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SAND2019-4055 PE

DOE Salt Research and WIPP Test

U.S. Nuclear Waste Technical Review Board Workshop
April 24-25, 2019
San Francisco, CA

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Salt as a Disposal Medium

Salt long-term benefits as disposal medium

- Low connected porosity ($0.1\ \text{vol-}\%$) and permeability ($\leq 10^{-22}\ \text{m}^2$)
- High thermal conductivity ($\sim 5\ \text{W}/(\text{m} \cdot \text{K})$)
- No flowing groundwater ($\leq 5\ \text{wt-}\%$ water)
- Hypersaline brine is biologically simple, has less-stable colloids
- Cl ($\sim 190\ \text{g/L}$) and B ($\sim 1\ \text{g/L}$) in brine reduce criticality concerns
- Excavations, damage, 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

Overview

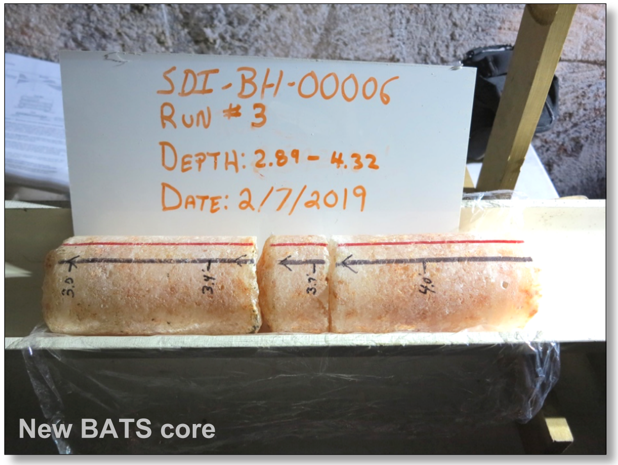
- Brine availability heater test in salt at WIPP
  - What we are measuring
  - Why it is important
  - What we expect
  - International Collaboration
- Numerical modeling in salt
  - What coupled processes are important
  - What constitutive laws are important
  - International collaboration on modeling Asse test
  - Modeling of WIPP brine availability test

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.



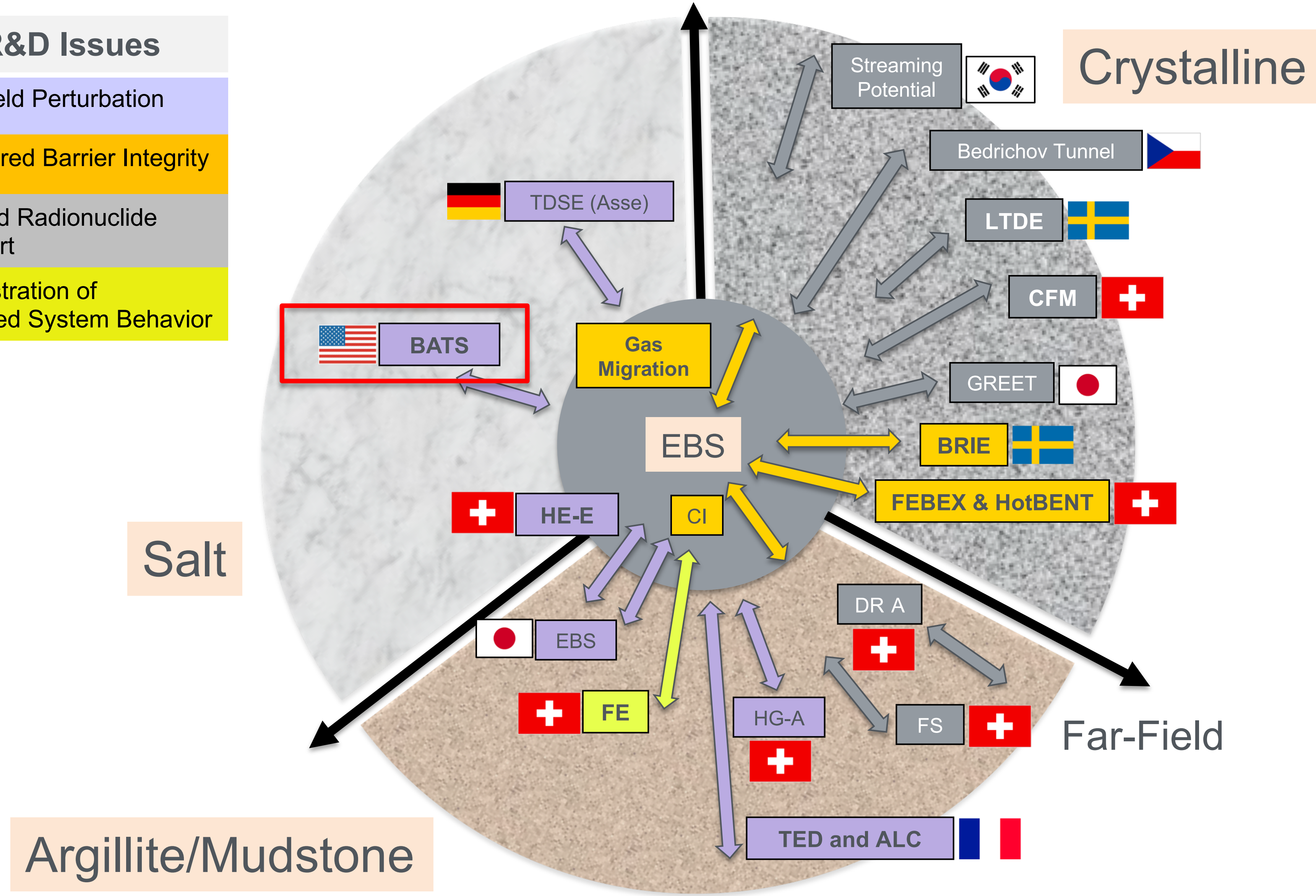
New BATS core


New BATS boreholes

International URL Portfolio in a Nutshell

Key R&D Issues

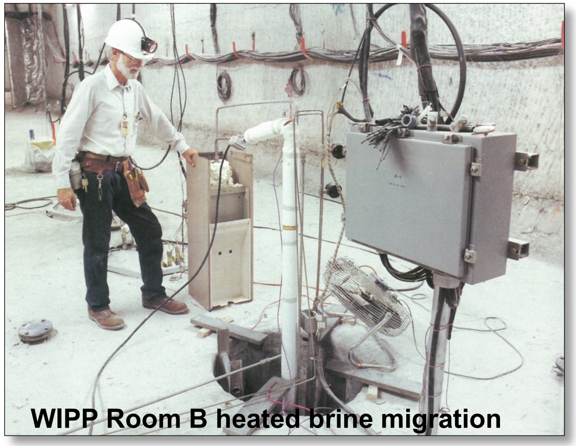
- Near-Field Perturbation
- Engineered Barrier Integrity
- Flow and Radionuclide Transport
- Demonstration of Integrated System Behavior



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

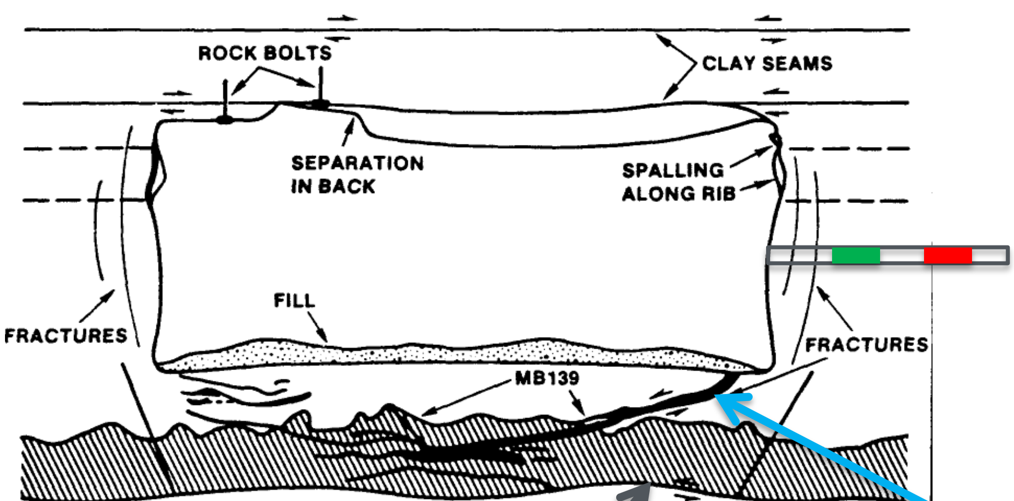

WIPP Room B heated brine migration


WIPP Room J canister tests


WIPP Room Q brine inflow

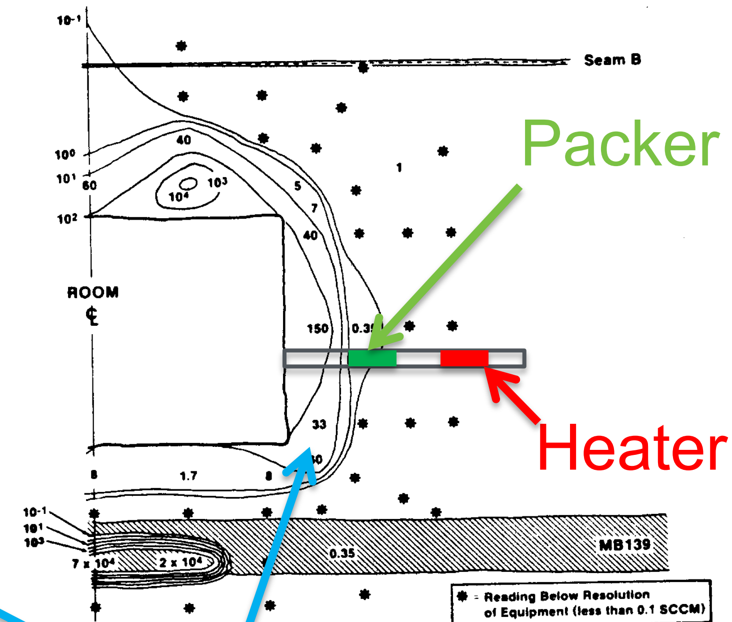
BATS Test in DRZ Conceptual Model

Cartoon representation of test interval relative to observed DRZ at WIPP



Borns & Stormont (1988)

Contours of gas flowrate at fixed pressure (i.e., damage)

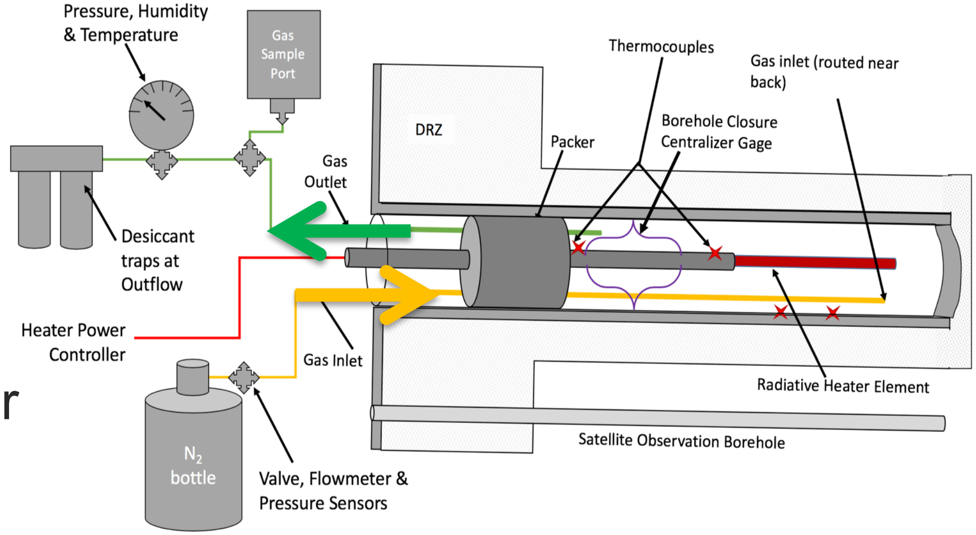


Borns & Stormont (1988)

Horizontal borehole avoids mapped clay / anhydrite layers (e.g., MB139) in Room A/B vertical heater tests

Near-drift DRZ and damage

BATS Test Instrumentation



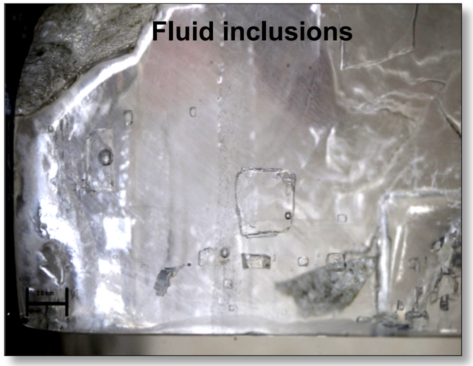
- Behind packer
  - Circulate dry N_2
  - Quartz lamp heater (750 W)
  - Borehole closure gage
  - Gas permeability before / after
- Samples / Analyses
  - Cores (X-ray CT and fluorescence at NETL)
  - Gas stream (natural / applied tracers, humidity and isotopic makeup)
  - Liquid brine (natural chemistry and natural / applied tracers)
- Geophysics
  - 3 × Electrical resistivity tomography (ERT)
  - 3 × Acoustic emissions (AE) / ultrasonic travel-time tomography
  - 2 × Fiber optic distributed strain (DSS) / temperature (DTS) sensing
  - +100 thermocouples

BATS Test Data

- Brine composition samples / H_2O isotope data
  - Measure change in brine sources with temperature
- Geophysics
  - Map 4D evolution of **saturation** / **porosity** / **permeability**
- 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
  - Thermal-hydrological-mechanical evolution of salt during heating
- Tracer migration through salt
  - Estimate rate of brine / vapor movement through salt DRZ
- Post-test overcoring
  - Cement seal, tracer distribution around source, damage

Brine in Salt

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

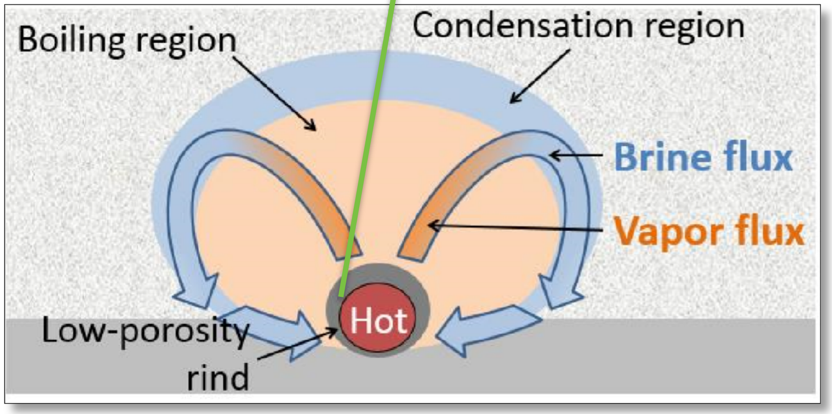


- Brine content correlates with clay content
- Only *intergranular* brine moves under pressure gradient
- Water types respond differently to heat
  – Hydrous minerals evolve water vapor, which can become brine
  – Intragranular brine migrates under thermal gradient
- Brine types have different chemical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

Q: How do 3 water types contribute to *Brine Availability?*

Salt Thermally-driven Conceptual Model

- Salt is “thermally activated”
  - High temperatures speed up creep closure
  - More brine available in hot salt
  - Salt more soluble 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
- Coupled models (Δ porosity / permeability)
  - Creep, damage & healing
  - Precipitation & dissolution
  - Brine migration (rel. permeability)
    - Gas-filled fractures
    - Liquid-saturated far field



BATS: What we expect

- Unheated array
  - Decay in brine inflow rate through time from peak at drilling
- Heated array when turned on
  - Increased brine inflow (new peak, decay to higher steady-state)
  - Dry-out near heater (two-phase flow)
  - *Decreased salt permeability / porosity* (expansion, creep)
- Heated array when turned off
  - *Increased salt permeability / porosity* (contraction)
  - Increased brine inflow
- Geophysical methods: observe Δ porosity & saturation
- Natural and man-made tracers
  - Effectiveness of gas / liquid transport through DRZ
  - Contributions from 3 water types in salt

Salt / GDSA Integration

- Salt engineered barriers systems (EBS)
  - BATS seal component will provide data on effects of heat and brine on cement in a salt repository
- Improvements to process models:
  - Models used to iteratively design the heater test
  - Models used to interpret data collected during the test
  - Benefits to Geologic Disposal Safety Assessment (GDSA)
- Future tests may benefit Dual-purpose Canisters (DPC) direct disposal issues
  - Possible higher temperatures, look at buoyancy issues

Ongoing International Collaboration

- Strong int’l salt repository research community
  - USA (SNL, LANL, LBNL), Germany (BGR, DBE, GRS), Netherlands (COVRA), UK (RWM)
- Variety of salt deposits around world
  - *Bedded* salt: flat-lying salt (i.e., WIPP)
  - *Domal* salt: less water, but more complex geometry
  - *Pillow* salt: between bedded & domal
- International meetings
  - 10th US / German Workshop (2019 Rapid City)
  - OECD Nuclear Energy Agency “Salt Club”
  - Model validation to lab experiments:
    - WEIMOS, KOMPASS, RANGERS

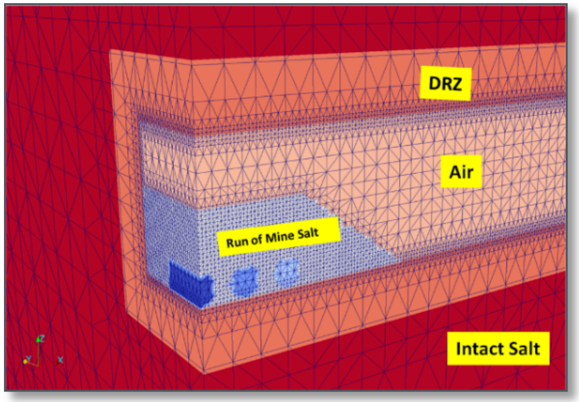
- Possible BATS DECOVALEX 2023 task

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 GDSA performance assessment (PA) tool

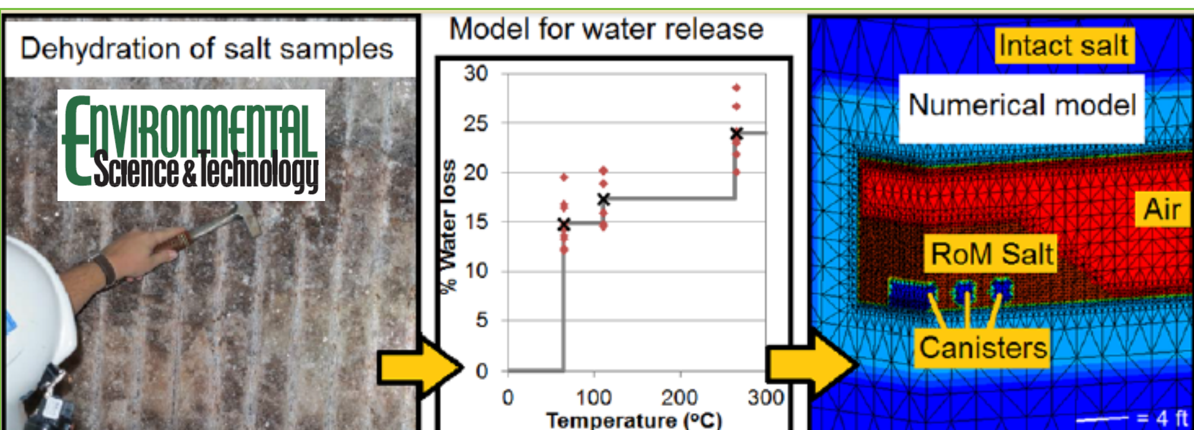
THMC Process-Level Modeling

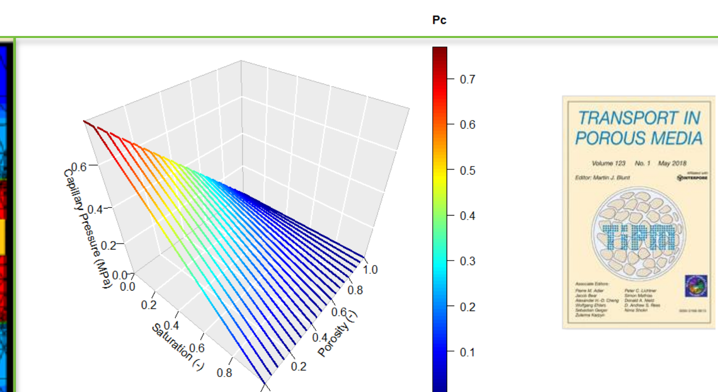
- Thermal-Hydrological-Mechanical-Chemical (THMC)
- TOUGH-FLAC simulates large-deformation THMC
- FEHM numerical model simulates small-deformation THMC
- Isolating specific processes allows more rapid validation
- Some processes are validated using TH, TM, THC, or THM



Salt THMC Couplings

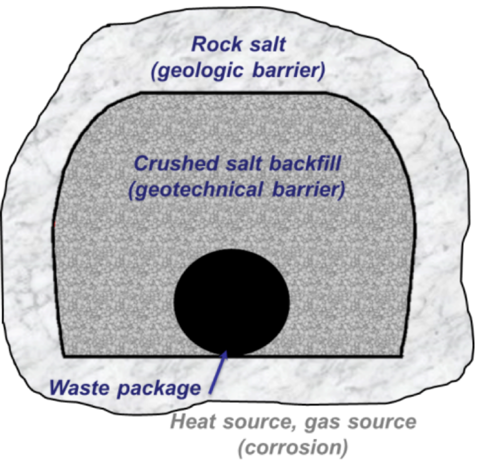
Deformation (strain)	***F***(*stress, time, saturation, temperature*)
Vapor pressure lowering	***F***(*capillary pressure, salinity*)
Porosity	***F***(*dissolution, precipitation, stress, strain*)
Thermal conductivity	***F***(*porosity, saturation, temperature*)
Permeability	***F***(*dissolution, precipitation,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

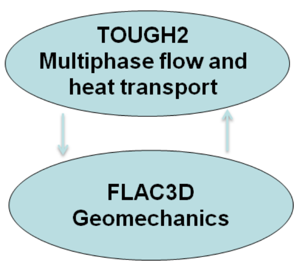


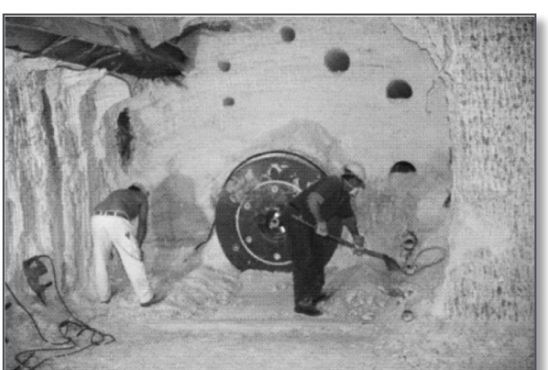


Capillary pressure / porosity function

Importance of Salt THMC Processes



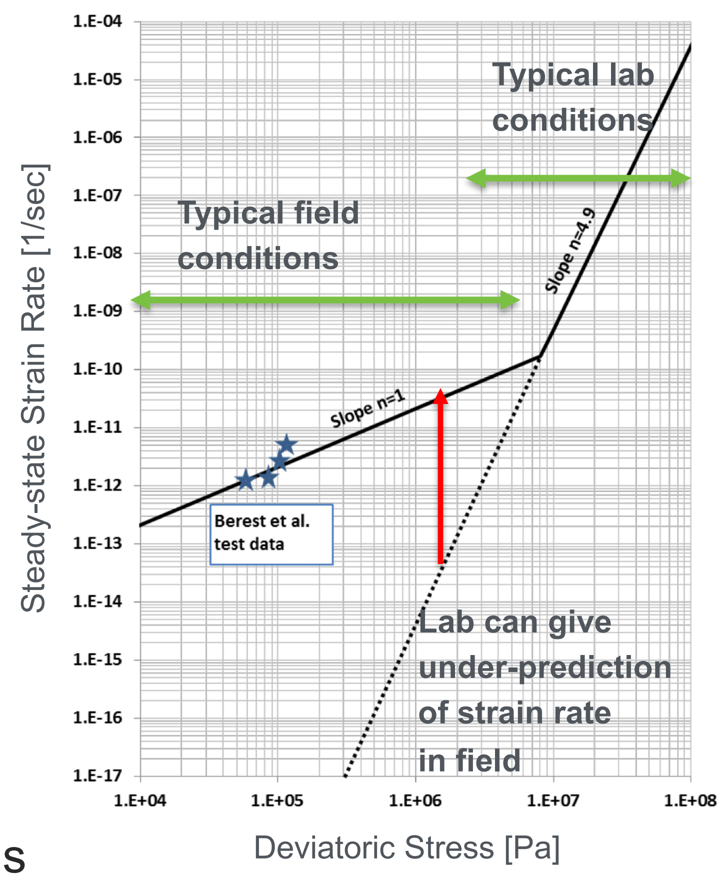




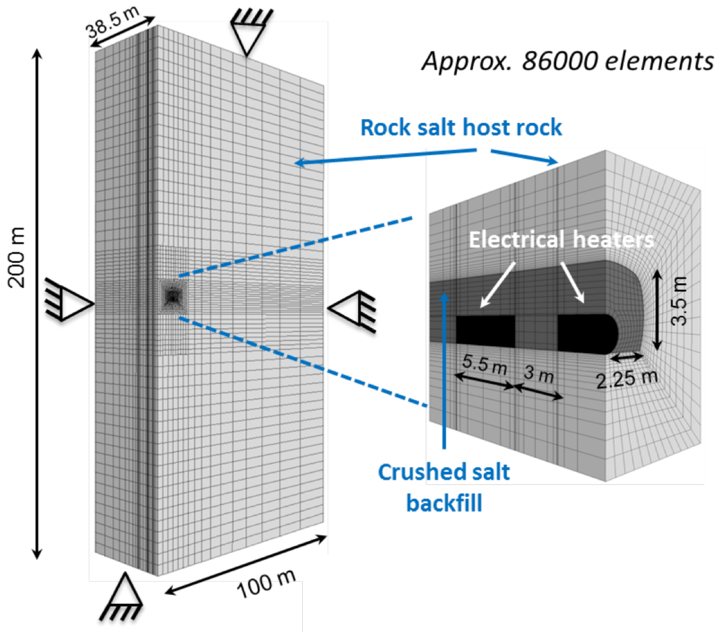
- Performance Assessment
  - Development of DRZ, a potential transport path
  - Compaction, sealing and healing (solidification)
- Safety Case
  - Post-closure safety assessment: barrier / safety function
  - Post-closure FEPs, including host rock / DRZ
  - Confidence enhancement, including validation
- 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)

Salt Mechanical Constitutive Models

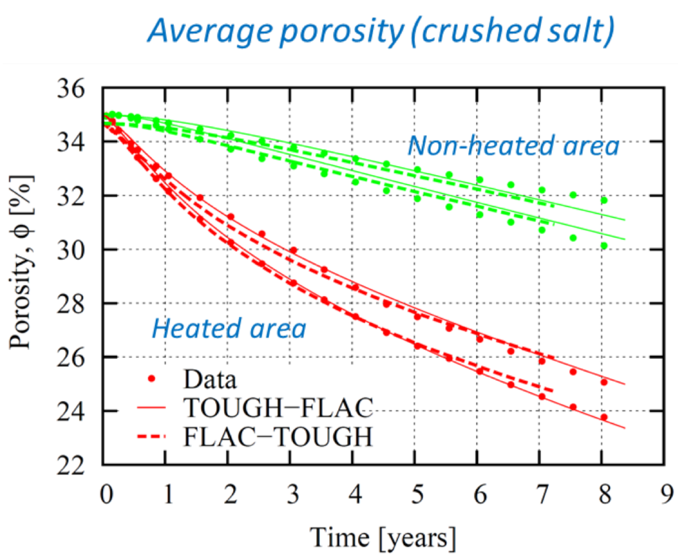
- Salt behavior is complex (elastic / creep / damage / healing)
  - Models are in general good, but
    - Constitutive laws have many parameters
    - Require carefully controlled lab experiments
      - temperature, moisture, loading path
- Strain at low deviatoric stress
  - Recent international focus
  - 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)
  - Crushing at high loads unlike field conditions



THM Model: Heater Test at Asse Mine

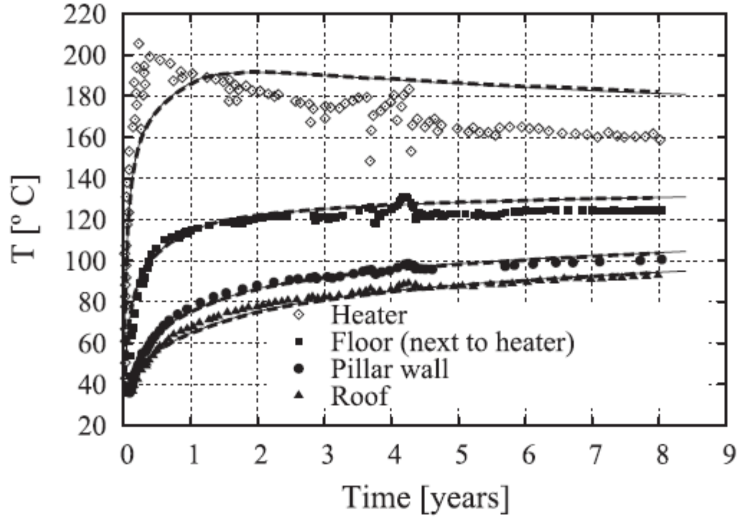


Blanco-Martin et al. (2016)

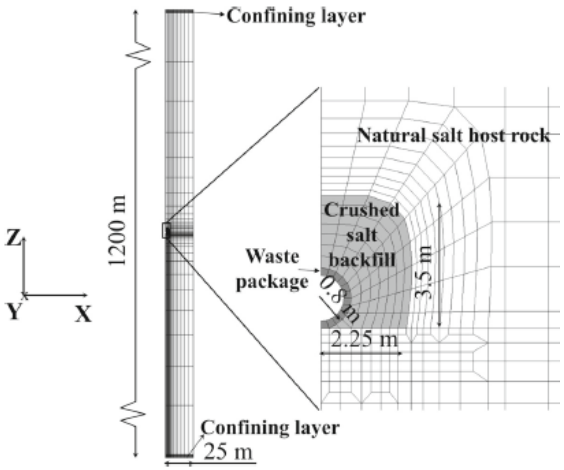


- THM constitutive model validation to 8 years
- Compaction driven by tunnel convergence
- Fastest compaction in the heated section

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



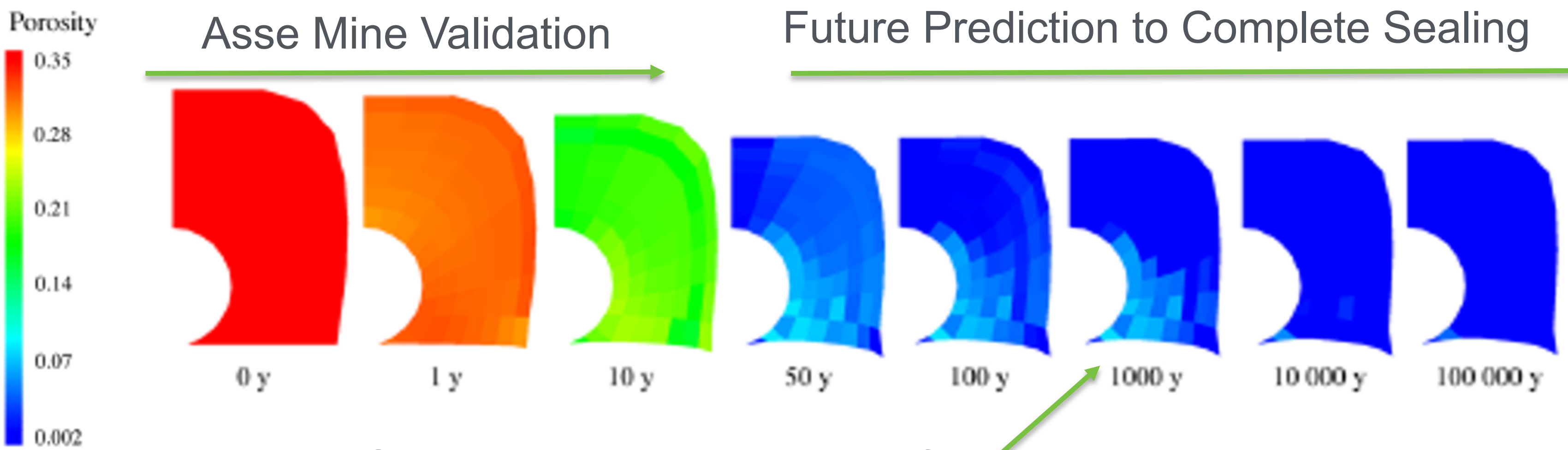
THMC: Long-term Compaction and Sealing



- 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

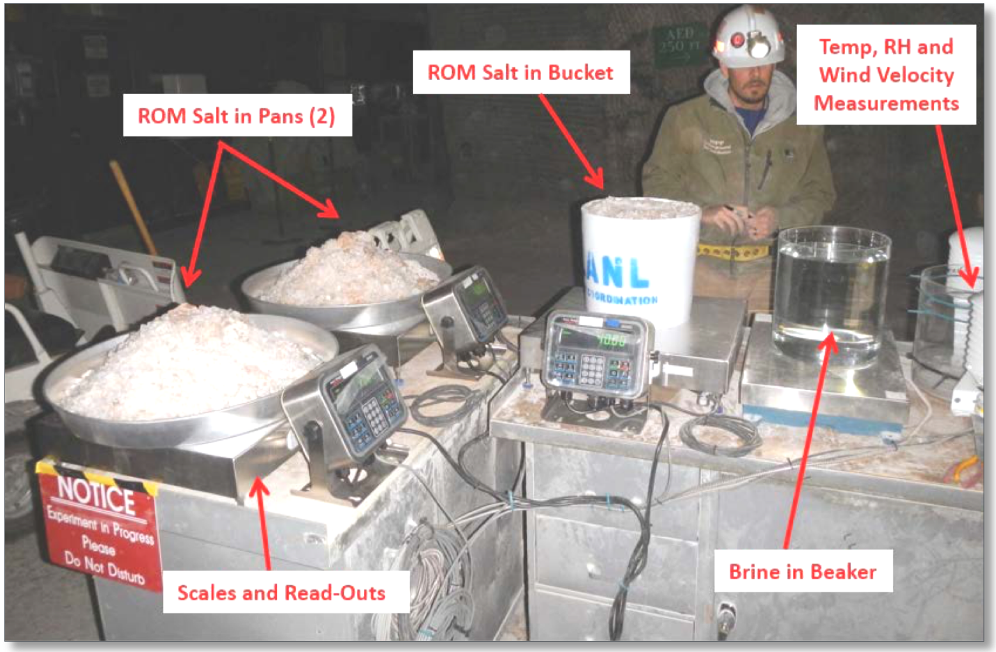
Future Prediction to Complete Sealing

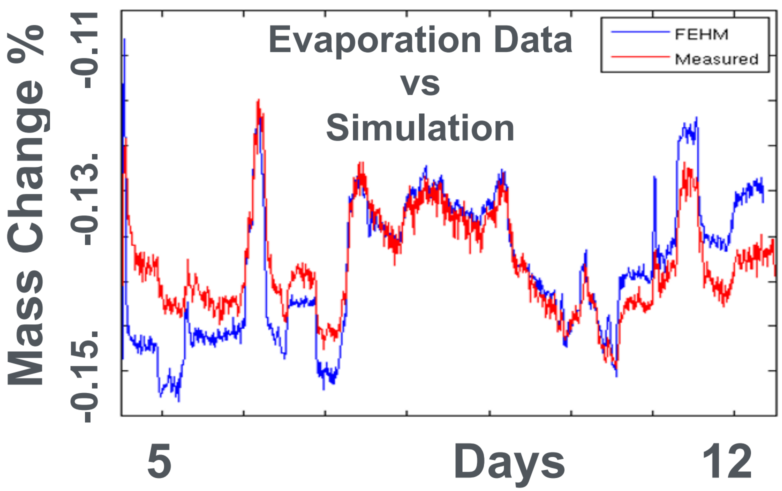


Simulation indicates areas of about 10% porosity at 1000 years (permeability ≈ 10^{-15} m^2)

THC Coupling: Evaporation example

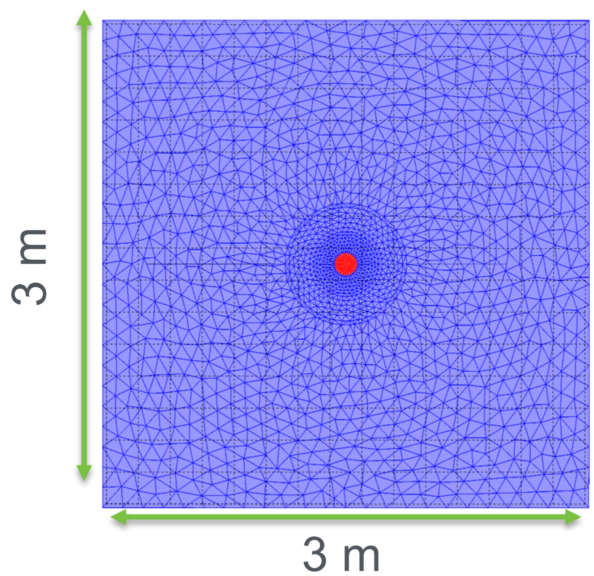
- WIPP evaporation experiment
  - Joint DOE-EM / DOE-NE
  - Ran in WIPP underground by LANL Carlsbad
- Simulated using FEHM
  - Implemented a new time-dependent FEHM relative humidity (RH) boundary condition
- Mine ventilation (RH) impacts better included in future test simulations





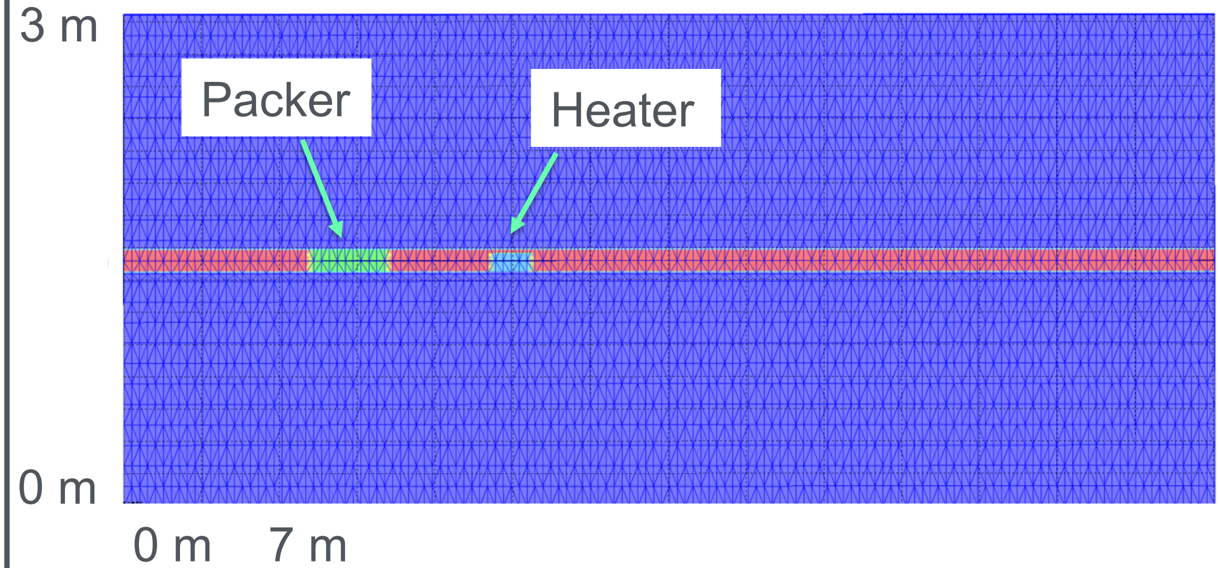
Shakedown: THC Model of Field Test

Shakedown Test
3D Borehole heater
simulation domain

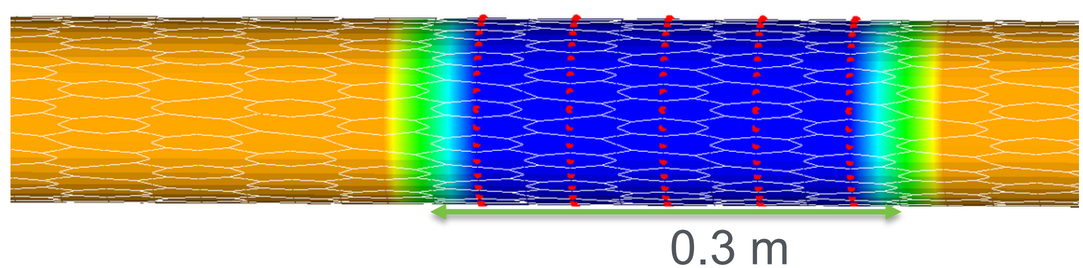


Drift view
looking into
horizontal hole

Side view along the horizontal hole



Meters from the drift face



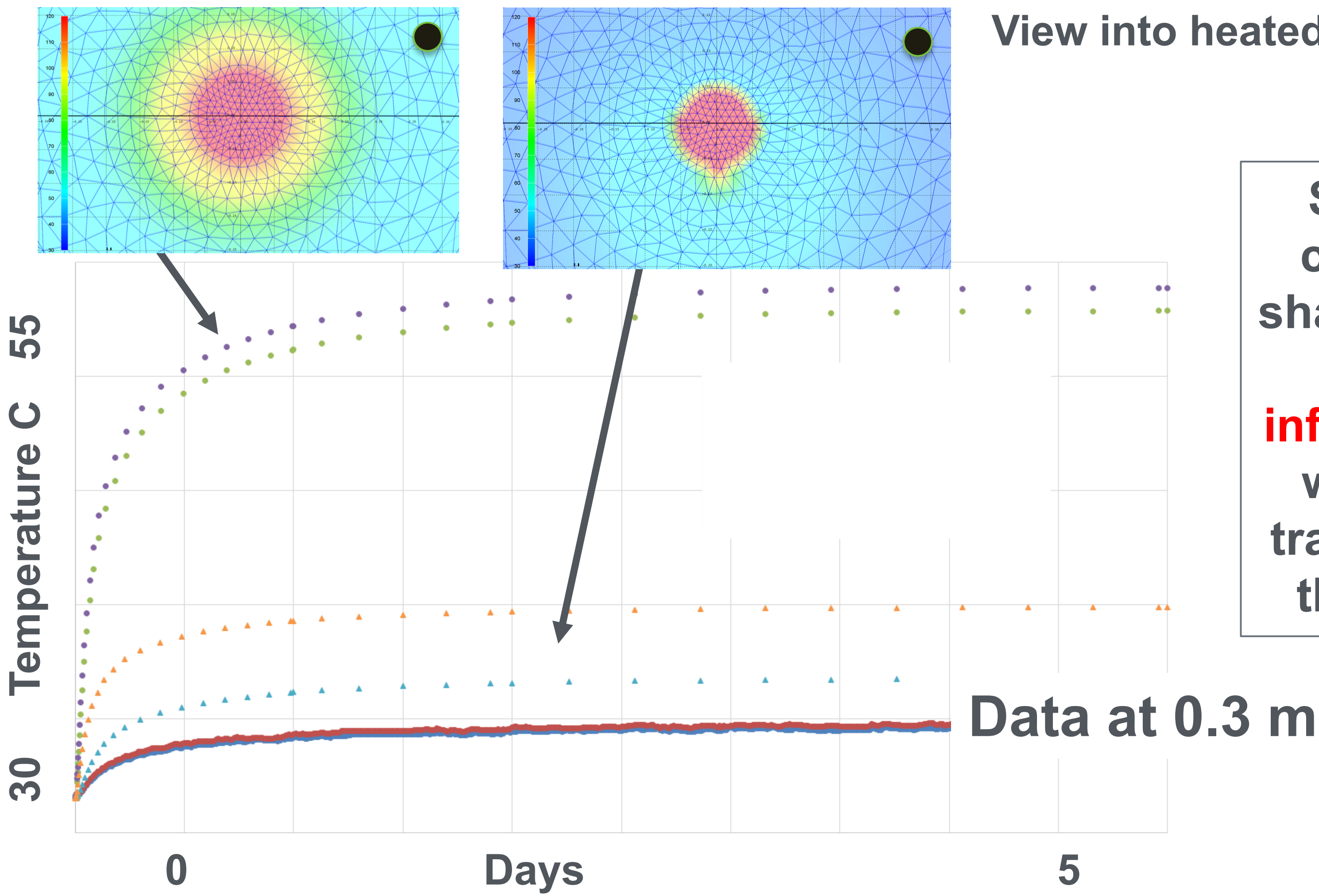
Zoom into the heater mesh

Shakedown: Simulations Assist Design

Full contact (radiation) sim

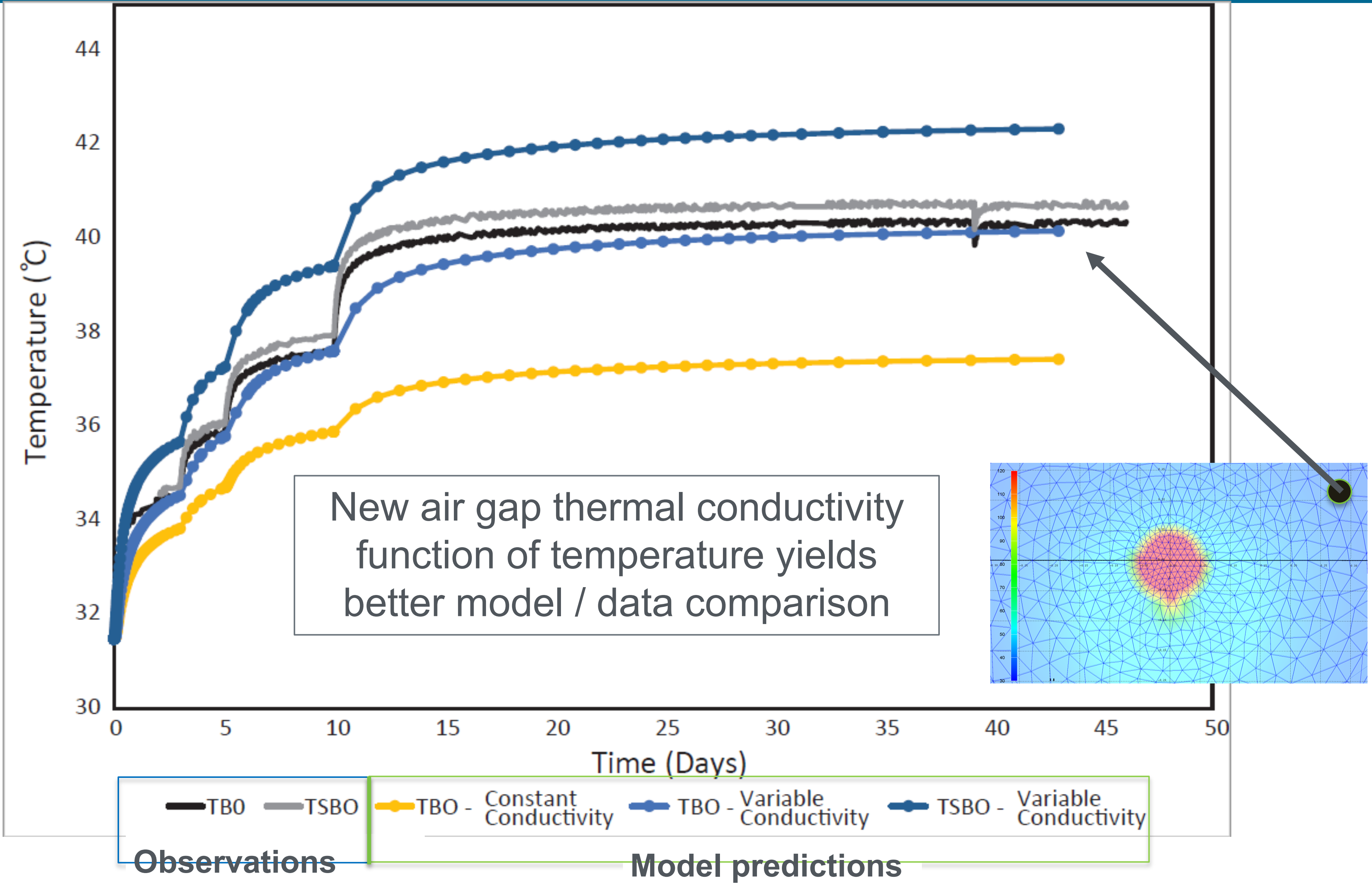
Small contact (conduction) sim

View into heated borehole



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

Shakedown: Modeling Thermal Step Test



New air gap thermal conductivity function of temperature yields better model / data comparison

Shakedown: Modeling Improved Heater Design

Initial metal block heater

Small infrared (IR) heater

Deisgn IR heater power

120 C

260 W

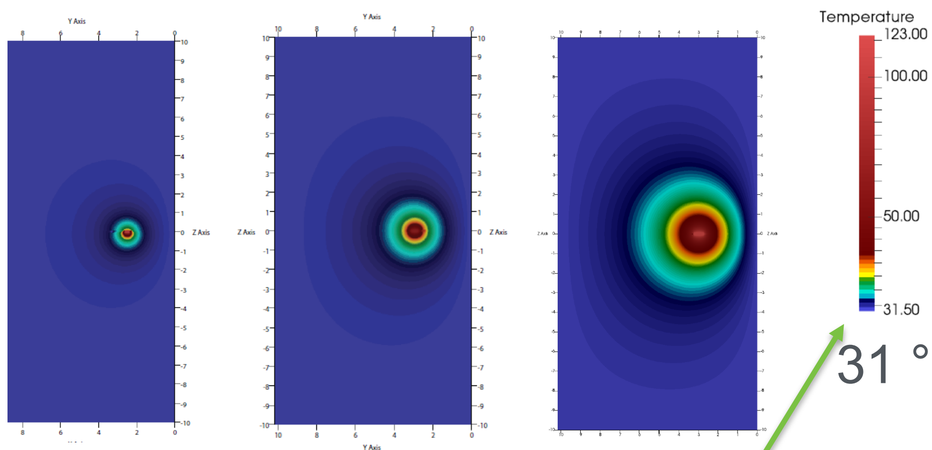
750 W

140 °C

+10 m

0

-10 m



31 °C

0 m

10 m

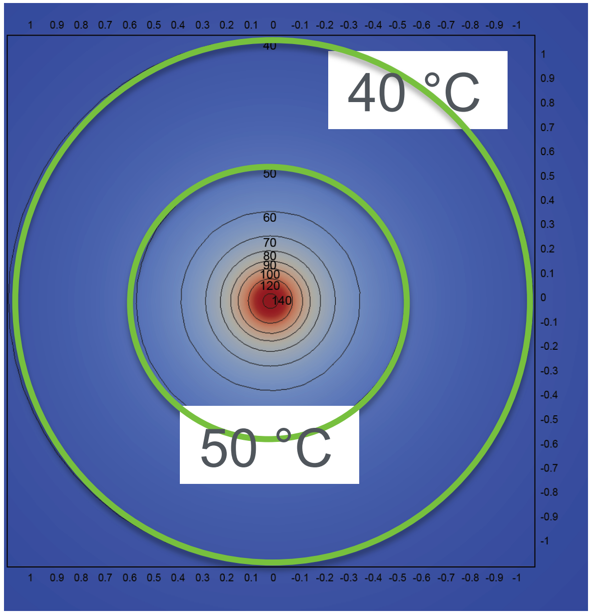
Colorbar axis skewed to increase contrast in temperature difference

+1 m

0

-1 m

Final IR heater 750W

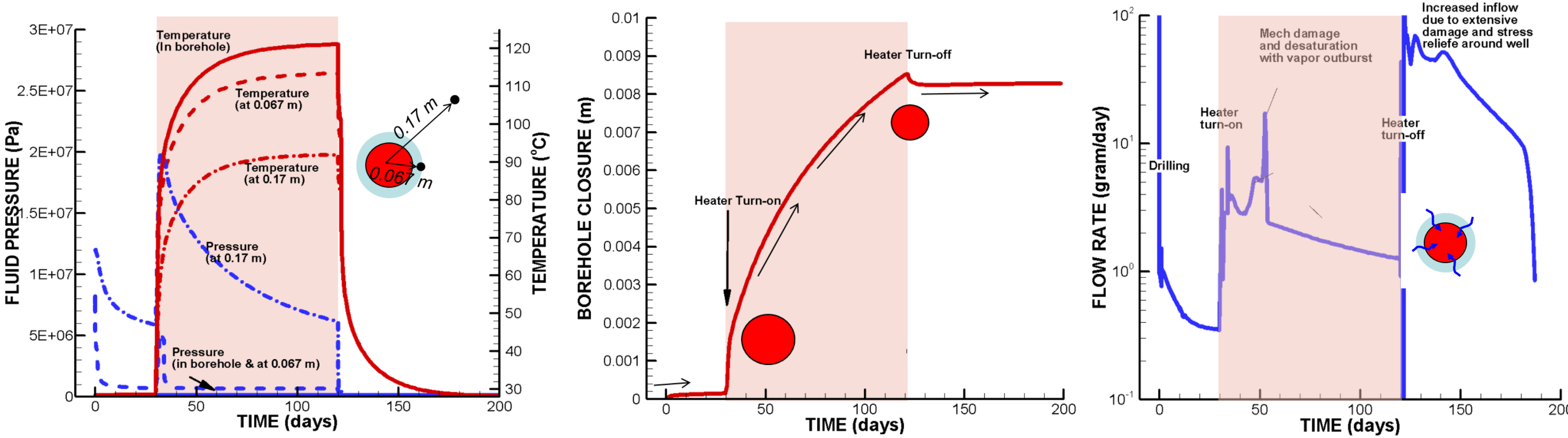


Temperature contours °C (@ heater midplane)

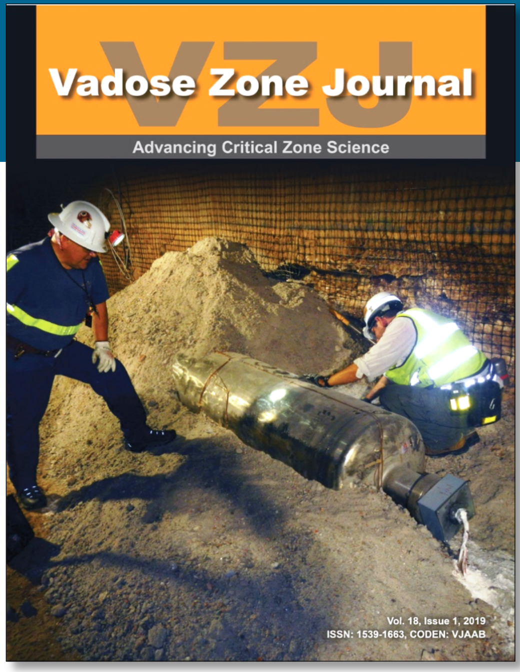
BATS: THM Model of Field Test

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



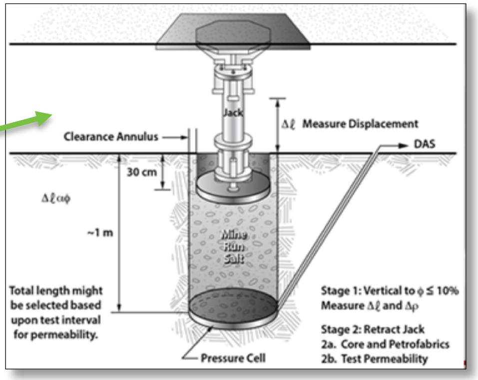
Salt Disposal R&D “Five-Year Plan”

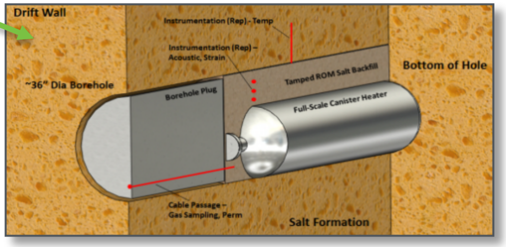


- WIPP Borehole Heater Test
  - FY19 execution (~120 ℃ & unheated)
  - Possible follow-on tests at higher temp

- 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 BATS: 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 geophysical methods to characterize salt DRZ / dryout
  - Possible BATS DECOVALEX 2023 task

- THMC in salt process-model improvements
  - Better design of ongoing field test
  - Better interpret field test results
  - Improvements feed back into conceptual and GDSA models

Questions?

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References

Beauheim, R.L., A. Ait-Chalal, G. Vouille, S.-M. Tijani, D.F. McTigue, C. Brun-Yaba, S.M. Hassanizadeh, G.M. van der Gissen, H. Holtman & P.N. Mollema, (1997). *INTRAVAL Phase 2 WIPP 1 Test Case Report: Modeling of Brine Flow Through Halite at the Waste Isolation Pilot Plant Site*. SAND97-0788. Sandia National Laboratories.

Blanco-Martin L., J. Rutqvist, A. Battistelli & J.T. Birkholzer, (2018). Coupled processes modeling in rock salt and crushed salt including halite solubility constraints: application to disposal of heat-generating nuclear waste. Transport in Porous Media, *Transport Porous Media*, 124, 159–182.

Blanco-Martín L., J. Rutqvist 7 J.T. Birkholzer, (2017). Extension of TOUGH-FLAC to the finite strain framework. *Computers & Geosciences*, 108, 64–71.

Blanco-Martín L., R. Wolters, J. Rutqvist, K.-H. Lux & J.T. Birkholzer, (2016). Thermal–hydraulic–mechanical modeling of a large-scale heater test to investigate rock salt and crushed salt behavior under repository conditions for heat-generating nuclear waste. *Computers and Geotechnics*, 77, 120–133.

Blanco-Martín L., J. Rutqvist & J.T. Birkholzer, (2015) Long-term modelling of the thermal-hydraulic-mechanical response of a generic salt repository for heat-generating nuclear waste. *Engineering Geology*, 193, 198–211.

Blanco-Martín L., R. Wolters, J. Rutqvist, K.-H. Lux & J.T. Birkholzer, (2015). Comparison of two simulators to investigate thermal-hydraulic-mechanical processes related to nuclear waste isolation in saliniferous formations. *Computers and Geotechnics*, 66, 219–229.

Borns, D.J., & J.C. Stormont, (1988). *An Interim Report on Excavation Effects Studies at the Waste Isolation Pilot Plant: The Delineation of the Disturbed Rock Zone*, SAND87-1375, Sandia National Laboratories.

Boukhalfa, H., P.H. Stauffer, P.J. Johnson, D.J. Weaver, S. Otto, B.L. Dozier, K. Kuhlman, C. Herrick, M. Mills, Y. Wu & J. Rutqvist, (2018). *Experiments and Modeling to Support Field Test Design*, LA-UR-18-29203, Los Alamos National Laboratory.

Coyle, A.J., J. Eckert, and H. Kalia, (1987). *Brine Migration Test Report: Asse Salt Mine, Federal Republic of Germany*, BMI/ONWI-624, Office of Nuclear Waste Isolation, Battelle Memorial Institute.

Czaikowski, O. & K. Wieczorek (2016). *Final technical report on ELSA related testing on mechanical-hydraulical behaviour - LASA. Full scale demonstration of plugs and seals (DOPAS) Deliverable D3.31*. GRS-A-3851. February, 29, 2016.

Harp, D.R., P.H. Stauffer, P.K. Mishra, D.G. Levitt, B.A. Robinson, (2014). Modeling of High-Level Nuclear Waste Disposal in a Salt Repository, *Nuclear Technology,* 187:294-307.

Holcomb, D.J., T. McDonald & R.D. Hardy, (2001). “Assessing the disturbed rock Zone (DRZ) at the WIPP (Waste Isolation Pilot Plant) in salt using ultrasonic waves” in *DC Rocks 2001, The 38th US Symposium on Rock Mechanics (USRMS)*. American Rock Mechanics Association. SAND2001-13055C.

Johnson, P.J., S. Otto, D.J. Weaver, B. Dozier, T.A. Miller, A.B. Jordan, N. Hayes-Rich & P.H. Stauffer, (2018) Heat-Generating Nuclear Waste in Salt: Field Testing and Simulation, *Vadose Zone Journal,* 18(1).

Johnson, P.J., G.A. Zyvoloski & P.H. Stauffer, (2018) Impact of a porosity dependent capillary function on simulations of porous flow, *Transport in Porous Media, 1-22*.

Jordan, A.B., H. Boukhalfa, F.A. Caporuscio, B.A. Robinson & P.H. Stauffer, (2015) Hydrous Mineral Dehydration around Heat-Generating Nuclear Waste in Bedded Salt Formations, *Environmental Science & Technology*, 5:1-13.

Kuhlman, K.L., & B. Malama, (2013). *Brine Flow in Heated Geologic Salt*, SAND2013-1944. Sandia National Laboratories.

Kuhlman, K.L. & S.D. Sevougian, (2013). *Establishing the Technical Basis for Disposal of Heat-Generating Waste in Salt*, SAND2013-6212P, Sandia National Laboratories.

Kuhlman, K.L., (2014). *Summary Results for Brine Migration Modeling Performed by LANL, LBNL, and SNL for the Used Fuel Disposition Program*, SAND2014-18217R. Sandia National Laboratories.

Kuhlman, K.L., M.M. Mills & E.N. Matteo, (2017). *Consensus on Intermediate Scale Salt Field Test Design*, SAND2017-3179R. Sandia National Laboratories.

Krause, W.B., (1983). *Avery Island Brine Migration Tests: Installation, Operation, Data Collection, and Analysis*. ONWI-190(4). Rapid City, SD: RE/SPEC, Inc.

Nowak, E.J., and D.F. McTigue, (1987). *Interim Results of Brine Transport Studies in the Waste Isolation Pilot Plant (WIPP)*. SAND87-0880. Sandia National Laboratories.

Reedlunn, B. (2016). *Reinvestigation into Closure Predictions of Room D at the Waste Isolation Pilot Plant*, SAND2016-9961, Sandia National Laboratories.

Reedlunn, B. (2018). *Enhancements to the Munson-Dawson Model for Rock Salt*, SAND2018-12601, Sandia National Laboratories.

Rothfuchs, T., K. Wieczorek, H.K. Feddersen, G. Staupendahl, A.J. Coyle, H. Kalia, & J. Eckert, (1988). *Brine Migration Test: Asse Salt Mine Federal Republic of Germany Final Report*, GSF-Bericht 6/88, Joint project between Office of Nuclear Waste Isolation (ONWI) and Gesellschaft für Strahlen- und Umweltforschung Munchen (GSF).

Sandia National Laboratories, Los Alamos National Laboratories, Lawrence Berkeley National Laboratories, (2018). *Project Plan: Salt in Situ Heater Test*, SAND2018-4673R.

Skokan, C.K., M.C. Pfeifer, G.V. Keller, and H.T. Andersen, (1989). *Studies of Electrical and Electromagnetic Methods for Characterizing Salt Properties at the WIPP Site, New Mexico*. SAND87-7174, Sandia National Laboratories.

Stormont, J.C., (1987). *Small-Scale Seal Performance Test Series "A" Thermal/Structural Data through the 180th Day*, SAND87-0178. Sandia National Laboratories.

Stauffer, P.H., A.B. Jordan, D.J. Weaver, F.A. Caporuscio, J.A. Tencate, H. Boukhalfa, B.A. Robinson, D.C. Sassani, K.L. Kuhlman, E.L. Hardin, S.D. Sevougian, R.J. MacKinnon, Y. Wu, T.A. Daley, B.M. Freifield, P.J. Cook, J Rutqvuist & J.T. Birkholzer, (2015). *Test Proposal Document for Phased Field Testing in Salt*, LA-UR-15-23154, Los Alamos National Laboratory.

Acronyms and Initialisms

AE	acoustic emissions
BATS	brine availability test in salt
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
CBFO	Carlsbad Field Office (DOE-EM field office at WIPP)
COVRA	Centrale Organisatie Voor Radioactief Afval (Netherlands)
CRDS	cavity ring-down spectrometer
CT	computed tomography
DBE	Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe
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
DRZ	disturbed rock zone
DSS	distributed strain sensing
DTS	distributed temperature sensing
EBS	engineered barrier system
ERT	electrical resistivity tomography
FEHM	LANL porous media flow and transport simulator
FLAC	Itasca geomechanical simulator
FY	fiscal year (Oct-Sept)
GDSA	geologic disposal safety assessment
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
HLW	high-level waste
IR	ifrared
KOMPASS	Joint Project on the Compaction of Crushed Salt for Safe Containment
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LVDT	linear variable differential transformer
MB139	Marker bed 139 (WIPP)
NETL	National Energy Technology Laboratory
OECD	Organisation for Economic Co-operation and Development
PA	performance assessment
RANGERS	Design and Integrity Guideline for Engineered Barrier Systems for a HLW Repository in Salt
R&D	research and development
RH	relative humidity
RWM	Radioactive Waste Management (UK)
SA	safety assessment
SDDI	Salt Disposal Defense Investigations
SDI	Salt Disposal Investigations
SFWST	Spent Fuel & Waste Science & Technology
SNL	Sandia National Laboratories
TCO	WIPP Test Coordination Office
THMC	thermal-hydrological-mechanical-chemical
TOUGH	LBNL porous media flow and transport simulator
URL	underground research laboratory
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)
XRD	X-ray diffraction
XRF	X-ray fluorescence