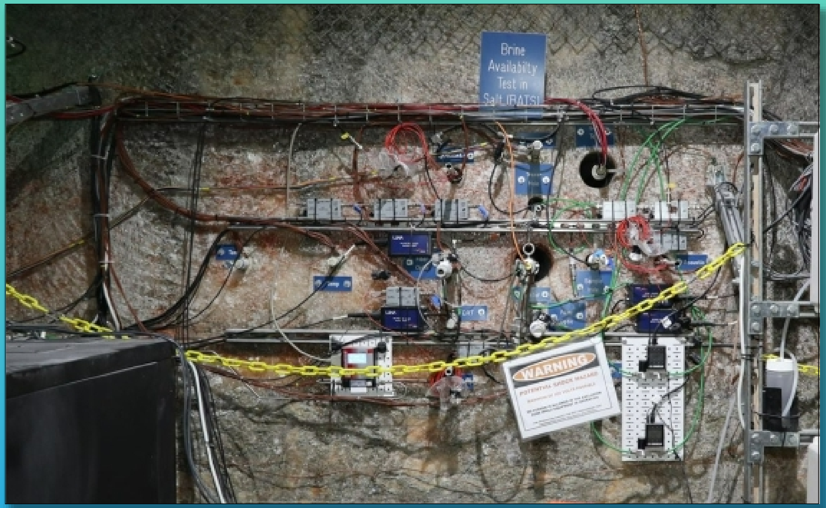
U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Spent Fuel and Waste Science and Technology (SFWST)

SAND2020-12658PE



DECOVALEX-2023 Task E (BATS) Introduction

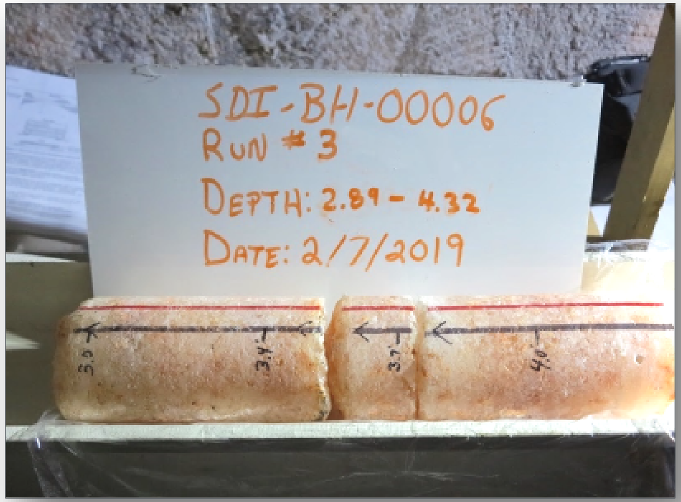
DECOVALEX-2023 Fall 2020 Meeting
Wednesday November 16, 2020
Virtual Workshop

Kristopher L. Kuhlman
Sandia National Laboratories

Outline

- Introduction
- 1992 Waste Isolation Pilot Plant (WIPP) data
- 2020 Brine Availability Test in Salt (BATS) data
- Fall 2020 Meeting
  - Work presented this week
  - New work moving forward

BATS 10-cm core



BATS test ready (Dec. 2019) in WIPP N-940 drift

Drilling BATS boreholes (Feb. 2019)

Motivation

Salt long-term ($10^4 - 10^6$ yrs.) benefits at km-scale

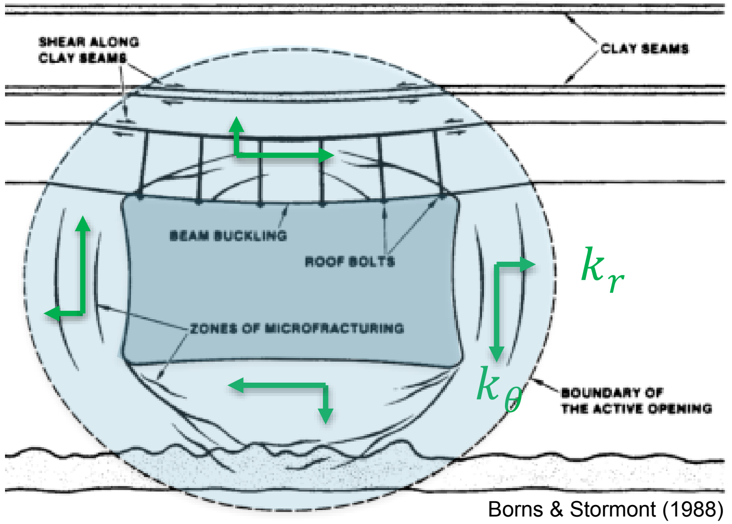
- Low porosity ($\phi \leq\ 0.1$ vol-%) and permeability ($k \leq 10^{-22}\ \mathrm{m}^2$)
- High thermal conductivity ($\sim 5\ \mathrm{W/(m \cdot K)}$)
- No flowing groundwater (≤ 5 wt-% water)
- Rooms, damage, and fractures will creep closed ($10^0 - 10^2$ yrs.)

Alpine miner at WIPP

Near-field (cm – 10 m) short-term (hr. – month) complexities

- Brine and salt are corrosive
- Evaporites are very soluble in water
- Salt creep requires drift maintenance
- Excavation Damaged Zone (EDZ):
  - Is main source of ϕ and k near drift
  - May be highly anisotropic ($k_r \ll k_\theta$)
  - Has steep gradients in properties and system state
  - Evolves with stress and temperature

Cross-section view of Excavation Damaged Zone (EDZ) around drifts

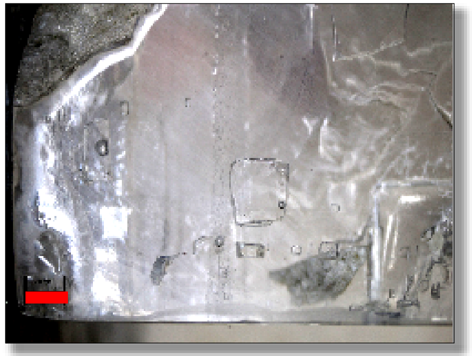


Borns & Stormont (1988)

Brine in Bedded Salt

- Water types in bedded salt
  1. Disseminated clay (< 5 vol-% total; ~25 vol-% brine)
  2. Intragranular brine (fluid inclusions; 1 – 2 vol-%)
  3. Hydrous minerals (e.g., polyhalite, bischofite, epsomite)
  4. Intergranular brine (between salt crystals; << 1 vol-%)

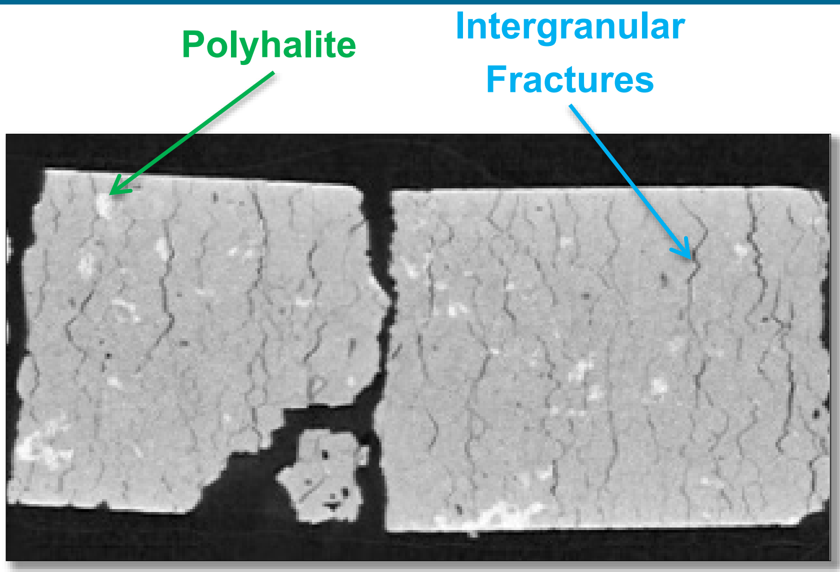
- These water types:
  - respond differently to heat & pressure
  - have varying chemical composition
  - differ in stable water isotope makeup

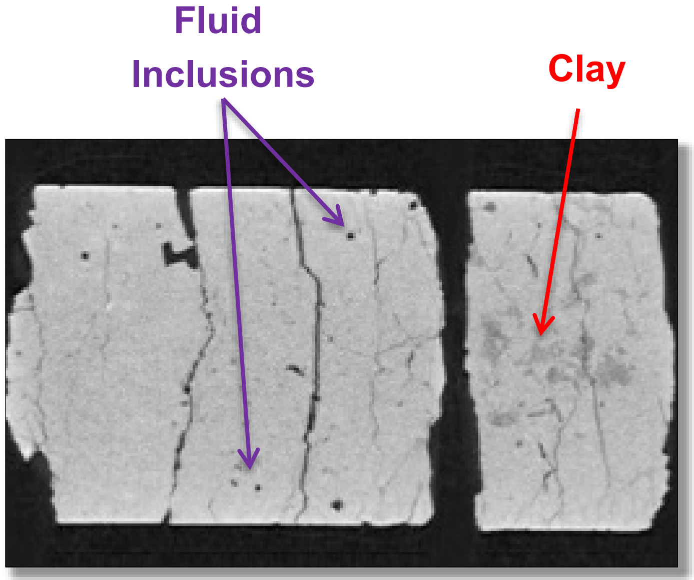


WIPP fluid inclusions, 2 mm scale bar (Caporuscio et al., 2013)

- EDZ increases intergranular ϕ → primary flow path

How do water types contribute to *Brine Availability?*





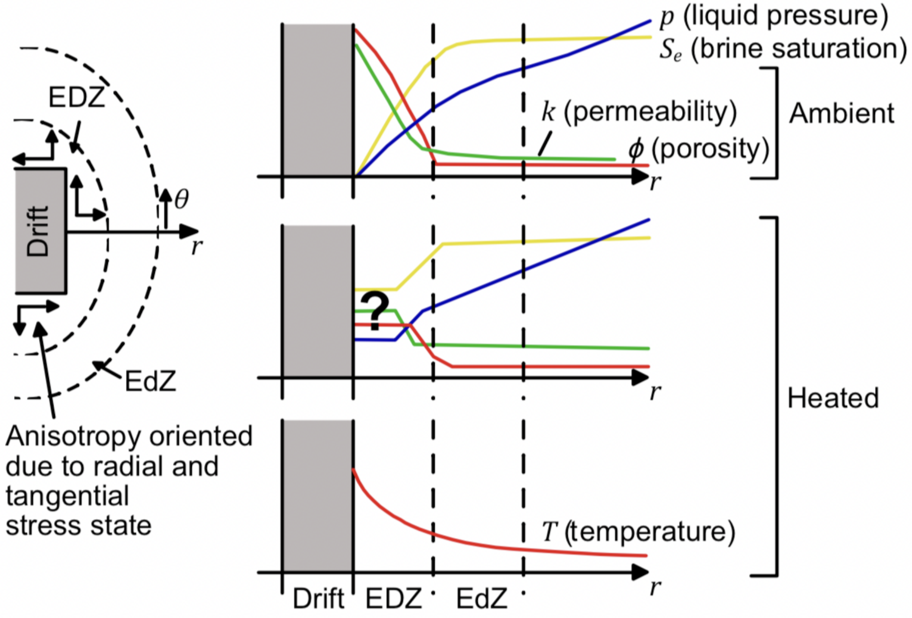
10.1 cm diameter core CT data (Betters et al., 2020)

Task E Goals

- Understand and predict THMC processes impacting *brine availability*
  - How much of each water type in bedded salt?
  - Water response to pressure (Δp), stress ($\Delta \sigma$), and temperature (ΔT)?
  - How does EDZ control migration of water (ϕ, k, relative perm. k_r)?
  - How does EDZ evolve with Δp, $\Delta \sigma$, and ΔT?

Q1: Is two-phase flow in EDZ important?

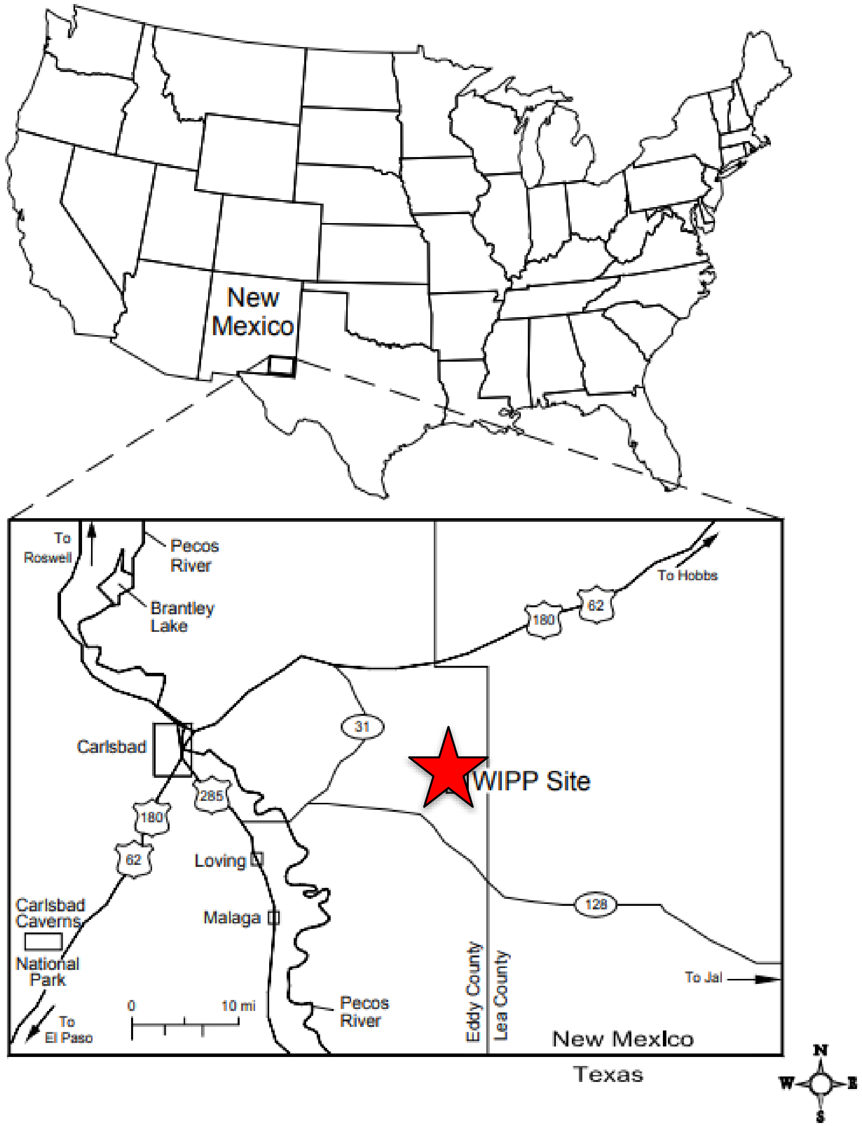
Q2: How to simulate brine pulse after heating?

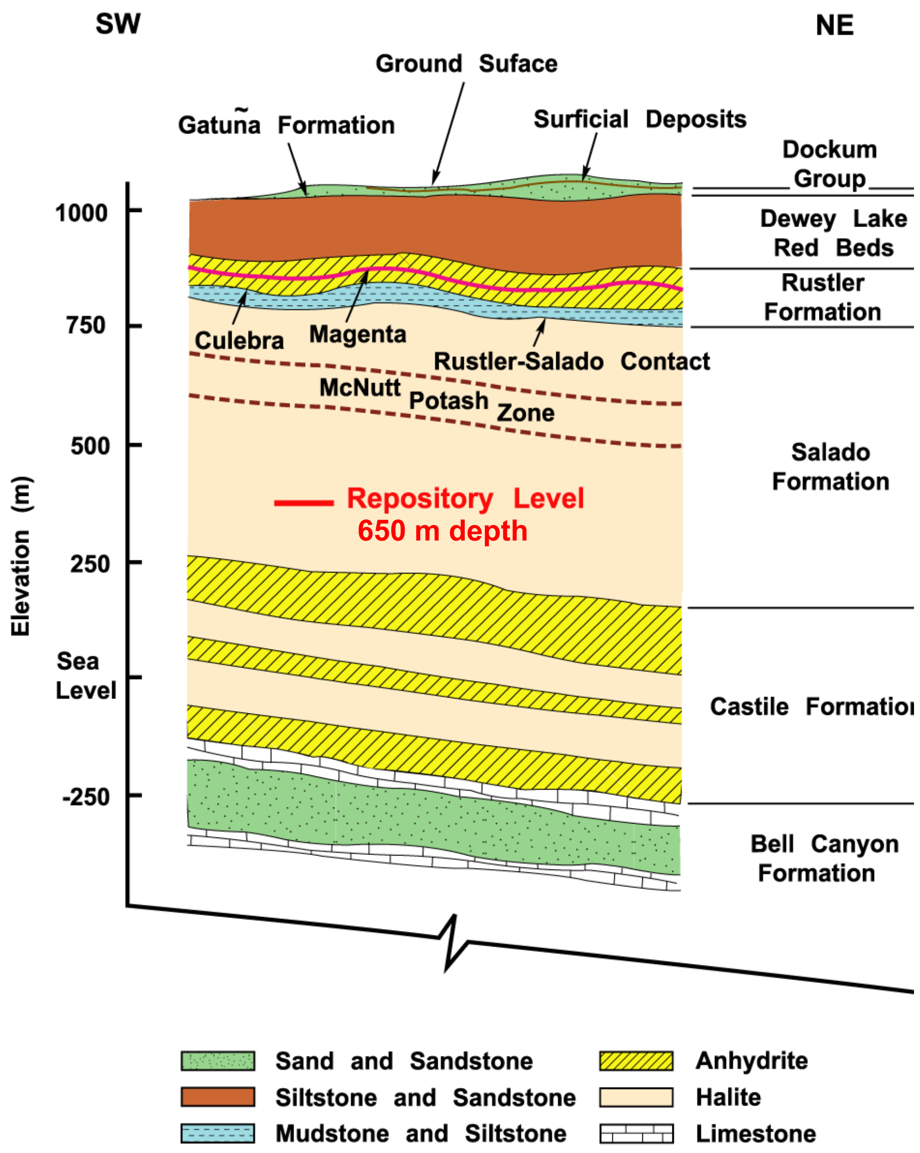


EDZ = Excavation Damaged Zone
EdZ = Excavation disturbed Zone

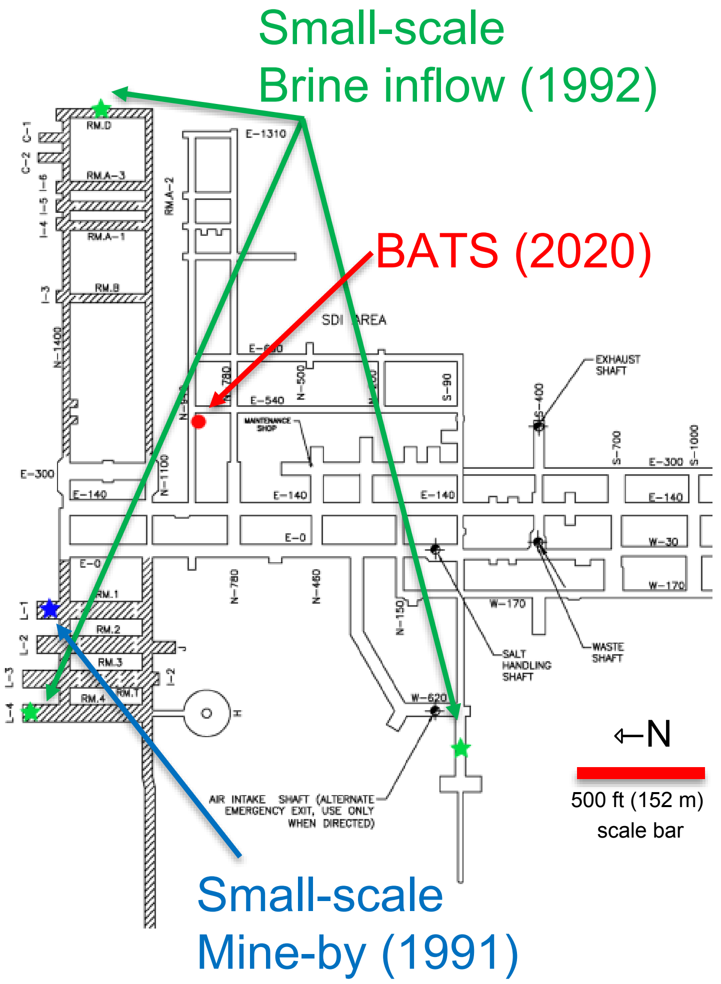
- WIPP Test Cases:
  - Small-Scale Brine Inflow test (1987-1992)
  - Small-Scale Mine-by experiment (1991)
  - Ongoing heated Brine Availability Test in Salt (BATS)

Waste Isolation Pilot Plant (WIPP) Context





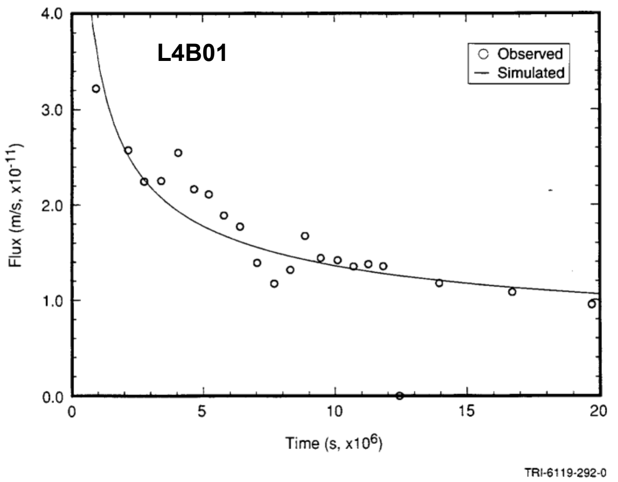
Layout of WIPP North End

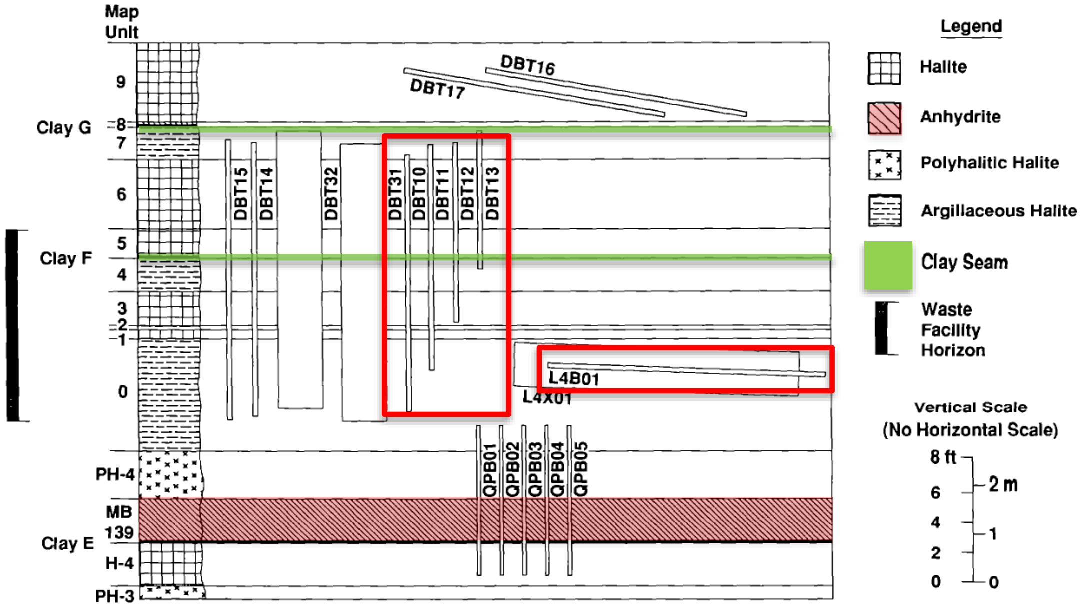


WIPP Small-Scale Brine Inflow Test (1987-1992)

- Monitored 17 unheated boreholes for years
- Soon after drilling (~new drifts)
- Weekly brine inflow data
- INTRAVAL study (Beauheim et al., 1997)
- Effects of stratigraphy / orientation / drift

(Beauheim et al., 1997)

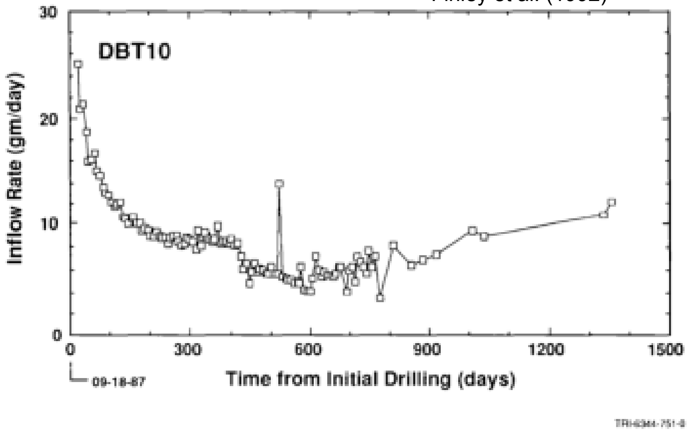


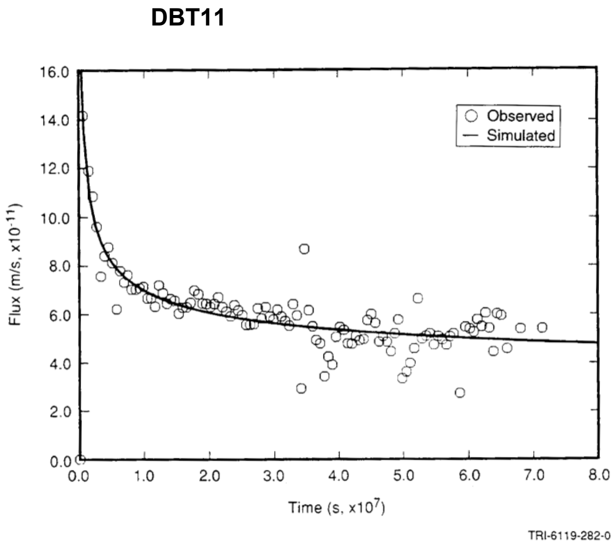


MB = marker bed
PH = polyhalite

Finley et al. (1992)

Finley et al. (1992)





Brine Availability Test in Salt (BATS) Team

Sandia National Laboratories (SNL)

Kris Kuhlman, Melissa Mills, Rick Jayne, Courtney Herrick, Ed Matteo, Charles Choens, Martin Nemer, Yongliang Xiong, Jason Heath

Los Alamos National Laboratory (LANL)

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

WIPP Test Coordination Office (TCO), LANL

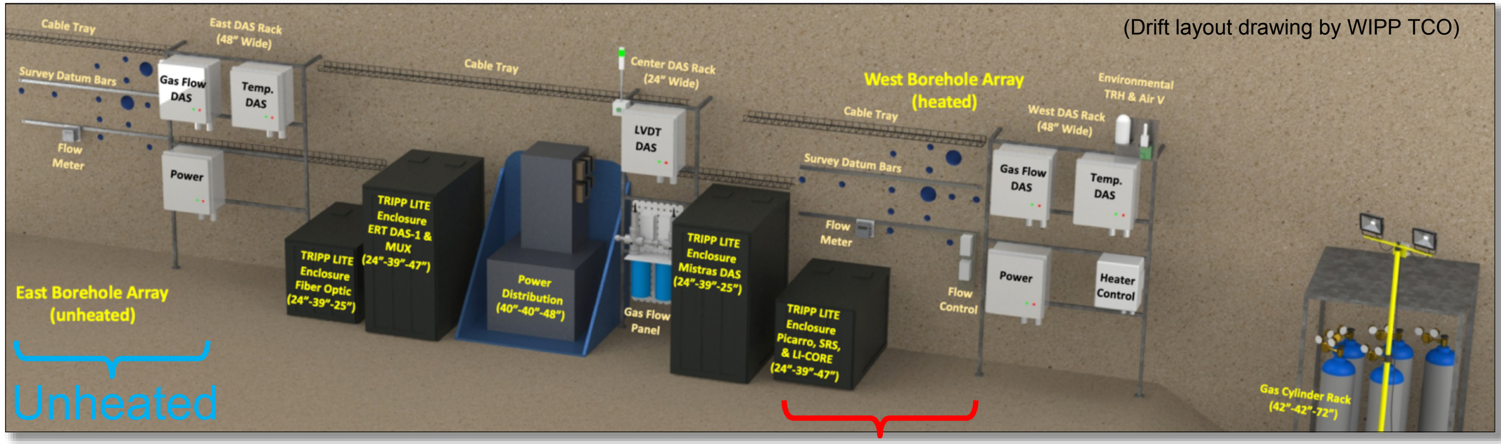
Doug Weaver, Brian Dozier, Shawn Otto

Lawrence Berkeley National Laboratory (LBNL)

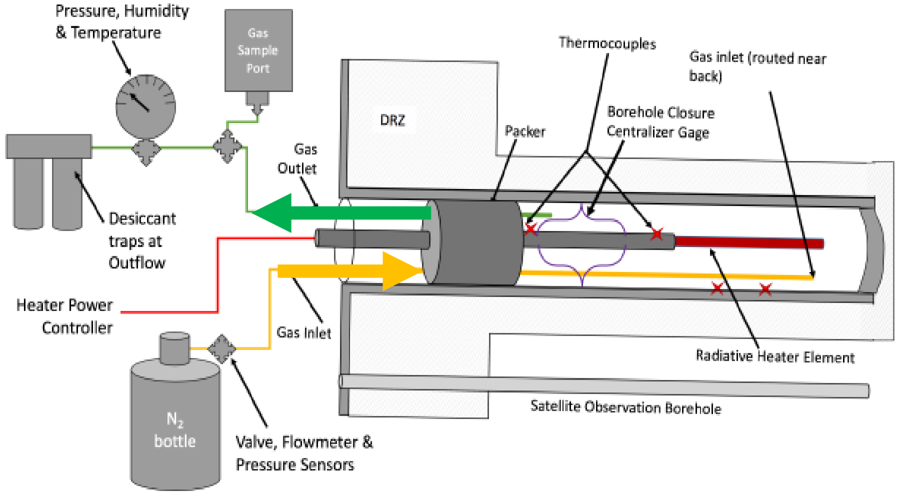
Yuxin Wu, Jonny Rutqvist, Mengsu Hu

Brine Availability Test in Salt (BATS)

- Two Arrays: Heated / Unheated
- Behind packer
  - Circulate dry N_2
  - Quartz lamp heater (750 W)
  - Borehole closure gage
- Samples / Analyses
  - Gas stream (natural / applied tracers and isotopic makeup)
  - Liquid brine (natural chemistry and natural / applied tracers)
  - Cores (X-ray CT at NETL); laboratory tests on samples
- Cement Seals
  - Sorel cement + Salt concrete: 3-axis strain & temperature
- Geophysics
  - 3× Electrical resistivity tomography (ERT)
  - 3× Acoustic emissions (AE)

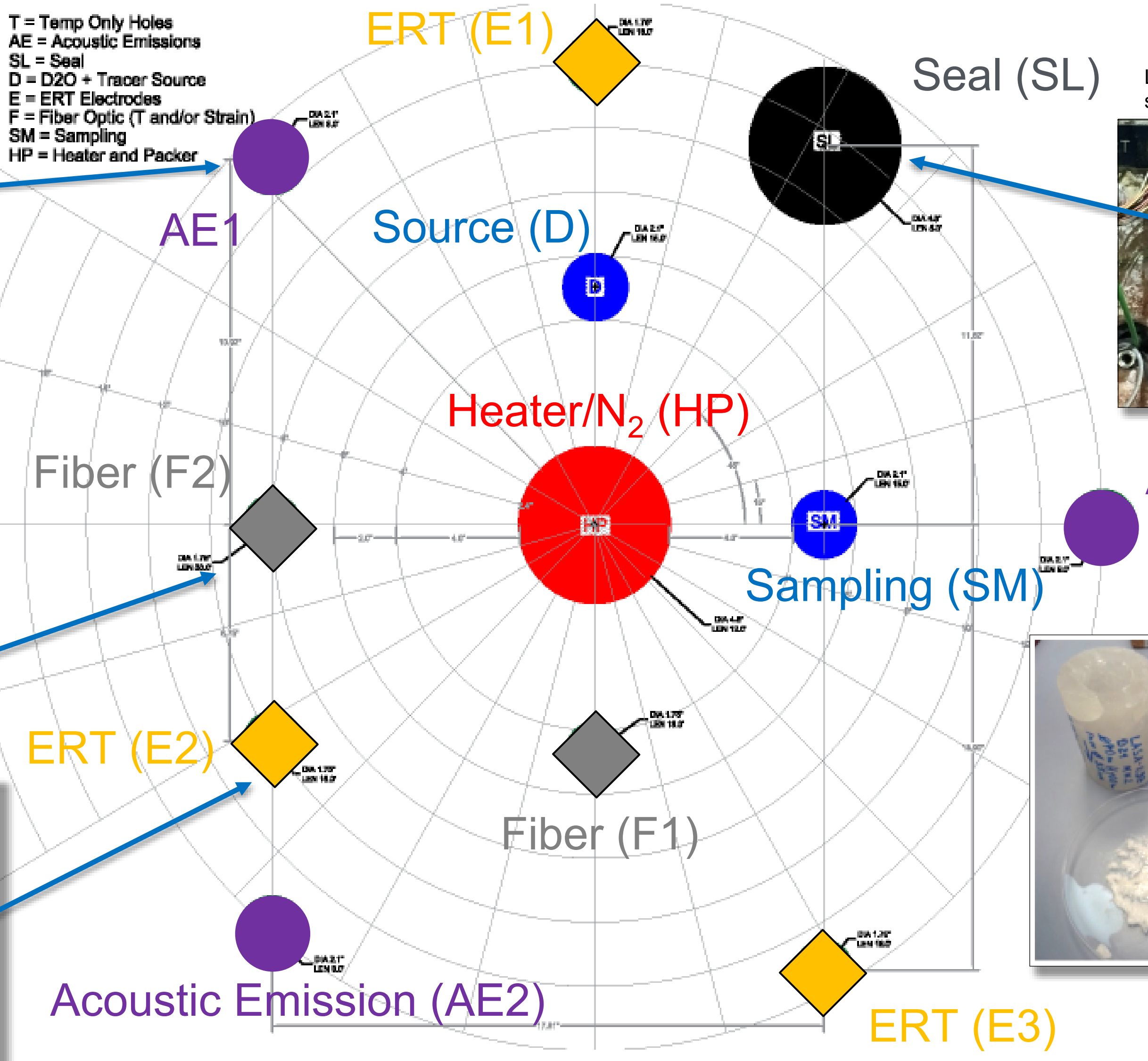


Cross-section of central [HP] borehole

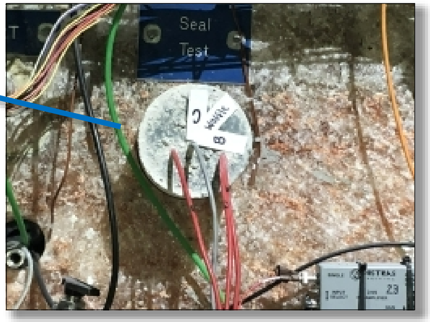


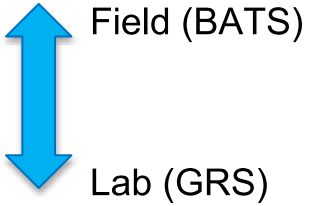
BATS Borehole Arrays

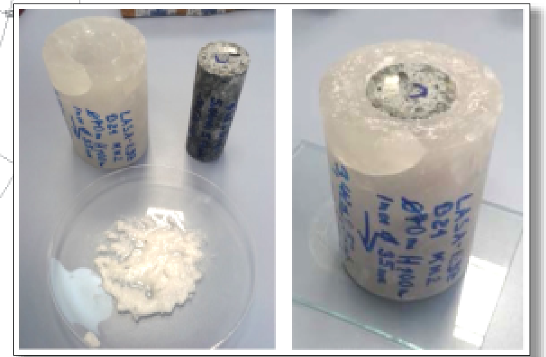
AE sensors on de-centralizers



Lab-made seal installed in borehole subsequently sealed behind packer







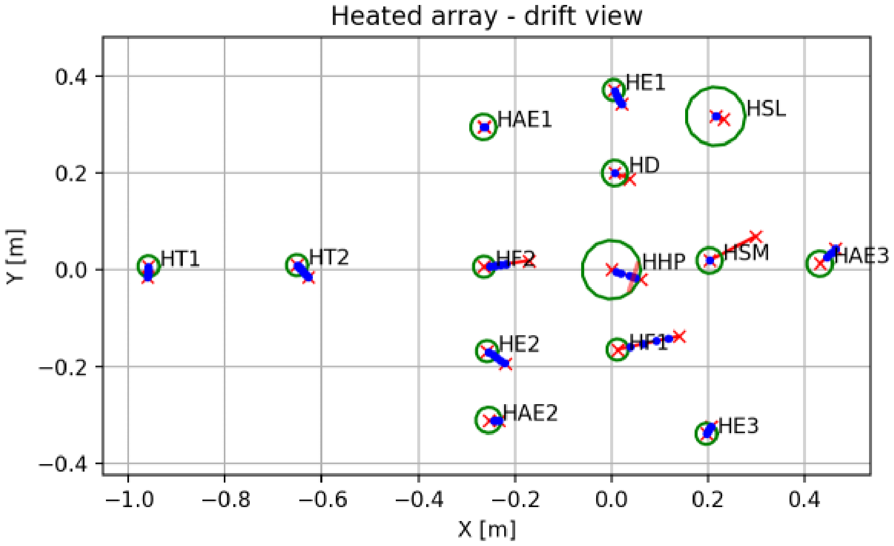
Czaikowski et al. (2016)

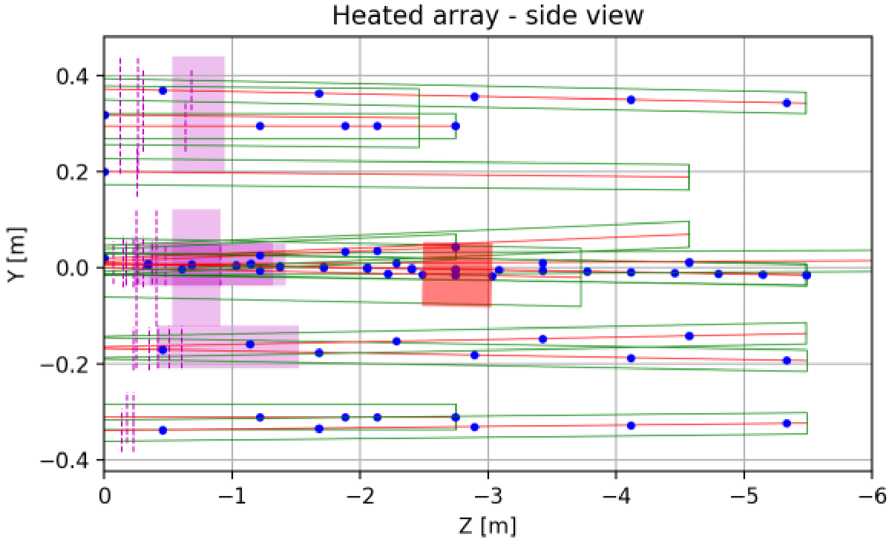
Fiber optic DSS/DST

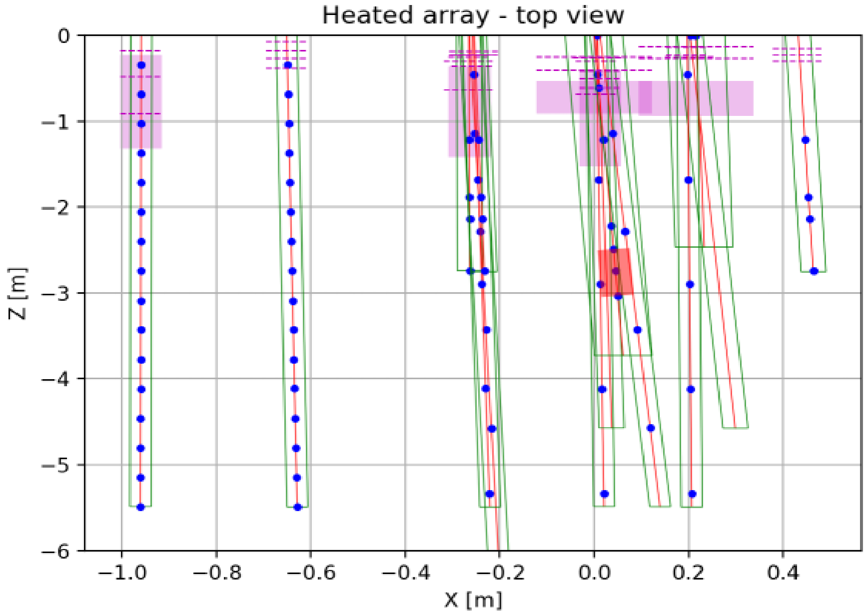
ERT controller

(Borehole layout drawing by WIPP TCO)

BATS As-Built





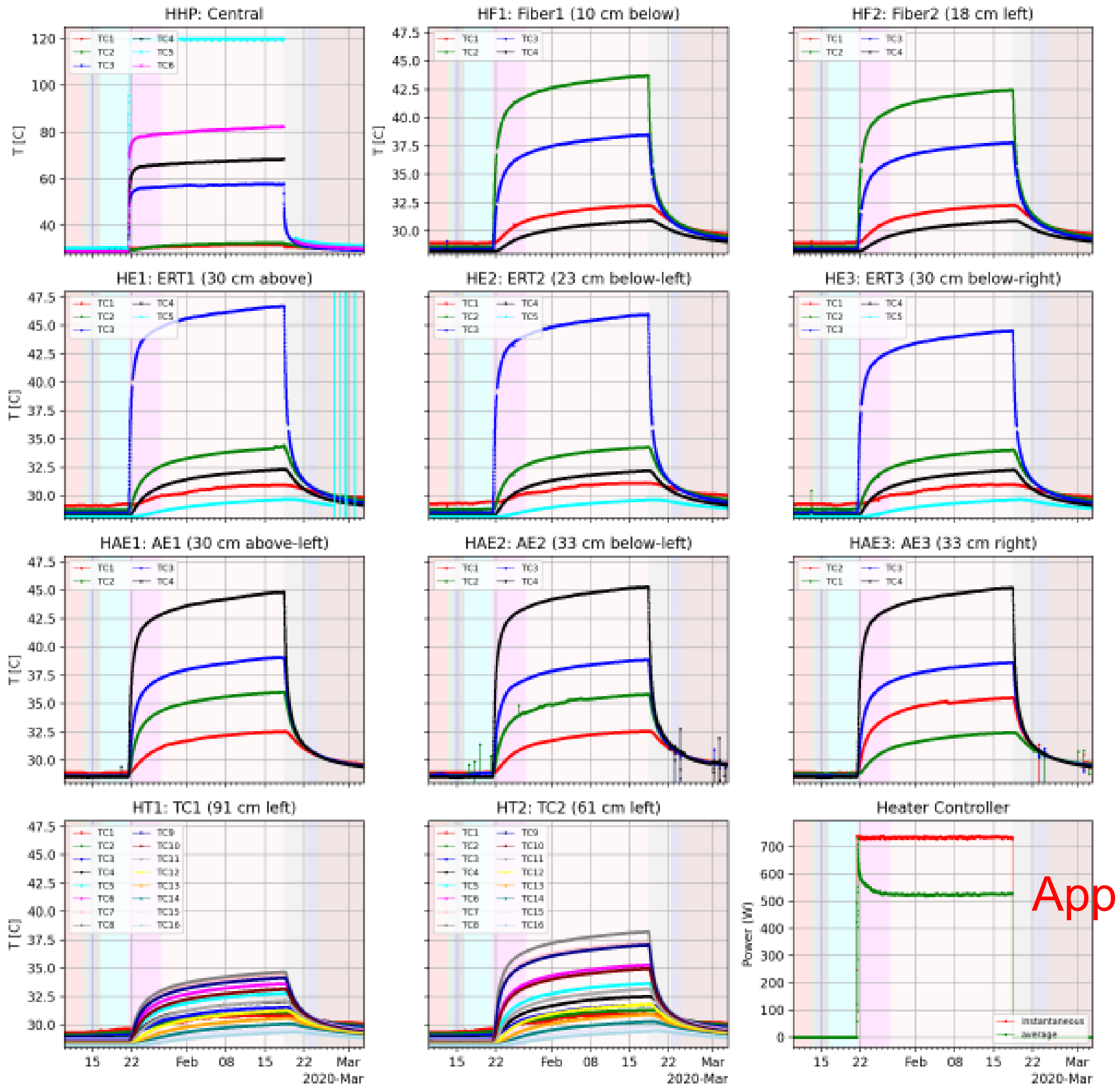


- Heated array as-built
- Drilled Feb-Apr 2019
- Side/ top view shows
  - thermocouples (blue dots)
  - Heated interval (red box)
  - Fractures/damaged zone (purple)

Discrete fractures in BATS near-drift EDZ

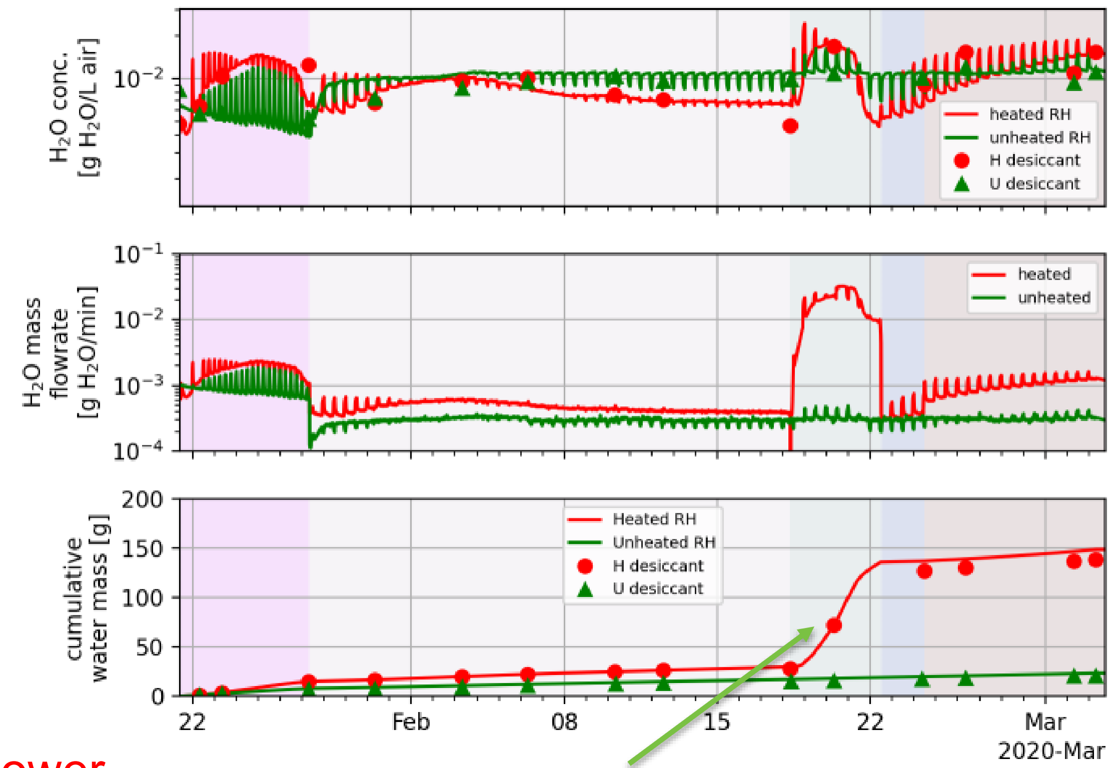
January-March 2020 BATS 1a Test Data

Temperature data during BATS 1a



Applied power

Brine production data during BATS 1a

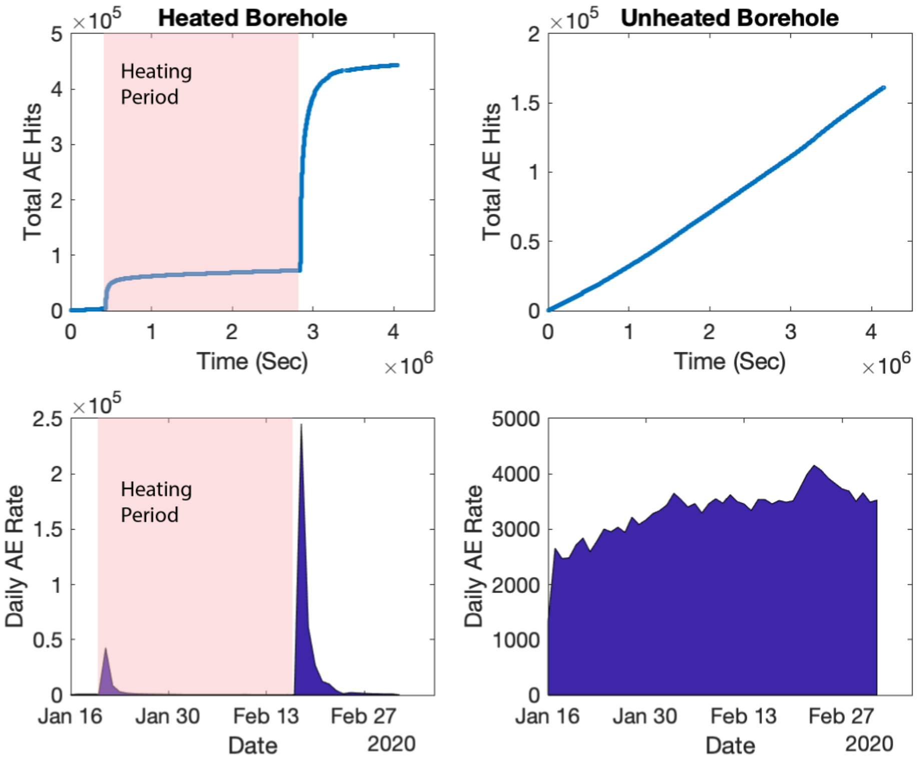


Brine inflow at heater shutdown

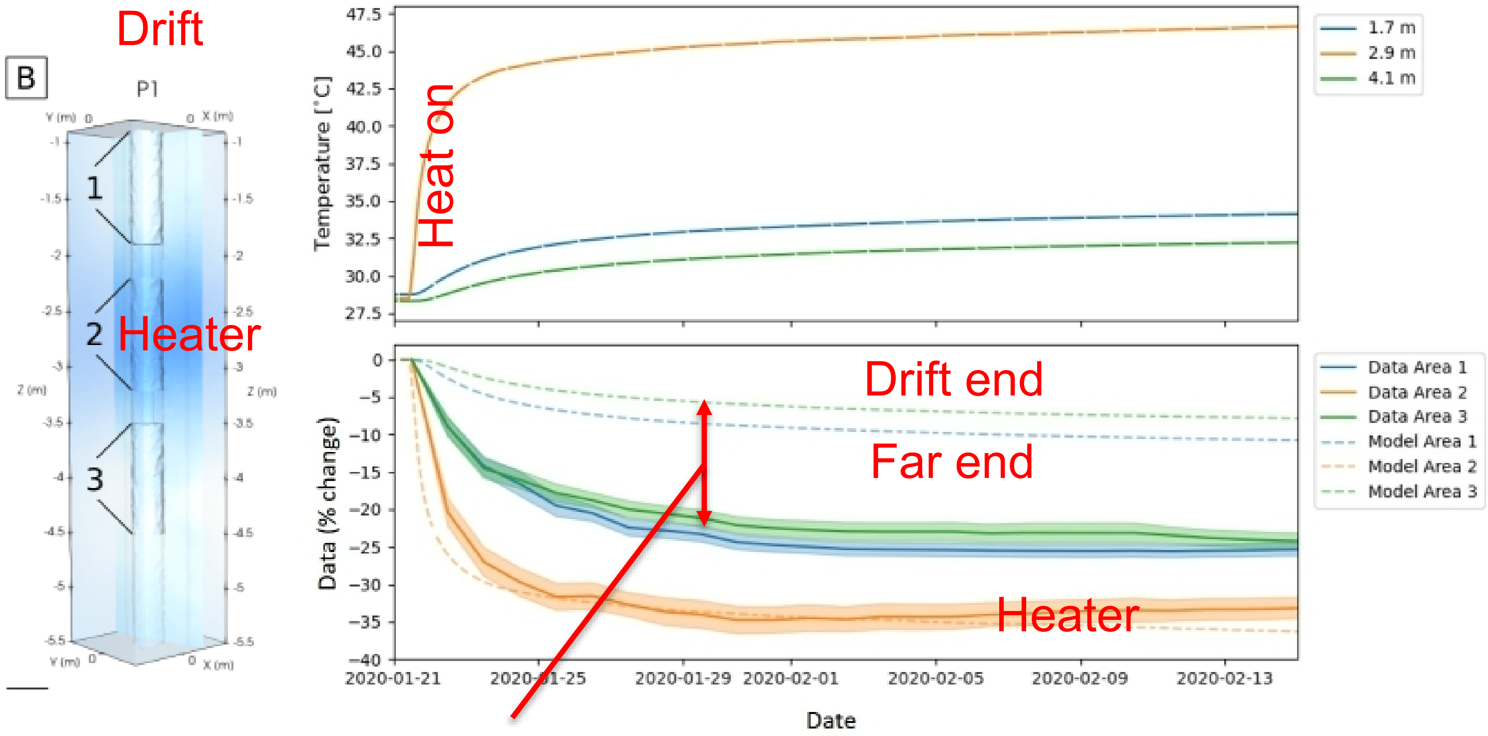
BATS test and data summarized in Kuhlman et al. (2020)

January-March 2020 BATS 1a Test Data

Acoustic Emissions (AE) during BATS 1a



Electrical Resistivity Tomography (ERT) during BATS 1a



Δ resistivity not explained by Δ temperature.

Brine migration away from heater due to thermal expansion?

BATS test and data summarized in Kuhlman et al. (2020)

Task E Steps

Step 0: Single-process H^1 and T benchmarks

Step 1: TH^1 benchmark & H^2M/H^2 unheated brine inflow test case

Step 2: TH^2M heated brine inflow test case

Step 3: Alternatives (ERT/AE joint inversion, seals, TH^2MC, creep)

Table 3. Proposed detailed Task E schedule of steps.

	Apr.	Nov.	Apr.	Nov.	Apr.	Nov.	Apr.	Nov.
	2020		2021		2022		2023	
Step 0								
Step 1								
		Midterm Report → (Nov 2021)						
Step 2								
Step 3								
					Papers and Final Report → (Nov 2023)			

Infrared heater in BATS HP borehole

H^1 = single-phase; H^2 = two-phase

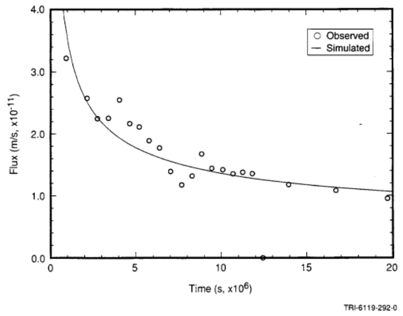
Task E Step 0 (Apr. 2020 - Apr. 2021)

0. Single-process H[1] and T benchmarks

a) H[1] brine inflow to boreholes (1991 small-scale brine inflow test)

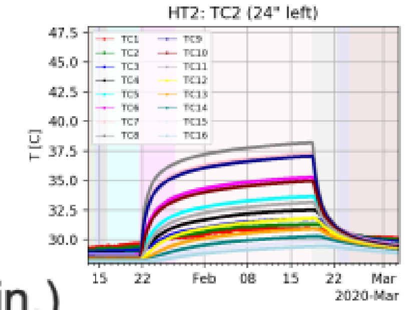
- Simulate brine inflow to 3 (of 17) boreholes in Finley et al. (1992) dataset
- Data: weekly mass of brine produced from sealed boreholes
- Brine flow down p gradient (borehole @ 0.1 MPa, far-field @ hydrostatic ~6 MPa)

(Beauheim et al., 1997)



b) T due to conduction (BATS; Kuhlman et al., 2020)

- Simulate T profile (heating and cooling) during heater test
- Data: 4 weeks heating, 2 weeks cooling: ΔT at 5 (of 66) remote locations (Δt 15 min.)
- Heat conduction: 60-cm interval of borehole wall is constant temperature (~100 ℃), heater midpoint is 2.75-m deep into 10-cm borehole,



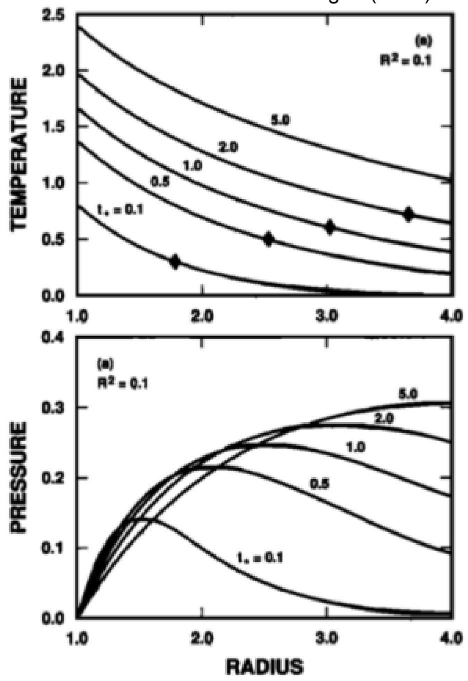
c) Estimate model parameter uncertainty and parameter sensitivity for both through time

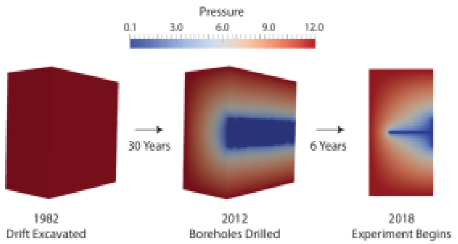
- *Quantify uncertainty* in prediction and measure Δ prediction with Δ input parameters (*sensitivity*)

Task E Step 1 (Nov. 2020 - Apr. 2021)

1. TH[1] benchmark & H[2]M/H[2] unheated brine inflow test case
   a) Benchmark TH[1] brine production to analytical solution (McTigue, 1990)
      - Compare numerical models against coupled linear solution (space & time)
      - Halite properties from Table 1, McTigue (1986)
      - Compare with/without model non-linearities (e.g., fluid viscosity $f(T)$)
   b) Parameterize two-phase flow in salt EDZ (few data exist)
      - *Laboratory imbibition test*. Mass imbibed & wetting front w/ time → estimate capillary pressure (p_c) & relative permeability (k_r) relationships
      - *CT core data*. Predict p_c & k_r from pore-network models
      - *Literature*. Granular salt: (Cinar et al., 2006; Olivella et al., 2011). Non-salt EDZ at WIPP (Davies, 1991; Howarth & Christian-Frear, 1997)
   c) H[2] brine inflow to boreholes (BATS) w/ H[2] characterization
      - H[2] or H[2]M simulation of "initial conditions" for BATS heater test

McTigue (1990)





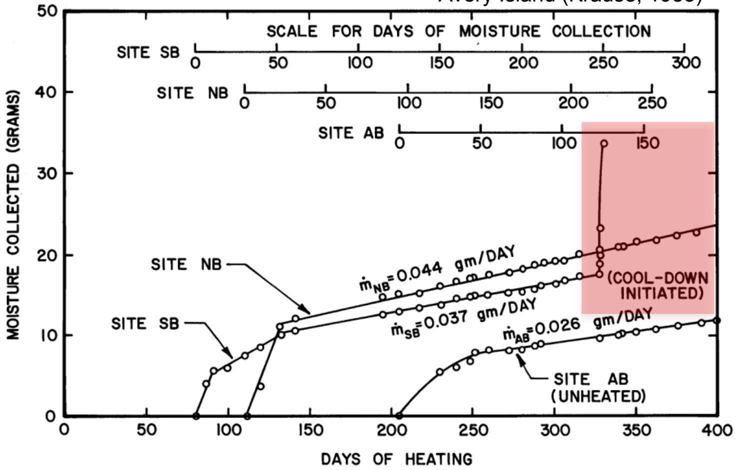
Guiltinan et al. (2020)

Task E Step 2 (Apr. 2021 - Apr. 2023)

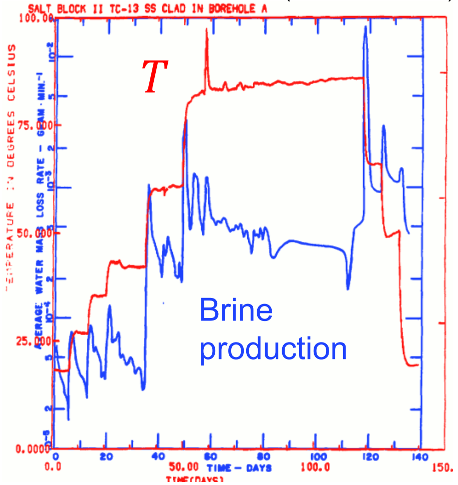
2. TH²M heated brine inflow test case

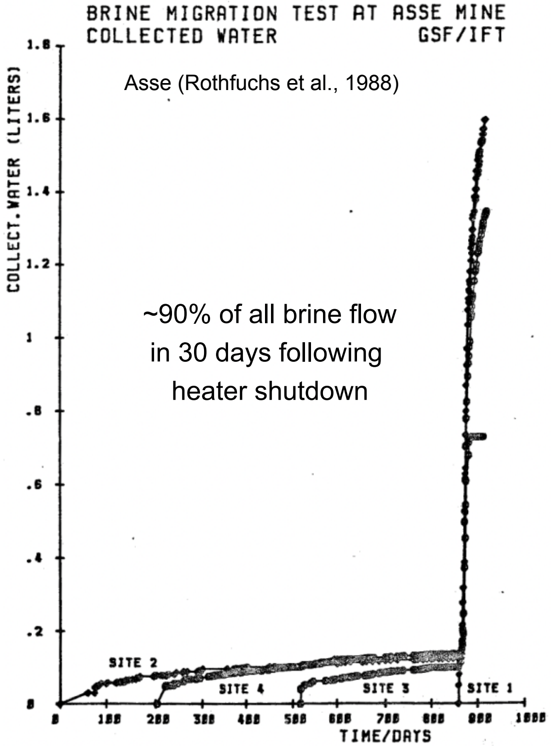
a) Predict brine production during increases and decreases in T

Avery Island (Krause, 1983)



1-m bedded salt lab test (Hohlfelder, 1979)





b) *Optional:* predict breakthrough of gases/liquid tracers in BATS tracer tests

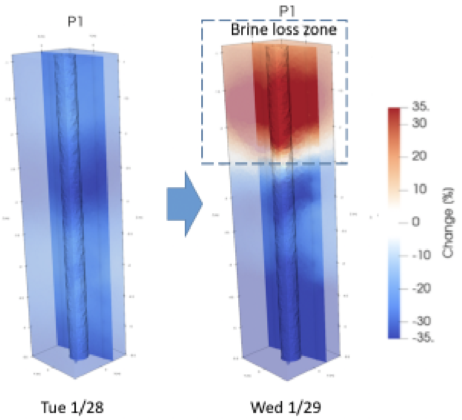
a) BATS 1b & 1c tracer tests to begin late 2020

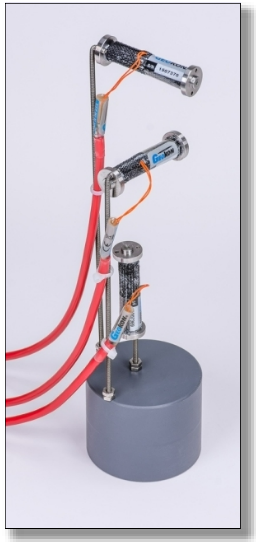
b) Gas tracers (N_2 + Kr, Ne, SF_6) between boreholes (D → HP)

c) Liquid tracers (water isotopes, fluorescein & perrhenate) between boreholes (D → SM & HP)

Task E Step 3 (Alternatives)

1. ERT/AE data to constrain brine inflow estimates
   - ERT sensitive to brine saturation, daily ERT tomograms
   - AE source locations to confirm changes in ϕ, k
2. Predict behavior of BATS seals / GRS lab tests
   - GRS laboratory experimental data (WIPP brine & salt)
   - BATS strain, T data in cement plugs (Sorel & salt concrete)
3. Additional C processes
   - Include water types explicitly in models (fluid inclusions, clay dehydration)
4. Effects of viscoplastic creep on brine production





Based on interest of teams: Chose one/two?

Summary

- Brine availability in bedded salt
  - 4 very different water types
  - EDZ is main source of k, ϕ
- Task E brine inflow test cases
  - Unheated: Small-scale brine inflow (1987-1991)
  - Heated & Unheated: BATS test (ongoing)
- Task E evolution
  - $H^1/T \rightarrow TH^1 \rightarrow H^2/H^2M \rightarrow TH^2/TH^2M \rightarrow TH^2MC$ (alternatives)
  - **Q: Is H^2 needed to explain brine inflow observations?**
  - **Q: Is $\Delta T \rightarrow \Delta\sigma \rightarrow k, \phi$ feedback needed to explain brine inflow observations?**
  - Uncertainty quantification & parameter sensitivity at each step (w/ added complexity)

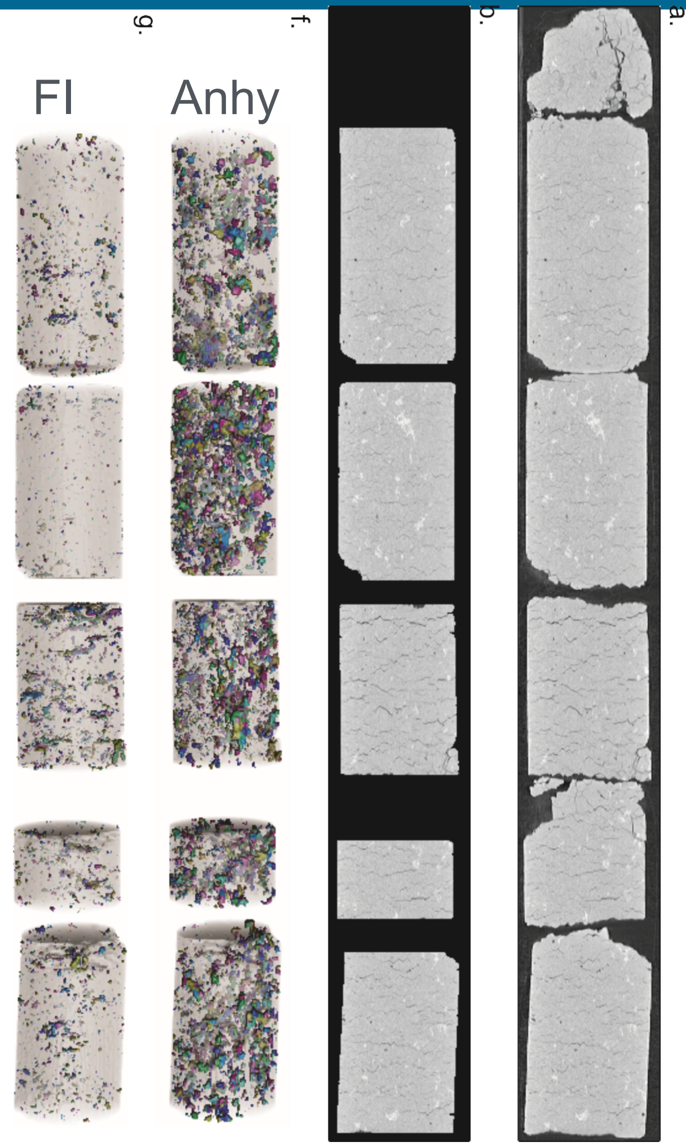
Continuous miner at WIPP

2020 Task E Interactions

- Summary of Task E Interactions
  - 27-30 April 2020: DECOVALEX-2023 **Spring 2020 Meeting**
  - 10 June 2020: Task E kickoff
  - 29 July 2020: Task E discussion #1
  - 16 Sept 2020: Task E discussion #2
  - 14 Oct 2020: Task E discussion #3
  - 16-20 Nov 2020: DECOVALEX-2023 **Fall 2020 Meeting**
- Continue "Optional" Discussions (~6 weeks)
  - Improve communication
  - Clear up data issues

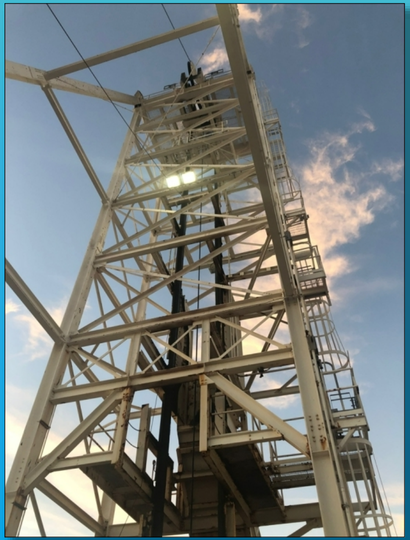
Task E (Wednesday, Stream 3) Preview

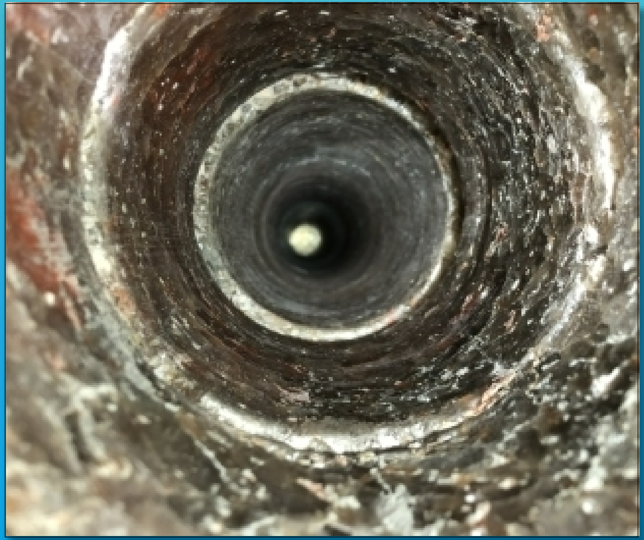
- Teams: DOE, COVRA, GRS, BGR, RWM
- Presentations on Results of Step 0
  - 1991 WIPP brine inflow data (INTRAVAL) H[1]
  - 2020 WIPP BATS temperature data T
  - Model Uncertainty + Sensitivity
- Planning Step 1
  - Matching analytical solution (McTigue, 1986) TH
  - 2020 BATS two-phase flow initial condition H[2]
- Discuss Schedule
  - Too fast? Too slow? Wrong material?



Analysis of X-Ray CT data for fluid inclusions and anhydrite

Thank you!





Sandia National Laboratories

BERKELEY LAB

WIPP

Los Alamos NATIONAL LABORATORY EST. 1943

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References and data can be downloaded from DECOVALEX-2023 fileshare system

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Acronyms and Initialisms

AE	acoustic emissions
BATS	brine availability test in salt
CT	computed tomography
DECOVALEX	DEvelopment of COupled models and their VALidation against Experiments
DOE	Department of Energy
DOE-EM	DOE Office of Environmental Management (energy.gov/em)
DOE-NE	DOE Office of Nuclear Energy (energy.gov/ne)
DOPAS	full-scale Demonstration Of Plugs And Seals
DRZ	disturbed rock zone
DSS, DTS	distributed strain, temperature sensing
EDZ, EdZ	Excavation Damaged Zone, Excavation disturbed Zone
ERT	electrical resistivity tomography
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
LANL	Los Alamos National Laboratory
LBL	Lawrence Berkeley National Laboratory
NETL	National Energy Technology Laboratory
SFWST	Spent Fuel and Waste Science & Technology (DOE-NE program)
SNL	Sandia National Laboratories
TCO	WIPP Test Coordination Office (LANL)
TH^2MC	thermal, two-phase hydrological, mechanical, and chemical (also TH^1, TH^2M, TH^2C)
US	United States
WIPP	Waste Isolation Pilot Plant (DOE-EM site, wipp.energy.gov)