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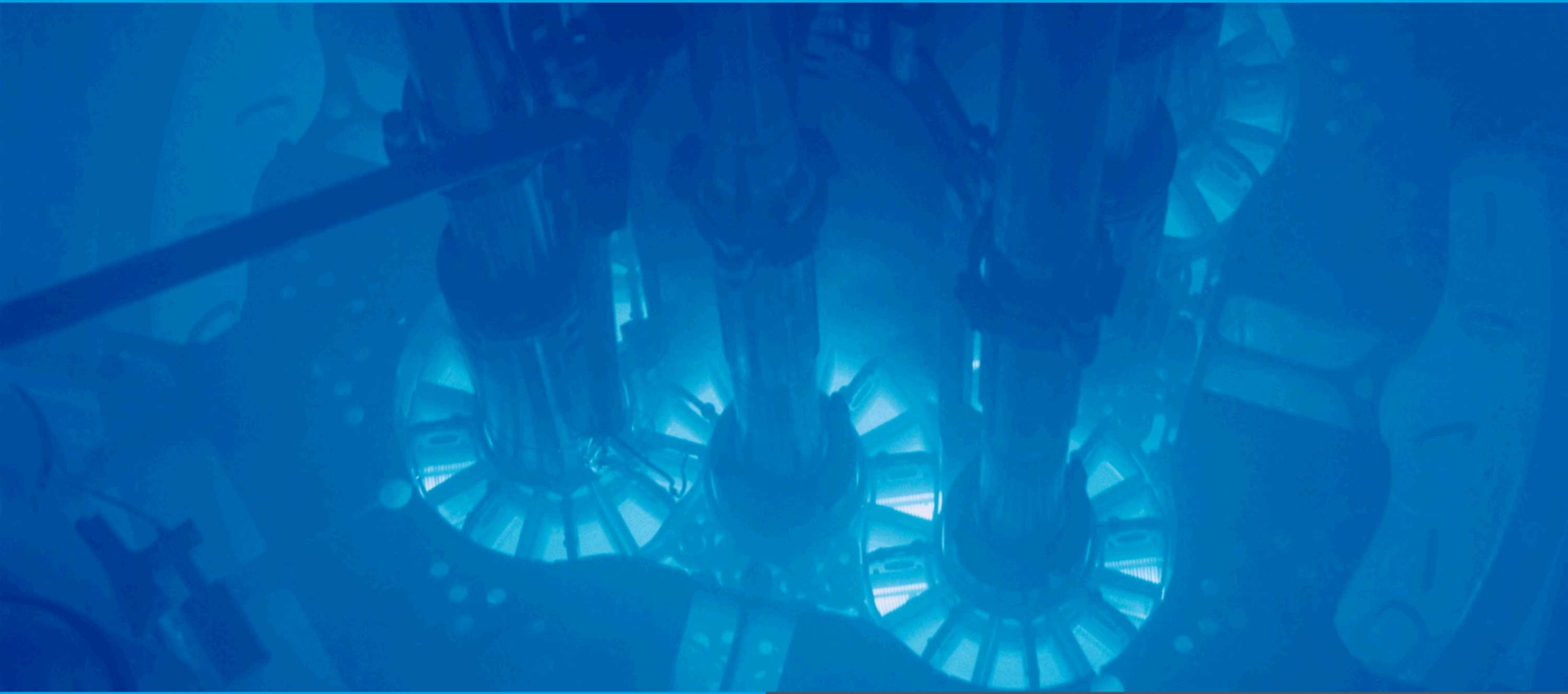

DOE Salt Research and WIPP Test

U.S. Nuclear Waste Technical Review Board Fact-Finding Meeting
February 26, 2019
NNSA NFO, Las Vegas, NV

Kristopher L. Kuhlman
Sandia National Laboratories
Philip H. Stauffer
Los Alamos National Laboratory

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WIPP Salt Field Test Team

Sandia National Laboratories

Kris Kuhlman, Melissa Mills, Courtney Herrick, Martin Nemer, Ed Matteo, Yongliang Xiong, Jason Heath

Los Alamos National Laboratory

Phil Stauffer, Hakim Boukhalfa, Eric Guiltinan, Doug Ware, Thom Rahn

WIPP Test Coordination Office (LANL)

Doug Weaver, Brian Dozier, Shawn Otto

Lawrence Berkeley National Laboratory

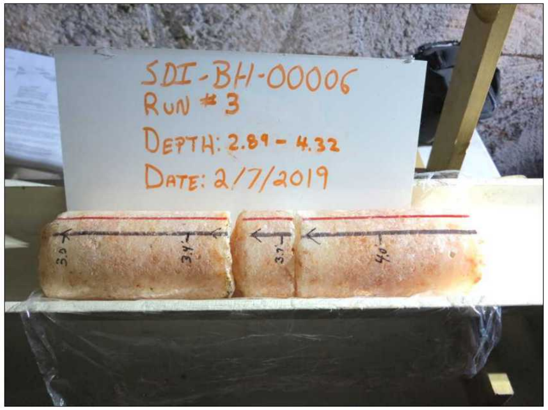
Yuxin Wu, Jonny Rutqvist, Jonathan Ajo-Franklin, Mengsu Hu

What Are We Doing?

Brine availability test in salt at WIPP (BATS)

Monitoring brine distribution, inflow, and chemistry from heated salt using geophysical methods and direct liquid & gas sampling.

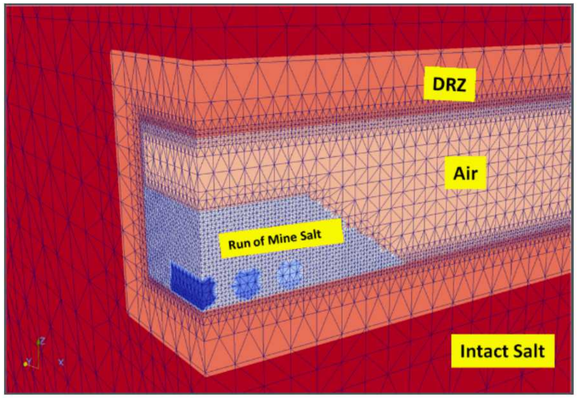
Boreholes currently being drilled in WIPP underground, testing begins Spring 2019, into FY20. Shakedown equipment tests ongoing.



Motivation: Importance to Safety Case

Brine Availability: *Distribution of brine in salt & how it flows to excavations or boreholes*

- Initial conditions to post-closure safety assessment
  - Brine migration and re-distribution
  - Evolution of disturbed rock zone (DRZ) porosity and permeability
- Brine causes corrosion of waste package / waste form
- Brine is primary radionuclide transport vector
- Liquid back-pressure can resist drift creep closure



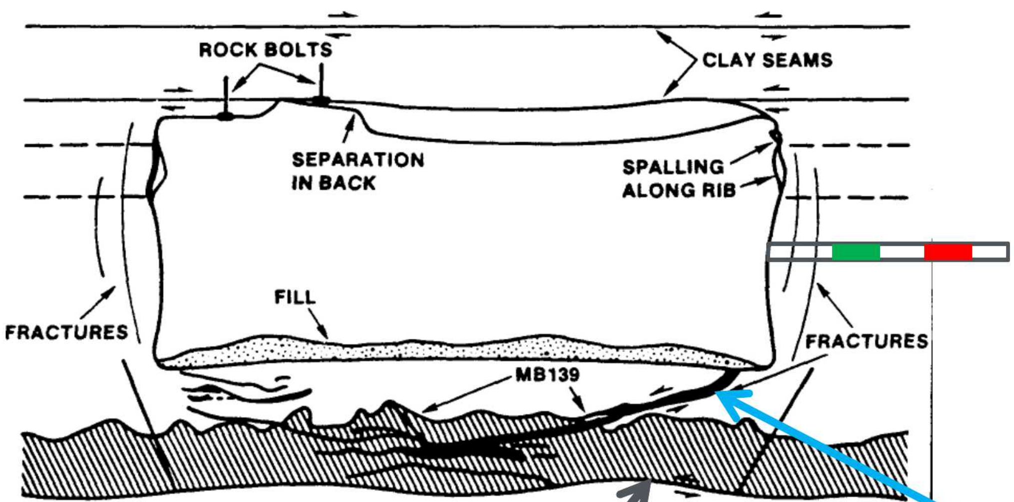
Motivation: Salt as Disposal Medium

- Salt long-term benefits as disposal medium
  - Low connected porosity (0.1 vol-%) and permeability ($\leq 10^{-22}\ \mathrm{m}^2$)
  - High thermal conductivity ($\sim 5\ \mathrm{W/(m \cdot K)}$)
  - No flowing groundwater (≤ 5 wt-% water)
  - Hypersaline brine is biologically simple, has less-stable colloids
  - Cl (~ 190 g/L) and B (~ 1 g/L) in brine reduce criticality concerns
  - Excavations, DRZ, and fractures will creep closed
  - Mined salt reconsolidates and heals to intact salt properties

- Near-field short-term complexities
  - Hypersaline brine is corrosive
  - Salt is very soluble in fresh water
  - Brine chemistry requires Pitzer
  - Salt creep requires drift maintenance

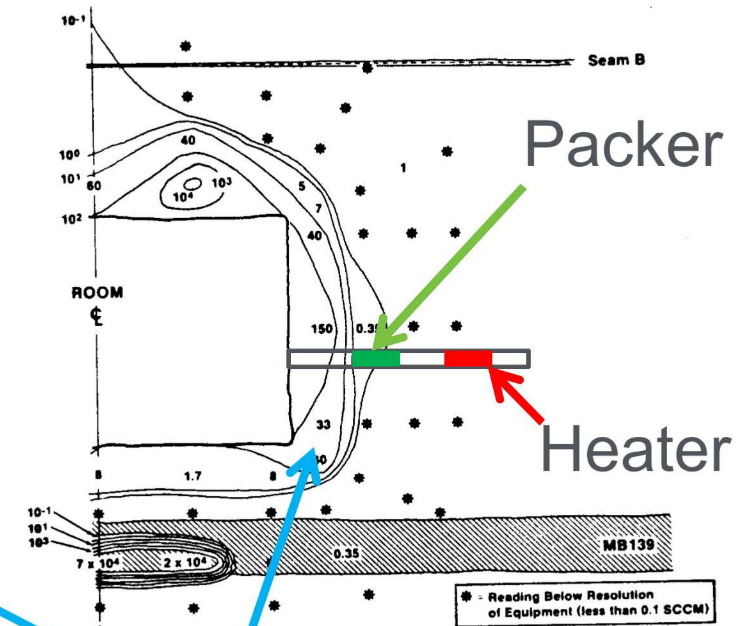
Motivation: Test Conceptual Model

Cartoon representation of test interval relative to observed DRZ at WIPP



Borns & Stormont (1988)

Contours of gas flowrate at fixed pressure (measure of damage)

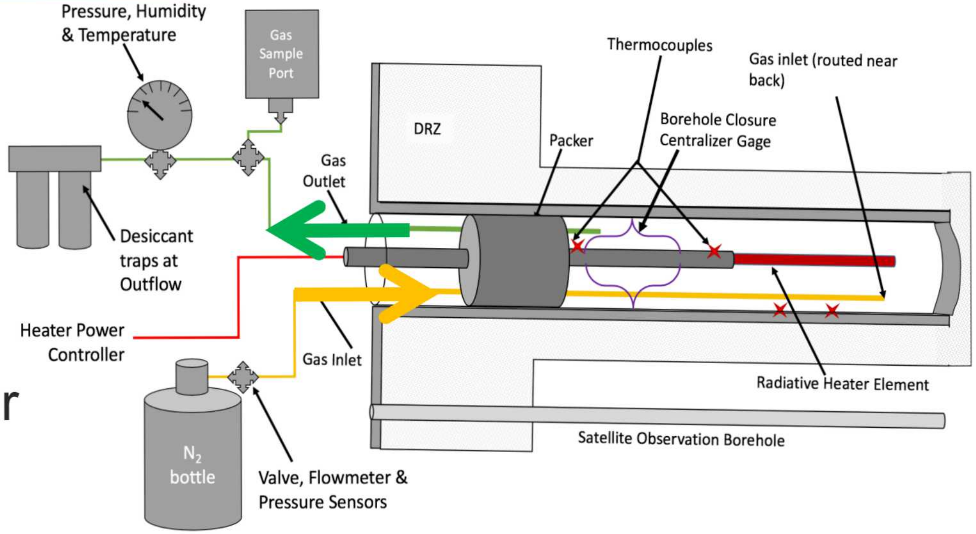


Borns & Stormont (1988)

Horizontal borehole avoids mapped clay / anhydrite layers (i.e., MB139) in historic vertical heater tests

Near-drift DRZ and damage

Motivation: Test Design



- Behind packer
  - Circulating dry N_2
  - Quartz lamp heater (750 W)
  - Borehole closure gage
  - Gas permeability before / after
- Samples
  - Cores (X-Ray CT and X-Ray Fluorescence at NETL)
  - Gas stream (natural / applied tracers, humidity and isotopic makeup)
  - Liquid brine (natural chemistry and natural / applied tracers)
- Geophysics
  - 3 × Electrical resistivity tomography (ERT)
  - 3 × Acoustic emissions (AE) / ultrasonic wave velocity
  - 2 × Fiber optic distributed strain / temperature
  - Many thermocouples

Motivation: Brine in Salt

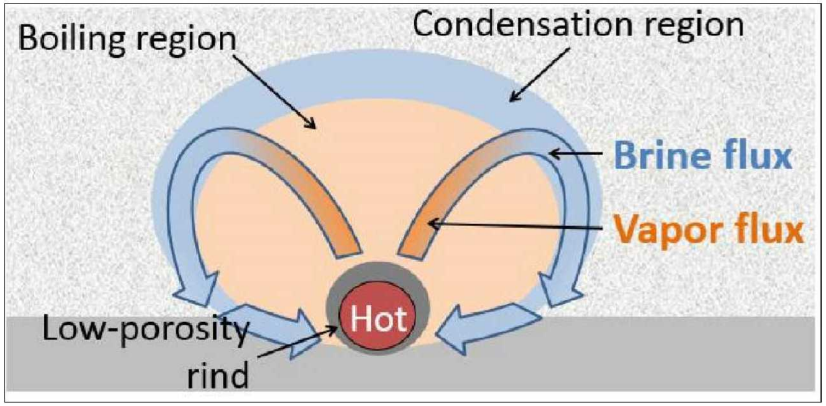
- No flowing groundwater, but not dry (≤ 5 wt-% water)
- Water sources in salt
  1. Hydrous minerals (clay, gypsum, bassanite)
  2. Intragranular brine (fluid inclusions)
  3. Intergranular brine (interconnected pores)

- Brine content correlates with clay content
- Only *intergranular* brine moves under pressure gradient
- Water types respond differently to heat
  – Hydrous minerals evolve water vapor, which can become brine
  – Intragranular brine migrates under thermal gradient
- Brine types have different chemical / isotopic composition

- **Q**: How do 3 brines contribute to *Brine Availability?*

Thermally-driven THMC Conceptual Model

- Salt HMC is “thermally activated”
  - High temperatures speed up creep closure
  - More of brine types available in hot salt
  - Salt solubility higher in hot brine
- High temperatures lead to dry-out
  - Water driven off as vapor, forming salt crust
  - Near-package permeability reduced
  - Less corrosion in dry environment
- THMC modeling (Δ porosity / permeability)
  - Creep, damage & healing
  - Precipitation & dissolution
  - Brine migration (rel. permeability)
    - Gas-filled fractures
    - Liquid-saturated far field



Motivation: Test Data

- Brine composition samples
  - Define how mix of brine sources change with temperature
- Geophysics
  - Map temporal 3D evolution of **saturation** / **porosity** / **permeability** distribution around heater
- Temperature distribution
  - More brine available at high temp (inclusions + hydrous minerals)
  - Thermal expansion brine driving force
  - Salt dry-out near borehole
- Gas permeability and borehole closure
  - THMC evolution of salt during heating
- Tracer migration through salt
  - Estimate rate of brine / vapor movement through salt DRZ

Salt - GDSA Integration

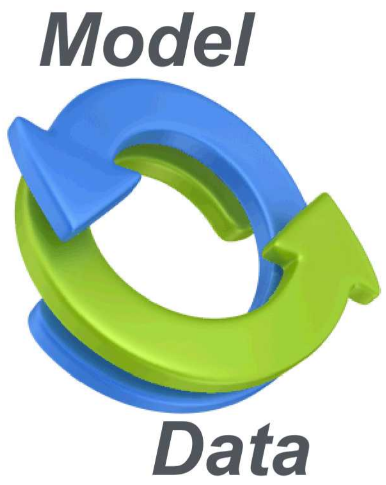
- Integration with engineered barriers systems (EBS):
  - WIPP heater test has an EBS / seal component – some field data on effects of heat on salt / cement interface
- GDSA model improvements to PA / process models:
  - Models used to design the heater test
  - Models used to interpret data collected during the test
  - Field test model improvements benefit GDSA
- Follow-on tests may benefit dual-purpose canisters (DPC) direct disposal issues
  - Possibly: higher temperatures, buoyancy issues

International Collaboration

- Strong int'l salt repository research community
  - USUSA (SNL, LANL, LBNL), DEGermany (BGR, DBE, GRS), NL Netherlands (COVRA), GBUK (RWM)
- Variety of salt deposits around world
  - Bedded salt: flat-lying salt @ WIPP
  - Domal salt: less brine, but more complex geometry
  - Pillow salt: between bedded & domal
- International meetings
  - 10th US / German Workshop (May 2019, in Rapid City SD)
  - OECD Nuclear Energy Agency "Salt Club"
  - Model validation to lab experiments:
    - WEIMOS, KOMPASS, RANGERS
- Possible salt DECOVALEX 2023 task

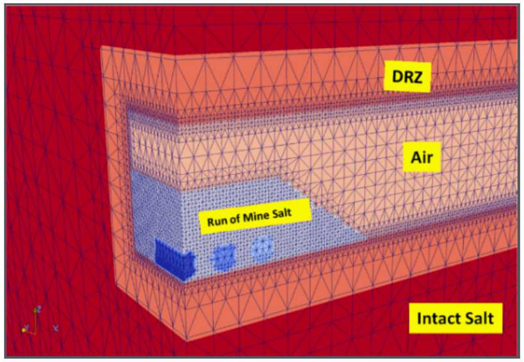
Process-level Modeling Goals

- Simulation tools demonstrate understanding of repository processes
- Gain confidence in long-term predictions
- Explore uncertain processes and inputs prior to designing new experiments to reduce uncertainty
- Integrate process-level physics into the generic Generic Disposal System Analysis (GDSA) performance assessment (PA) tool



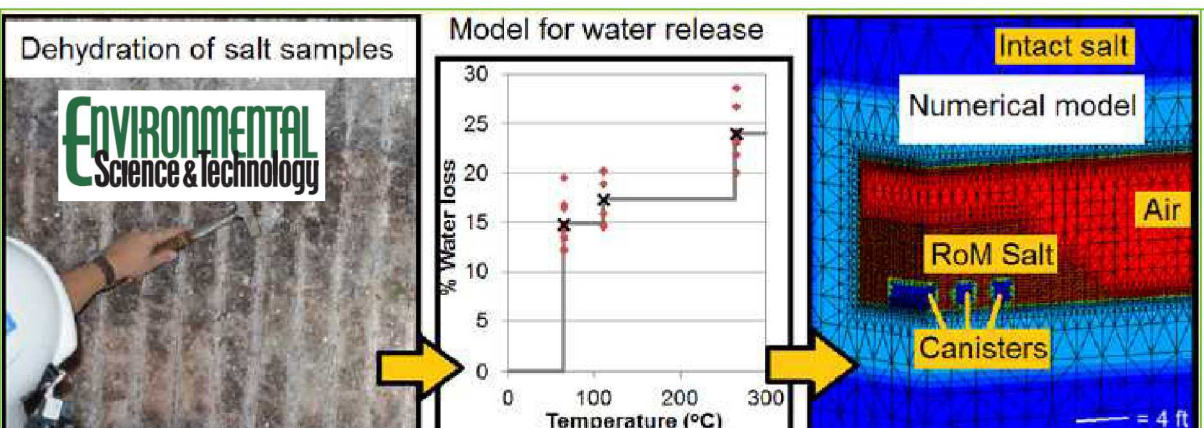
THMC Process-Level Modeling

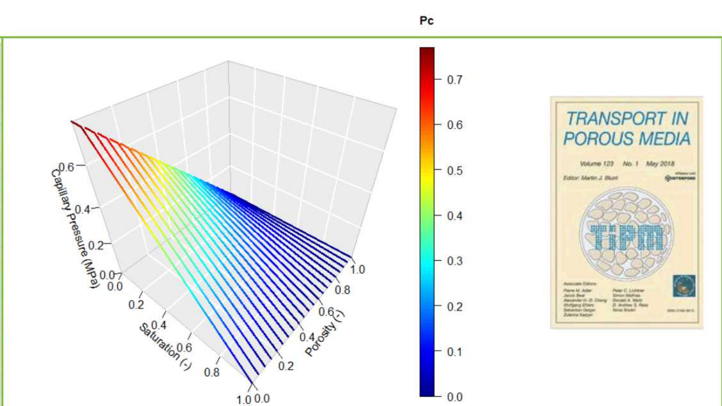
- Thermal-Hydrological-Mechanical-Chemical (THMC)
- TOUGH-FLAC simulates large-deformation THMC
- FEHM numerical model simulates small-deformation THMC
- Isolating specific processes allows more rapid validation
- Some processes are validated using TH, TM, THC, or THM



Salt THMC Couplings

- *Deformation* — ***F****(temperature, stress, time, saturation)*
- *Vapor pressure lowering* — ***F****(capillary pressure, salinity)*
- *Porosity* — ***F****(dissolution, precipitation, stress, strain)*
- *Thermal conductivity* — ***F****(temperature, porosity, saturation)*
- *Permeability* — ***F****(porosity, saturation)*
- *Capillary pressure* — ***F****(porosity, saturation, temperature)*
- *Water vapor diffusion* — ***F****(porosity, saturation, temperature)*
- *Clay dehydration* — ***F****(temperature)*

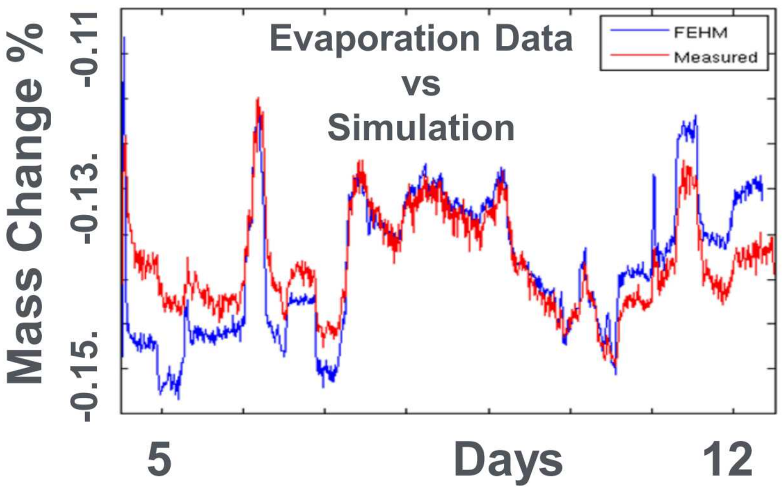




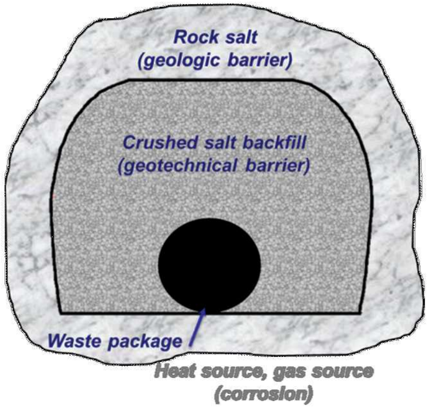
Capillary pressure / porosity function

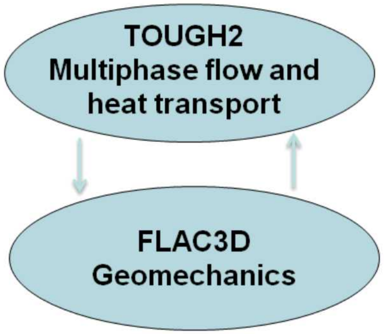
THC Couplings : Evaporation example

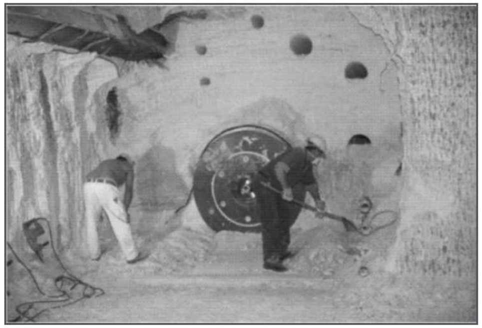
- WIPP evaporation experiment
  - Joint DOE-EM / DOE-NE
  - Ran in WIPP underground by LANL Carlsbad
- Simulated using FEHM
  - Implemented a new time-dependent FEHM relative humidity (RH) boundary condition
- Mine ventilation (RH) impacts better included in future test simulations



Importance of THMC Processes

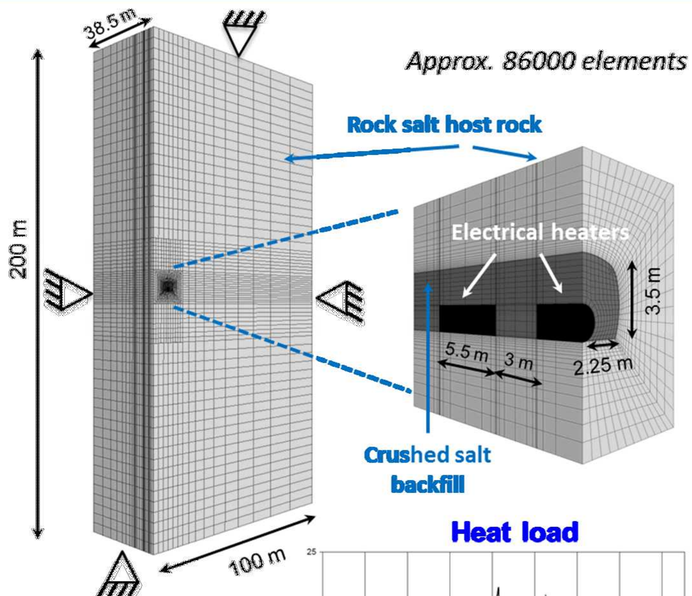


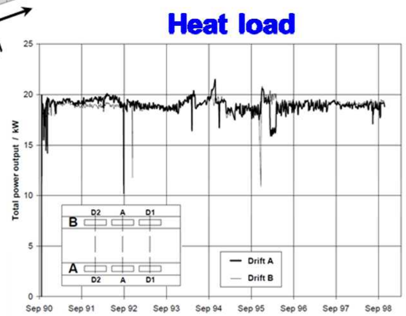




- Performance Assessment
  - Development of DRZ, a potential path for transport
  - Compaction, sealing and healing (solidification)
- Safety Case
  - Post-closure SA [4.2], including barrier / safety function
  - Post-closure FEPs [3.3], including host rock / DRZ
  - Confidence enhancement [4.3], including validation
- Roadmap
  - THMC model development
  - Validation against field (WIPP) and lab experiments
  - THMC model demonstration (long-term, GDSA)
- International
  - Salt constitutive model development and validation with Clausthal Technical University (Germany)
  - Access to field test data in various salt types (e.g. bedded vs. domal salt in Asse Mine URL, possible WIPP contributions)

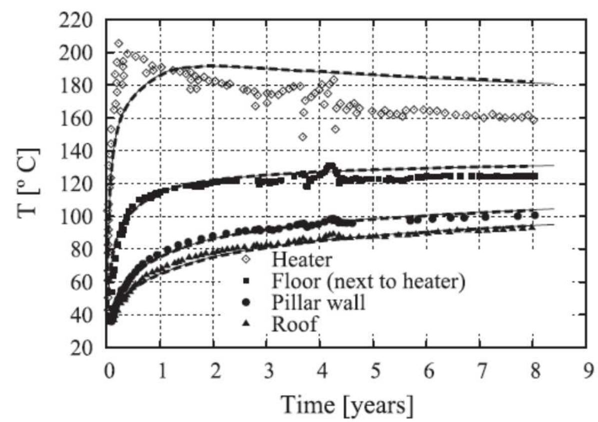
International: Heater Test at Asse Mine

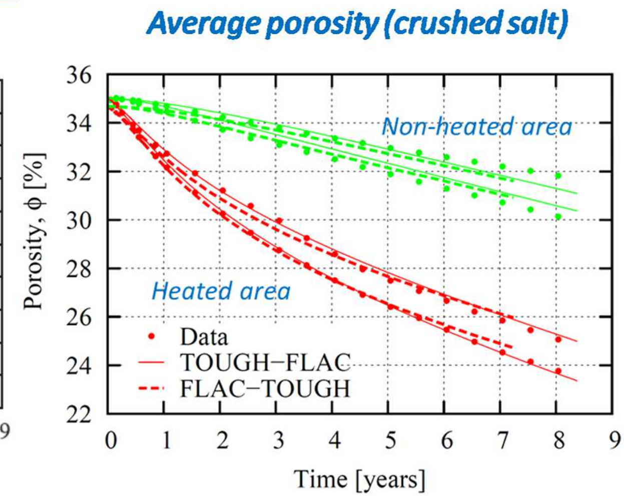




T_0=36.4 °C

Blanco-Martin et al. (2016)

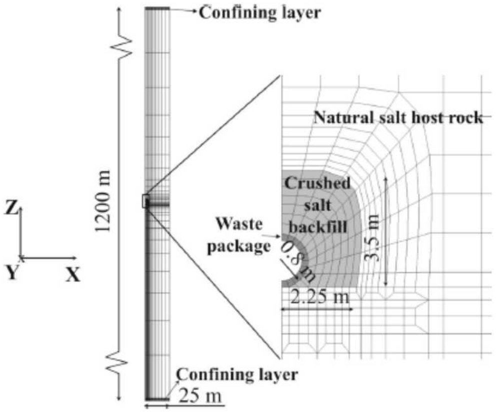




- THM model validation of compaction to 8 years (backfill and host rock THM constitutive models)
- Compaction driven by tunnel convergence
- Fastest compaction in the heated section (high temperature accelerates creep)

- Constitutive model validation **includes** temperature dependent creep
- Constitutive model **does not include** moisture impact on creep (still good agreement with laboratory tests)
- How long does it take to complete compaction and sealing of backfill?

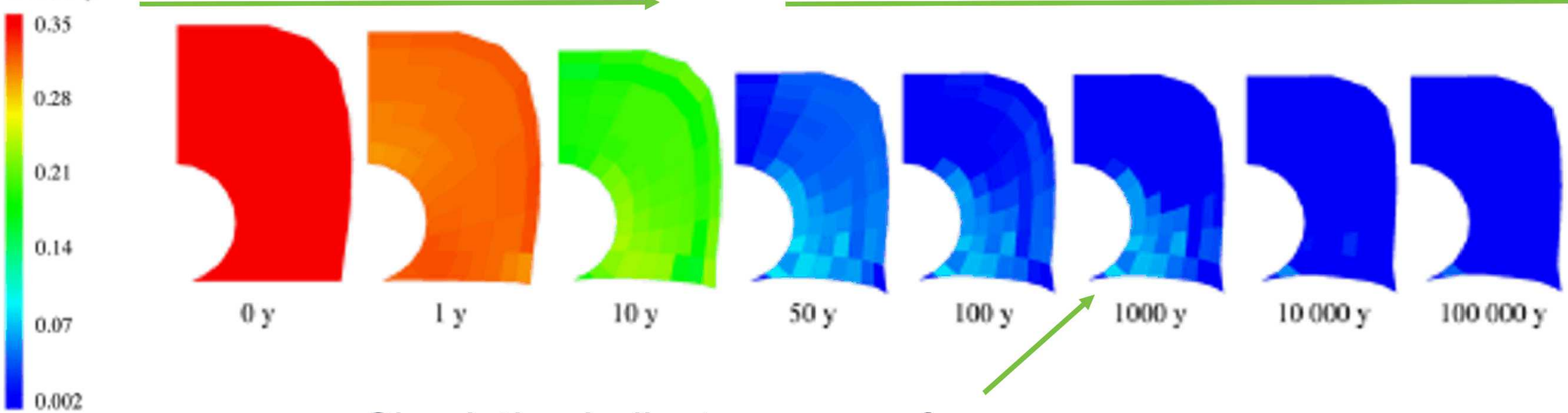
Long-term Compaction and Sealing



- THMC modeling of compaction with salt dissolution / precipitation in backfill (Blanco-Martin et al., 2018)
- Thermal-mechanical-induced compaction most important **at this scale**

Asse Mine Validation

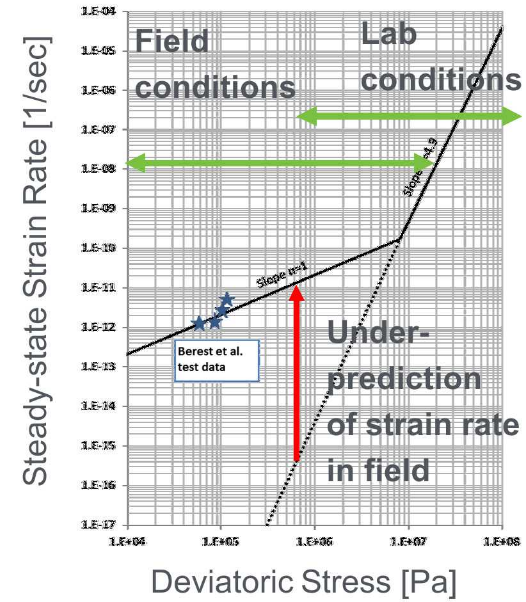
Future Prediction to Complete Sealing

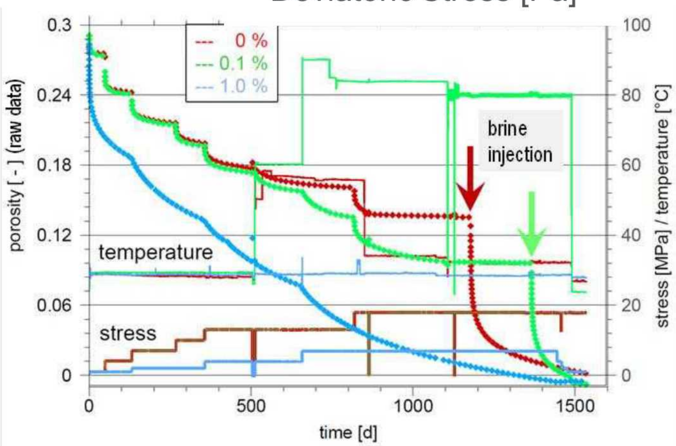


Simulation indicates areas of about 10% porosity at 1000 years (permeability ≈ 10^{-15} m^2)

Salt Constitutive Models

- Salt behavior is complex (elastic / creep / damage / healing)
  - Models are in general good, but
    - Constitutive laws have many parameters
    - Require carefully controlled lab experiments
      - temperature, moisture, loading path
- Strain at low deviatoric stress
  - Recent international focus
  - Important for far field and long times
  - Lab vs. field conditions make tests difficult
- Granular salt reconsolidation
  - Water content (faster with moisture)
  - Temperature (faster at high temp)
  - Loading history

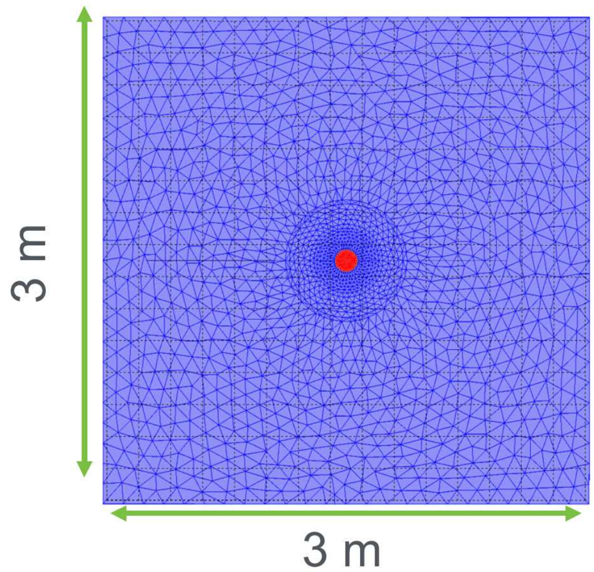




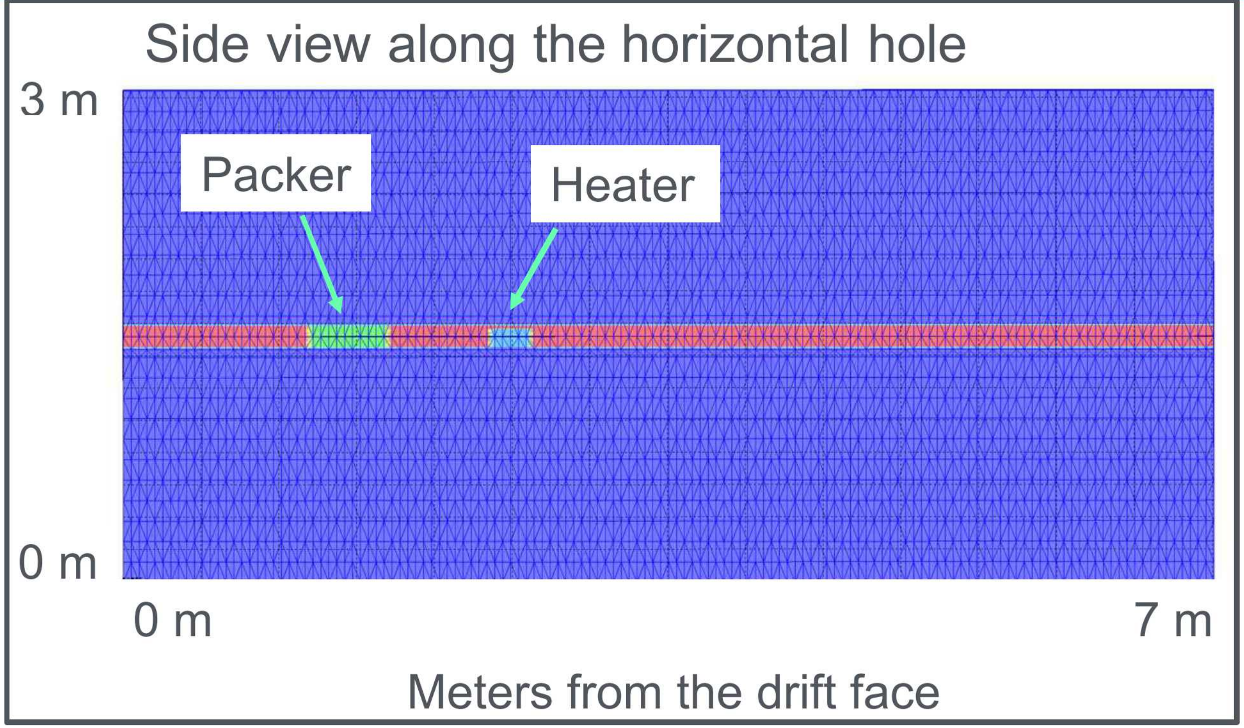
Oedometer tests in REPOPERM 2

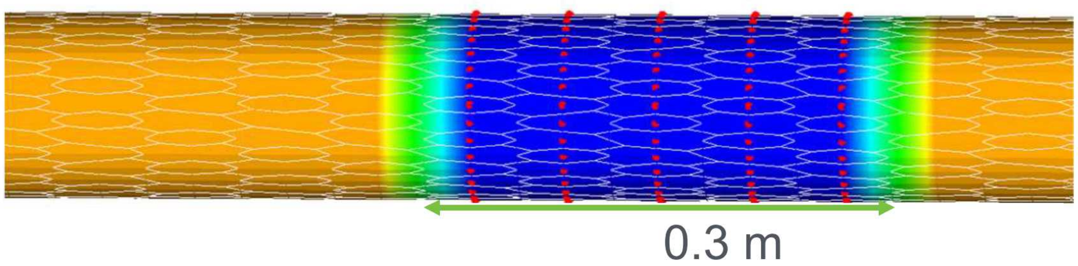
WIPP Heater Test: THC Model of Field Test

Shakedown Test
3D Borehole heater simulation domain



Drift view looking into horizontal hole





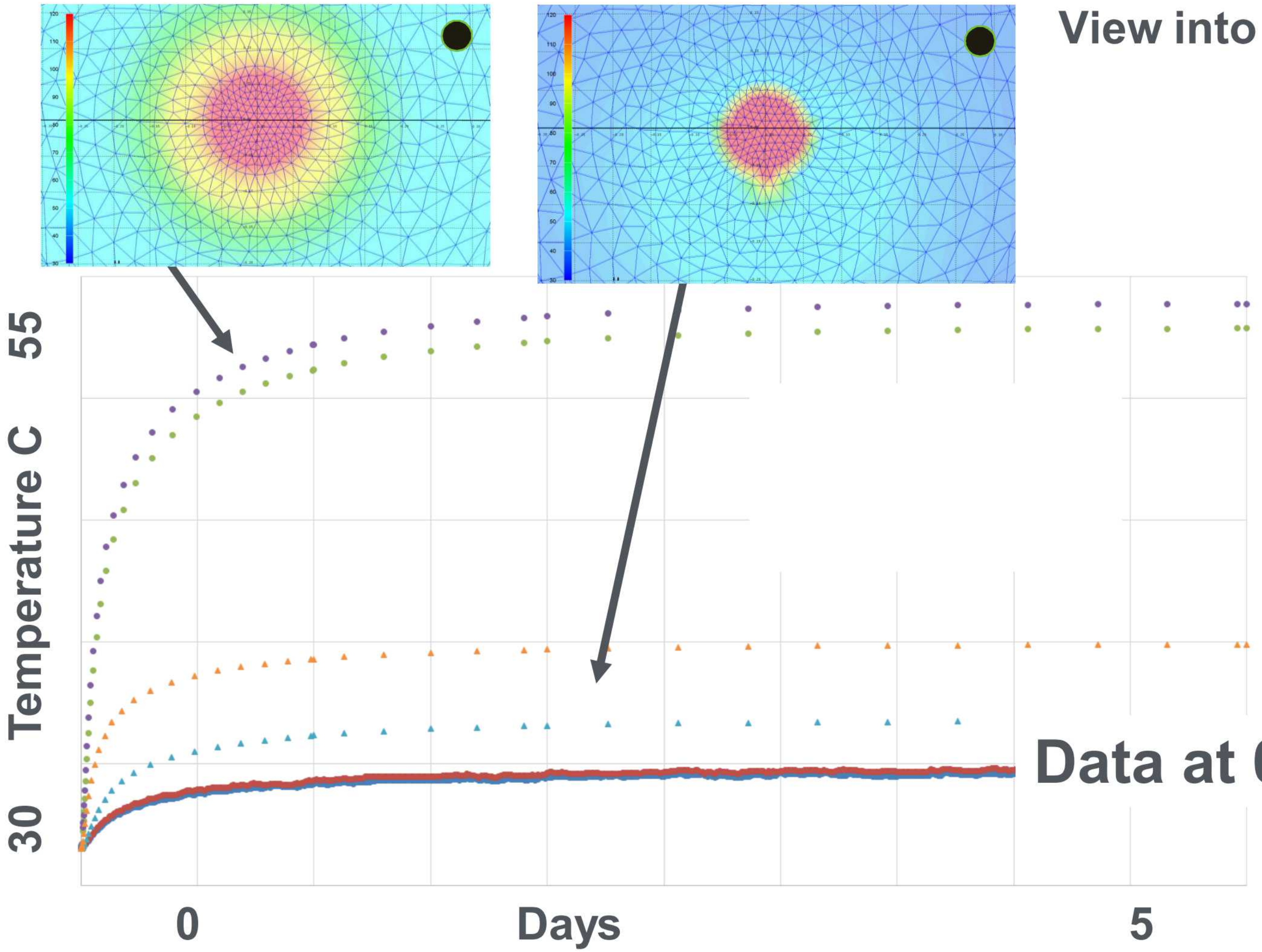
Zoom into the heater mesh

WIPP Heater Test: Simulations Assist Design

Full contact (radiation) sim

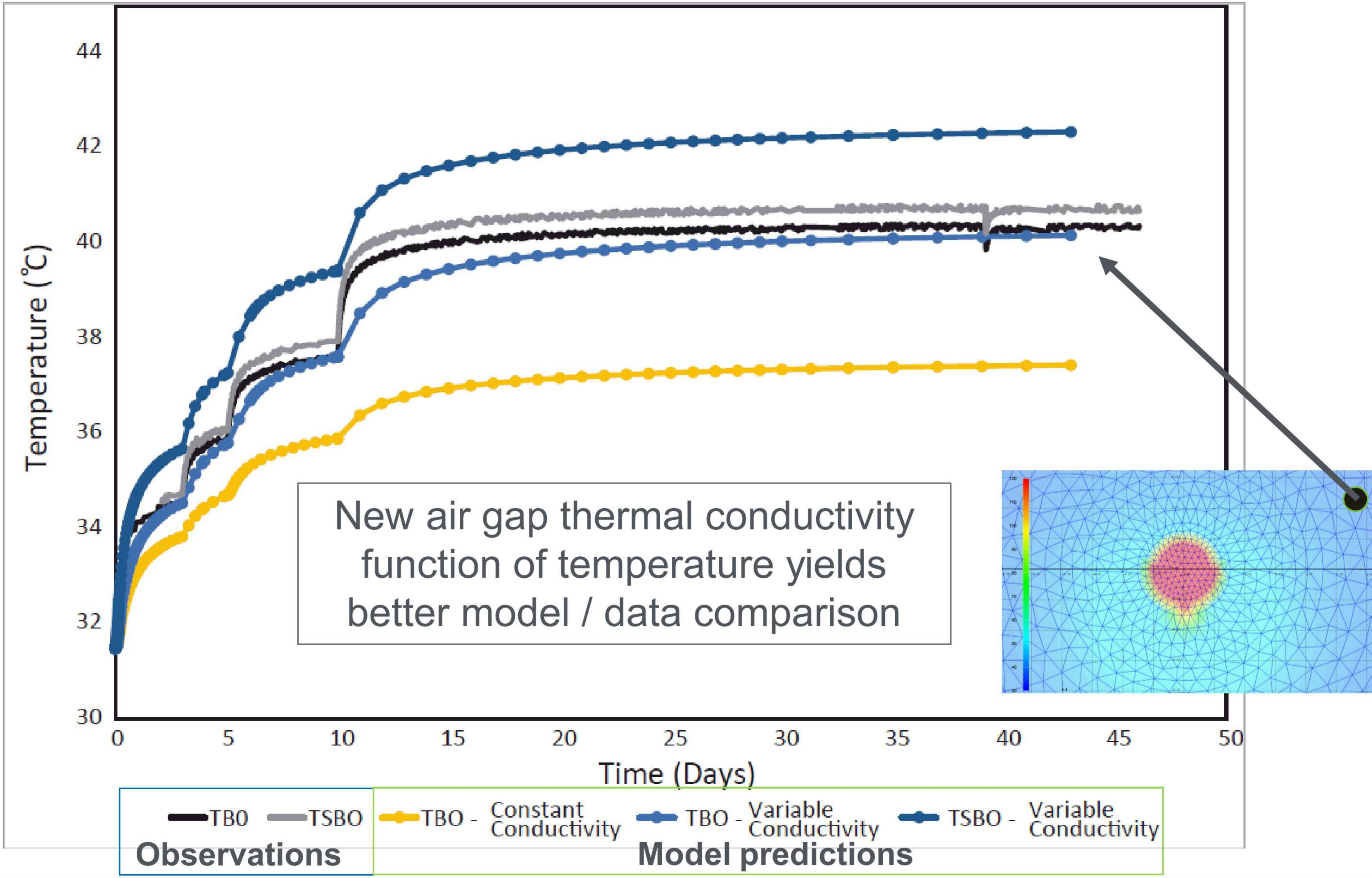
Small contact (conduction) sim

View into heated borehole



Simulations compared to shakedown data show that infrared heating would better transfer heat to the rock salt.

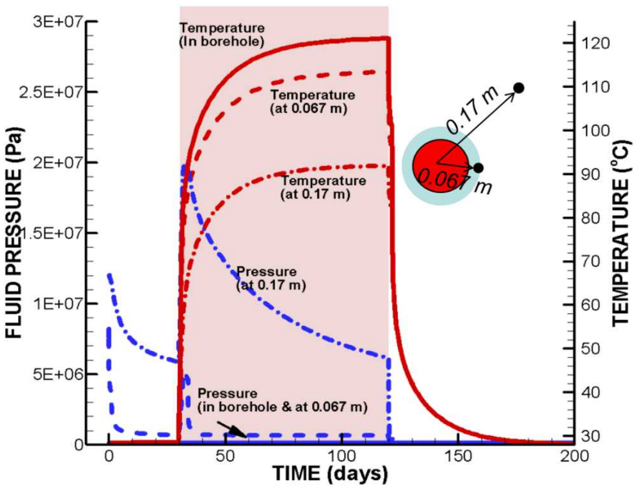
WIPP Heater Test: Modeling Thermal Step Test

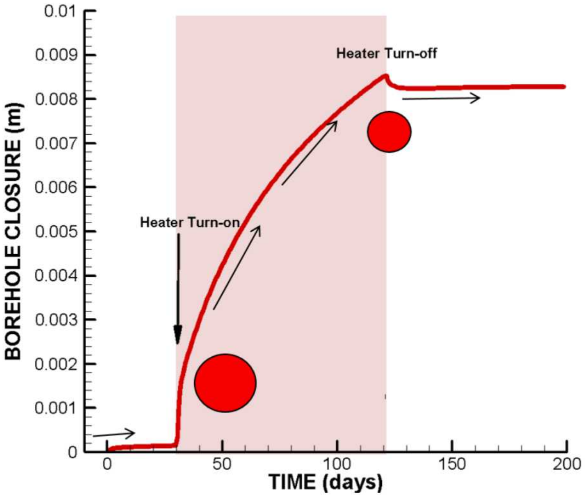


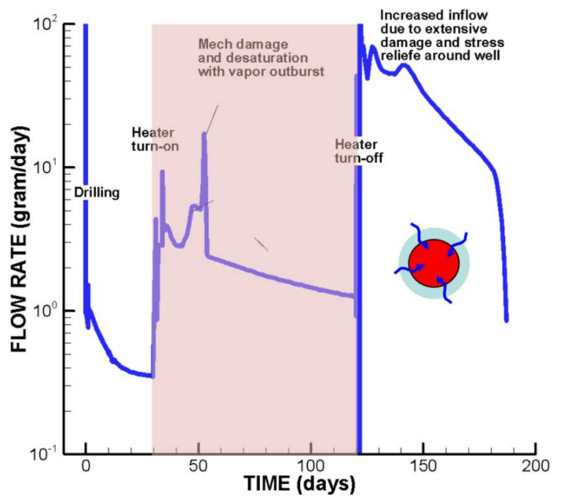
WIPP Heater Test: THM Model of Field Test

Prediction of WIPP heater test THM behavior: TOUGH-FLAC

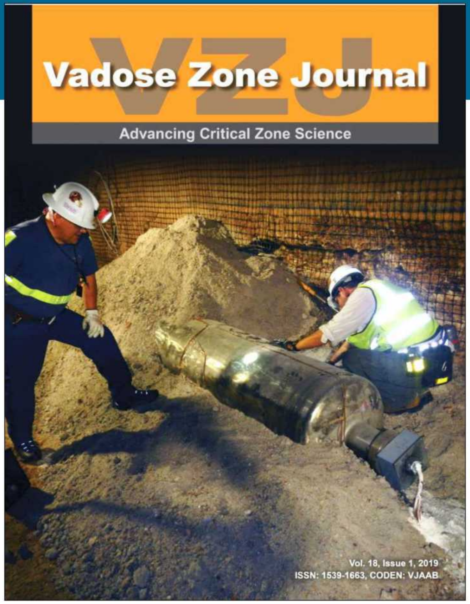
- The constitutive THM model (Lux-Wolters) was developed from a large number of laboratory experiments in domal salt (Germany)
- Parameters for bedded salt more uncertain
- WIPP heater test will provide in situ data for improving confidence in heat-driven salt convergence and brine release





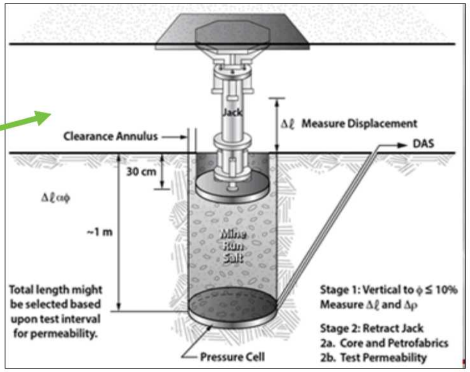


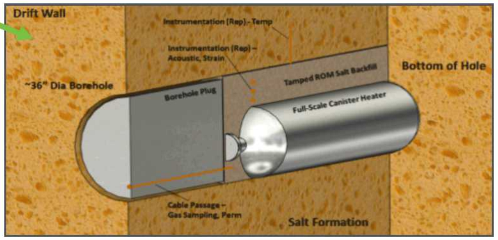
Salt Disposal R&D "Five-Year Plan"



- WIPP Borehole Heater Test
  - FY19 execution (~120 °C & unheated)
  - Possible follow-on tests at higher temp

- Possible Follow-on Tests
  - Further borehole test configurations
  - Moving towards larger-scale tests
  - Intermediate-scale testing
    1. Large-scale granular salt reconsolidation
    2. Single-canister thermal test





- Laboratory / Modeling Investigations
  - Investigations supporting field test design or data interpretation

Salt Research and WIPP Test: Summary

- **FY19-20: Brine Availability Test in Salt at WIPP**
  - Monitoring brine sources, inflow, and composition in heated salt through geophysical methods and direct liquid & gas sampling
  - Characterize brine source and their response to temperature
  - Assess new methods to characterize salt DRZ

- THMC process-model developments to better design & interpret field tests
- International collaborations on field test and models to leverage expertise in Germany, Netherlands, UK
- Possible salt DECOVALEX 2023 task
- *Improve safety salt case for heat-generating waste*

Questions?

Clean. **Reliable. Nuclear.**

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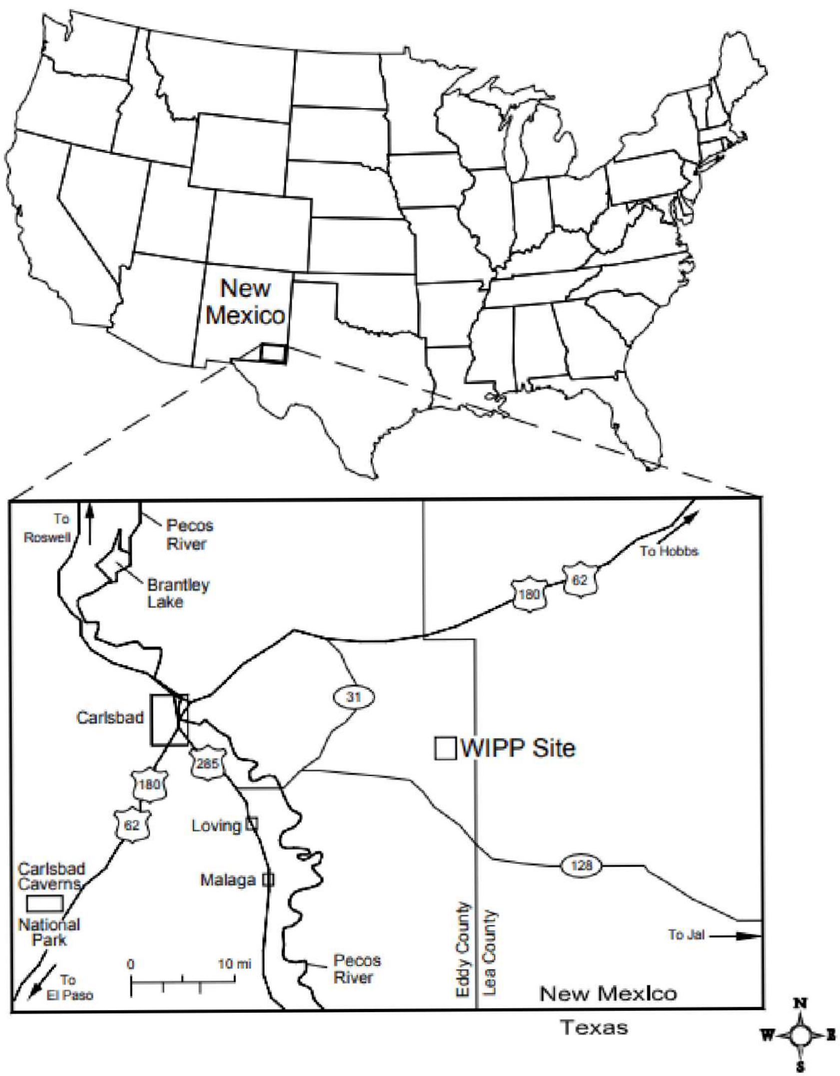
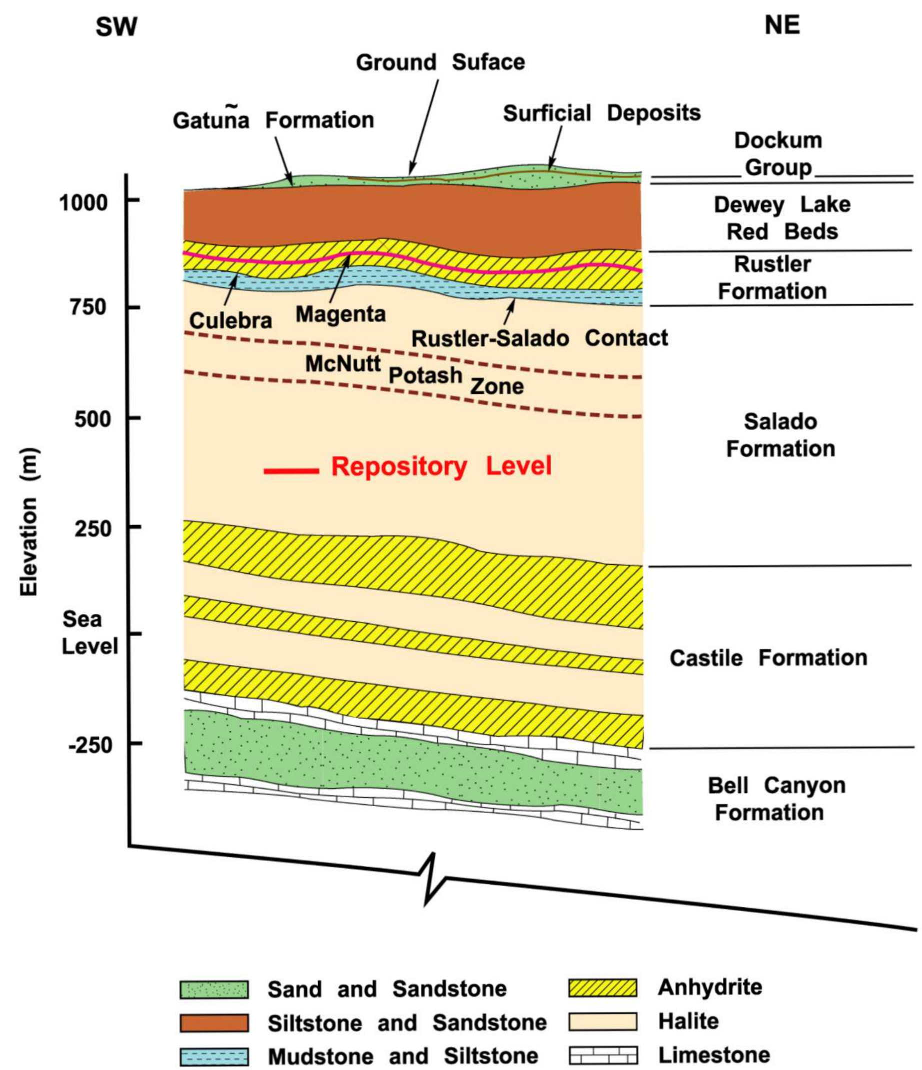
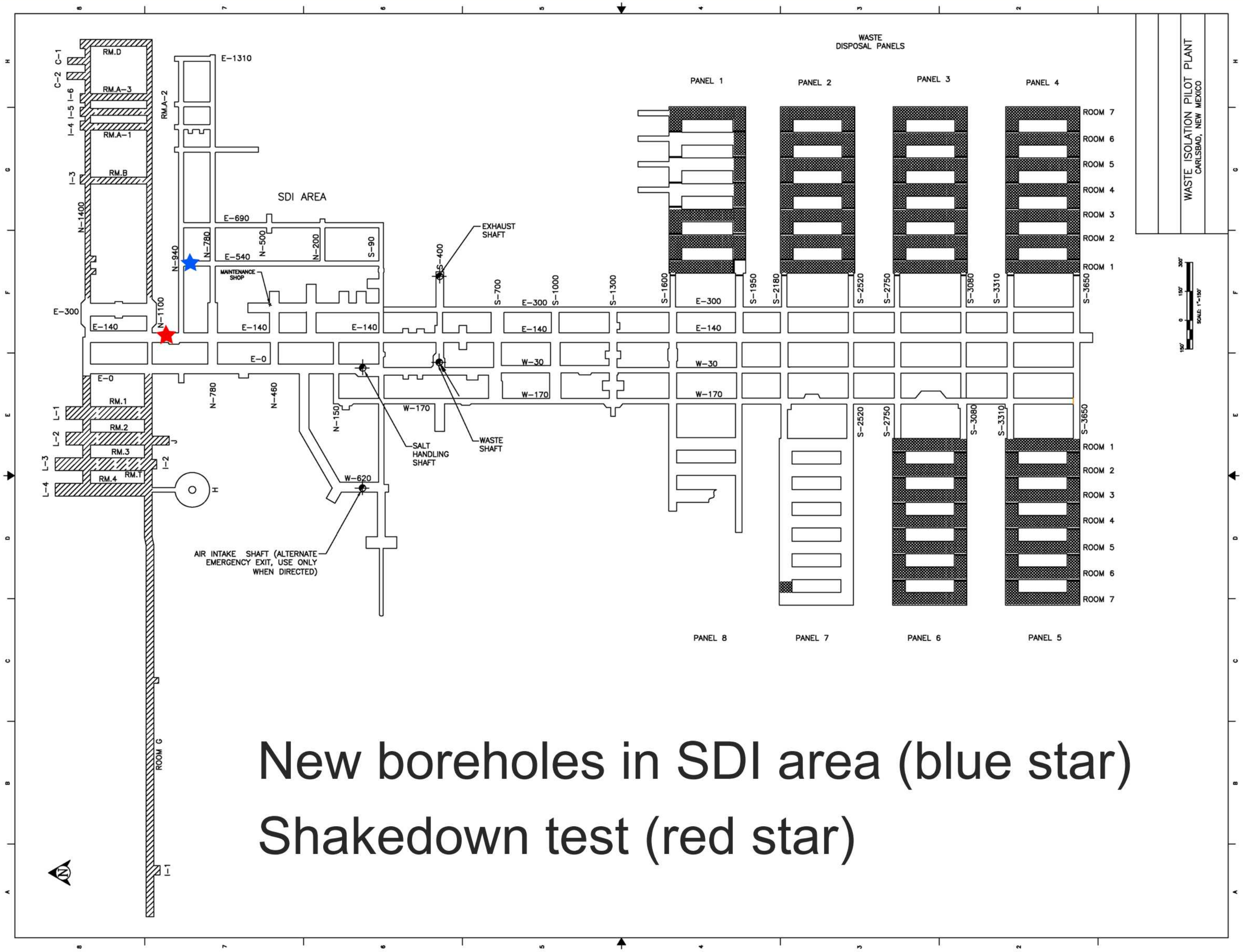
Backup Slides

WIPP Location





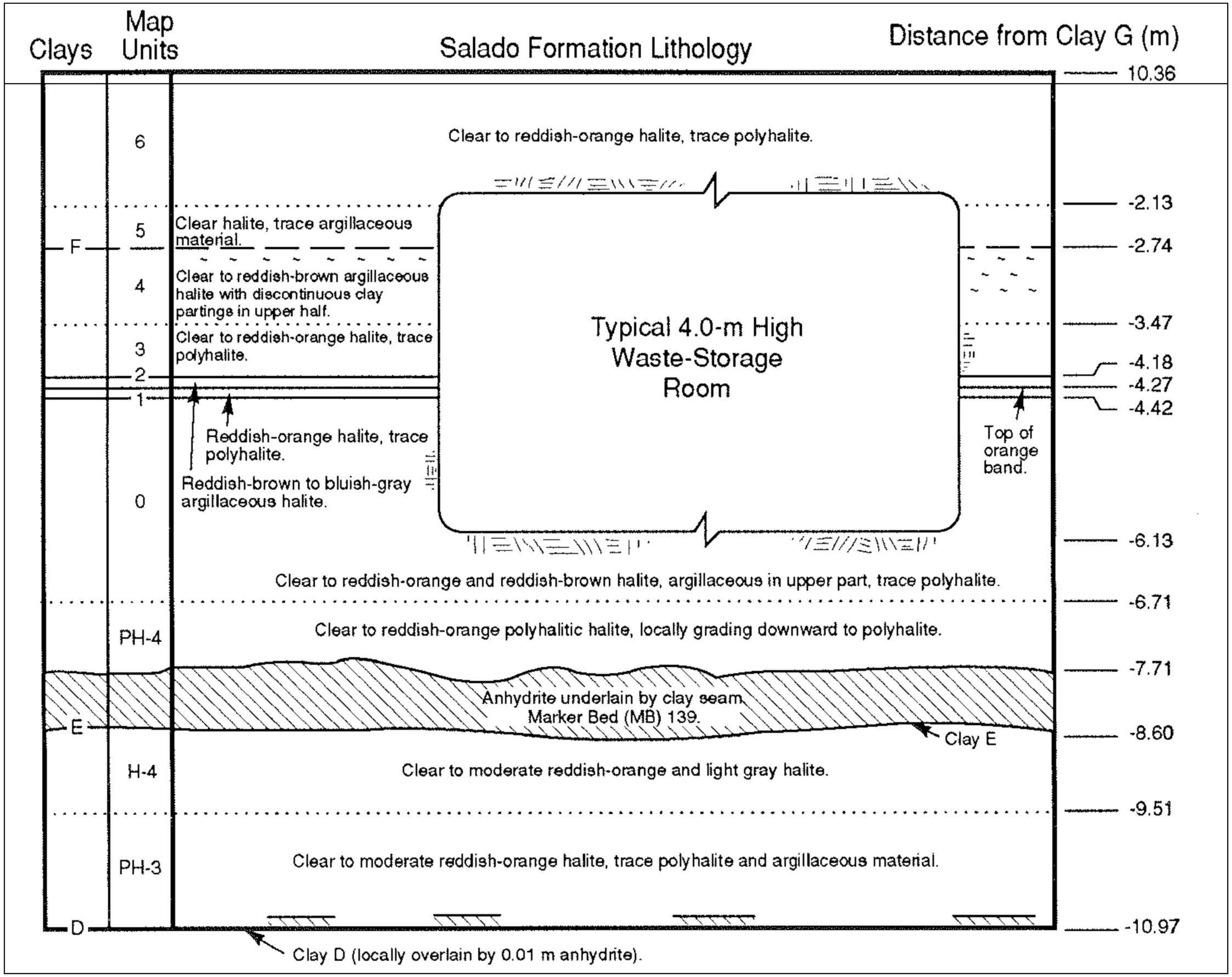
WIPP Underground Layout



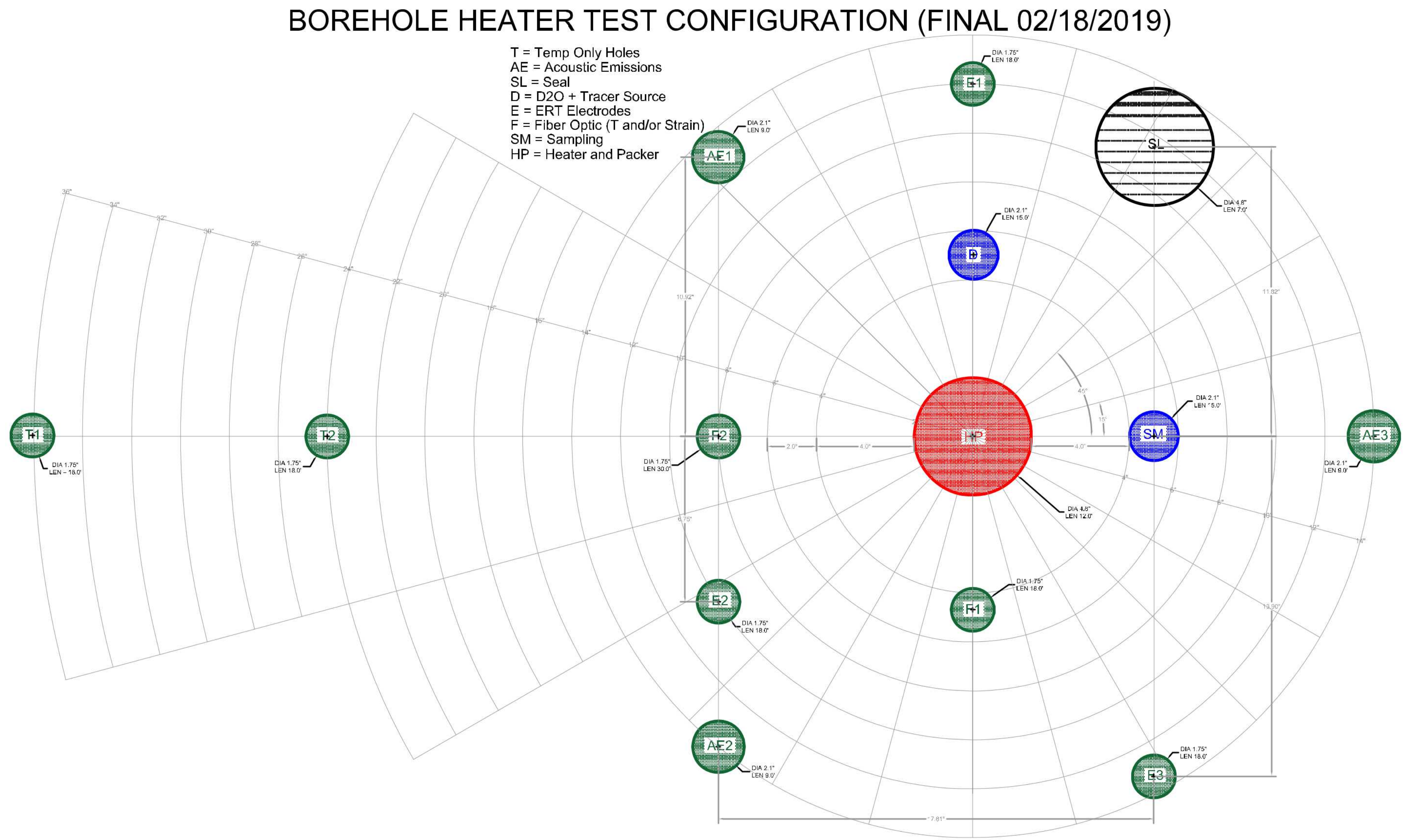
New boreholes in SDI area (blue star)

Shakedown test (red star)

WIPP Underground Stratigraphy

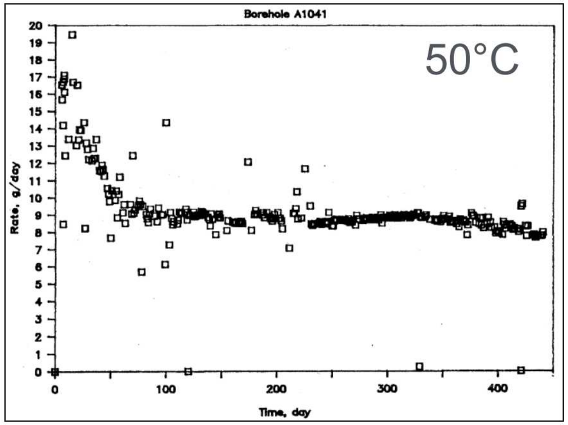


WIPP Test Borehole Layout

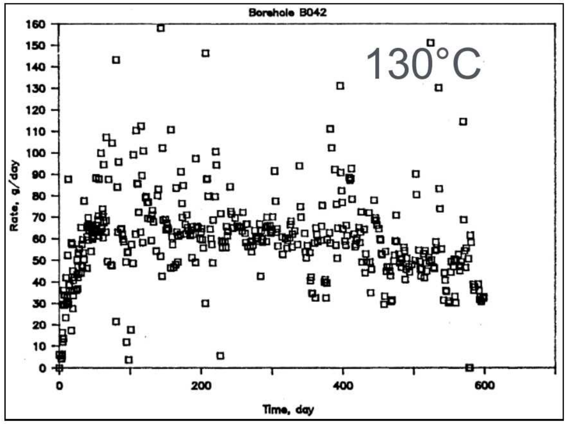


Brine Inflow Expectations

- Brine inflow
  - Highest inflow rate initially
  - Exponential decay of rate with time
- More brine inflow at higher T
  - Vapor from dehydration of clay & gypsum
  - Brine from fluid inclusions
- 1997 Unheated brine inflow study
  - INTRAVAL Study (Beauheim et al., 1997)

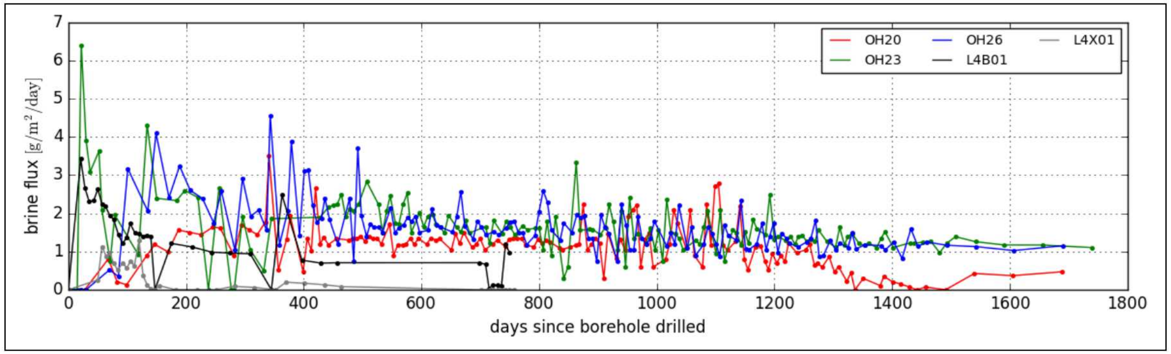


Vertical WIPP boreholes



Vertical boreholes intersected clay layers (Rooms A & B) Nowak & McTigue (1987)

Kuhlman et al. (2017)



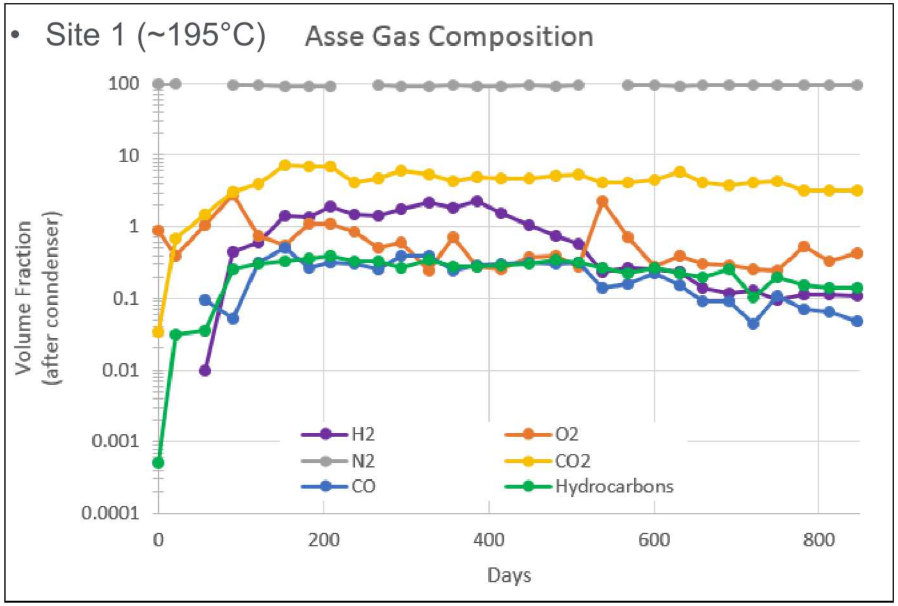
Unheated borehole brine inflow at WIPP in MU-0
(did not cross mapped clay layer)

Gas Composition Expectations

- Gases from
  - Possible volatiles in salt (e.g., hydrocarbons at Asse)
  - Dissolved gas in brine (~15 MPa pore pressure in far field)
  - Components in seals and packers?

- Water Vapor from brine
  - Natural H_2O
  - “Light” water breakthrough
    - Transport time through salt
    - Fractionation in borehole
    - D_2O tracer at Avery Island salt dome (Krause, 1983)
- Acid gas from salt / brine
  - Decomposition of hydrous Mg salts
  - Equilibration of $P_{HCl(g)}$ into condensed steam

- Site 1 (~195°C)

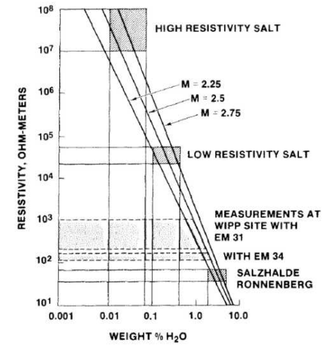


- Data from Coyle et al. (1987) BMI/ONWI-624

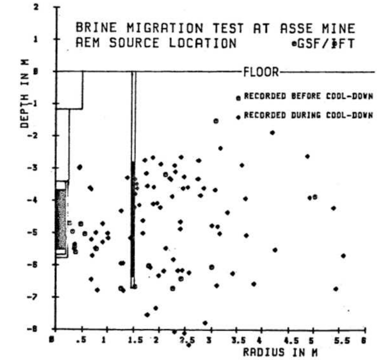
ERT / AE Expectations

- Electrical Resistivity Tomography (ERT)
  - ERT electrodes cemented into 2 boreholes
- Salt Apparent Resistivity
  - Function of porosity and brine saturation
- Conduct 3D ERT surveys through time
  - Estimate evolution of porosity / saturation
  - ERT conducted in heated test only

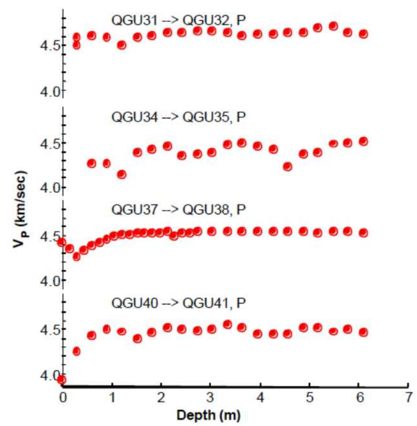
- Acoustic Emissions (AE)
  - AE monitored during heat up & cooldown
  - Locate AE sources near heated borehole
  - AE correlated with permeability increases
  - AE system installed in heated test only
- Ultrasonic Wave Travel-time Data
  - May estimate extent/evolution of DRZ



Skokan et al. (1989)



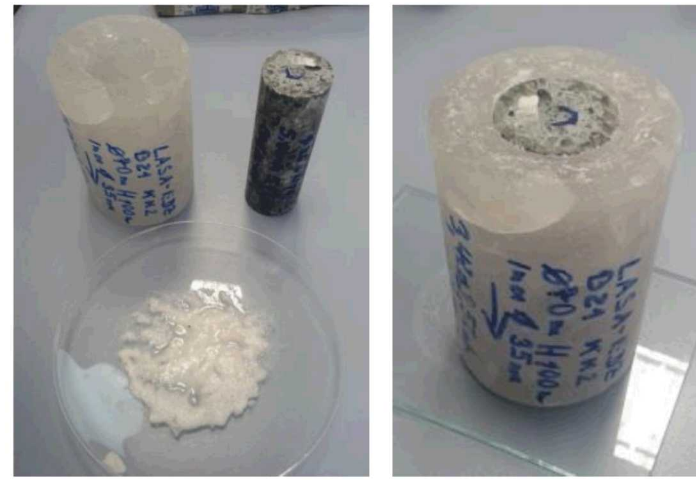
Rothfuchs et al. (1988)



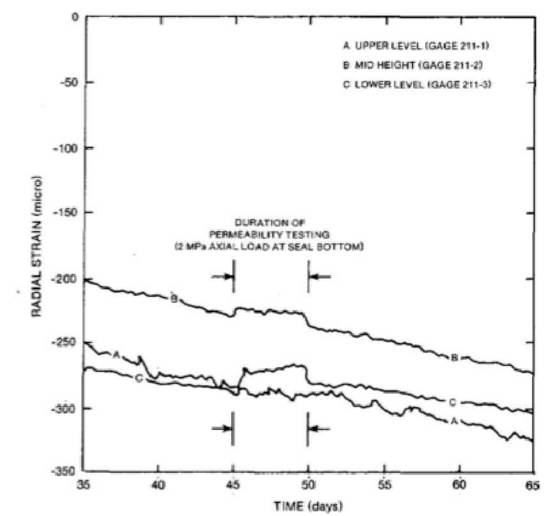
Holcomb et al. (2001)

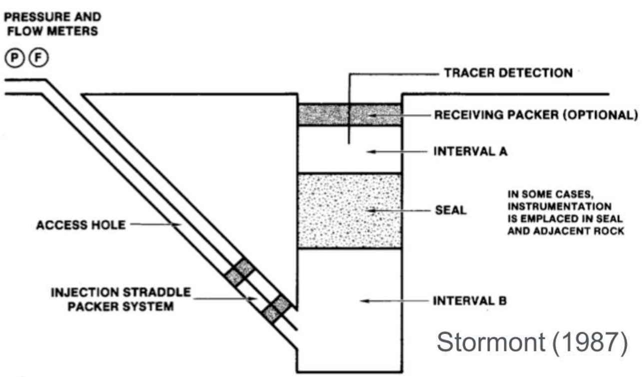
Cementitious Seals Expectation

- Emplace pre-fabricated cement plug
  - Snug fit into satellite borehole
  - Gas line embedded in plug
  - Monitor seal evolution as borehole closes
- Upscale German laboratory seals tests
- Compliment field scale sealing tests
  - ERAM Test Seal - salt concrete
  - Asse tests - Sorel cement and salt concrete
  - WIPP Field Seals Tests
- Post-test overcore of salt / cement interface



Czaikowski & Wieczorek (2016)





Stormont (1987)