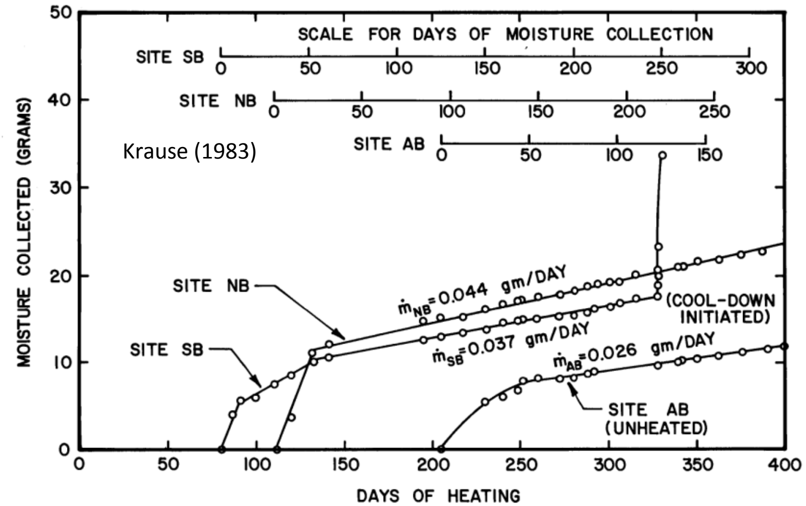

Personal photo by Wes Deyonge

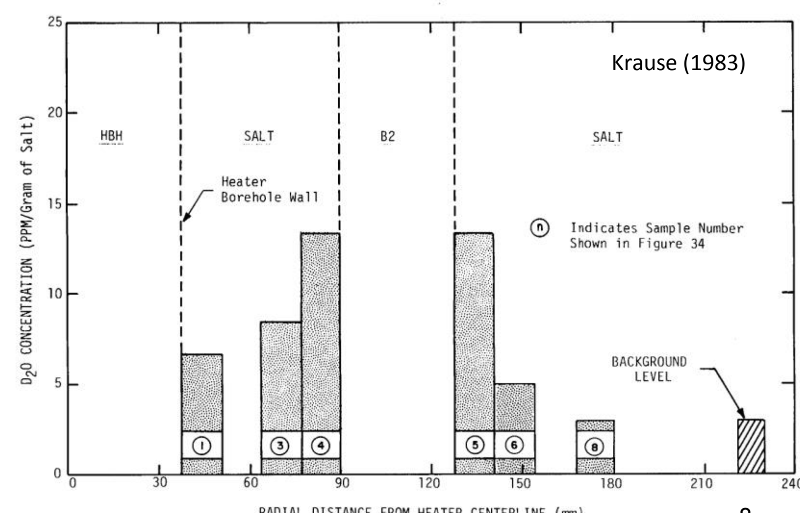


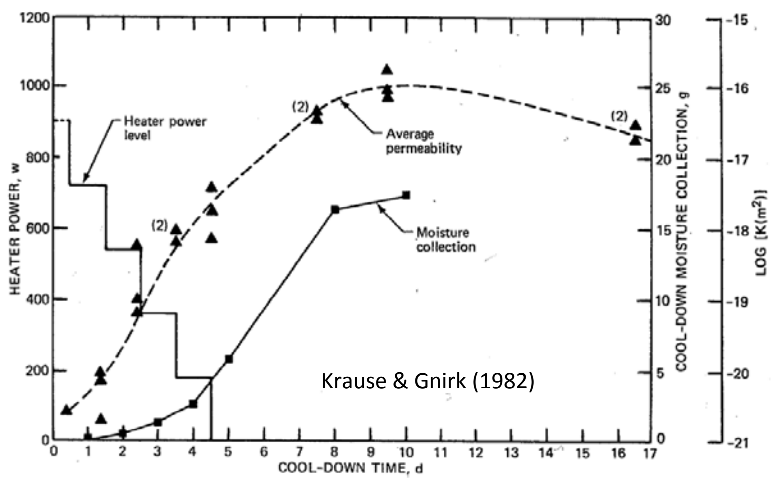
Waldman & Stickney (1984)

OWI/ONWI (RESPEC) Avery Island, LA

- ***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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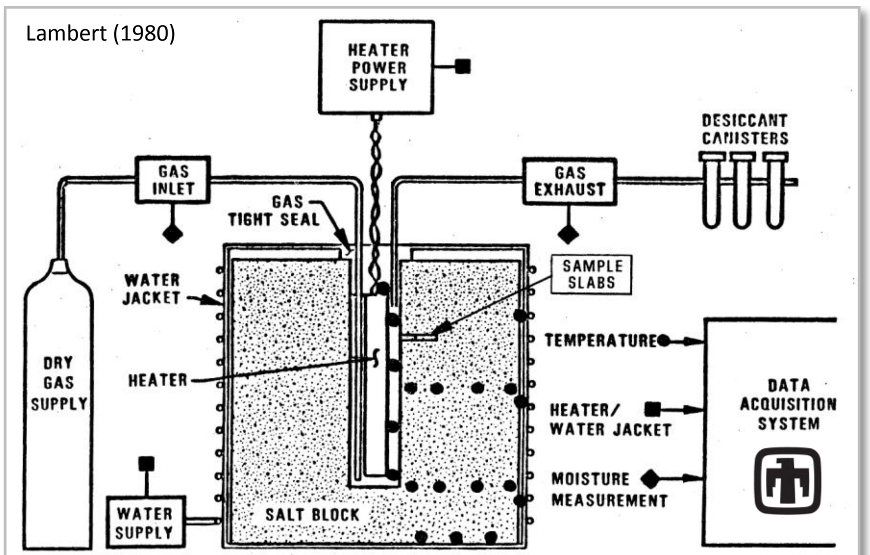
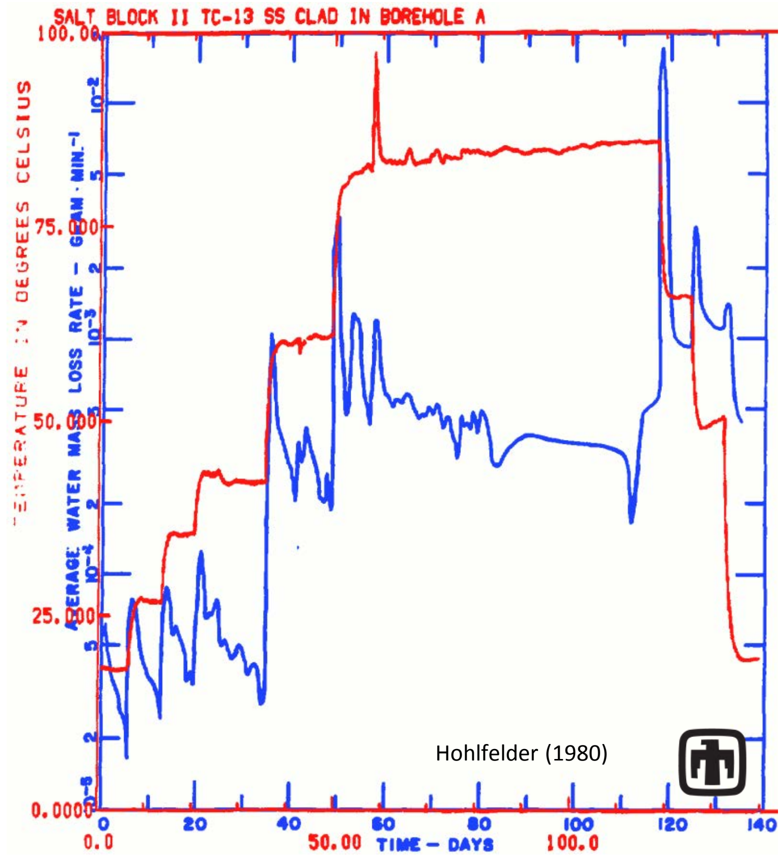
SNL Lab Test: Salt Block II (‘78 – ’79)

- ***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*



Lambert (1980)



Hohlfelder (1980)

±Temperature changes lead to spikes in brine inflow

Largest spike in brine inflow @ first cool-down step

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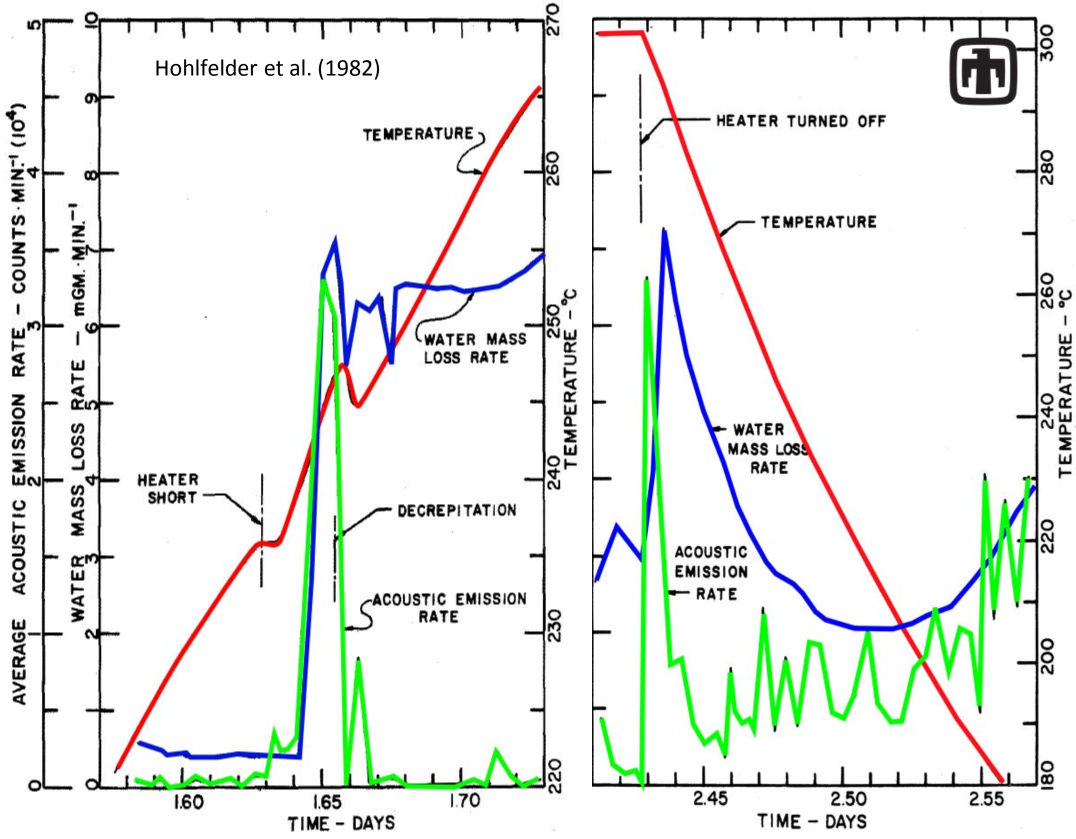
SNL Lab Test: Salt Cracker ('80)

- ***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*

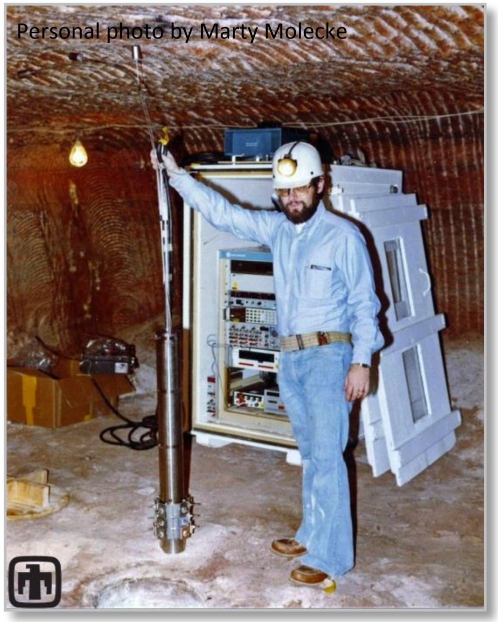
Decrepitation *Cool-down*

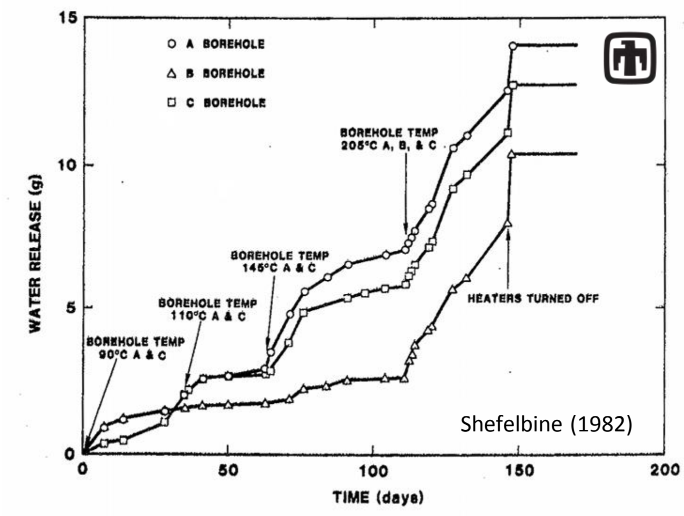


Used Fuel Disposition

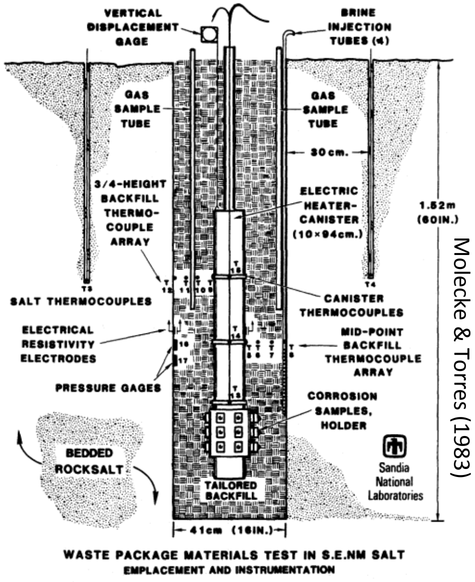
SNL Pre-WIPP Potash Mine Tests ('80 – '81)

- ***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*

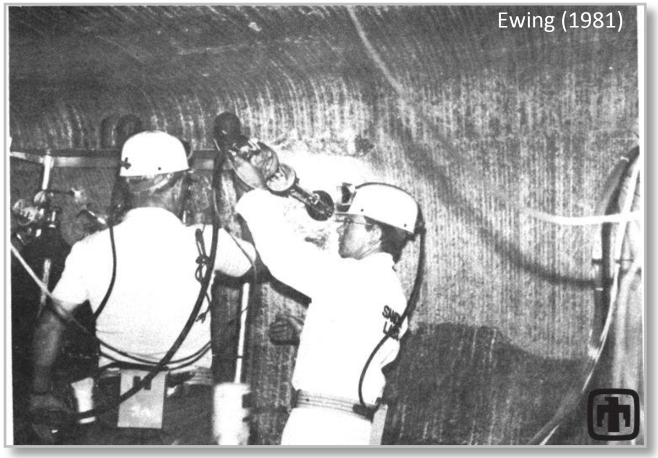

Personal photo by Marty Molecke



Shefelbine (1982)



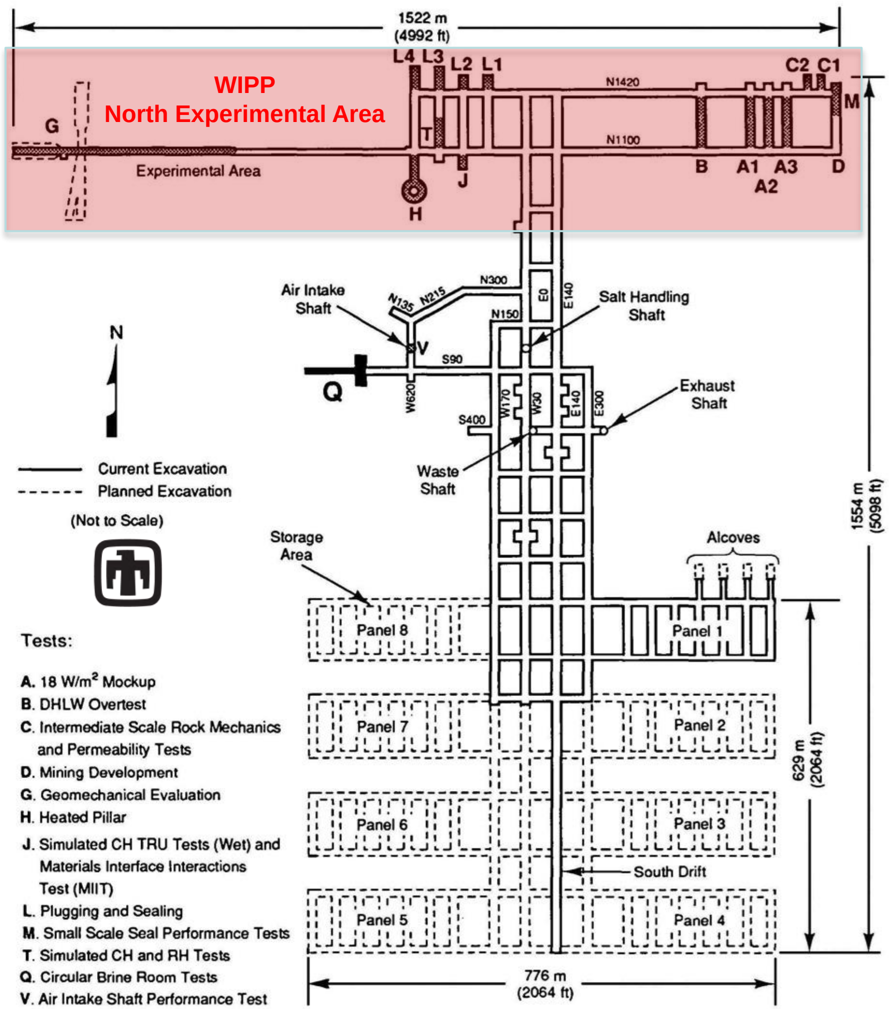
Molecke & Torres (1983)


Ewing (1981)

Used Fuel Disposition

*Waste Isolation Pilot Plant (WIPP)**

- ***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.



Jensen et al. (1993)

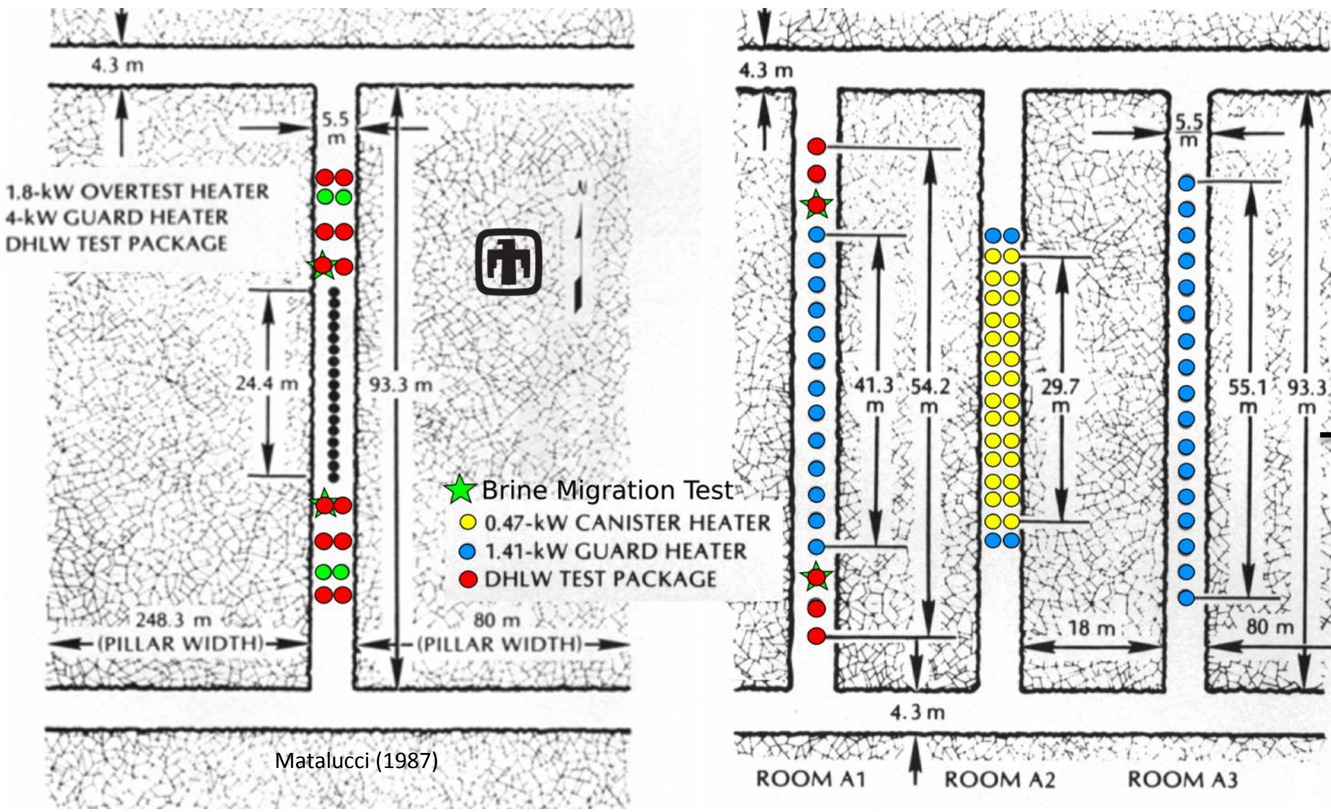
* Tyler et al. (1988) is comprehensive summary of DHLW testing at WIPP

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



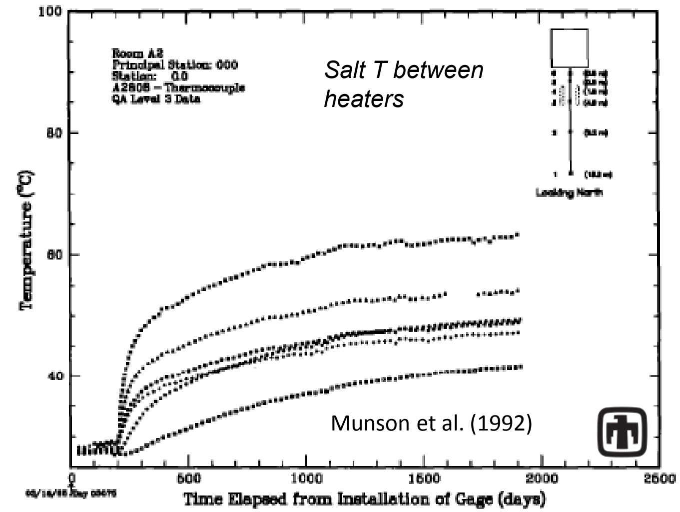
Matalucci (1987)

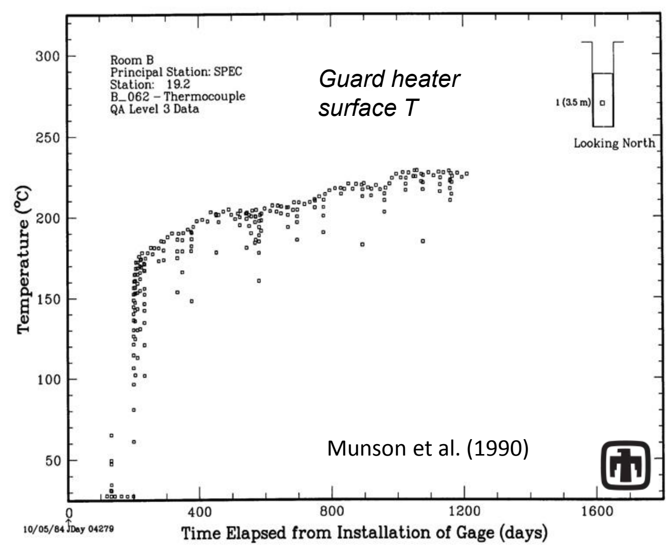
Rooms A1-A3
34 @ 0.47 kW
34 @ 1.41 kW

63.9 kW total

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 ➞ corrosion-resistant canisters*



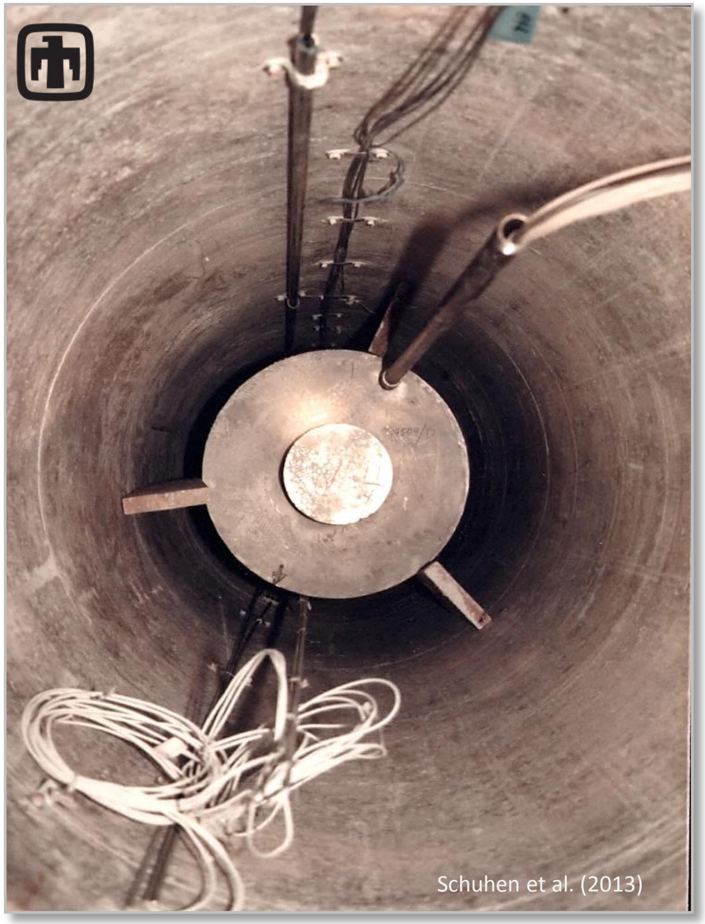


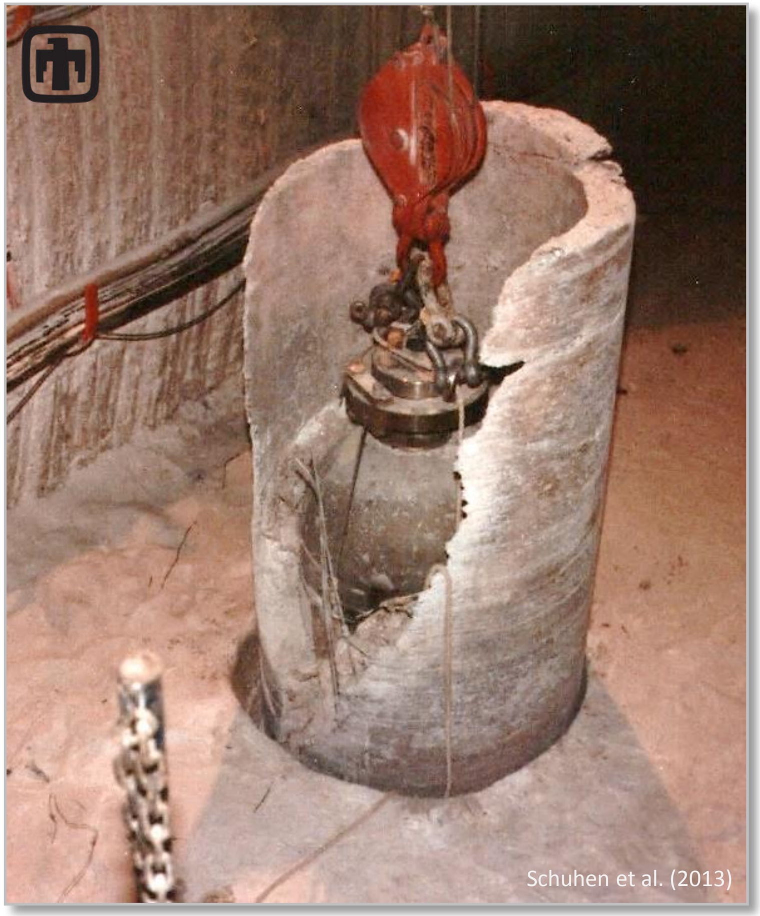
Room	Mining	Heat on	Heat off
D	Mar-Apr 1984		
B	May-June 1984	Apr 1985	Jan 1989
A2	June-July 1984	Oct 1985	Jun 1990
A1	Sep-Oct 1984	Oct 1985	July 1990
A3	Oct-Nov 1984	Oct 1985	Aug 1990

Kuhlman et al. (2012)

SNL WIPP DHLW: Room A2 ('85-'90)

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

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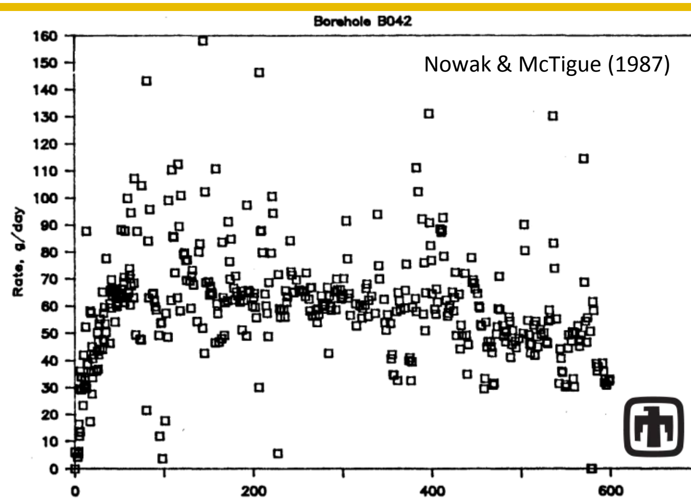
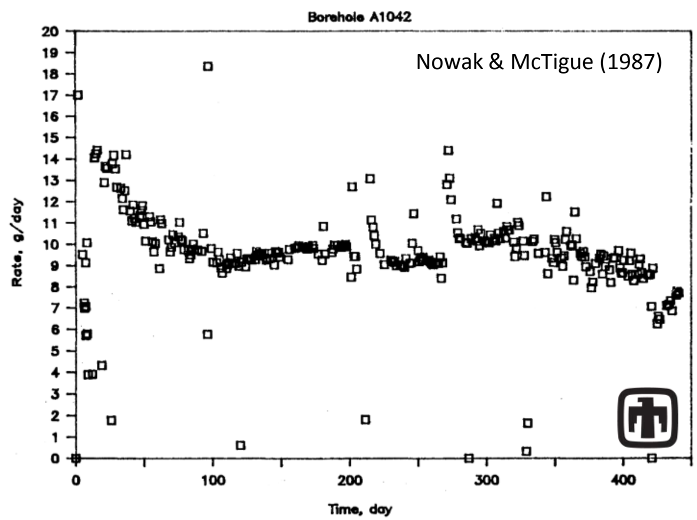
SNL WIPP DHLW: A1/B Brine Release

- ***Brine release:***
  - Quantified before and during heating.
  - Room B produced ≈8× more brine from same geology @ ≈3× *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)*



Room B: 130° C, 35 L brine/borehole
Room A1: 50° C, 4.5 L brine/borehole



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^{o} 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)

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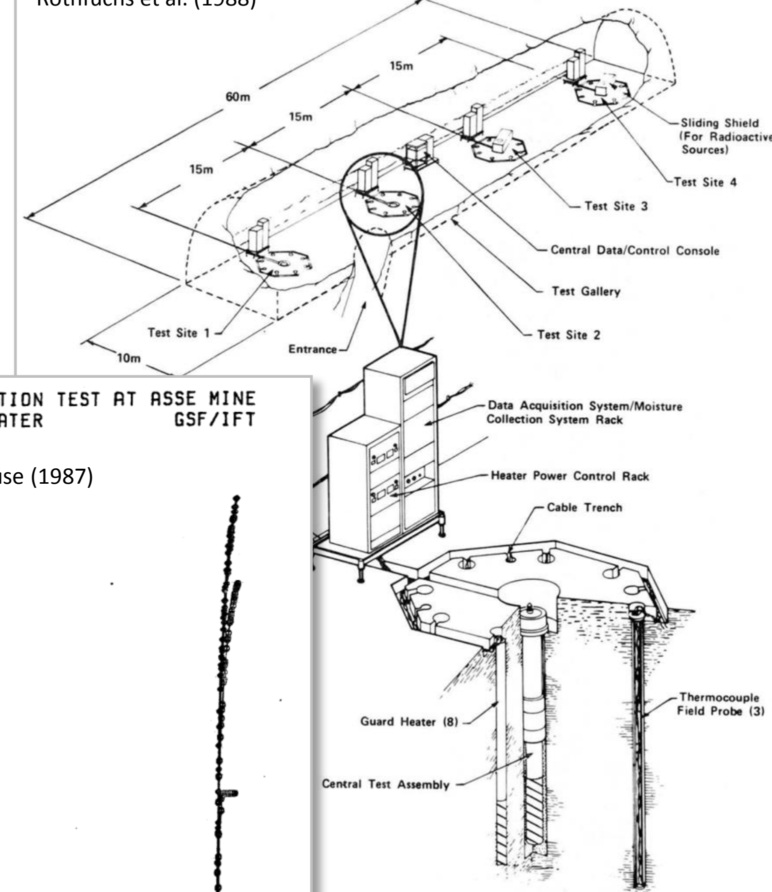
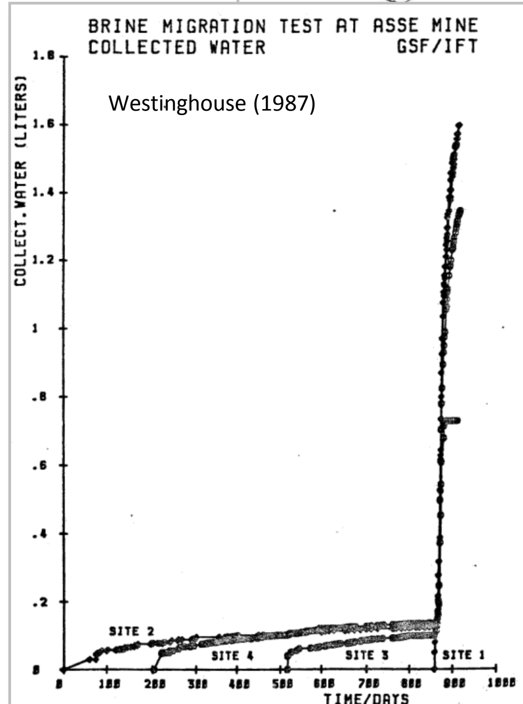
Asse Brine Migration

- ***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 ≪ bedded*
  - *Radiation had minimal effect*



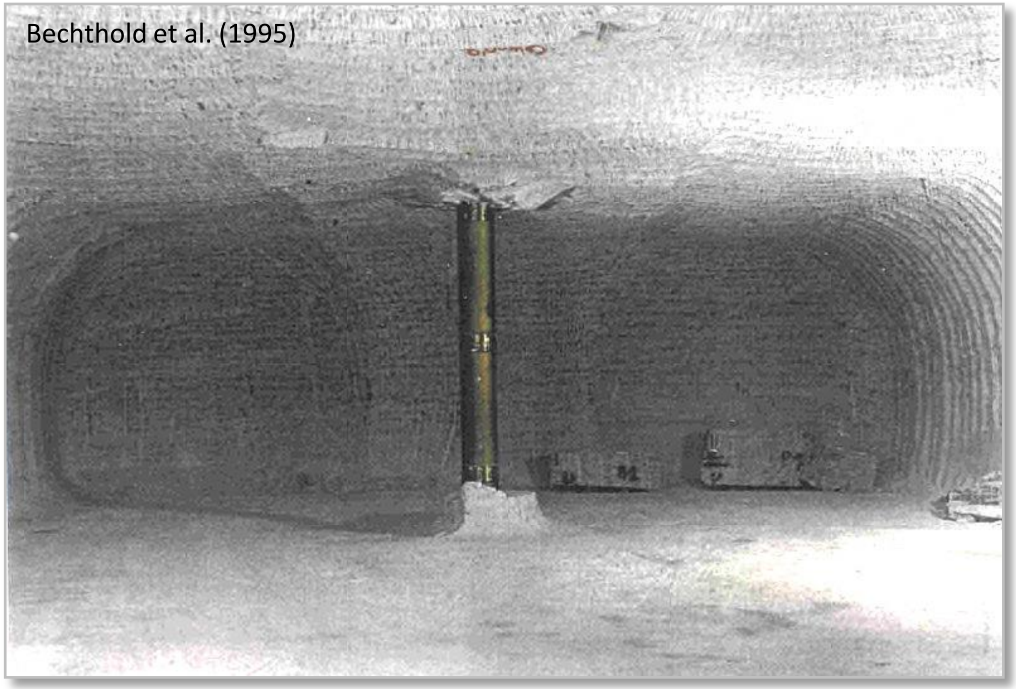
Rothfuchs et al. (1988)

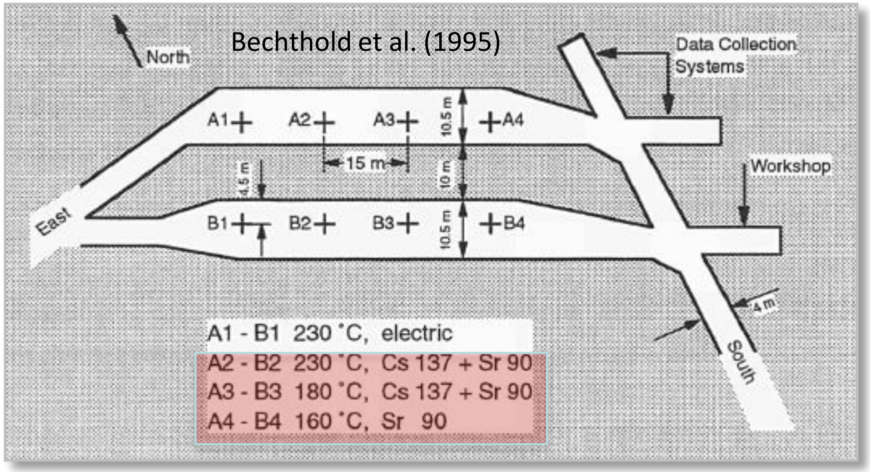


Westinghouse (1987)

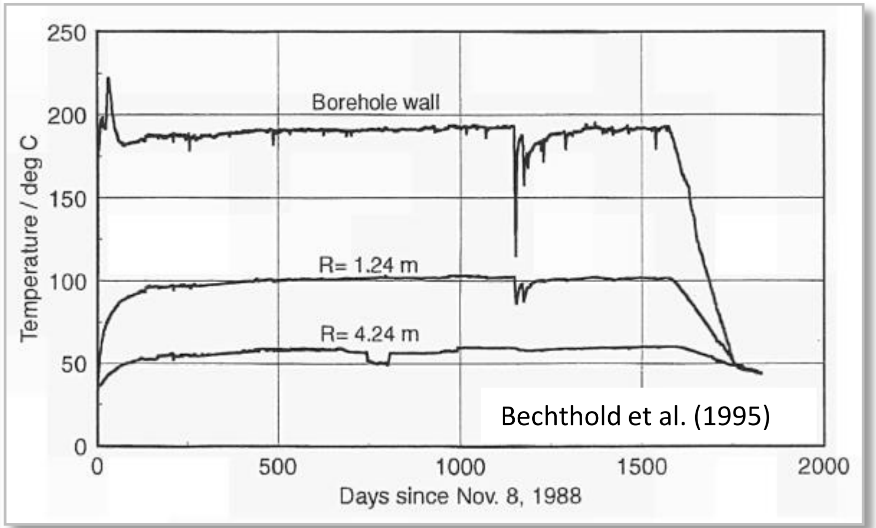
Asse HAW Heater Tests

- ***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)



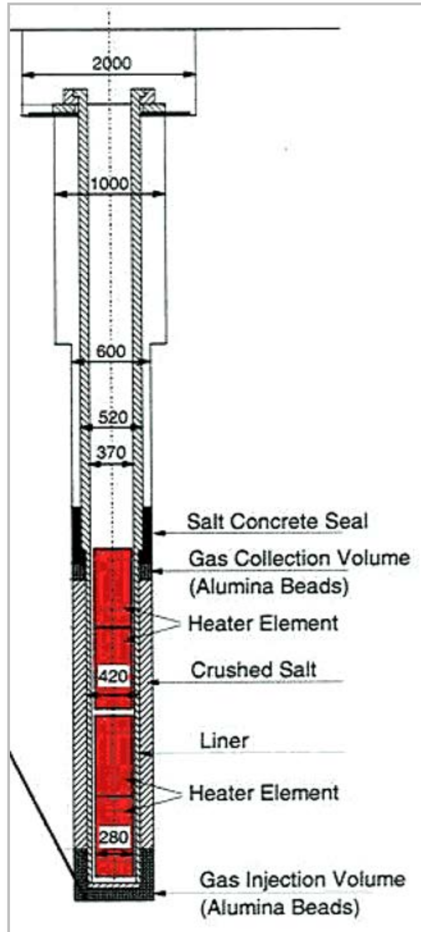
Bechthold et al. (1995)



Bechthold et al. (1995)

Asse Borehole Salt Reconsolidation

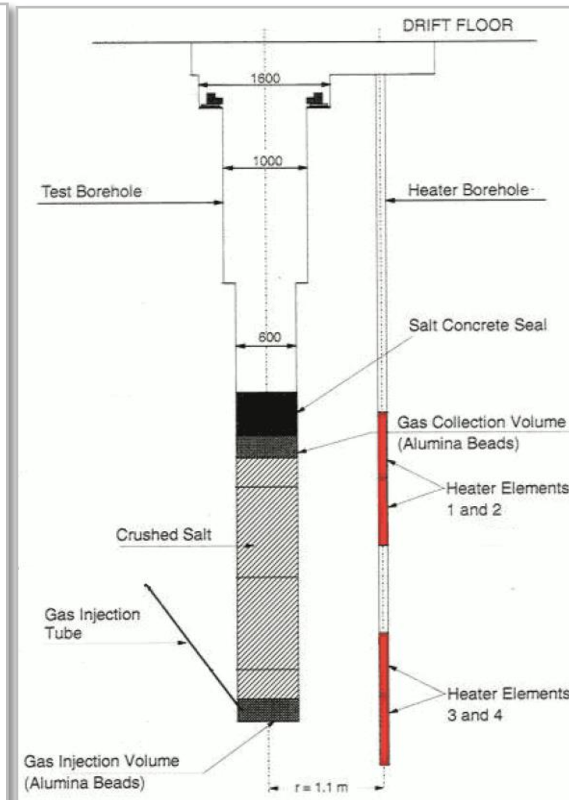
- ***Measured***
  - Corrosion,
  - Temperature, pressure,
  - Borehole convergence,
  - Crushed salt *k* & *n*
- ***DEBORA-1 ('97 – '98)***
  - 9-kW heater *in* 15-m borehole
- ***DEBORA-2 ('97 – '98)***
  - 15-kW heaters *around* 15-m borehole
- ***Learned:***
  - *Crushed salt reconsolidated significantly in months in boreholes*



DEBORA-1

n: 38% → 9%

k: $5{\times}10^{-12} \rightarrow 7{\times}10^{-14}$ m^2



DEBORA-2

n: 37% → 12%

k: $1{\times}10^{-10} \rightarrow 4{\times}10^{-13}$ m^2

Bechthold et al. (1999)

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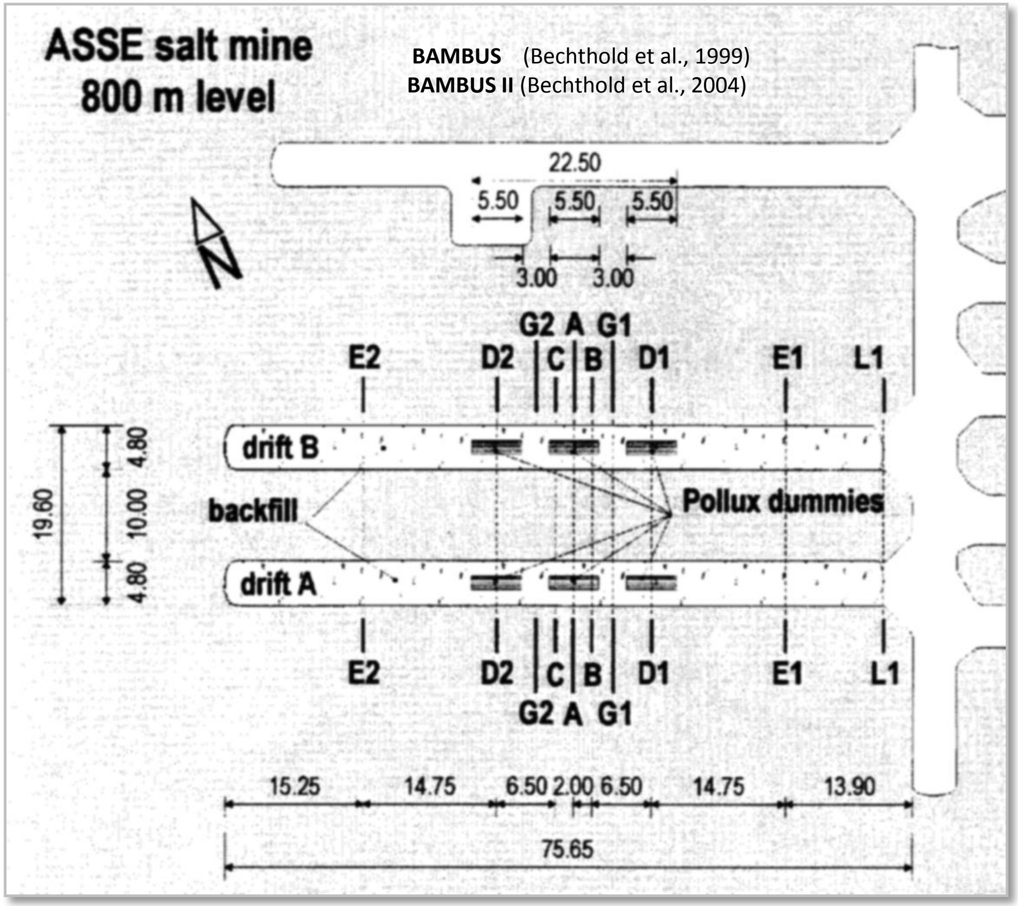
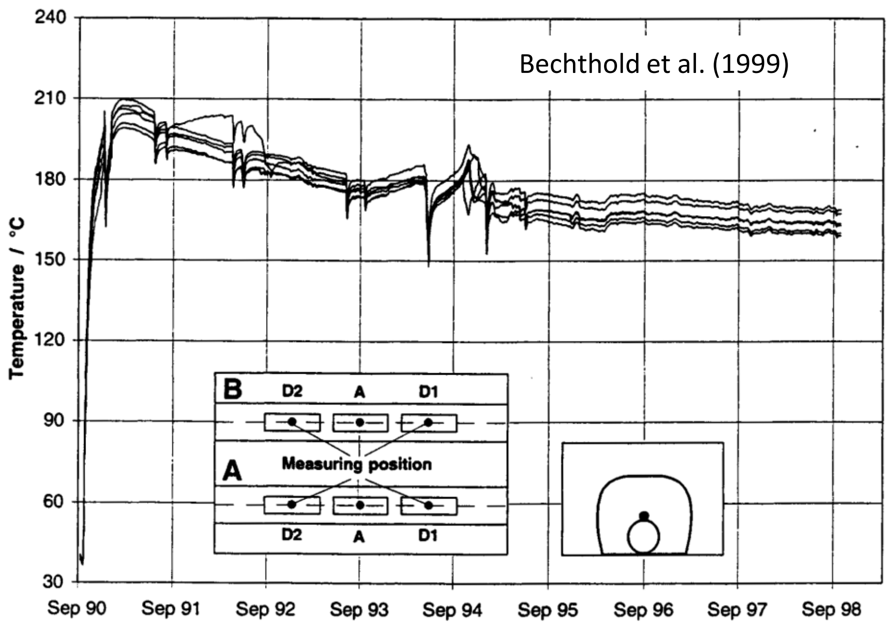
Asse In-Drift Salt Reconsolidation

- ***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*

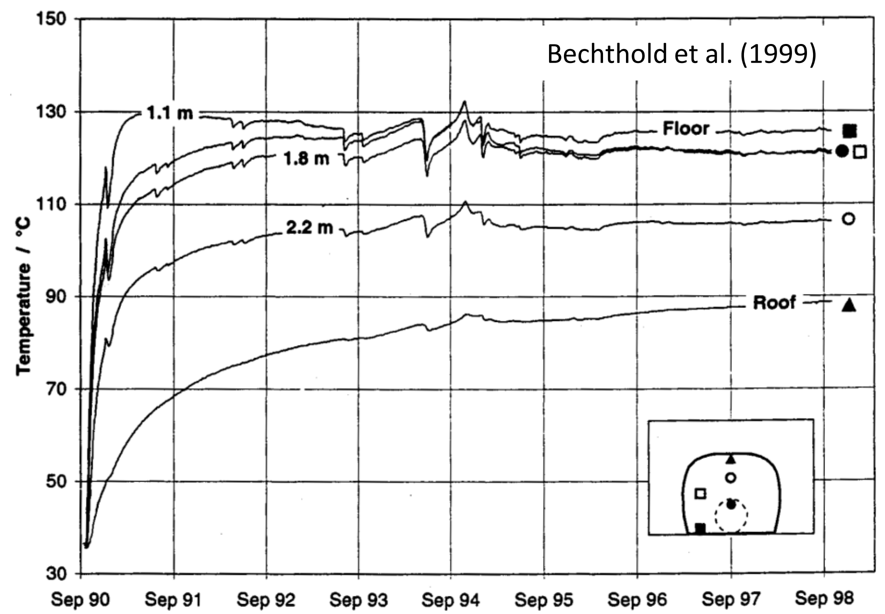


Asse TSDE Timeseries Observations

- ***Heater T decreased (at constant power)***
  - Backfill α 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)***



Cask temperature



Backfill temperature

Technical Basis for HLW in Salt

- ***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*

Test Locale	Bedded vs. Domal	Crushed vs. Intact	Borehole vs. In-Drift
Salt Vault	B	I	B
Avery Island	D	I	B
WIPP DHLW	B	I	B
Amélie	B	C + I	B
Asse	D	C + I	B + D
?	B	C	D

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