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Spent Fuel and Waste Science and Technology

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

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WIPP Coupled Processes 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 similar 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 or plug isolation of boreholes from drift air
  - Two parallel tests: heated (120 C) and unheated (~30 C) conditions

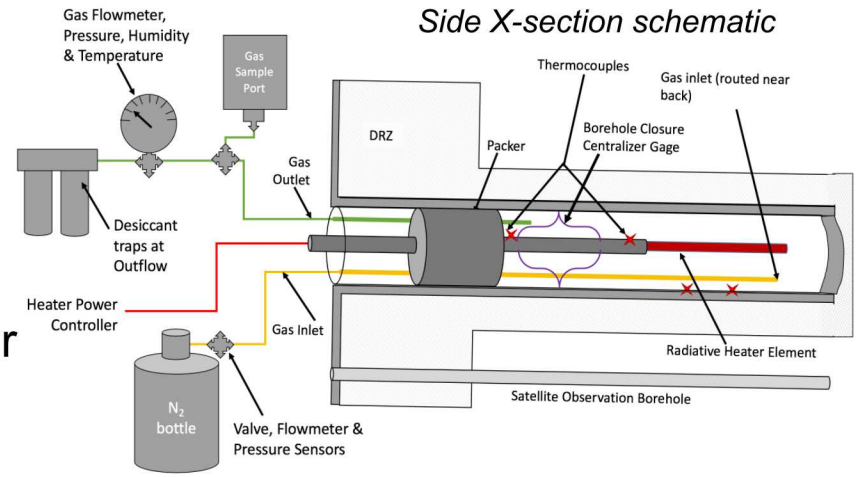
Test Motivation

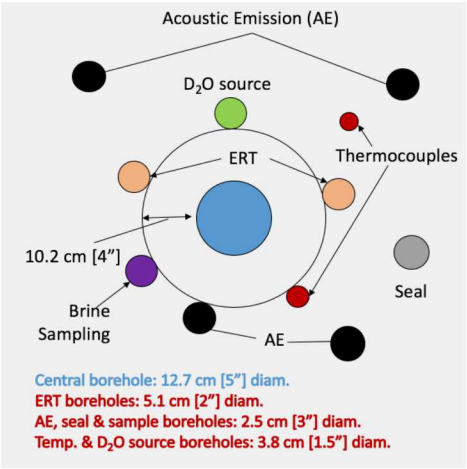
- **Generic Investigation of Processes in Bedded Salt**
  - Validation data for numerical models
  - Generic investigation of bedded salt formation
- **Bedded vs. Domal Salt**
  - Bedded salt is layered and includes clay, polyhalite, or anhydrite layers
  - Bedded salt has higher brine content than domal salt
  - Previous German heater tests in domal salt
- **Previous Heater Tests in Bedded Salt**
  - Large-diameter vertical boreholes
  - Crossed significant (i.e., mapped) clay layers
  - Test response was dominated by non-salt layers
  - Previous Results more difficult to transfer generically
- **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 Design

- **Two test arrangements (heated + unheated)**
- **Packer-isolated interval in 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

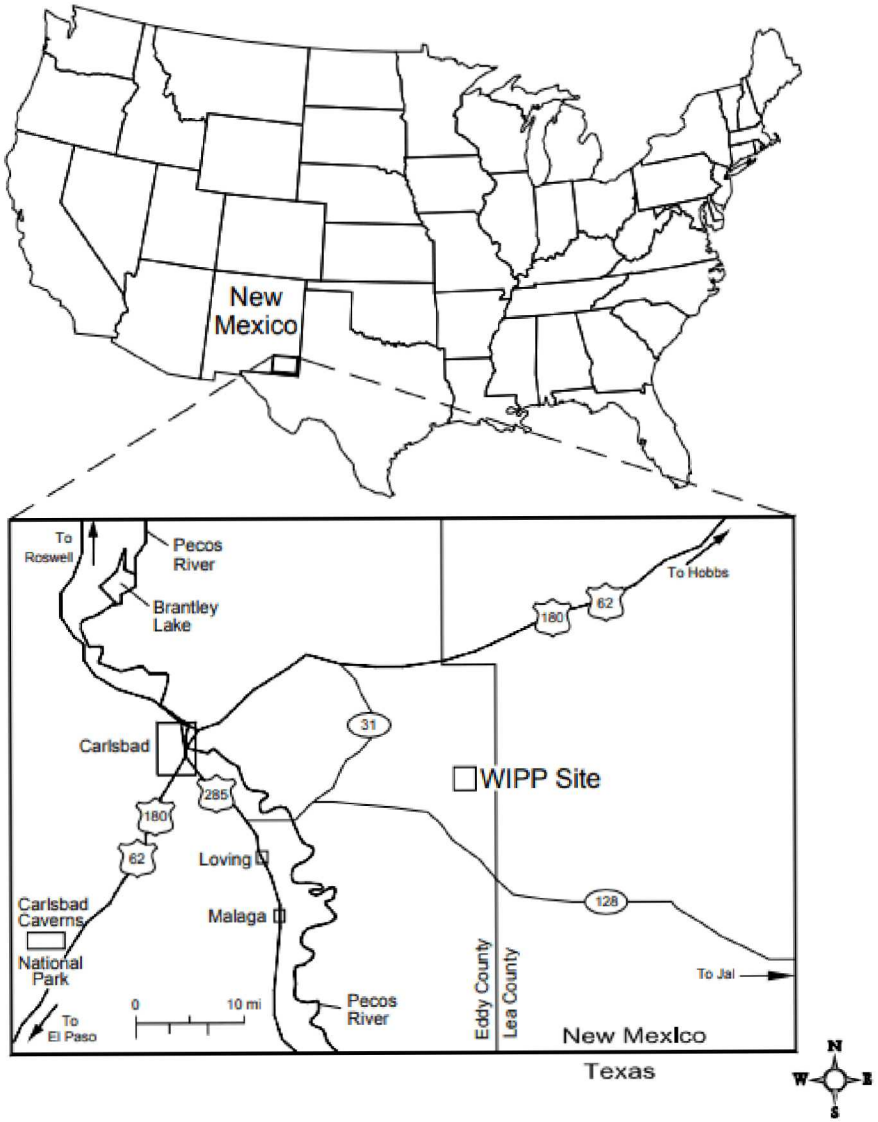
** Heated test only*

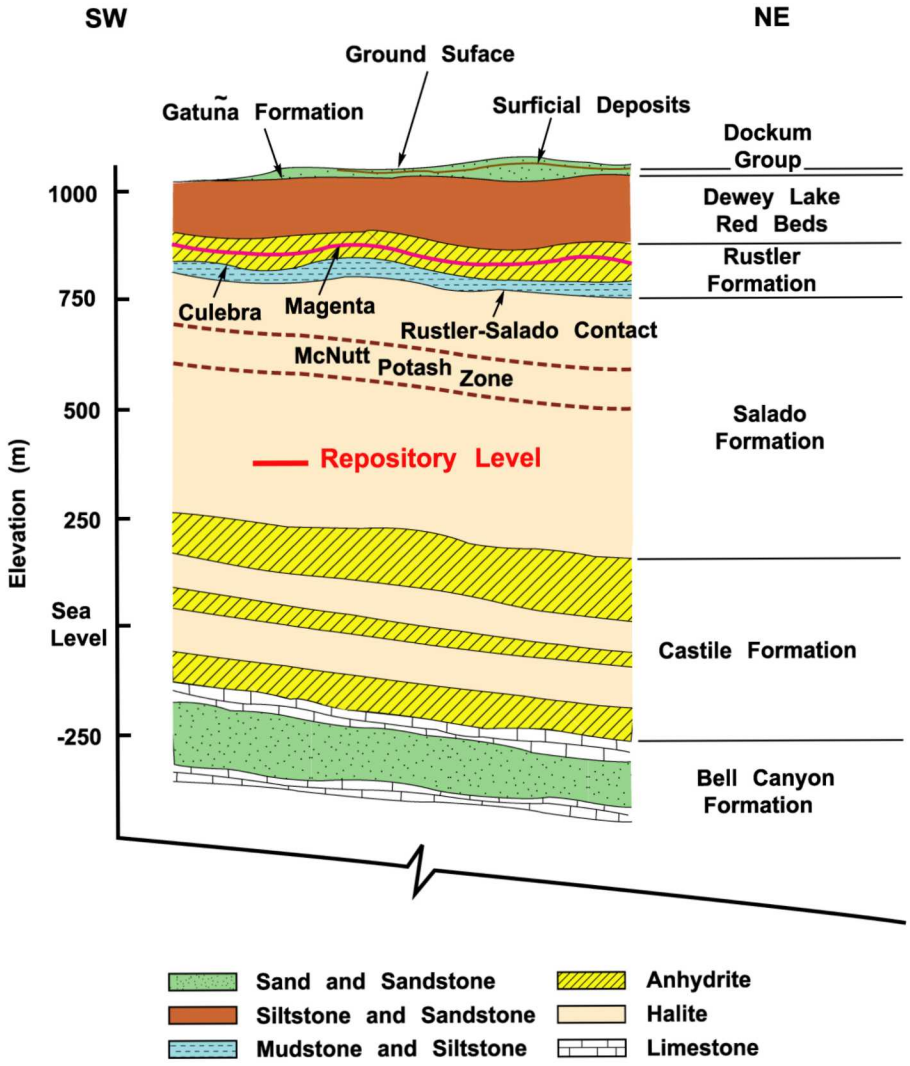




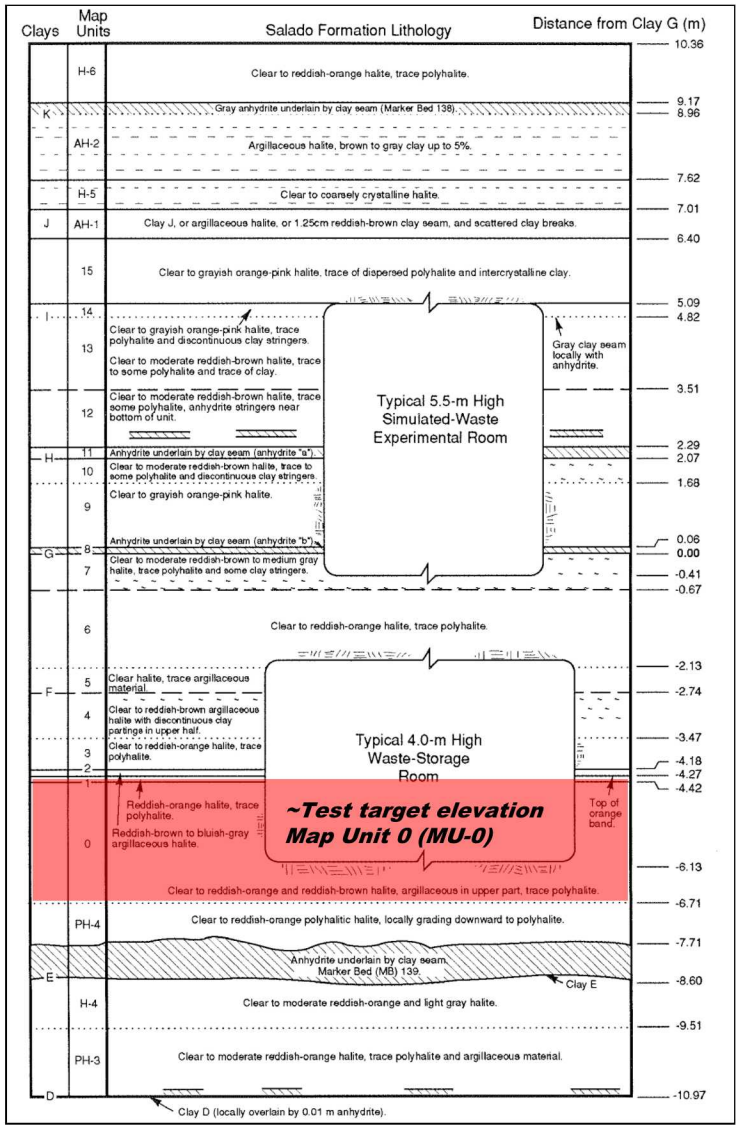
Drift view of borehole locations

WIPP Context

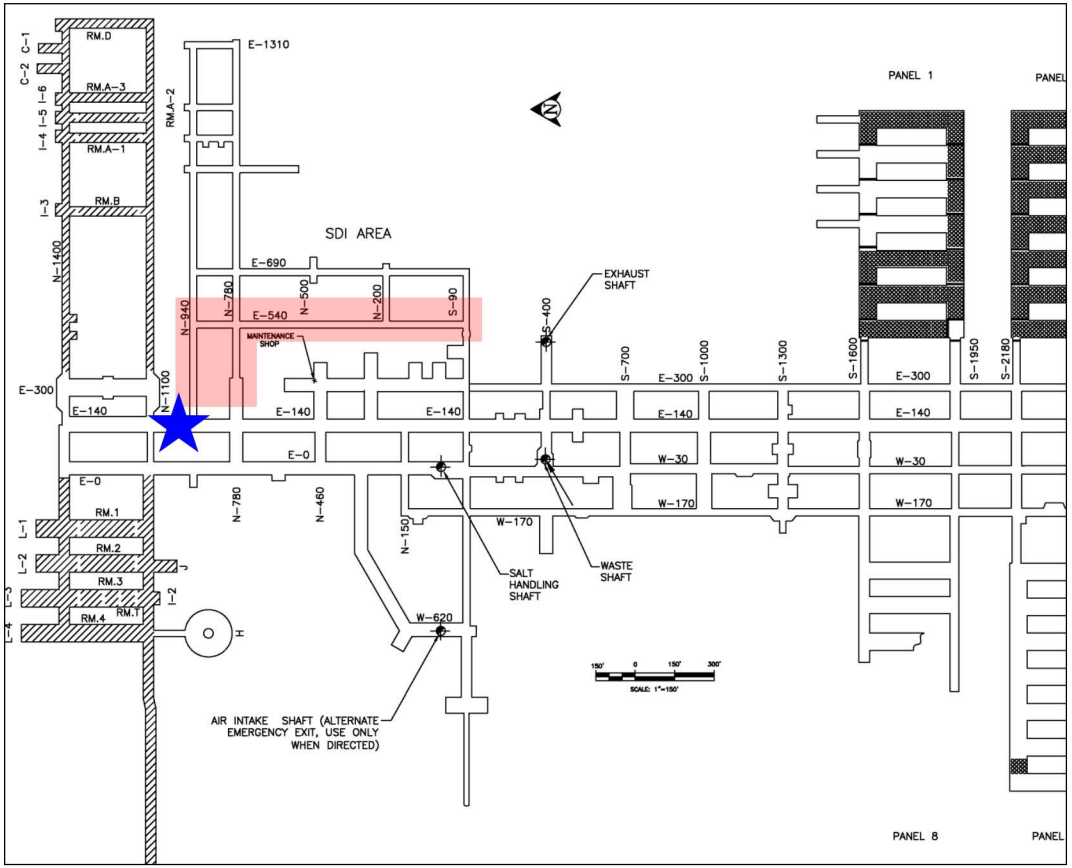




WIPP Bedded Salt Test Location



- **New Boreholes to be drilled late 2018**
  - Boreholes located in SDI area (red)
  - Current location is blue star



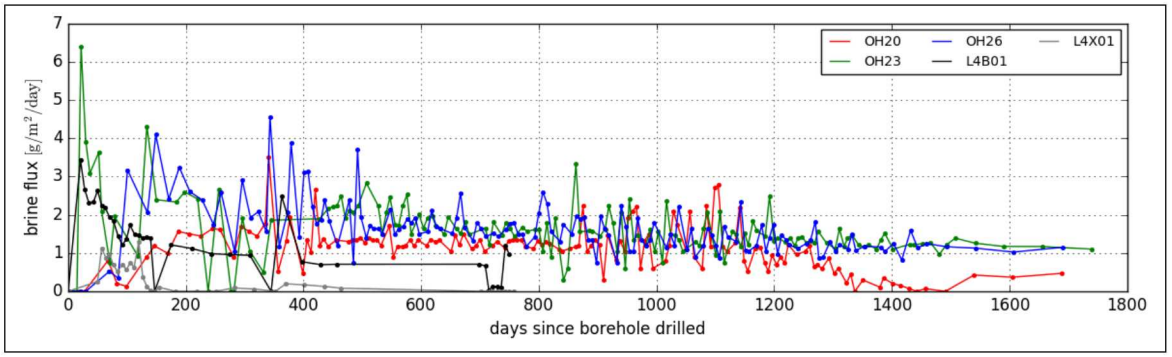
Heated Borehole Expectations

- **Three Sources of Water in Salt**
  - Intergranular brine
    - *Moves due to liquid pressure, thermal expansion & vapor transport*
  - Intragranular brine (fluid inclusions)
    - *Moves due to thermal gradients (becomes intergranular brine)*
  - Hydrous minerals
    - *Dehydration temperatures for each hydrous mineral (steam transport)*
- **Heated Borehole Wall ~120 C**
  - Borehole closure due to salt thermal expansion + accelerated creep
  - Increased brine flow due to thermal expansion of brine
  - Permeability of salt will decrease during heating
  - Acoustic emissions due to cracking from heating and creep
- **Monitoring will continue after shutdown of heater**
  - Permeability will increase significantly at cool down (brine pulse)
  - Acoustic emission burst during cooldown
  - Some borehole closure will be reversed (while some lost to creep)

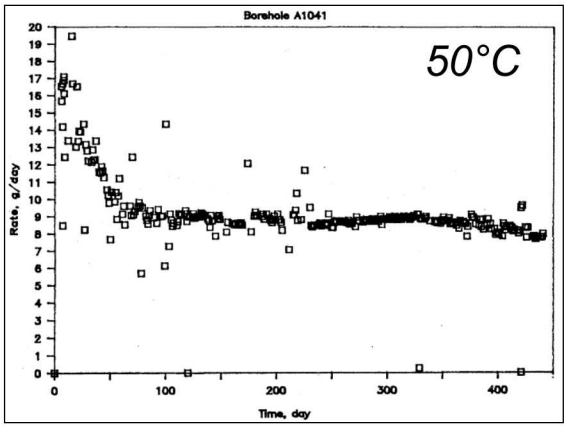
Brine Inflow Expectations

- **Brine inflow**
  - Highest flowrate 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)

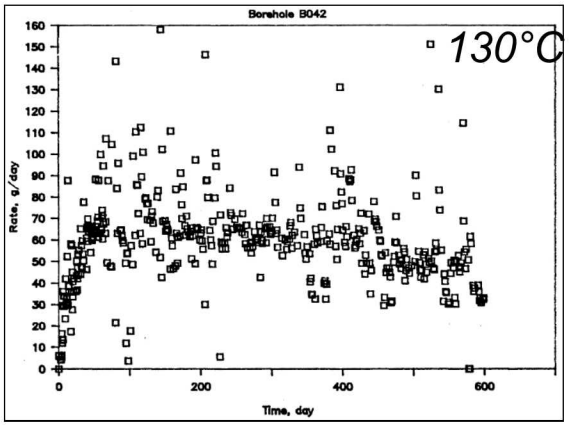
Kuhlman et al. (2017)



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



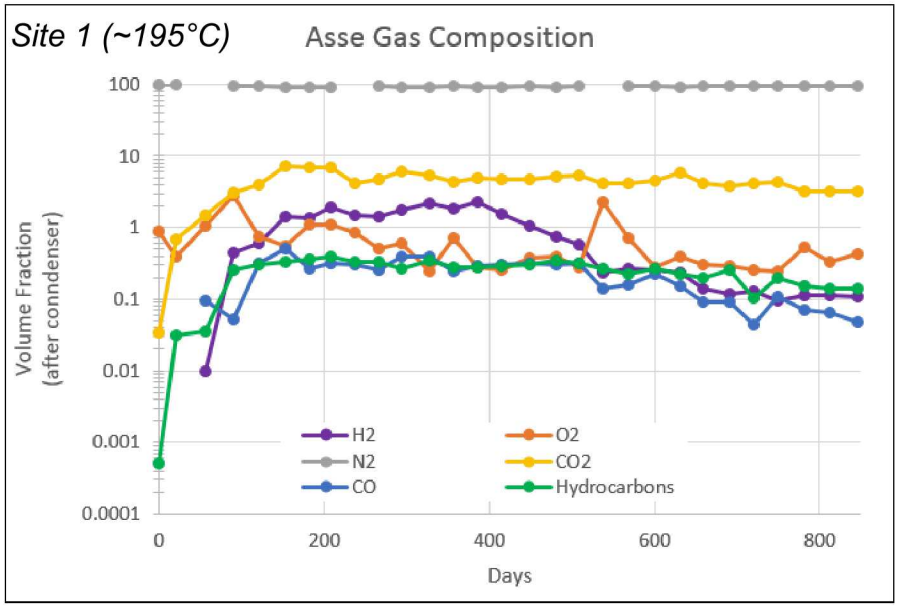
Vertical WIPP boreholes



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

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
  - D_2O tracer breakthrough
    - 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

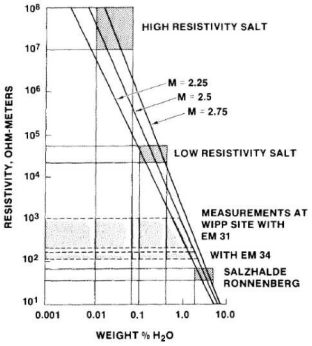


Data from *Coyle et al. (1987) BMI/ONWI-624*

ERT/AE Expectations

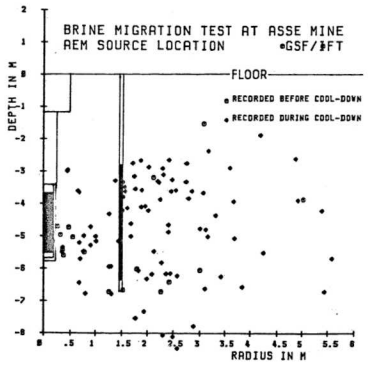
- **Electrical Resistivity Tomography (ERT)**
  - ERT electrodes cemented into 2 boreholes
- **Salt Apparent Resistivity**
  - Function of porosity and brine saturation
- **Conduct 3D ERT surveys through time**
  - Estimate evolution of porosity/saturation
  - ERT conducted in heated test only

- **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

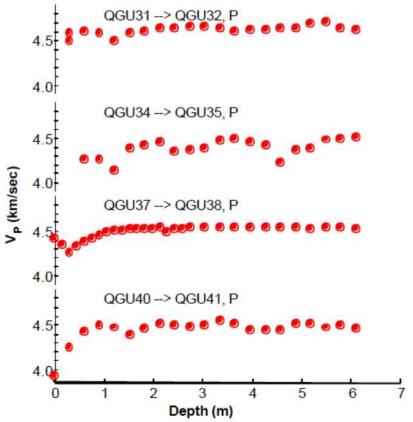


Skokan et al. (1989)

Rothfuchs et al. (1988)

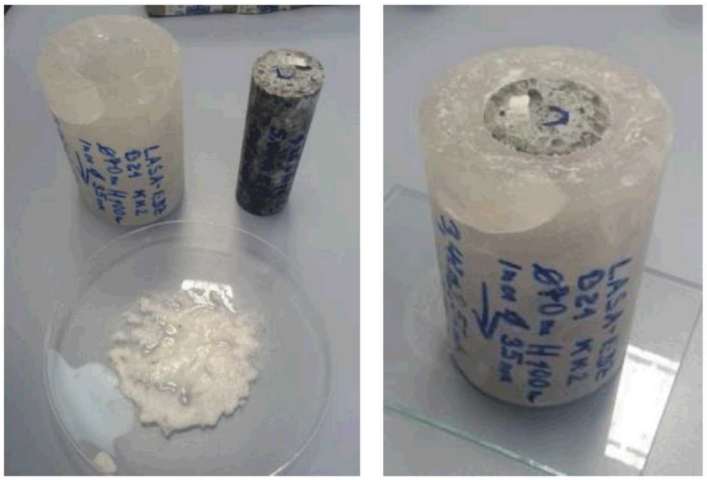


Holcomb et al. (2001)

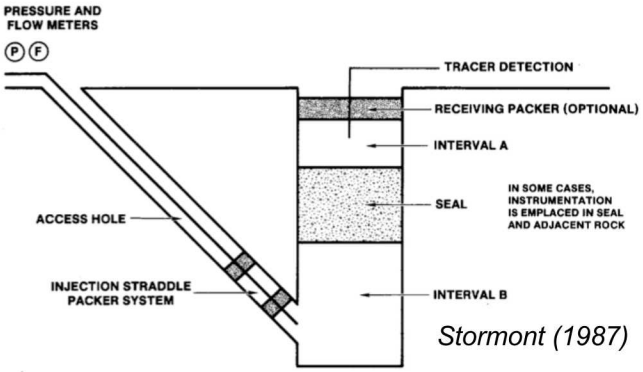


Cementitious Seals Expectation

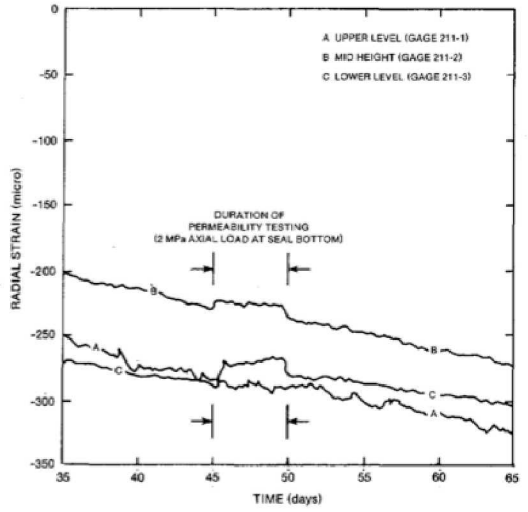
- **Emplace Pre-fabricated Cement Plug**
  - Snug fit into satellite borehole
  - Gas line embedded in plug
  - Monitor seal evolution as borehole closes
- **Upscale GRS Lab Seals Tests (DOPAS)**
- **Compliment Field Scale Sealing Tests**
  - ERAM Test Seal - salt concrete
  - Asse tests - Sorel cement and salt concrete
  - WIPP Field Seals Tests
- **Post-test Overcore to Analyze Interfaces**



Czaikowski & Wieczorek (2016)



Stormont (1987)



Probable Test Data for Comparison

- **Central Borehole**
  - Water production and temp/power time series
  - Borehole permeability measurements before/during/after test
  - Borehole diameter time series
- **Acoustic Emissions (AE) timeseries**
  - Location and timing of AE during heating/cooling
- **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., D_2O) samples to delineate 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 late 2018
  - 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 power/temp.

- ***2019:* Initial test execution**
- ***2020:* Distribute initial test data**
- ***2021:* Simulate single processes (+ thermal)**
  - Brine production, D_2O 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, Germany, UK, Spain, Netherlands, Poland

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