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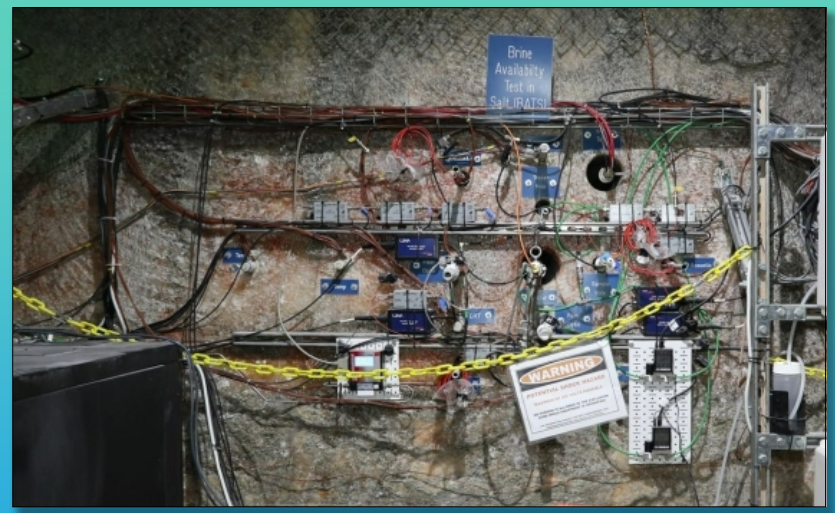

DECOVALEX-2023 Task E (BATS) Introduction

DECOVALEX-2023 Meeting 4
Monday November 8, 2021
Virtual Workshop

Kristopher L. Kuhlman
Sandia National Laboratories

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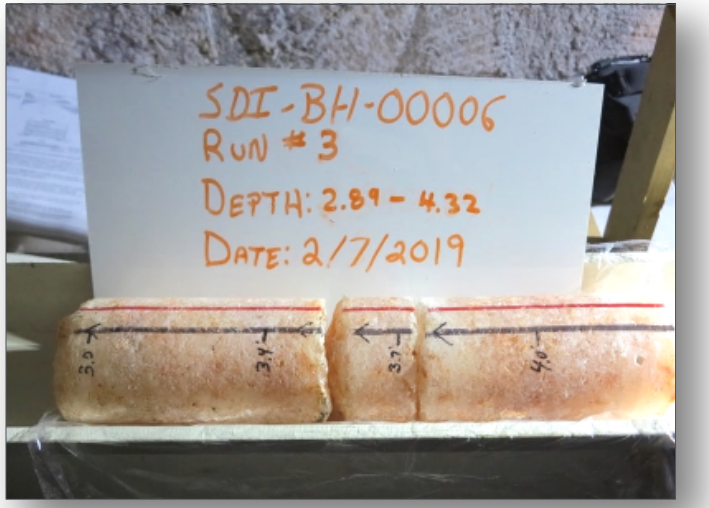
Outline

- Introduction
- 1992 Waste Isolation Pilot Plant (WIPP) data
- 2020 Brine Availability Test in Salt (BATS) data
- Next Steps

BATS 10-cm core



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

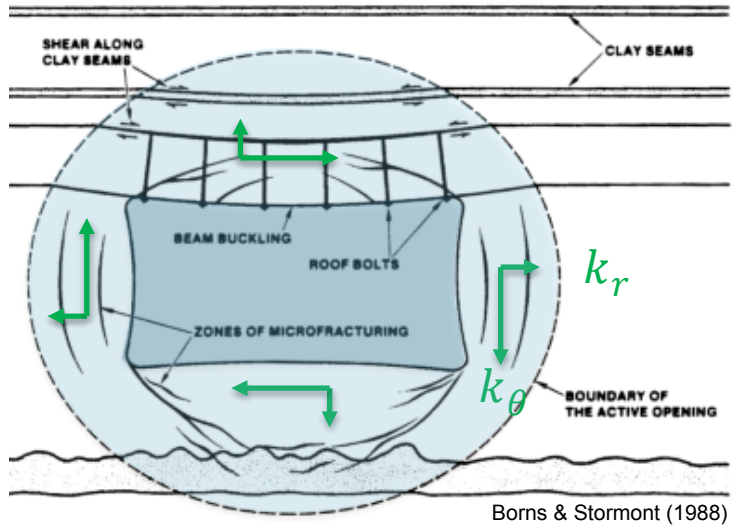
Drilling BATS boreholes (Feb. 2019)

Motivation

No Image

Alpine miner at WIPP

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



Borns & Stormont (1988)

Task E Goals

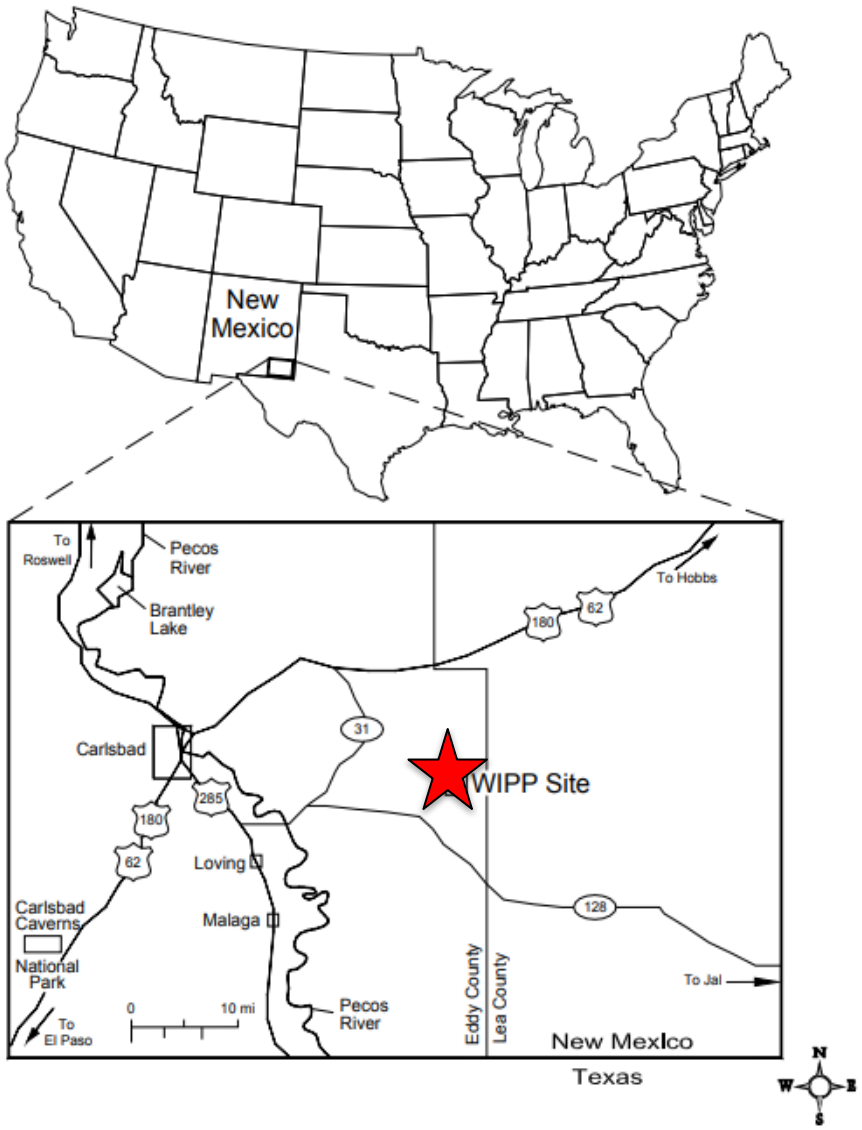
- Understand and predict THMC processes impacting *brine availability* in salt
  - Water response to pressure (Δp), stress ($\Delta \sigma$), and temperature (ΔT)?
  - How does EDZ control migration of water (ϕ, k, relative perm. k_r)?
  - How does EDZ evolve with Δp, $\Delta \sigma$, and ΔT?

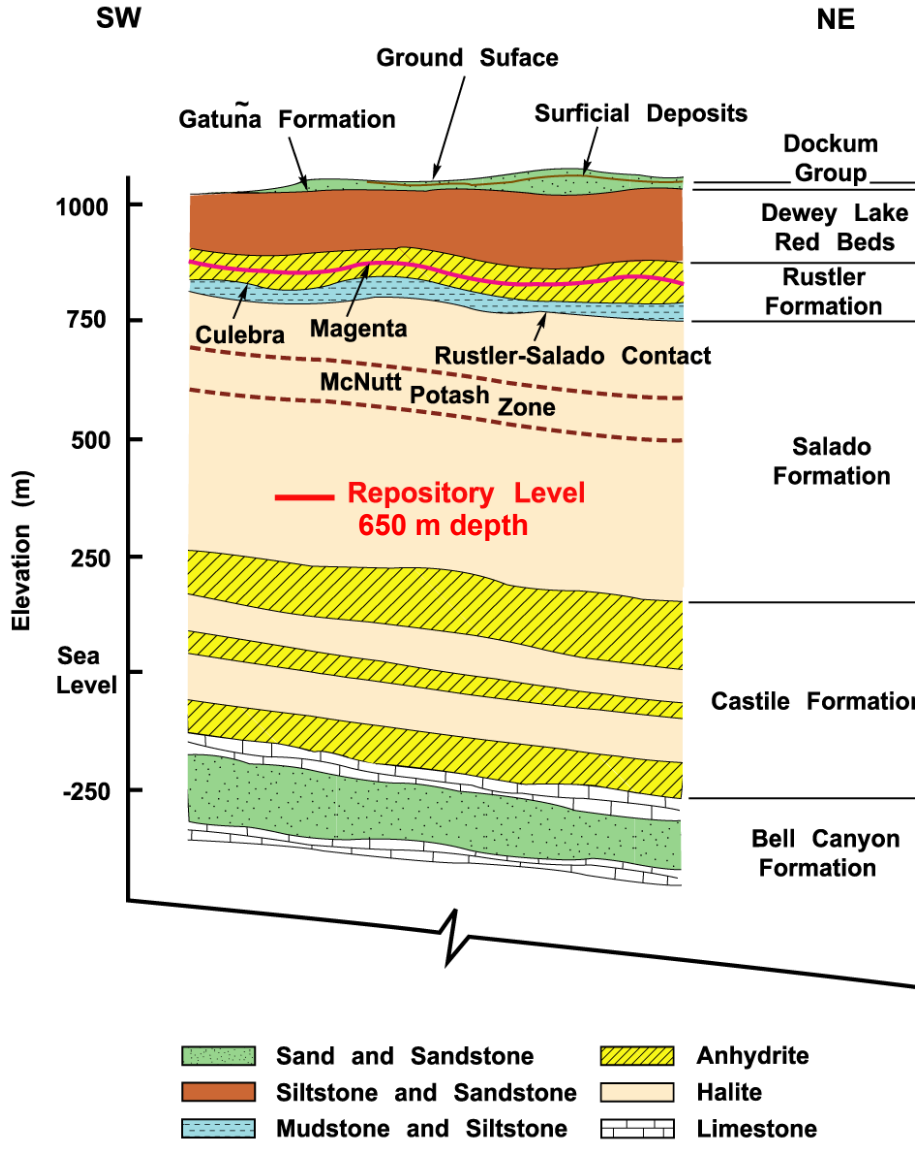
Q1: Is two-phase flow in EDZ important?

Q2: How to simulate brine pulse after heating?

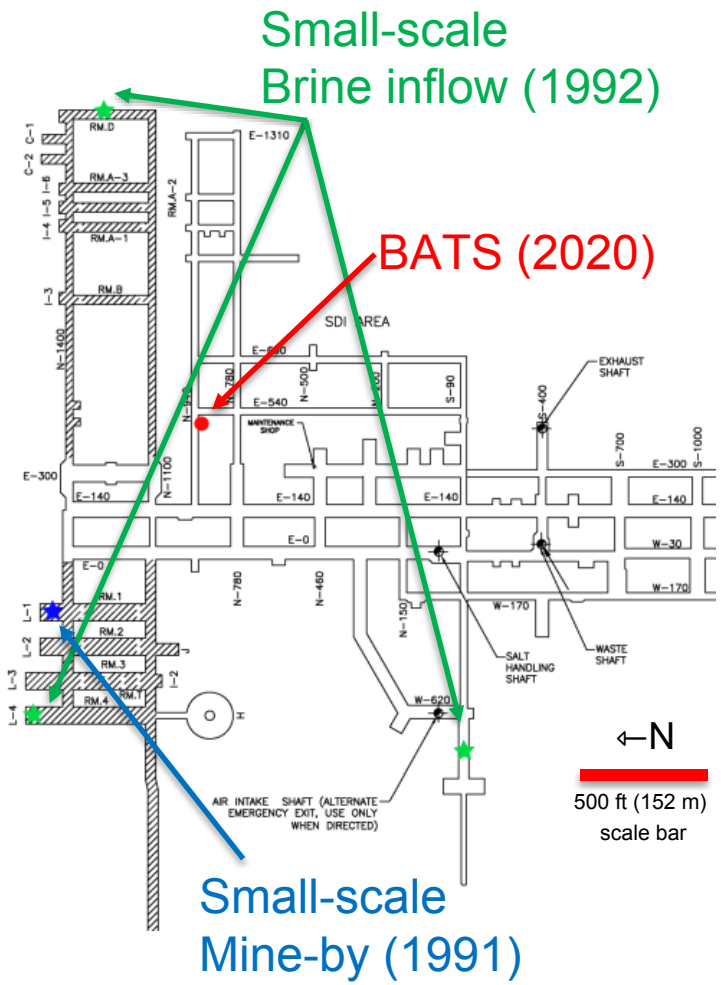
- WIPP Test Cases:
  - Small-Scale Brine Inflow test (1987-1992)
  - Ongoing heated Brine Availability Test in Salt (BATS)

Waste Isolation Pilot Plant (WIPP) Context



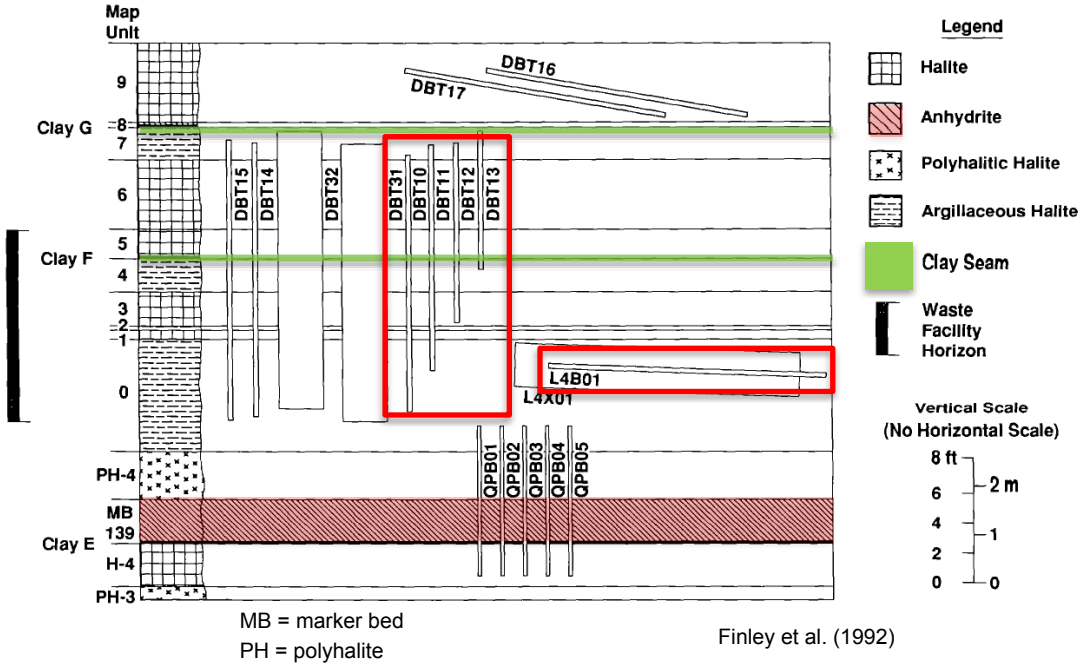


Layout of WIPP North End



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

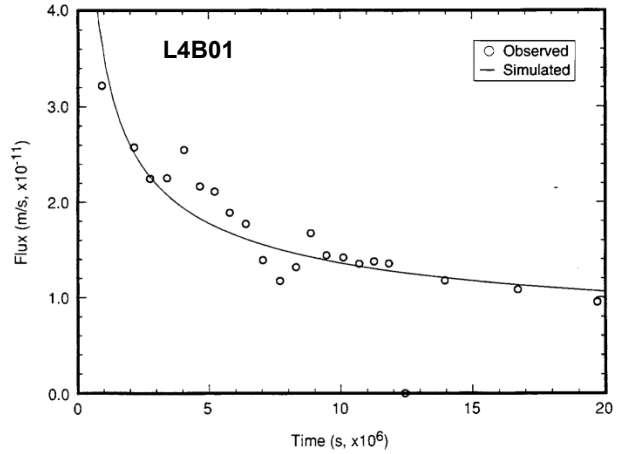
- Monitored 17 unheated boreholes
- Weekly brine inflow data
- INTRAVAL study (Beauheim et al., 1997)
- Effects of stratigraphy / orientation / drift
- Considered single-phase brine flow



MB = marker bed
PH = polyhalite

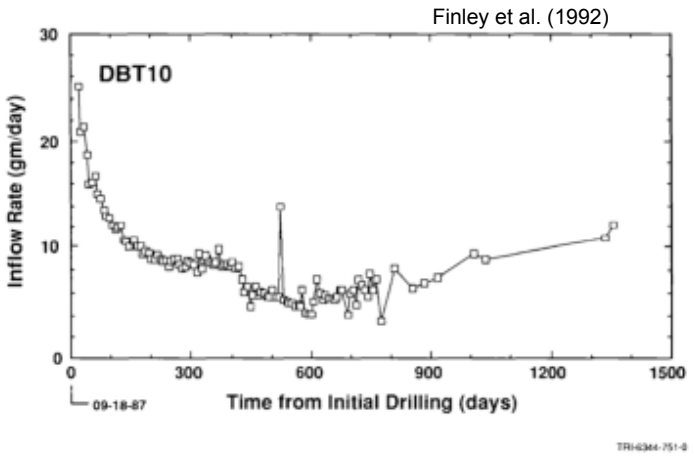
Finley et al. (1992)

(Beauheim et al., 1997)

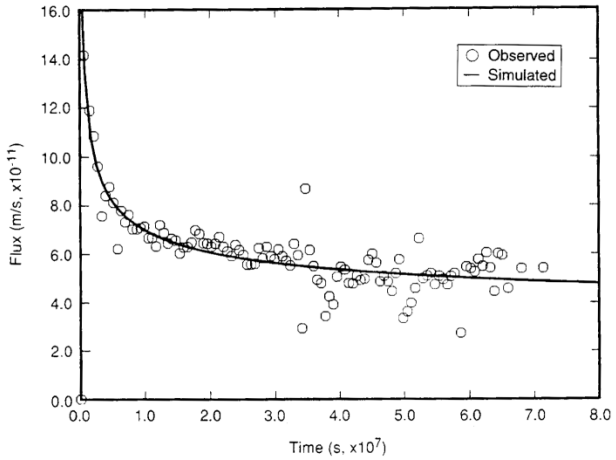


TRI-6119-292-0

Finley et al. (1992)



DBT11



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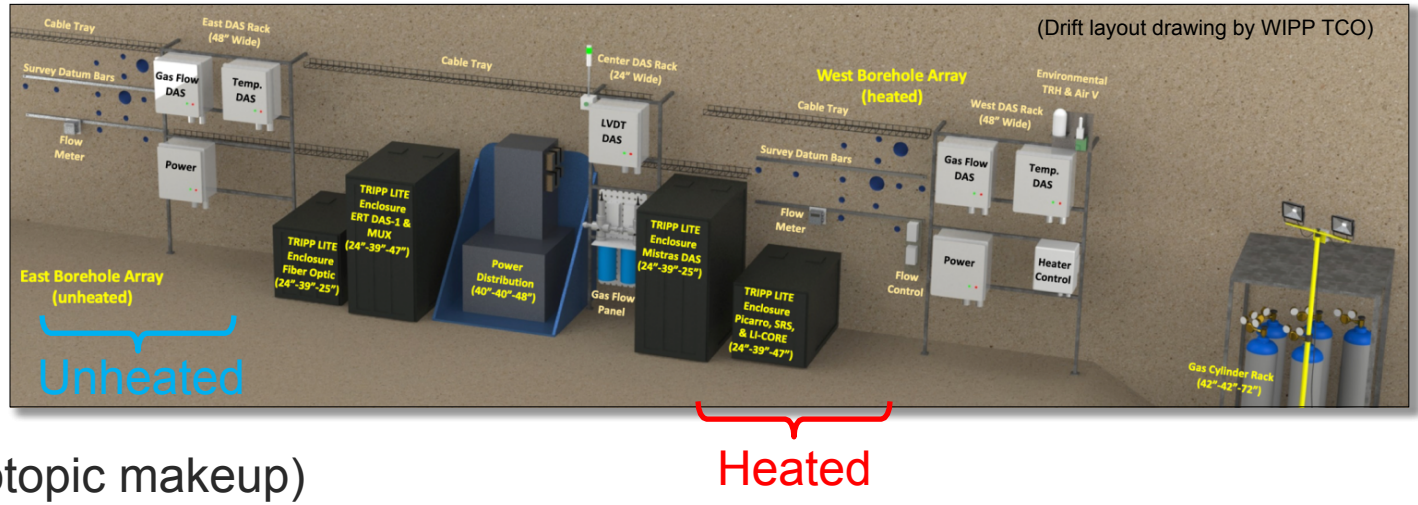
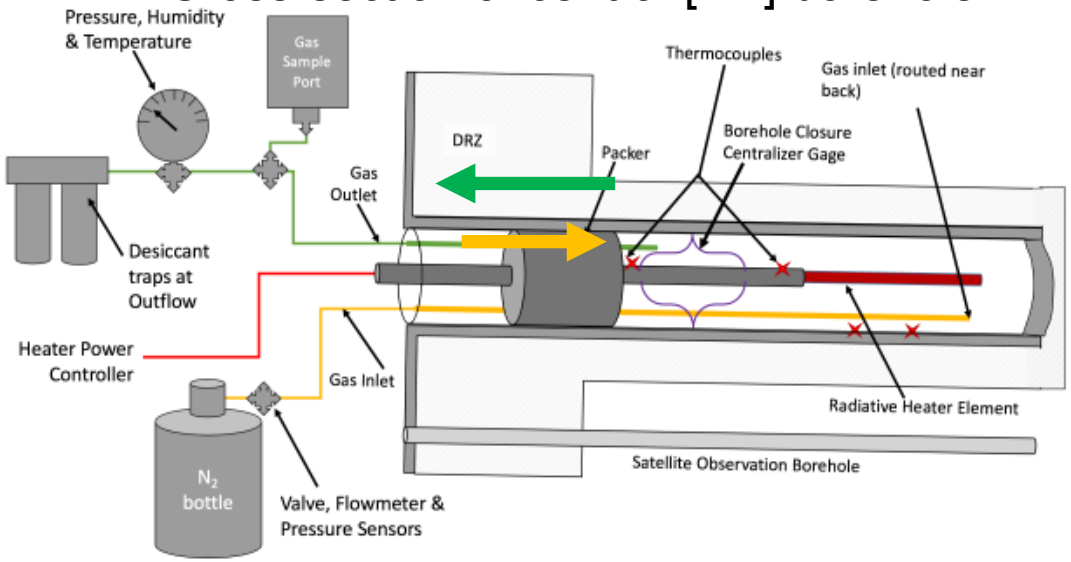
Brine Availability Test in Salt (BATS)

- Two Arrays: Heated / Unheated
- Behind packer
  - Circulate dry N_2
  - Quartz lamp heater (750 W)
- Samples / Analyses
  - Gas stream (natural / applied tracers and isotopic makeup)
- Cement Seals
  - Sorel cement + Salt concrete: 3-axis strain & temperature
- Geophysics
  - 3× Electrical resistivity tomography (ERT)
  - 3× Acoustic emissions (AE)
- Phases:
  - BATS 1a: first heating cycle (Jan-Mar 2020)
  - BATS 1b-1c: Tracers (Jan-May 2021)
  - BATS 2: drill new heated array (Oct 2021)

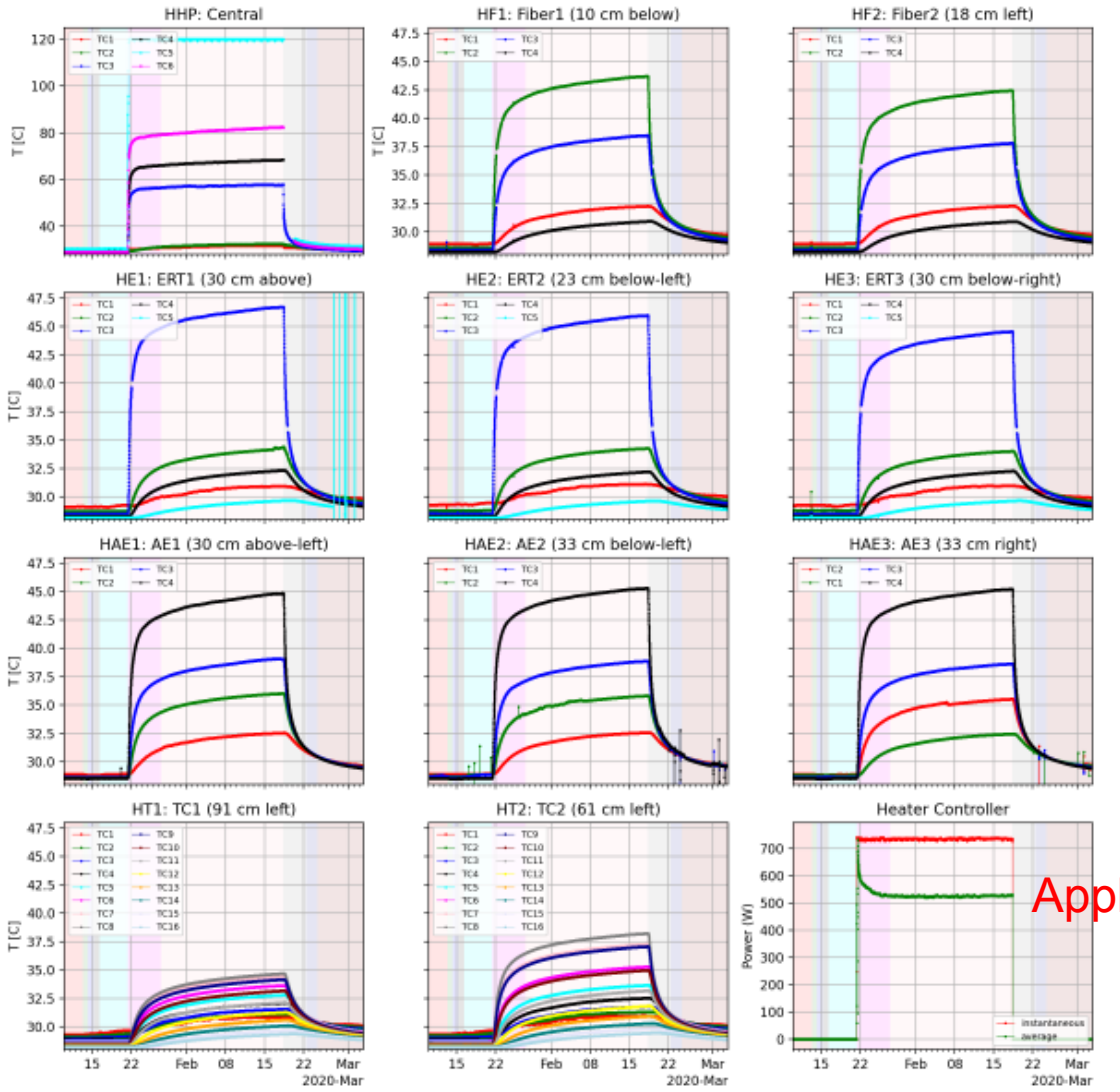


Cross-section of central [HP] borehole

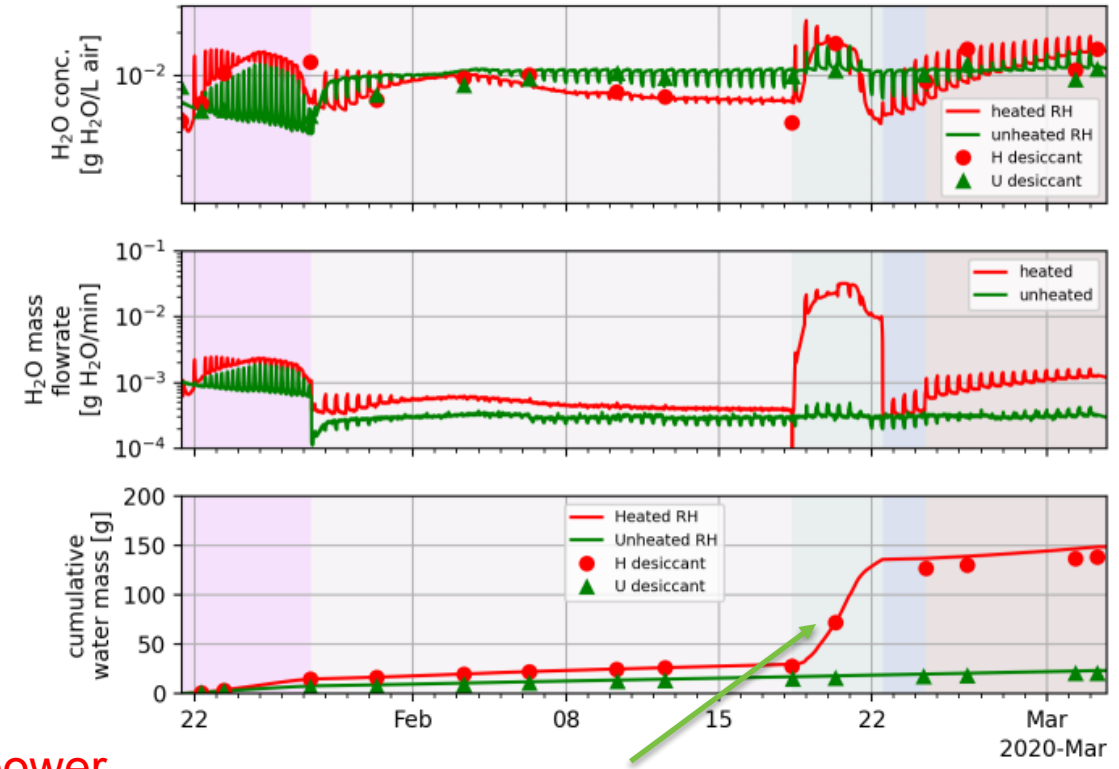


January-March 2020 BATS 1a Test Data

Temperature data during BATS 1a



Brine production data during BATS 1a



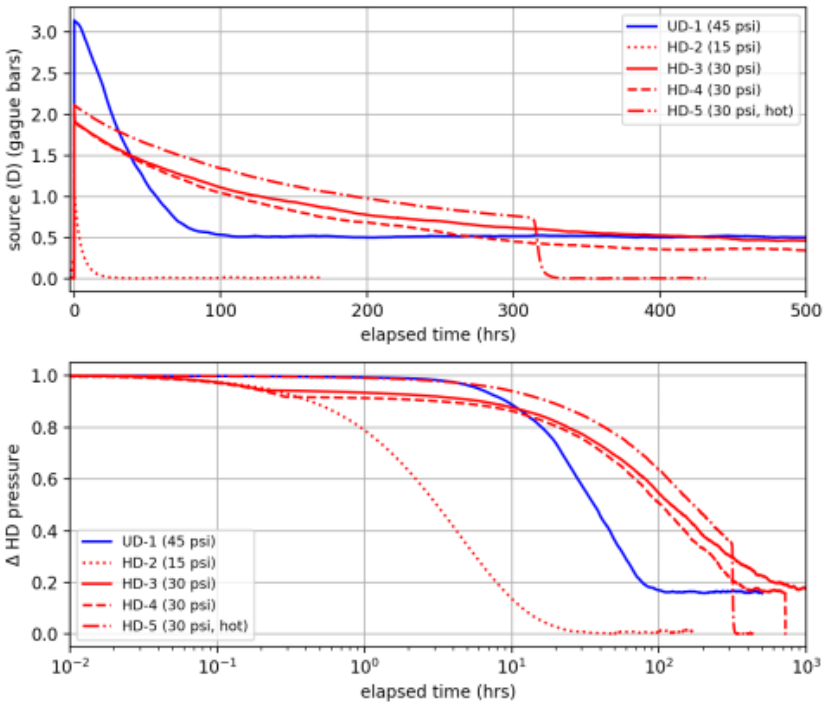
Applied power

Brine inflow at heater shutdown

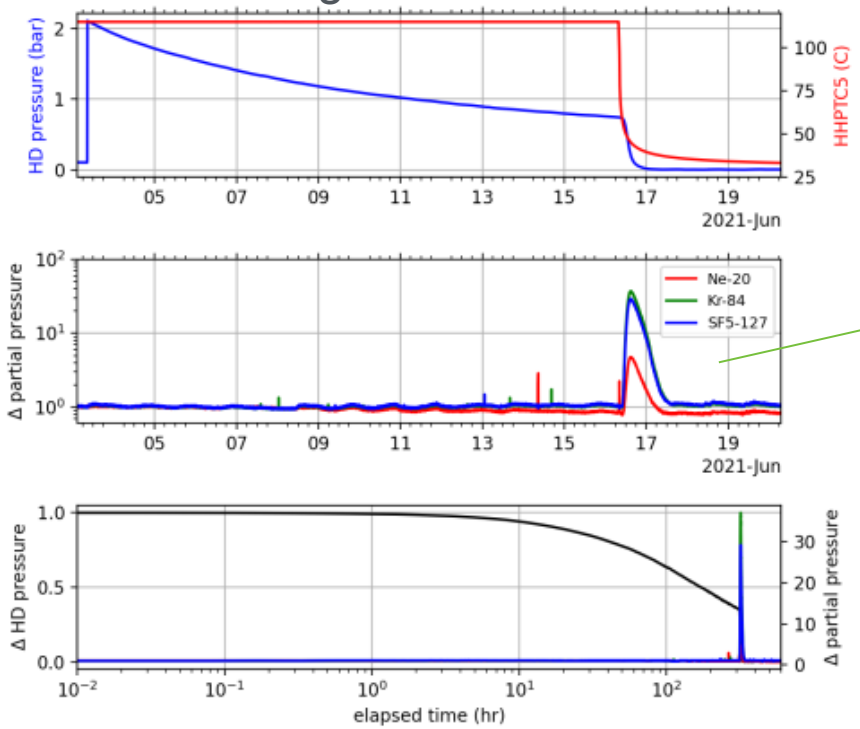
BATS 1a test and data summarized in Kuhlman et al. (2020)

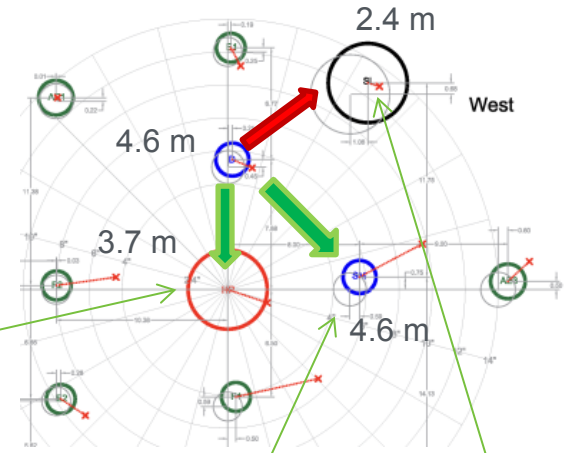
May-Aug 2021 BATS 1b Gas Tracer Test Data

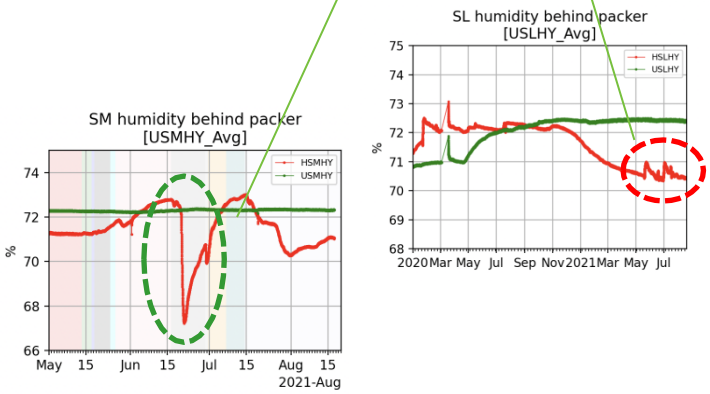
Pressure in Source Borehole



Breakthrough to Heated Borehole







Humidity behind packers

Gas Tracer Test Responses

- Unheated pressure response is repeatable
- Pressure maintained at source (D) until heat off
- No tracer breakthrough to heater (HP) until heat off
- Drop in humidity in adjacent borehole (SM) when heat off
- No response in seal (SL) borehole

Task E Steps

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

Step 1: TH^1 benchmark & H^2M/H^2 initial condition setup

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)			

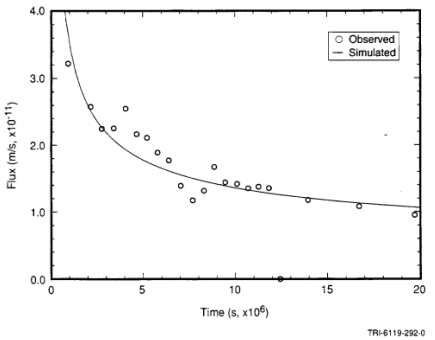
Infrared heater in BATS HP borehole

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

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

0. Single-process H^1 and T benchmarks

(Beauheim et al., 1997)

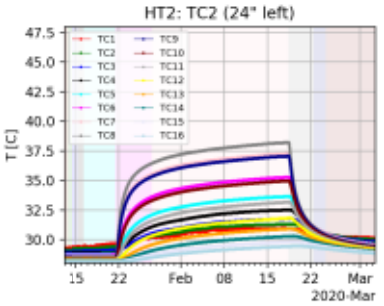


a) H^1 brine inflow to boreholes (1991 small-scale brine inflow test)

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

b) Heat conduction (BATS; Kuhlman et al., 2020)

- Simulate T profile (heating and cooling) during heater test
- Heat conduction: 60-cm interval of borehole wall is constant temperature (~100 °C), heater midpoint is 2.75-m deep into 10-cm borehole,



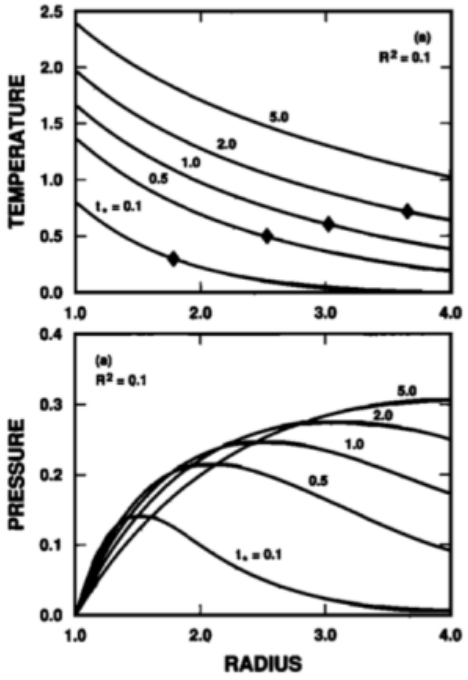
c) Estimate model parameter uncertainty and parameter sensitivity for both through time

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

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

1. TH[1] benchmark & H[2] initial conditions setup
   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 $f(T)$)
      - Thermal pressurization response from flat initial pressure

McTigue (1990)

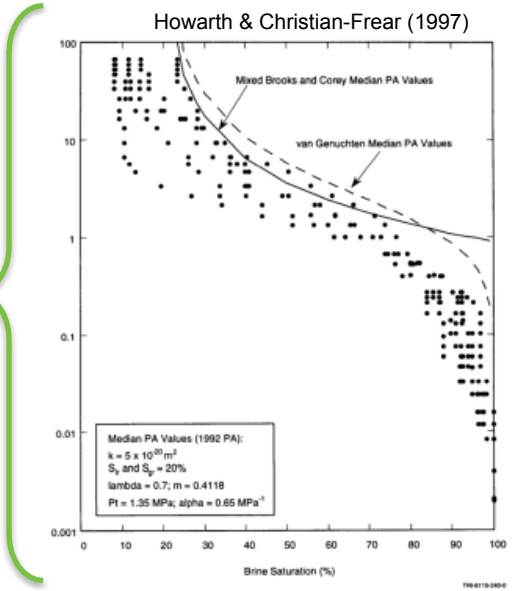


- ***Two Types of Responses***
  1. Classical TH response (fluid expansion only)
  2. Mechanically coupled THM response (fluid + solid expansion)
- McTigue (1986): paper discusses (2) but gives parameters for (1)!
- Different thermal pressurizations predicted, based on conceptual model

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

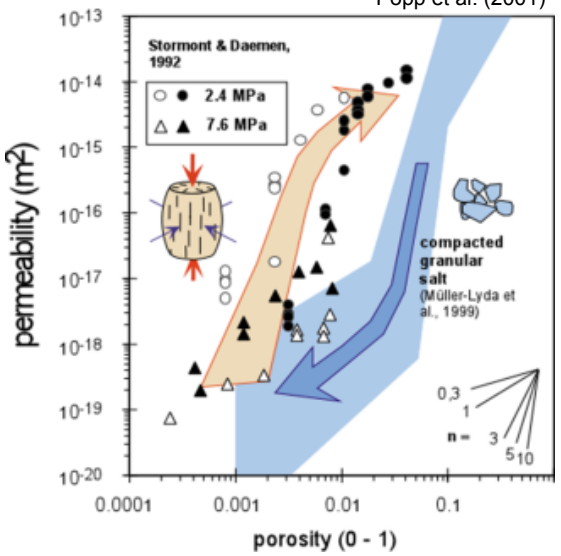
1. TH[1] benchmark & H[2] initial conditions setup
   - b) Parameterize two-phase flow in salt EDZ (few data exist)
     - *Literature capillary pressure data*
       - Recompacting granular salt
       - anhydrite EDZ at WIPP
       - Salt “analogues” (tight sandstone or shale)

Howarth & Christian-Frear (1997)

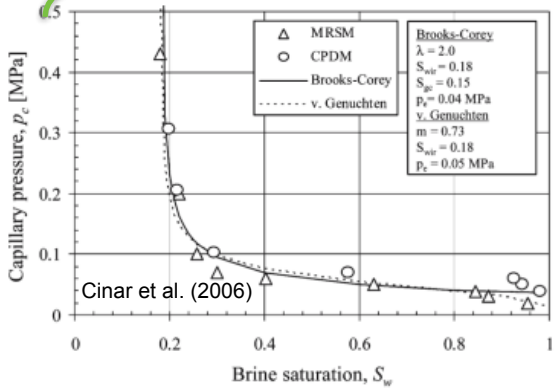


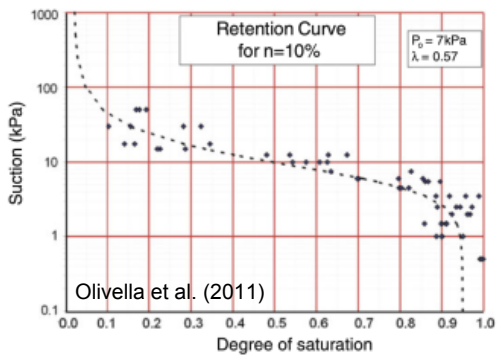
Fractured WIPP anhydrite from EDZ

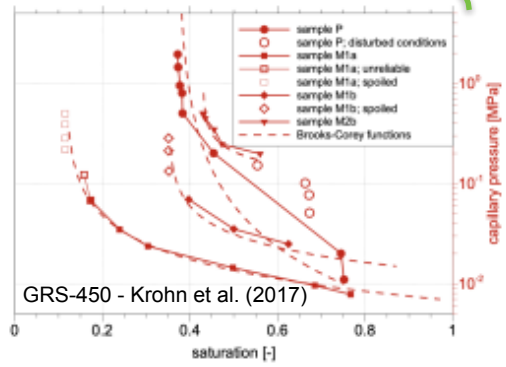
Popp et al. (2001)



Recompacting granular salt

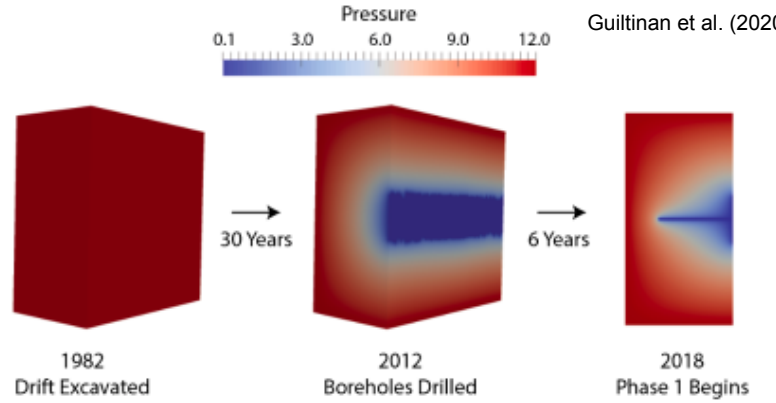




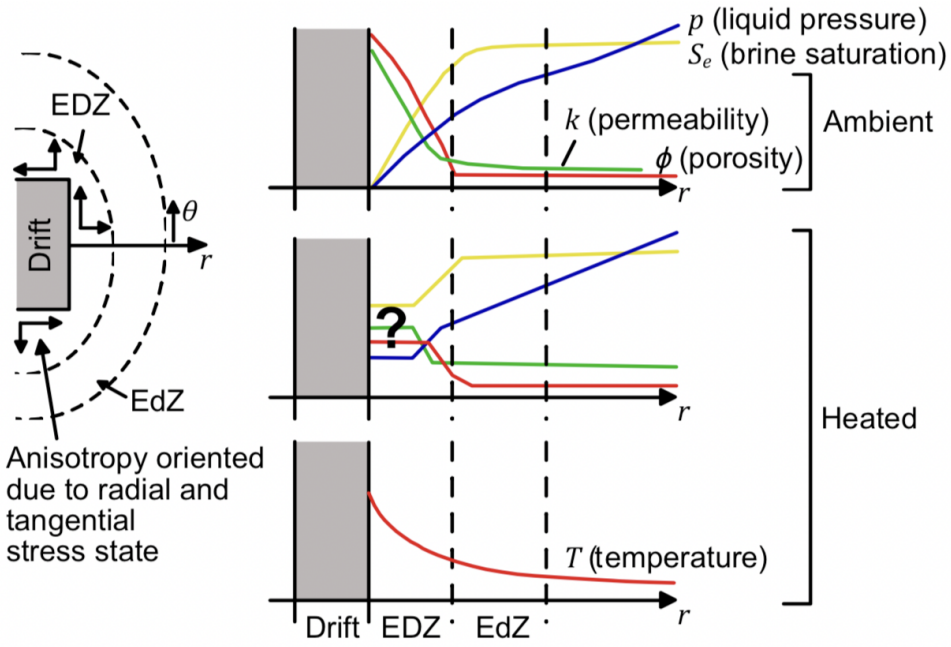


Task E Step 1c (Nov. 2020 - Nov. 2021)

1. TH[1] benchmark & H[2] initial conditions setup
   c) H[2] brine inflow to in BATS drift (1D radial profile) w/ H[2] characterization
      - DRZ to 1 drift radius ($k_{\mathrm{DRZ}} \gg k_{\mathrm{far}}$)
      - Initialize two-phase flow models
        - Pressure distribution ($p_{\mathrm{DRZ}} \approx p_{\mathrm{ATM}} \ll p_{\mathrm{far}}$)
        - Brine saturation distribution ($S_{e,\mathrm{DRZ}} \ll S_{e,\mathrm{far}}$)
      - Increased porosity (damage) also desaturates medium
        - Quickly dry out from fully saturated IC?
        - Slowly evolve from variably saturated IC?
      - Relative permeability to brine may be *lower* in DRZ



Guiltinan et al. (2020)



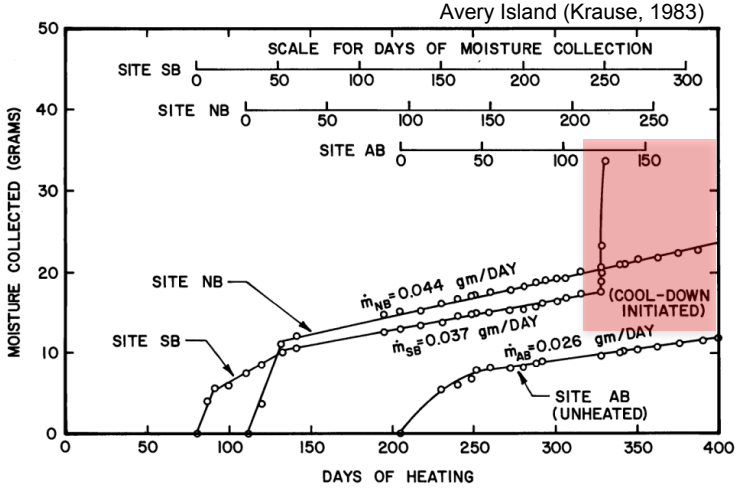
IC = initial conditions
EDZ = Excavation Damaged Zone
EdZ = Excavation disturbed Zone

Task E Step 2

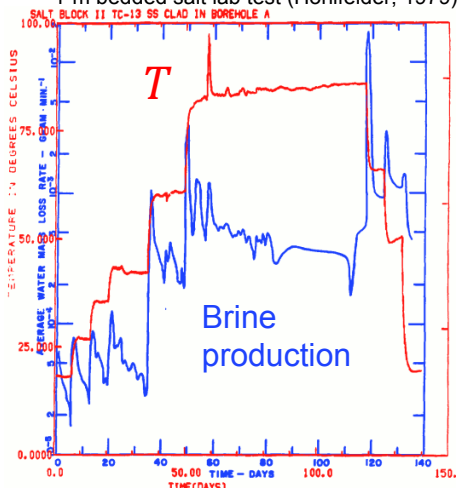
2. TH²M heated brine inflow test case

a) Predict brine production during increases and decreases in T

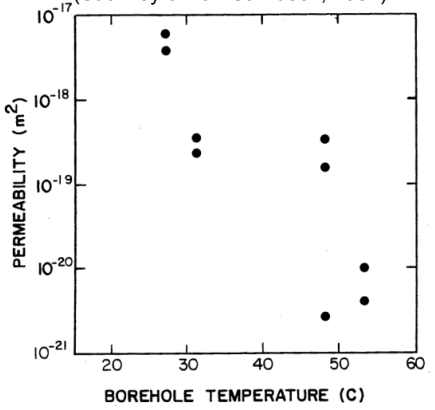
Avery Island (Krause, 1983)

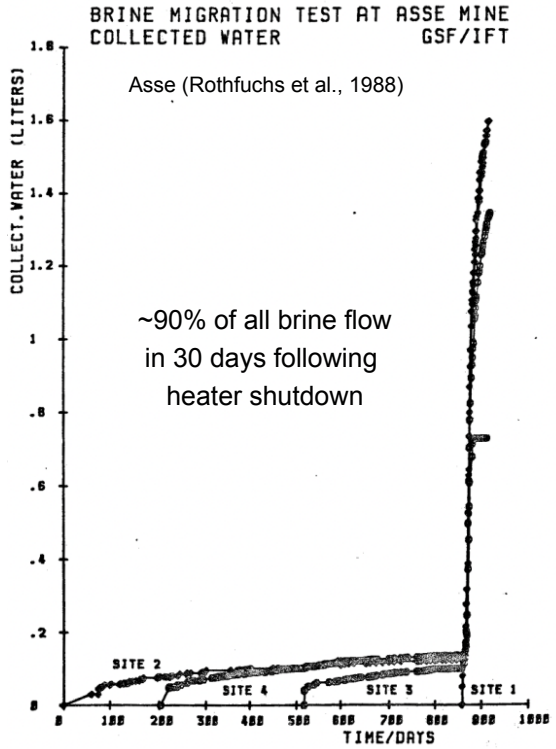


1-m bedded salt lab test (Hohlfelder, 1979)



Avery Island permeability data (Stickney & Van Sambeek, 1984)



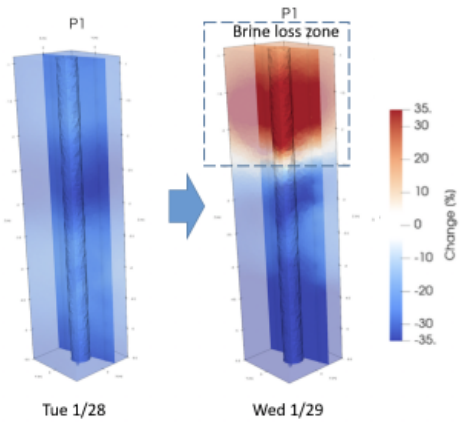


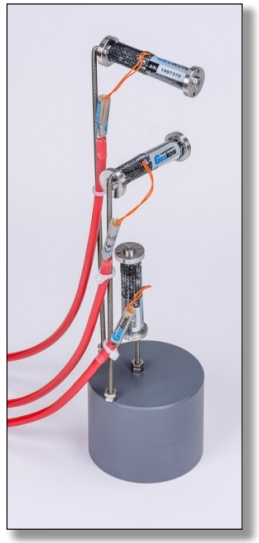
- $k[\epsilon(\sigma(T))]$ Permeability as a function of strain, due to stress, due to thermal expansion
- Slower permeability decrease and thermal expansion during heating (i.e., creation of dam)
- Quick permeability increase and thermal contraction during cooling (i.e., release dam)

Task E Step 3 (Alternatives)

1. BATS brine / gas tracer tests
2. 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
3. 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)
4. Additional C processes
   - Include water types explicitly in models (fluid inclusions, clay dehydration)
5. Effects of viscoplastic creep on brine production

Based on interest of teams: Chose one/two?





Summary

- Task E brine inflow test cases
  - Unheated: Small-scale brine inflow (1987-1991)
  - Heated & Unheated: BATS test (ongoing)
- Task E evolution
  - $H^1/T \rightarrow TH^1 \rightarrow H^2/H^2M \rightarrow TH^2/TH^2M$
  - **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

Task E Interactions M3 – M4

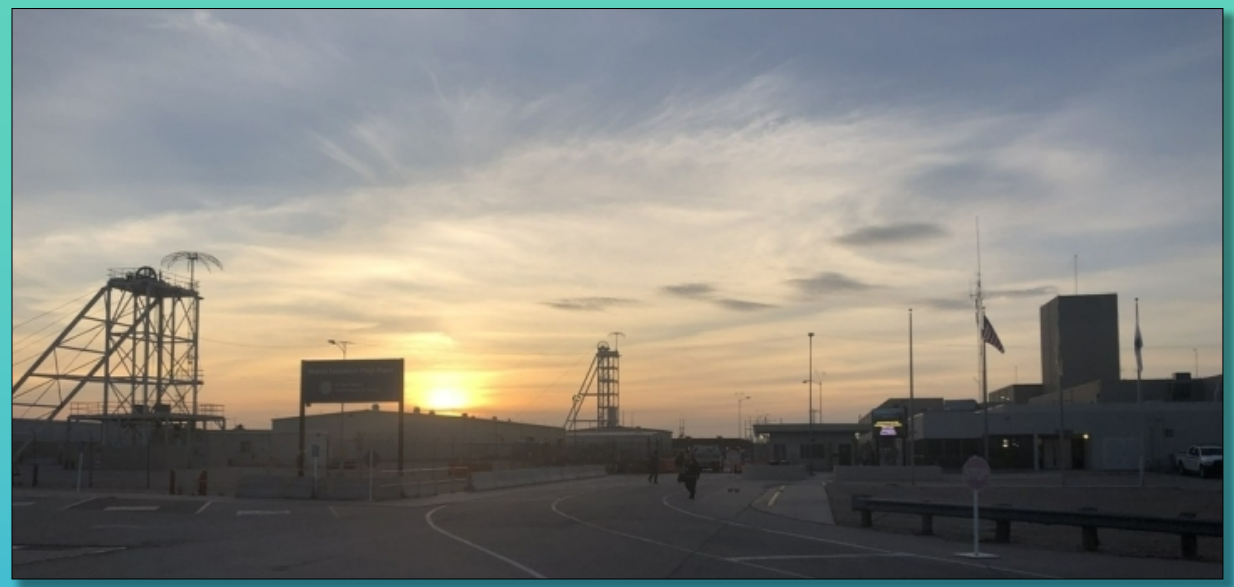
- Summary of Task E Interactions
  - 26-30 Apr 2021: DECOVALEX M3
  - 16 Jun 2021: Task E optional #1
  - 11 Aug 2021: Task E optional #2
  - 29 Sep 2021: Task E optional #3
  - 8-12 Nov 2020: DECOVALEX M4
- “Optional” Discussions Meetings are Successful
  - <90 minutes each
  - Discussion between participants
  - Clear up data issues
  - Point out errors/inconsistencies in task specification

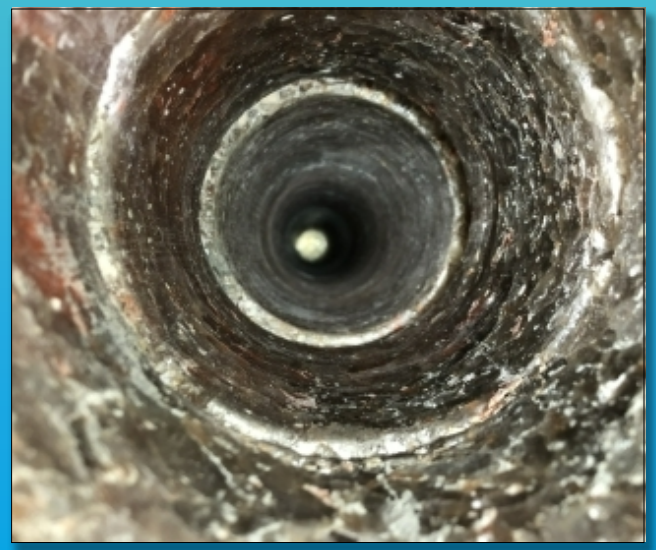
Task E (Thursday, Stream 3) Preview

- Teams: DOE, COVRA, GRS, BGR, RWM
- Results and Discussion on Step 1b
  - BATS two-phase flow
  - Two-phase flow model initialization
- Next steps
  - BATS heater and brine production
  - BATS gas tracer test

BATS 1.0 over coring Oct 2021

Thank you!





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