SAND2010-3248P

WIPP Hydrologic Investigations in the Salado Formation

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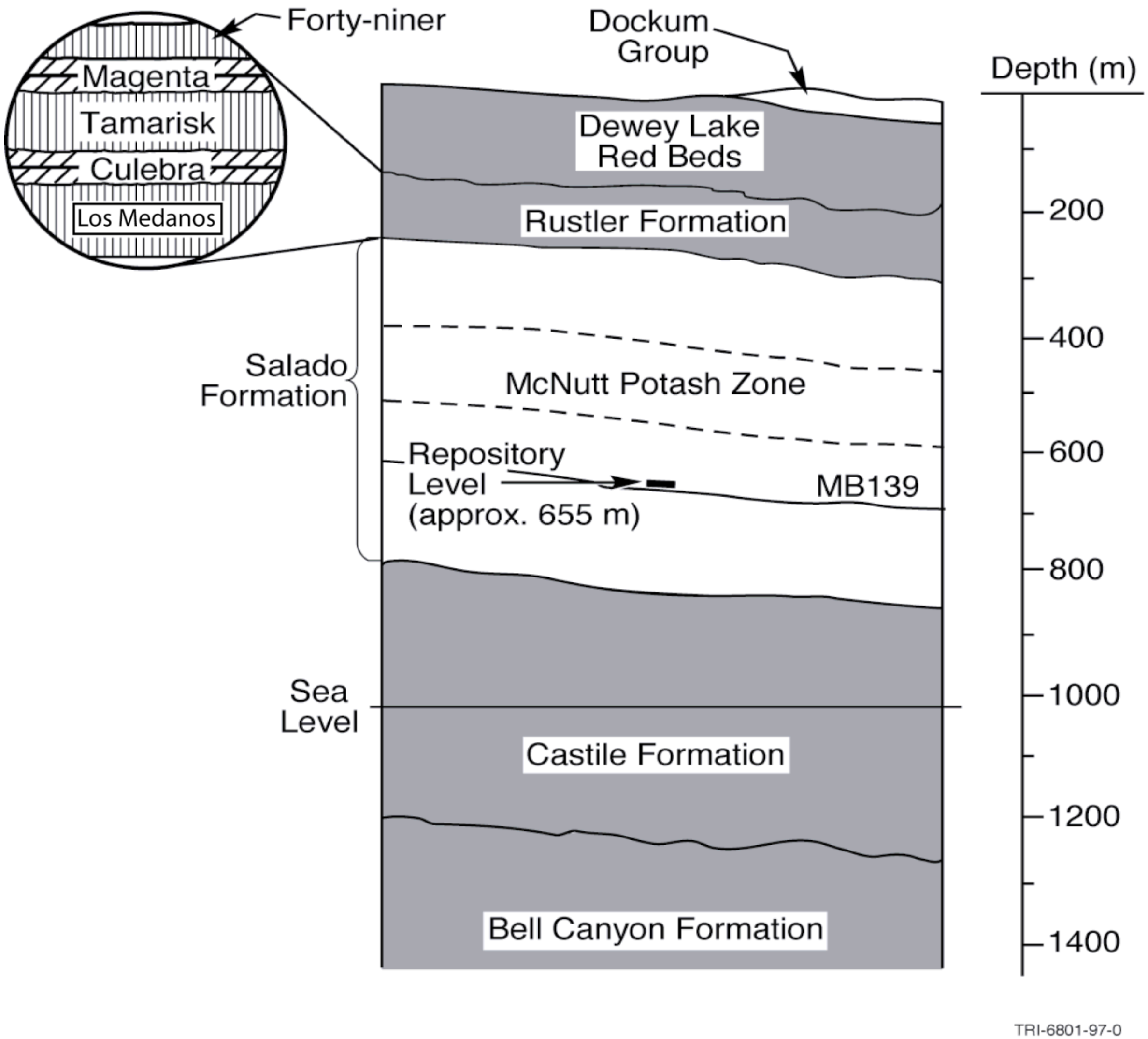
US-German Workshop on Salt Repository Research, Design, and Operation

Jackson, MS, USA

May 25, 2010

Sandia is a multi program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S. Department of Energy

WIPP Stratigraphy



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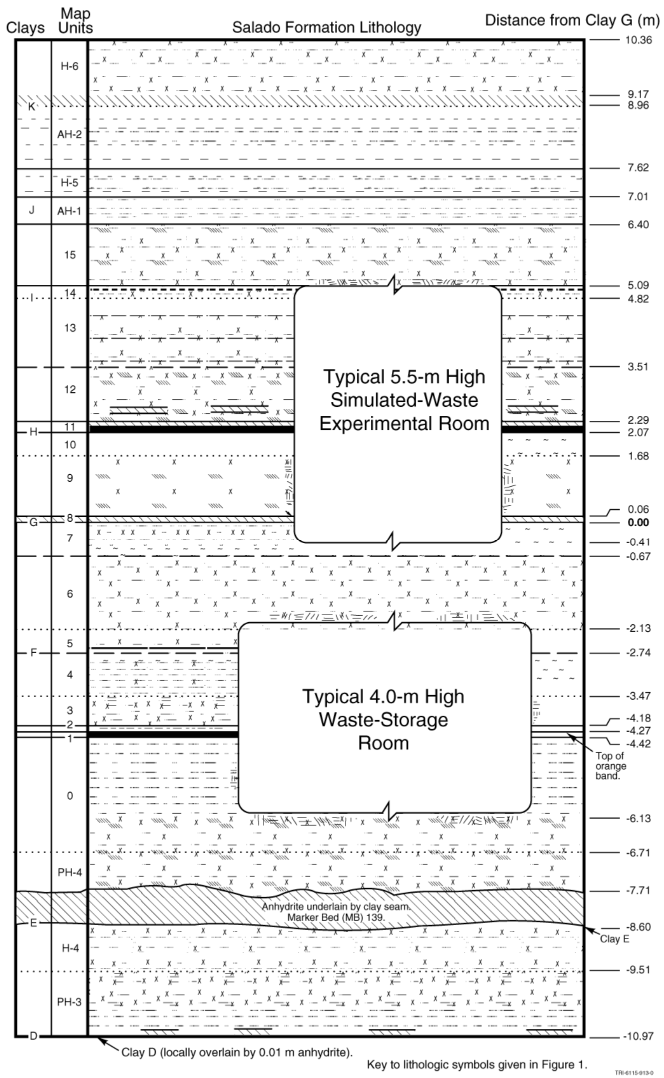
Questions to be Addressed about Salado

- Brine inflow—how much brine might enter the repository after it is closed?
- DRZ/EDZ—how extensive will the damaged zone around the excavations be, and how will rock properties be altered?
- Gas threshold pressure—if gas is generated in the repository, what pressure must it reach before it can flow into the rock?
- Fracture pressure—at what pressure will the repository host rocks fracture, and will the fractures be horizontal or vertical?
- Brine chemistry—what is the chemistry of the brine(s) that might enter the repository, and what can we infer about its origin(s) and mobility?
- Transport—can radionuclides (in brine or gas) be transported away from the repository in the Salado?

Experimental Programs

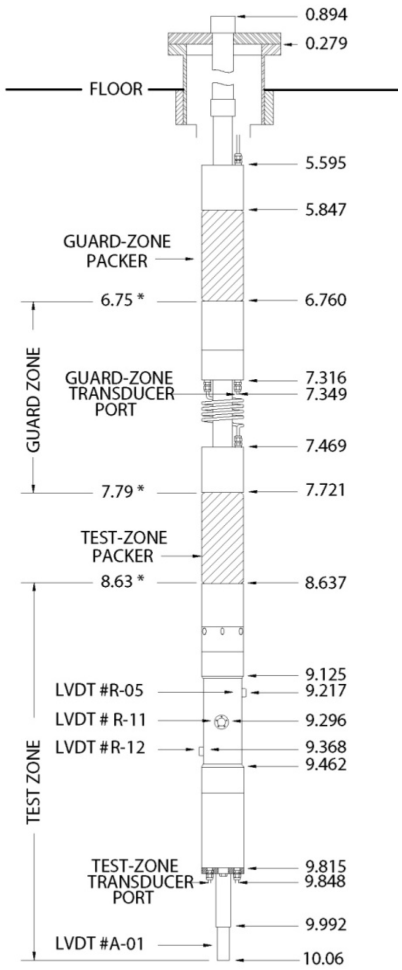
- Permeability testing—addresses brine inflow, DRZ, and transport
- Room Q—addresses brine inflow, DRZ, and transport
- Simulated DHLW heater experiments—addresses brine inflow to HLW boreholes
- Gas threshold pressure testing
- Coupled permeability testing and hydraulic fracturing
- Brine chemistry—also addresses transport

Underground Stratigraphy



- **Salado stratigraphy consists primarily of relatively pure halite, argillaceous and/or polyhalitic halite, and anhydrite beds underlain by clay seams**
- **Individual beds can be traced over the area of the repository in excavations and/or core**
- **No disruptions in bedding over a meter scale have been found**
- **Identify geologic variability relevant to hydraulic properties**
- **Determine representative hydraulic properties for each important rock type**

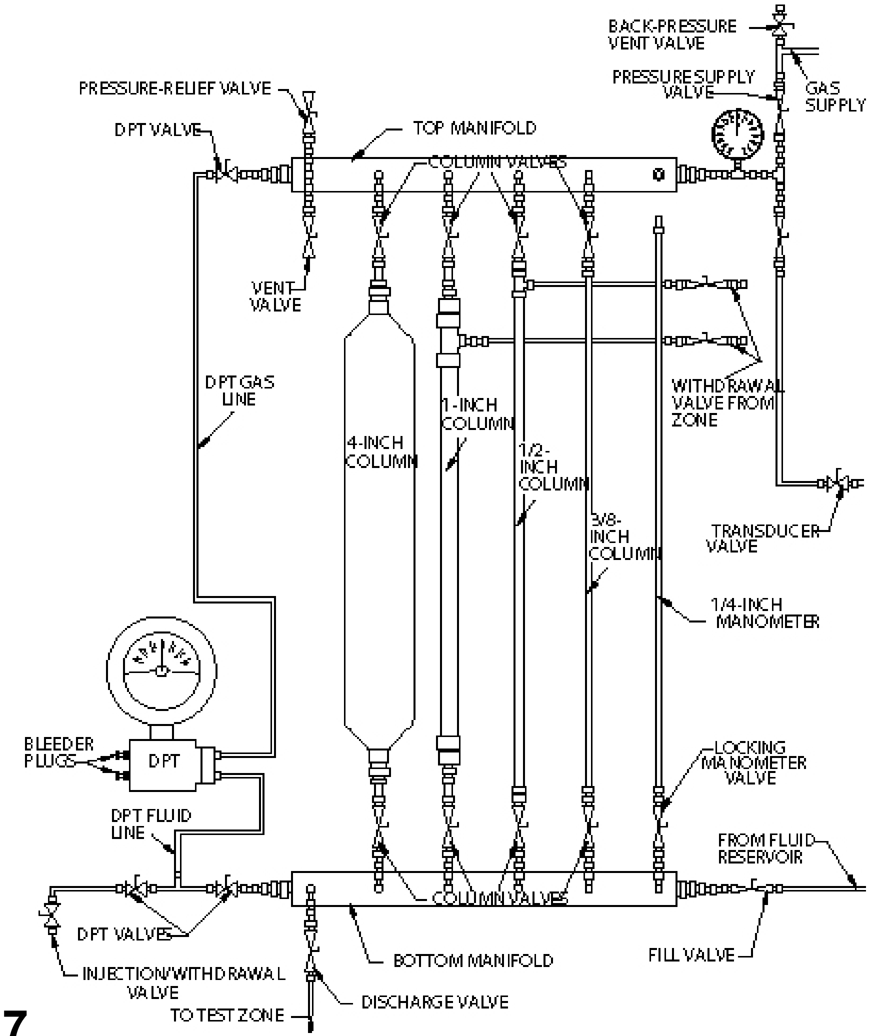
Development of Specialized Equipment for Low-K Testing



NOTE: MEASUREMENTS IN METERS FROM FLOOR BEFORE PACKER INFLATION.
* ESTIMATED POSITION AFTER PACKER INFLATION.

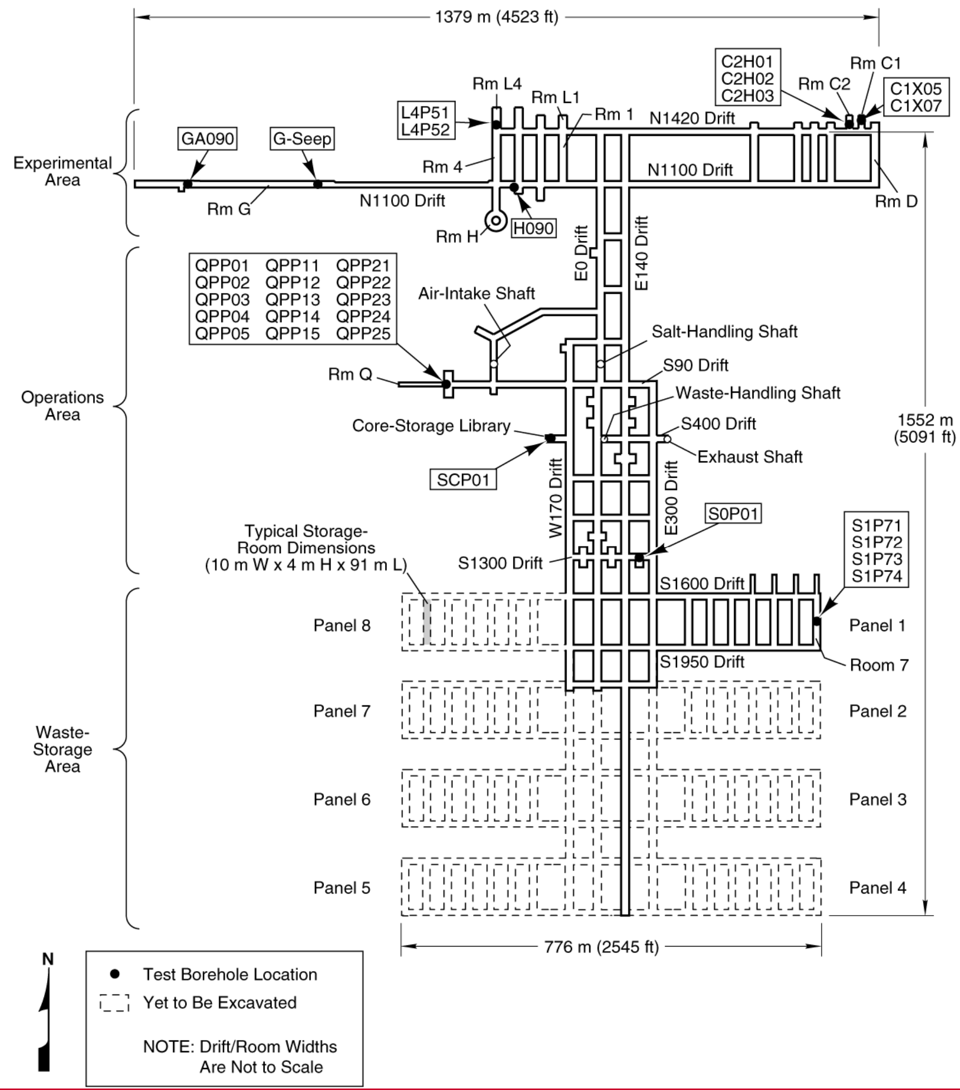
- **Guard zones to reduce pressure differential across packers**
- **Maximize tool volume to minimize fluid volume**
- **Radial LVDT's to measure borehole deformation**
- **Axial LVDT to measure borehole elongation**

Equipment Design to Maximize Measurement Sensitivity



Multiple reservoir columns for constant-pressure flow tests with different diameters arranged in parallel to allow optimization to flow rates encountered

Test Locations



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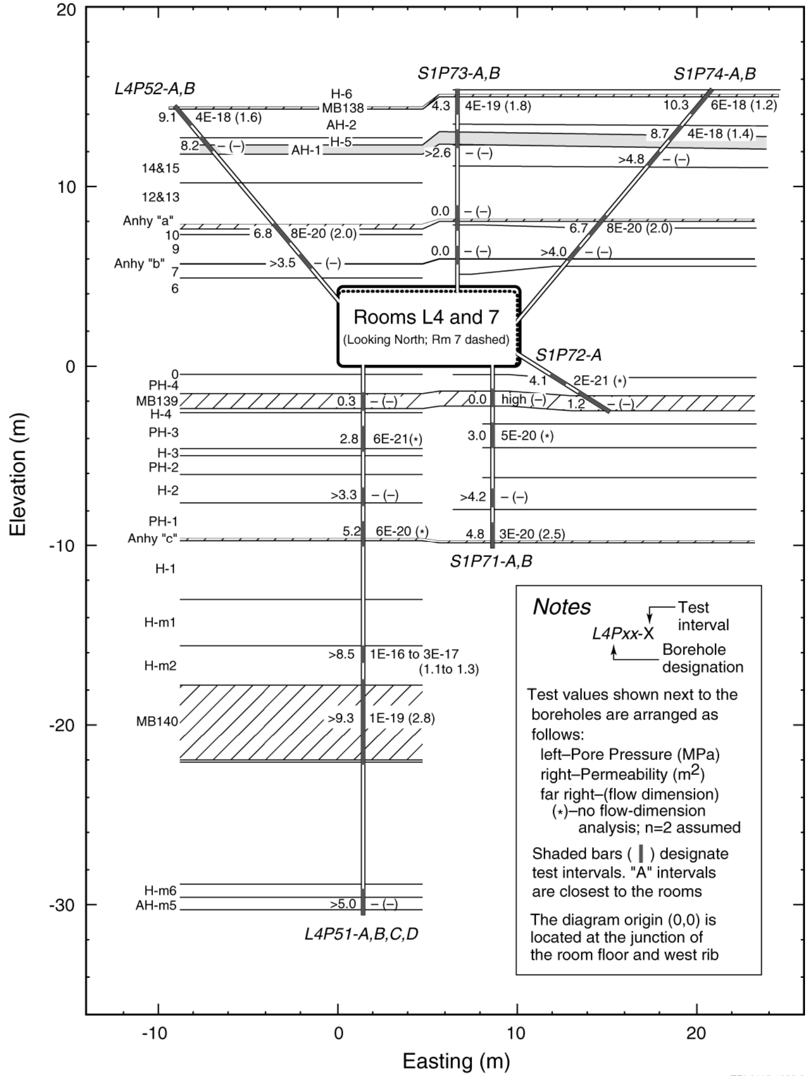
Rooms L4 and 7 Testing



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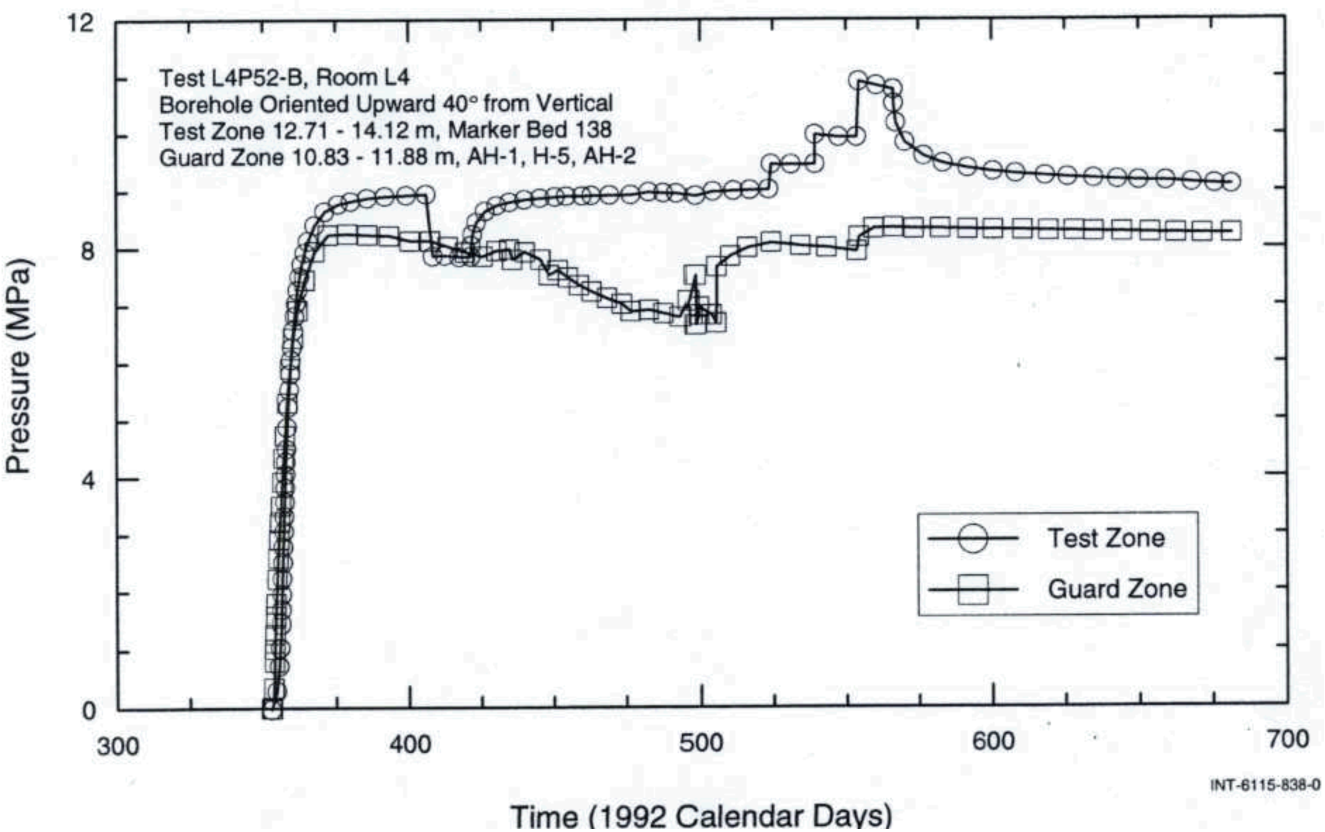
Testing for Pressure-Dependent Permeability



- Perform constant-pressure withdrawal test followed by constant-pressure injection tests at 3 successively higher pressures
- Test showed that permeability increased with test pressure

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Permeability Testing Results

- Anhydrite permeability outside the DRZ ranges from ~10^{-20} to 10^{-18} m^2
- The permeability of pure halite outside the DRZ is too small to measure (<10^{-22} m^2)
- Impure halite permeability is <10^{-20} m^2
- Testing at different pressures (L4P52-B) showed that permeability of anhydrite interbeds is pressure-dependent
- DRZ for permeability seems to be ~2.5 m thick in floor, more in roof
- Depressurization extends tens of meters from rooms

Room Q

- The Room Q experiment was designed to evaluate brine inflow to the repository and geomechanical effects on hydraulic properties
- Room Q was bored into an undisturbed area to the west of existing WIPP excavations
- Room Q is a 109-m-long cylindrical excavation, 2.9 m in diameter

Room Q Entryway

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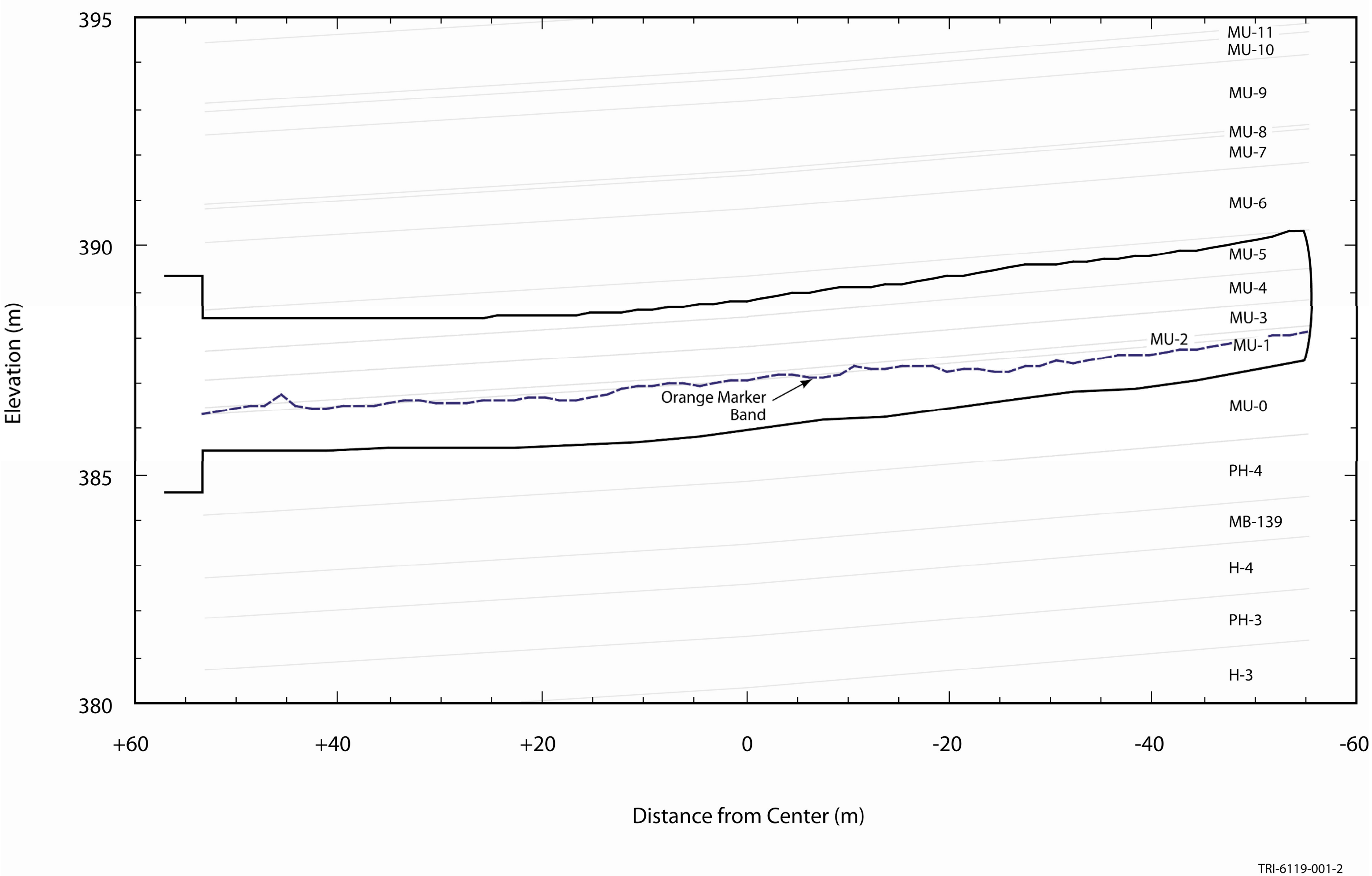
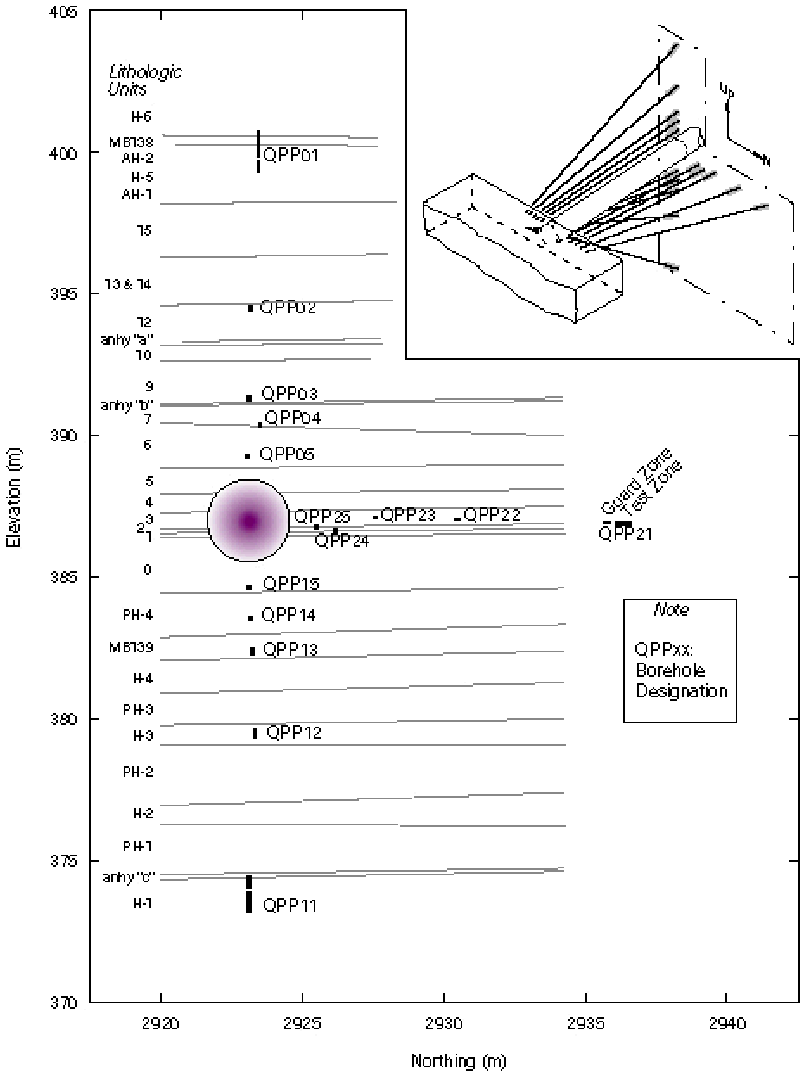
Room Q Cross Section



Monitoring Locations Around Room Q



- **Before excavating Room Q, 15 boreholes were drilled to terminate in a plane 22.9 m along the length of the room**
- **3 arrays of 5 boreholes terminated ~2.4, 3.3, 4.5, 7.6, and 13.6 m from the centerline of the room, vertically above and below and horizontally north of the room**
- **The ends of the boreholes were isolated with packers to allow pressure monitoring and hydraulic testing**

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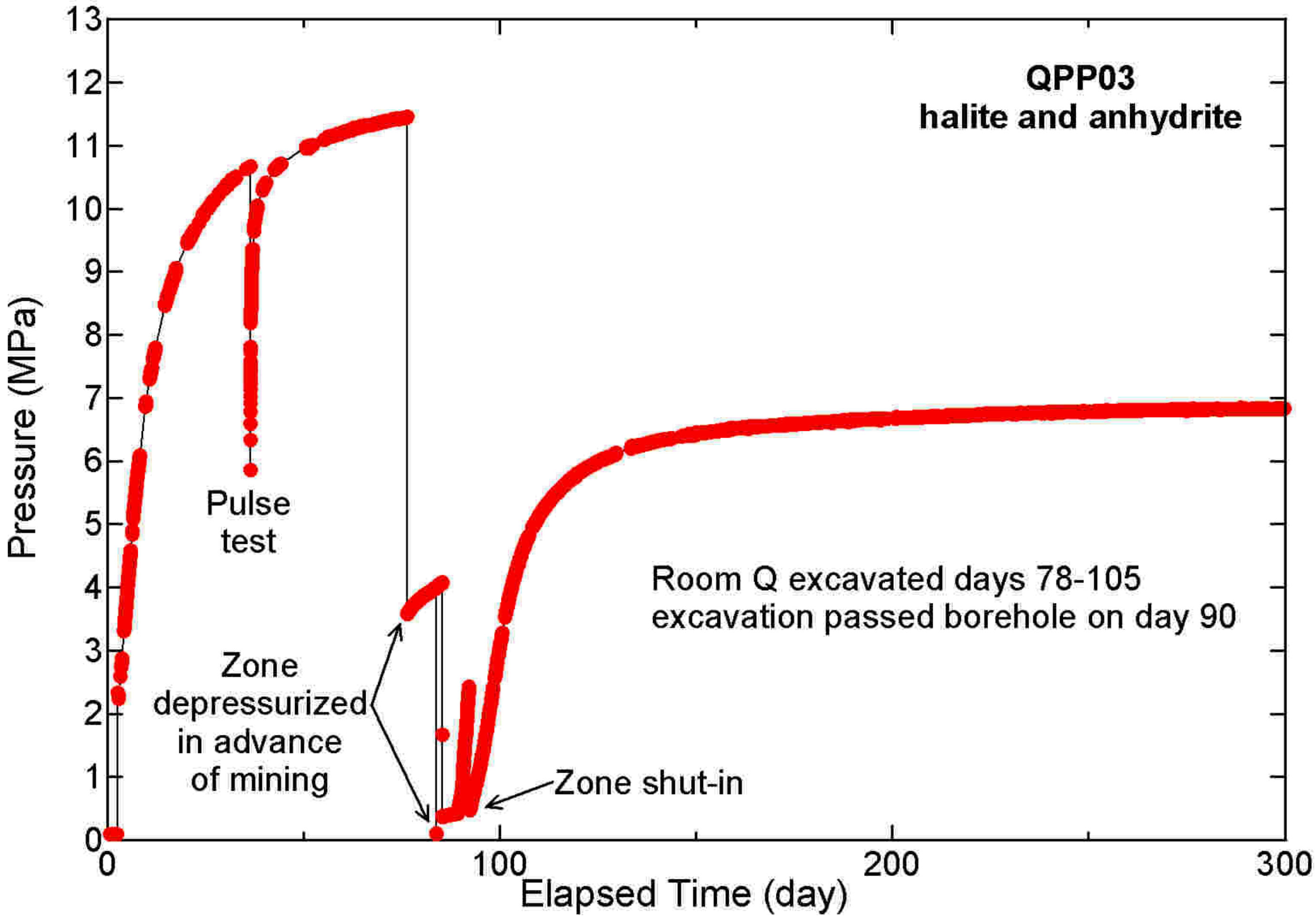
Response 4.4 m from Room Q



- **Permeability and pressure clear before mining**
- **Pressure reduced by mining**

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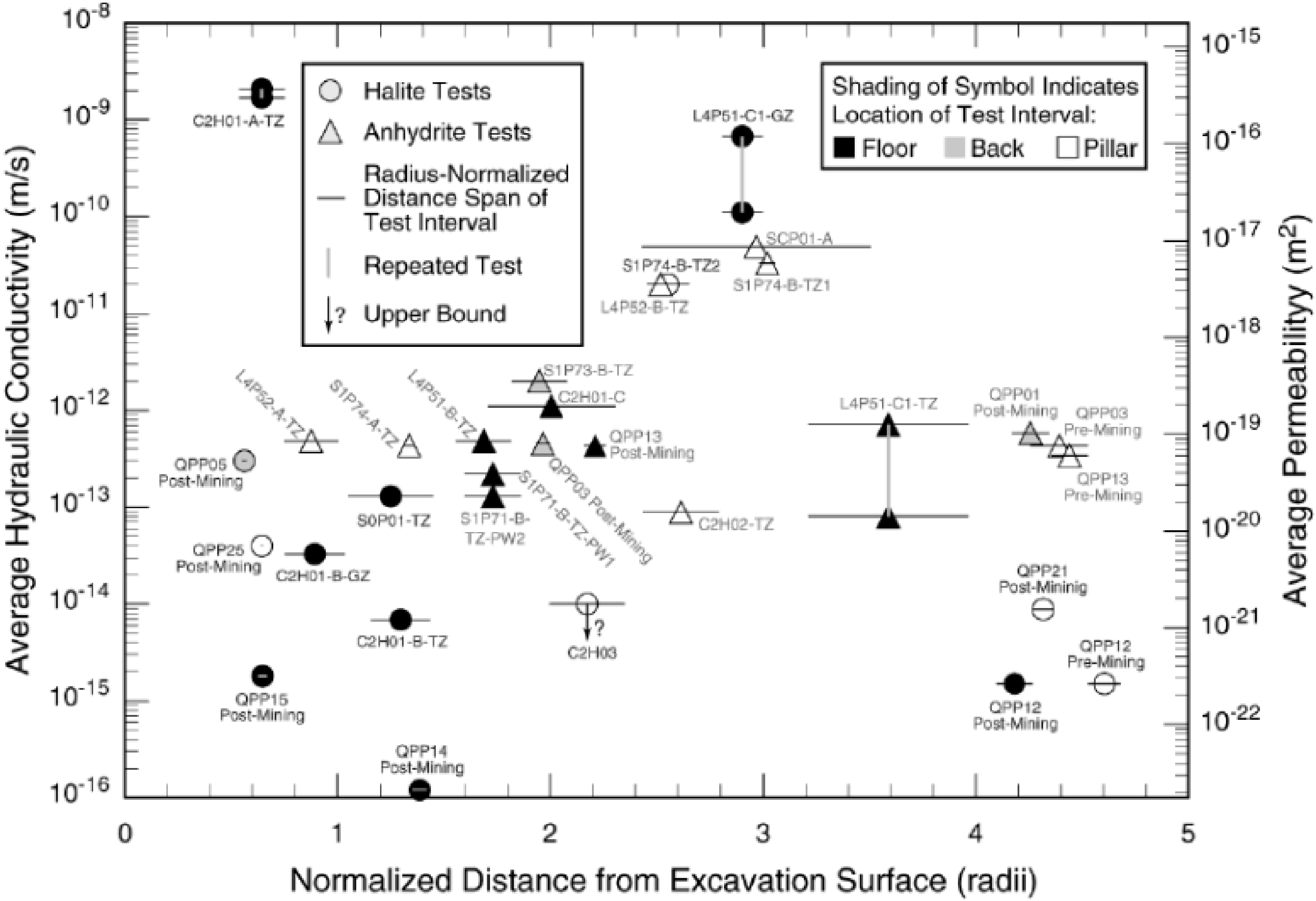
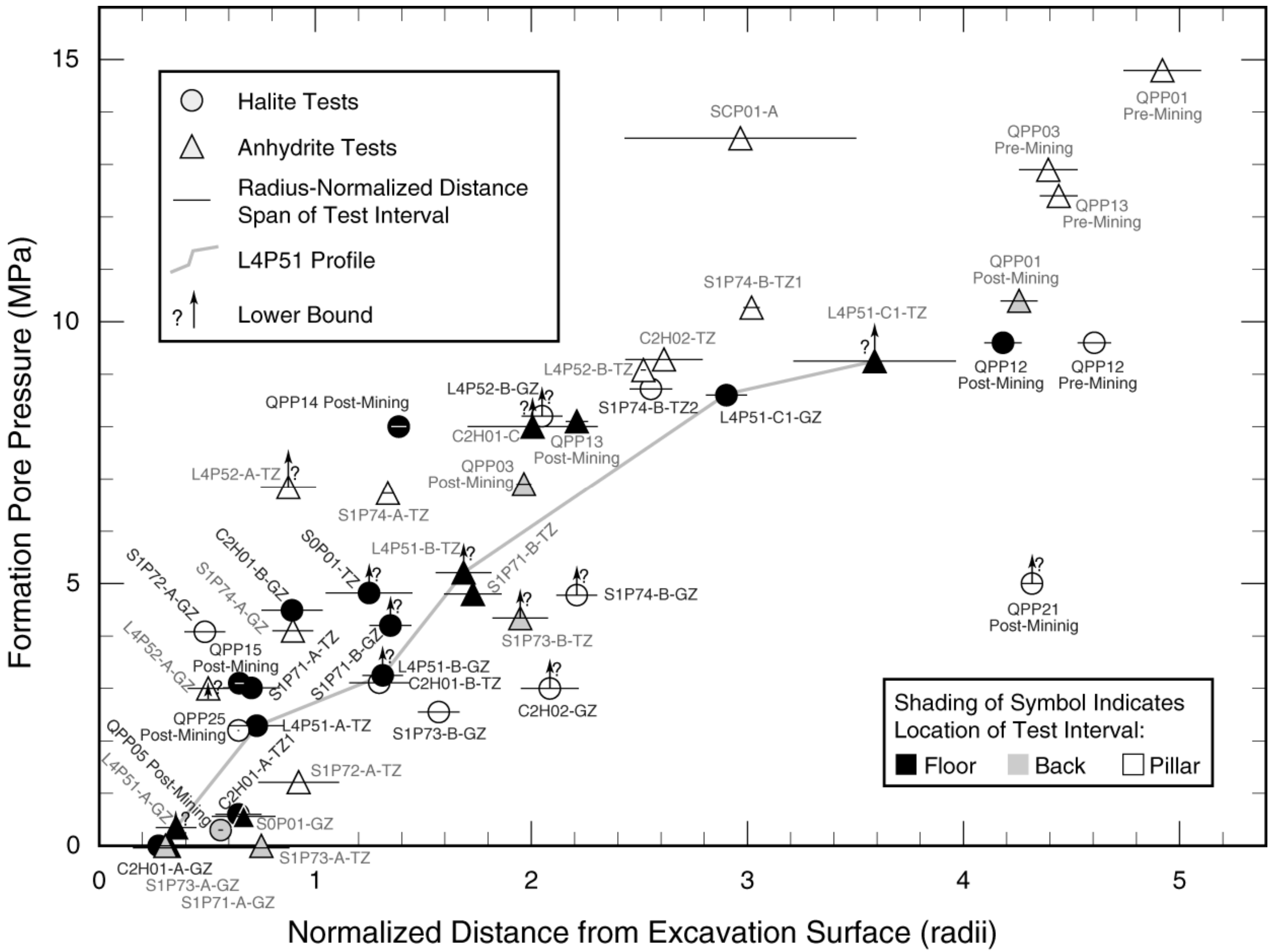
Summary of Room Q Observations

- After Room Q was finally sealed (>600 days after mining), inflow averaged ~200 mL/day
- No clear evidence of permeability or pore pressure in 6 of 12 halite intervals before mining of Room Q; all showed such evidence after mining
- Pore pressure reductions were observed in all boreholes except one
- Pore pressures were reduced by:
  - Stress relief
  - Flow to Room Q
- Pore connectivity (permeability) was increased in boreholes closest to Room Q

Salado Hydraulic Test Results--Permeability



Salado Hydraulic Test Results--Pressure



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DHLW Experiments

- 470 and 1500 W heaters were placed in 0.8-m-diameter vertical boreholes to simulate the heat generation from defense high level waste
- 4.3 kg of brine were collected in 441 days from the holes with 470 W heaters
- 36 to 38 kg of brine were collected in 600 days from the holes with 1500 W heaters
- Fluid inclusions migrated toward the boreholes

Coupled Permeability Tests and Hydraulic Fracturing

- Perform permeability tests before and after hydraulic fracturing of anhydrite interbeds
- Objectives
  - Determine pressure at which fracturing occurs, both when stress field is disturbed and undisturbed
  - Determine if pre-existing fractures open, or new fractures form
  - Determine if fractures stay confined to interbeds
  - Determine whether or not stress field is isotropic
  - Compare interbed permeabilities close (MB139) and far (MB140) from excavations
  - Determine how hydraulic fracturing affects permeability

Permeability and Hydraulic Fracturing Results

- MB139 fractured at a pressure of ~19 MPa and MB140 fractured at a pressure of ~22 MPa—both were affected by the nearby excavations
- Once initiated, fracture propagation pressures were only 12-13 MPa
- Pre- and post-fracturing permeability tests showed:
  - Flow was not radial because of asymmetric stress field below Room C1
  - Permeability and flow dimension increased as a result of fracturing, and were more pressure-dependent than before

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Gas Threshold Pressure

- Gas threshold pressure is the pressure at which gas first enters a brine-saturated medium. It corresponds to the point on a capillary pressure curve at full wetting-phase saturation.
- Gas threshold pressure is the only two-phase property that can be measured in the field
- Literature data show a correlation between permeability and gas threshold pressure
- Based on this correlation and the observed permeability range of WIPP anhydrite interbeds, gas threshold pressures could be as high as 7 MPa. This raised the possibility that hydraulic fracturing might occur before gas could enter the interbeds.

Gas Threshold Pressure Testing

- Start with a brine-saturated system at equilibrium
- Exchange gas for brine, maintaining pressure
- Allow pressure to stabilize
- Inject gas at a constant mass rate
- Threshold pressure is reached when the pressure buildup deviates from the wellbore-storage line, indicating movement into the formation
- The test can also be repeated at a different injection rate to improve resolution of the threshold pressure estimate

Conclusions from Gas Threshold Pressure Testing

- Threshold pressure of MB139 is less than 1 MPa
- Gas will be able to enter anhydrite interbeds at pressures well below the hydraulic fracturing pressure

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Summary of Salado Hydrology Investigations

- Anhydrite beds are fractured and have more permeability than other Salado lithologies
- Argillaceous halite may have some permeability where undisturbed by excavation effects
- Pure halite appears to have no permeability except within the DRZ
- Pore pressures are approximately lithostatic where undisturbed by excavations
- Brine inflow to a closed, unheated repository will be minor
- More brine inflow would occur to a repository with heat-generating waste

Summary of Salado Hydrology Investigations (2)

- Hydraulic fracturing increases anhydrite permeability and makes it more pressure-dependent
- Gas threshold pressure of anhydrite interbeds is below the fracturing pressure
- Gas generated within the repository will be able to dissipate through anhydrite interbeds without fracturing the rock
- Differences in brine chemistry in nearby boreholes show that Salado brine is not mobile—radionuclides will not be transported away from the repository

Remaining Questions/Issues

- Factors affecting brine flow to heat sources are incompletely understood
- How can we characterize the undisturbed saturation state in anhydrite interbeds?
  - Fully brine saturated?
  - Partially gas saturated?
- How can we characterize the saturation state in the DRZ/EDZ?
- How do we quantify the relationship between repository pressure and fracture dilation and permeability?
- How do we understand/predict gas/brine transport through fractured anhydrite?
- *In situ* measurement of gas threshold pressure needs refinement