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US DOE Office of Nuclear Energy (DOE-NE) Borehole Heater Tests at WIPP on Coupled Processes

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WIPP Coupled Processes Field Test

- **Goals of Bedded Salt Field Test**
  - Brine availability, transport, and chemistry in bedded salt formation
  - Changes in permeability, porosity, and borehole closure during test
  - Compare heated/unheated tests
  - Collect data to validate numerical/constitutive models
- **Modular Design**
  - Waste Isolation Pilot Plant (WIPP) providing test access/infrastructure
  - Central test borehole
    - *(~12.7-cm [5”] diameter, 6 m long, 2 m test interval)*
  - Satellite observation boreholes
    - *(multiple locations and various diameter)*
  - Packer/plug isolation of boreholes from drift air
  - Multiple parallel tests: heated (120 °C) and unheated (30 °C) conditions

Test Motivation

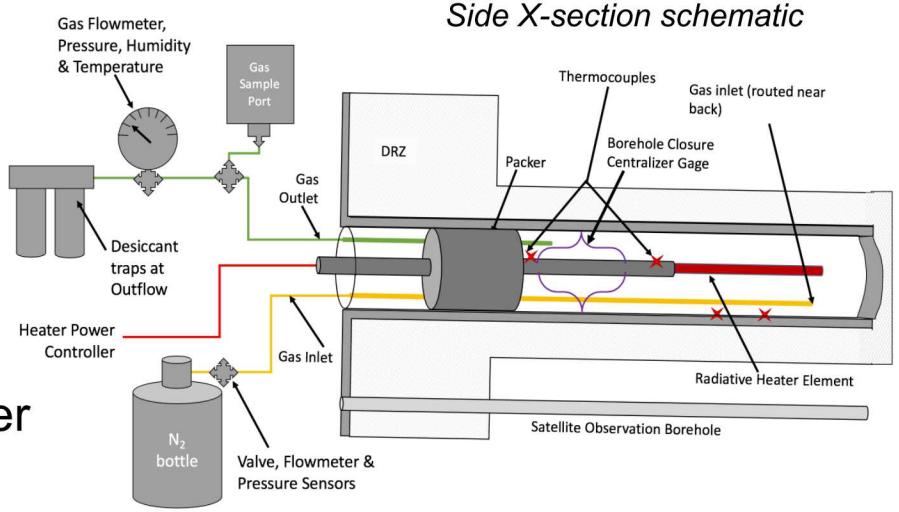
- **Generic Process Investigation in Bedded Salt**
  - Validation data for numerical models
  - Generic investigation of bedded salt formation
- **Bedded vs. Domal Salt**
  - Bedded salt is layered and includes clay, polyhalite, or anhydrite layers
  - Bedded salt has higher brine content than domal salt
- **Previous Heater Tests in Bedded Salt**
  - Large-diameter (1-m) vertical boreholes
  - Crossed significant (i.e., mapped) clay/anhydrite layers
  - Test response was dominated by non-salt units
- **Planned Horizontal Test Orientation**
  - Avoids mapped clay, polyhalite, or anhydrite layers
  - Test interval beyond room disturbed rock zone (DRZ)
  - Interval completed in single geologic unit (MU-0 at WIPP)

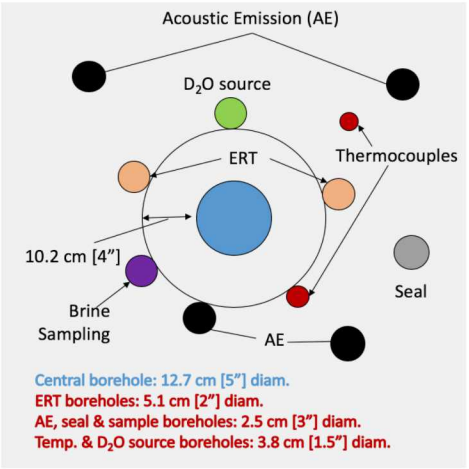
Test Components

- **2 Test Arrangements (heated + unheated)**
- **Packer-isolated Central Borehole**
  - Single inflatable packer
  - Infrared radiative heater* (~400 W)
  - Vapor extraction with dry N_2
  - Gas/vapor sampling
  - Thermocouples
  - Gas permeability tests behind packer
  - Borehole closure
- **Satellite Observation Boreholes**
  - 2 Electrical resistivity tomography boreholes*
  - 4 Acoustic emission monitoring boreholes*
  - 2 Temperature observation boreholes
  - 1 Liquid brine sampling borehole
  - 1 Deuterated water tracer spike
  - 1 Cement-plug/borehole interaction test

** Heated test only*

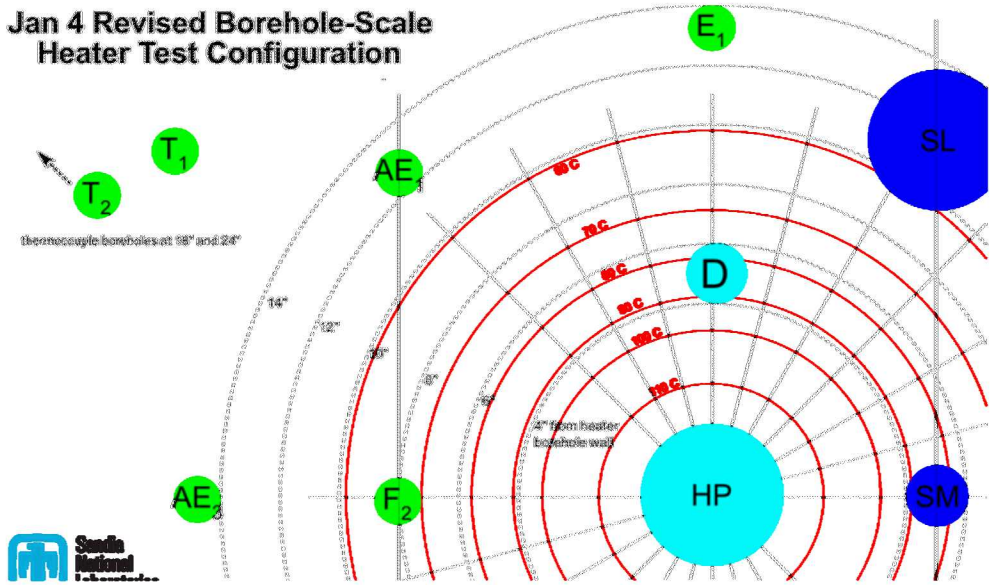
Side X-section schematic



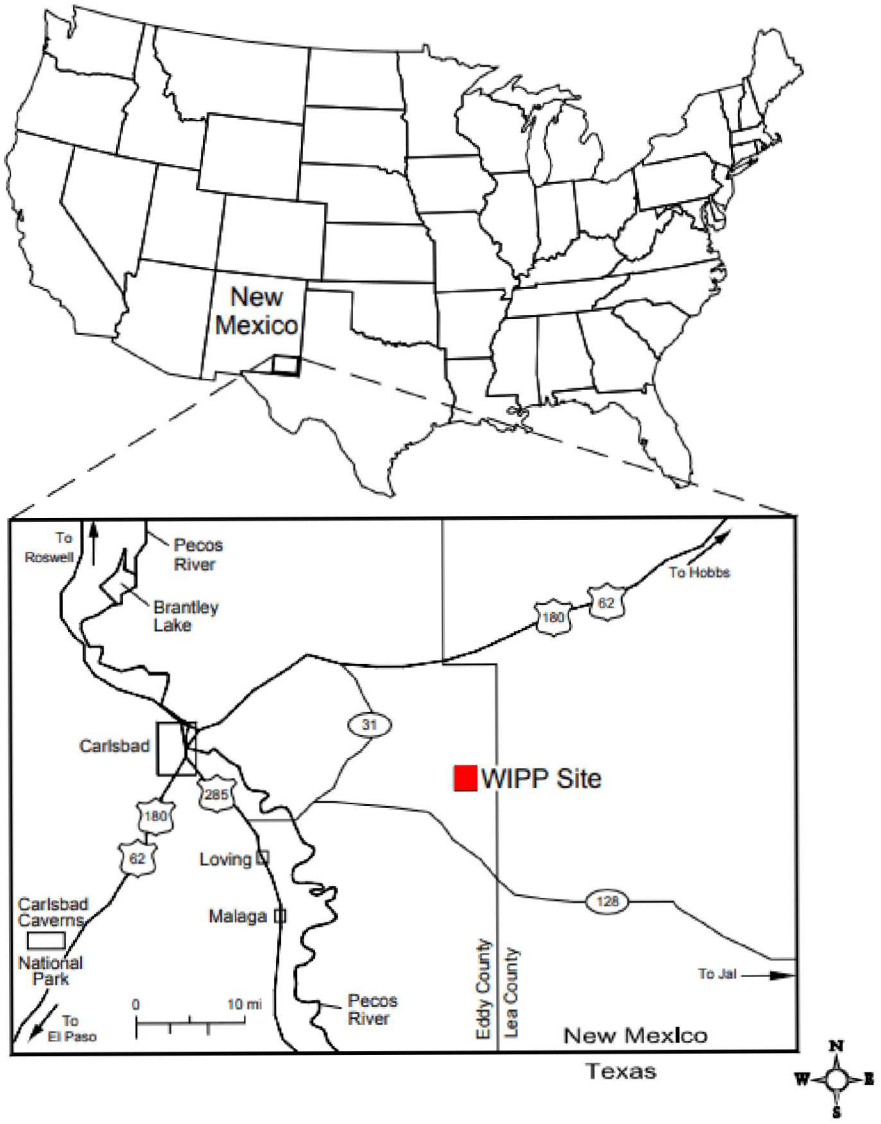


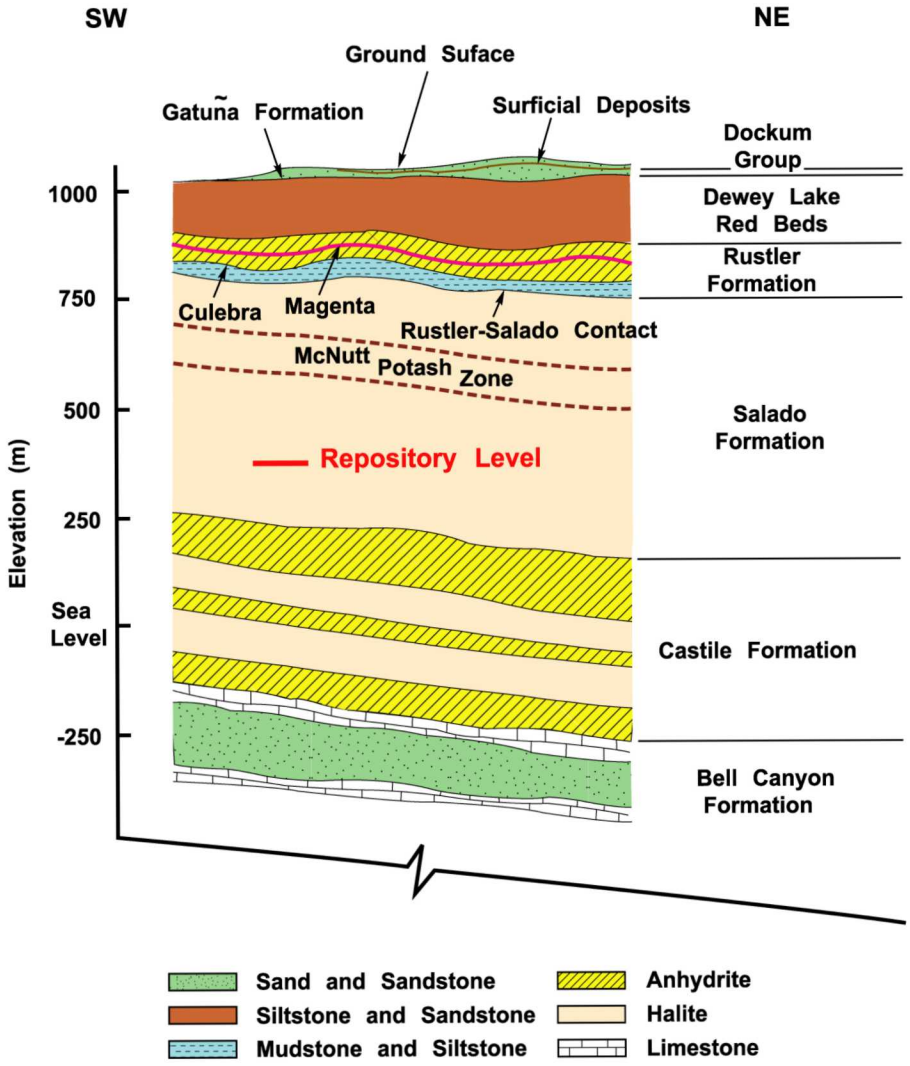
Drift view of borehole locations

More Detailed View



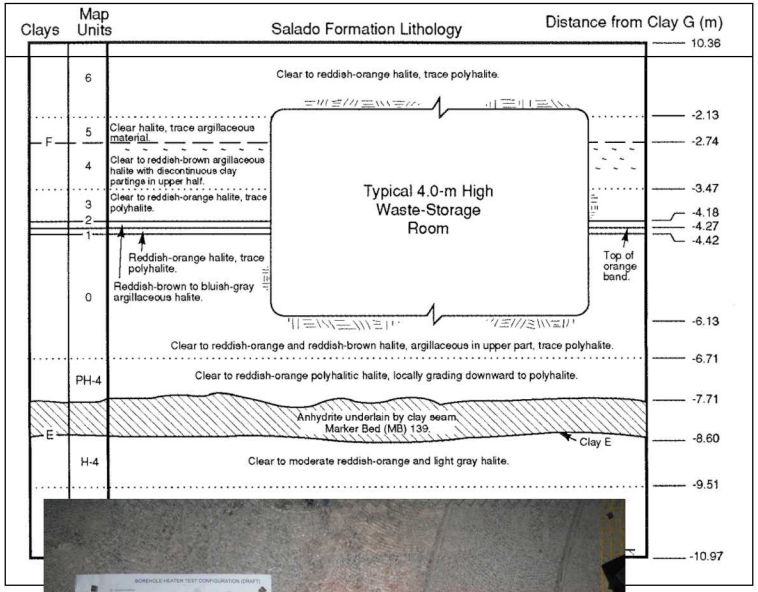
WIPP Context

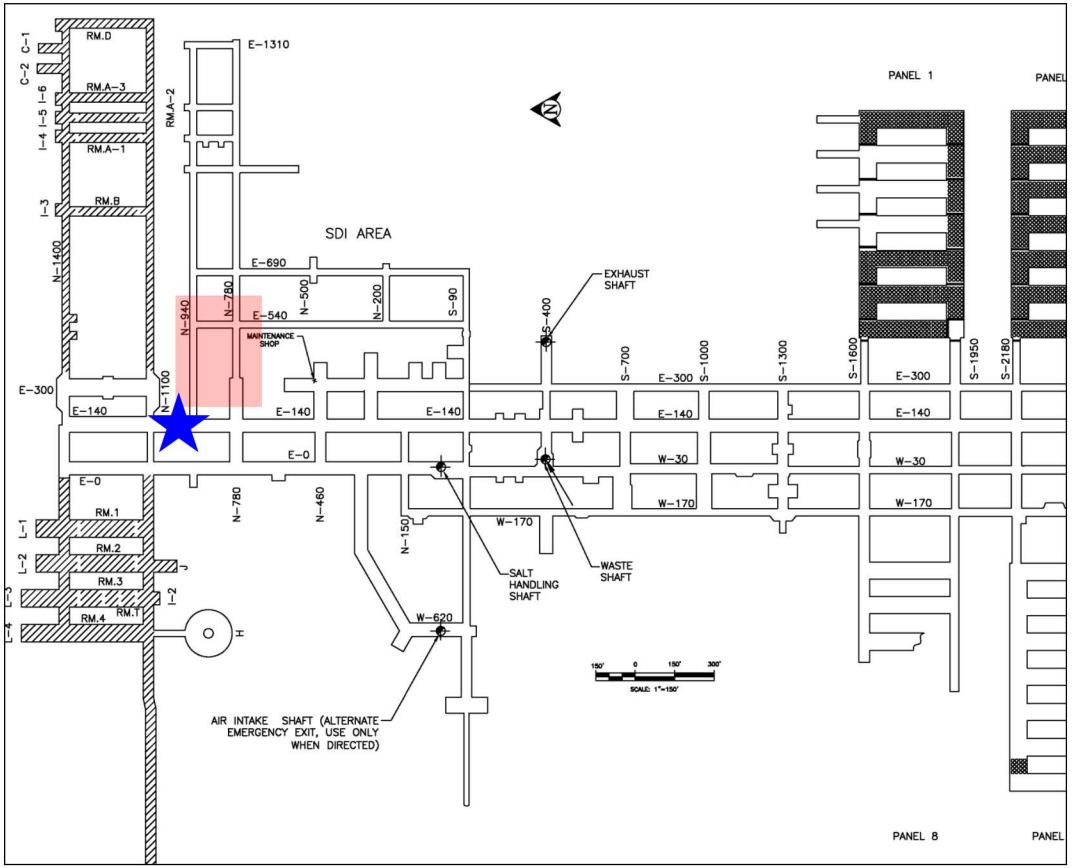




WIPP Bedded Salt Test Location

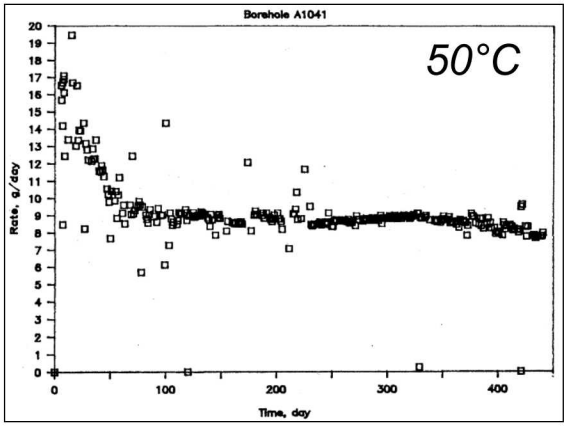
- **New Boreholes in Early 2019**
  - Boreholes located in SDI area (red)
  - Cores analysis via X-Ray CT, XRF & photographs at NETL



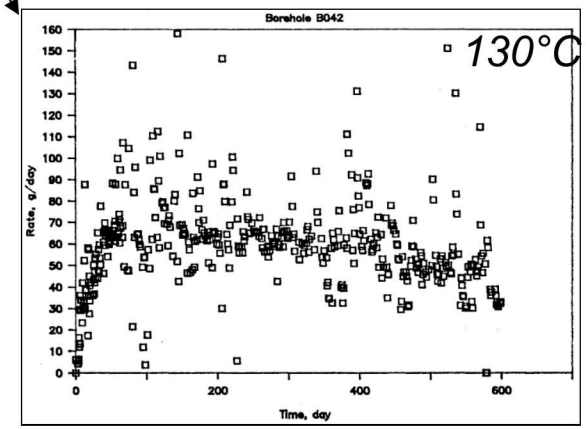


Brine Inflow Expectations

- **Brine Inflow**
  - Highest inflow rate initially
  - Exponential decay of rate with time
- **Higher Temperature → More Brine**
  - Vapor from dehydration of clay & gypsum
  - Brine from fluid inclusions
- **1997 WIPP Unheated Brine Inflow Study**
  - INTRAVAL Study (Beauheim et al. 1997)

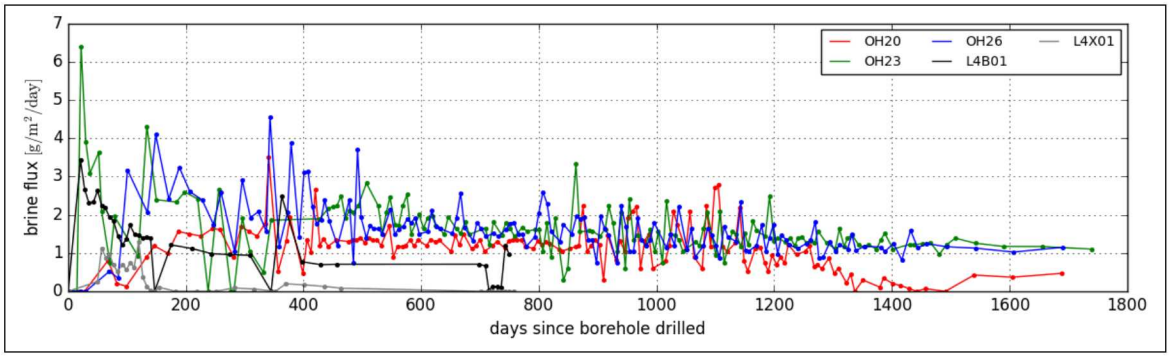


Inflow to Vertical Boreholes



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

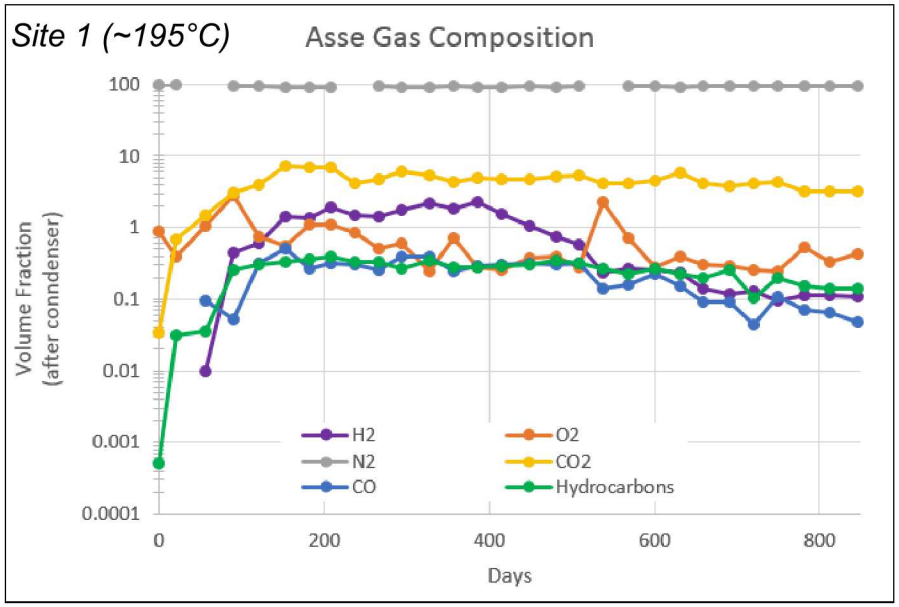
Kuhlman et al. (2017)



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

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?
  - Noble gas tracers
- **Water Vapor from Brine**
  - Natural H_2O
  - Breakthrough Stable H_2O tracers
    - Transport time through salt
    - Fractionation in borehole
    - Tried at Avery Island (Krause, 1983)
- **Acid Gas from Salt & Brine**
  - Decomposition of hydrous Mg salts
  - Equilibration of $P_{HCl(g)}$ into condensed steam

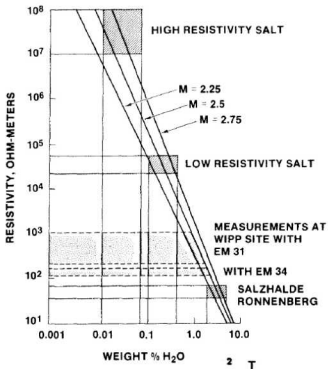


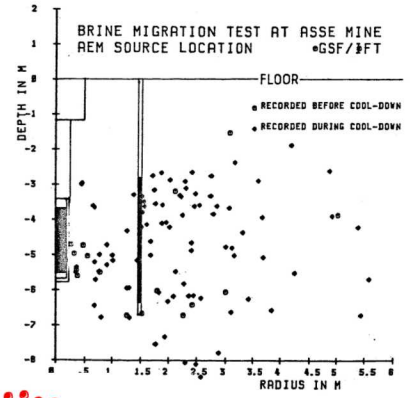
Data from *Coyle et al. (1987) BMI/ONWI-624*

ERT/AE Expectations

- **Electrical Resistivity Tomography (ERT)**
  - ERT electrodes cemented into 2 boreholes
- **Salt Apparent Resistivity**
  - Function of temp., porosity & 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

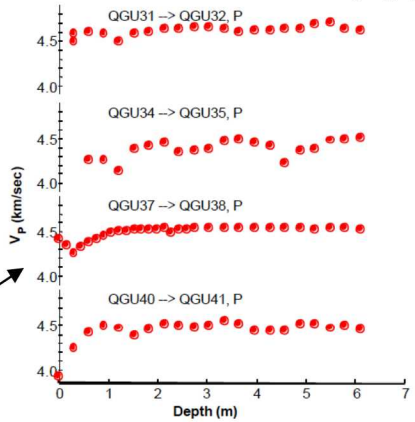
Skokan et al. (1989)





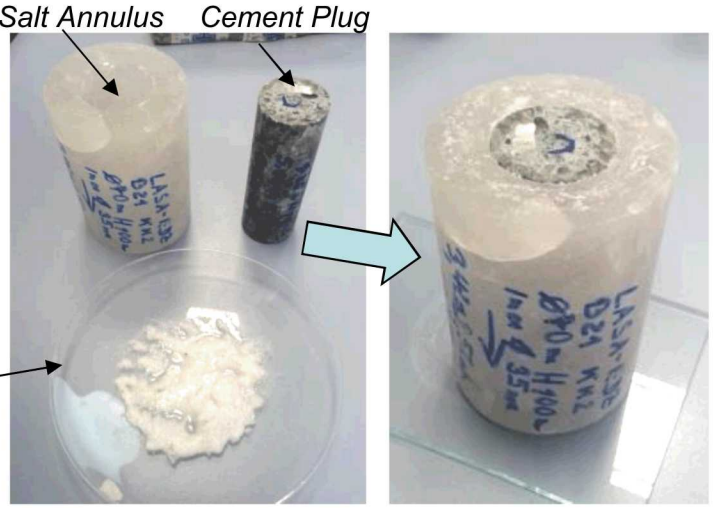
Rothfuchs et al. (1988)

Holcomb et al. (2001)

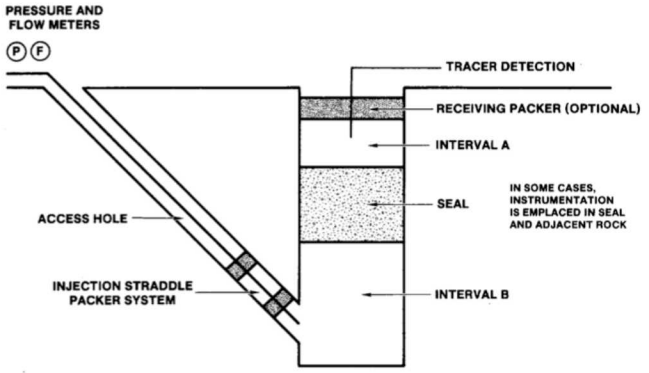


Cementitious Seals Expectation

- **Emplace Pre-fabricated Cement Plug**
  - Snug fit into satellite borehole
  - Tubing embedded in plug (perm. test)
  - Monitor seal evolution as borehole closes
  - Parallel tests: ambient + heated conditions
- **Upscale GRS Lab Seals Tests**
  - GRS test monitored permeability evolution
  - We will implement at borehole scale
- **Compliment Field Scale Sealing Tests**
  - Previous WIPP field tests were complex
  - Would require separate research program
- **Overcore Post-test to Analyze Interfaces**



Czaikowski & Wieczorek (2016)



Stormont (1987)

Probable Test Data for Comparison

- **Central Borehole**
  - Water production and temp/power time series
  - Borehole permeability estimates before/during/after test
  - Borehole diameter time series
- **Acoustic Emissions (AE) timeseries**
  - Location and timing of AE during heating/cooling
- **Fiber optic distributed sensing timeseries**
  - Temperature and strain sensing through time in 4 boreholes
- **4D Electrical Resistivity Tomography**
  - 3D evolution of porosity/saturation during heating/cooling
- **Brine and Gas Composition**
  - Brine and gas composition samples collected before/during/after
  - Water isotope (i.e.,O & H) samples to observe tracer breakthrough
- **Comparison of parallel heated and unheated tests**
  - Effects of heat on borehole closure, borehole permeability, brine production, brine composition & gas composition

Proposed Project Timeline

- **Construction/Testing**
  - New boreholes to be cored Jan/Feb 2019
  - Test constructed/installed ASAP in new boreholes
  - Heated test conducted for ~9 months
  - Unheated test conducted ~12 months
  - Likely follow-on test (similar setup) at different powers/temperatures

- ***2019:* Initial test execution**
- ***2020:* Distribute benchmark (thermal or hydro only) test data**
- ***2021:* Simulate single processes (+ thermal)**
  - Brine production, tracer transport
  - Thermal-Hydrologic, Thermal-Mechanical, Thermal-Chemical
  - Follow-on test data available
- ***2022:* More coupled processes**
  - Salt permeability/porosity as a function of damage
- ***2023:* Include data from ERT/AE/brine composition**

- **Possibly Interested Parties**
  - US (SNL, LANL, LBNL), Germany (BGR, BAM), UK (RWM), Netherlands (COVRA)

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