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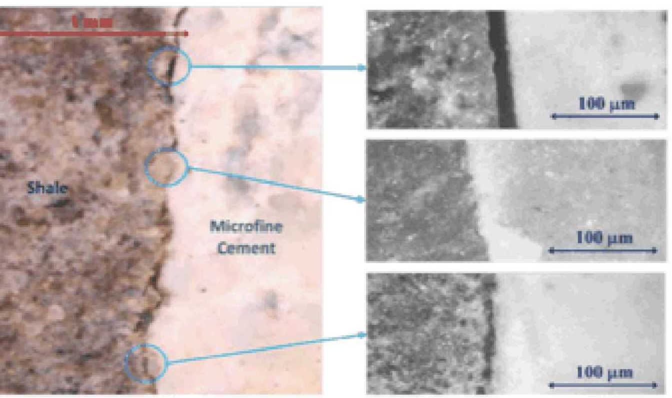

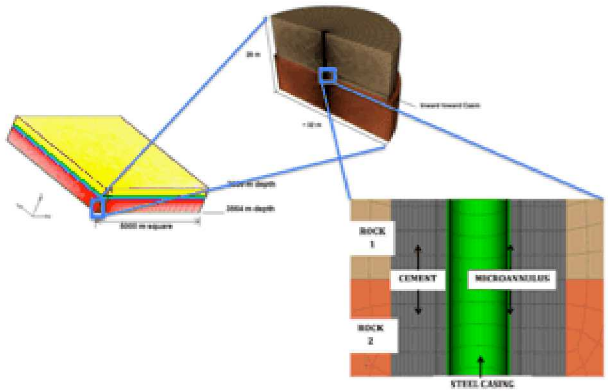

Design and Testing of Subsurface Seals

Ed Matteo

Sandia National Laboratories

June 28, 2019

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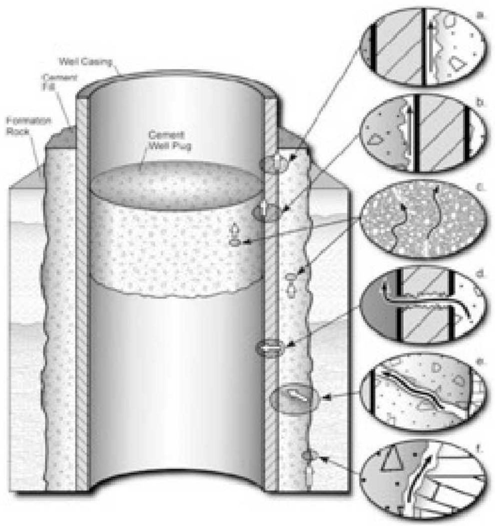
- Kris Kuhlman, Clay Payne (SNL - WIPP Brine Availability Test in Salt (BATS) Team)

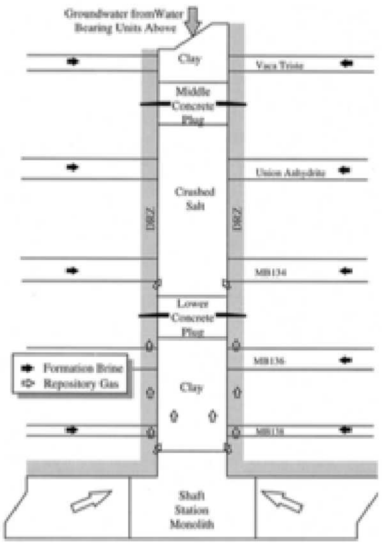
Overview

- Intro and Background
  - What are the major engineering challenges associated with nuclear waste disposal?
  - Types of Seals – materials and functions
- Case Studies
  - Nuclear Waste Disposal
    - Background on waste inventory, disposal concepts, etc.
    - Seal design evolution at WIPP
  - Wellbore Integrity during Geologic Storage of CO_2
    - Seal repair development and performance
    - Microannulus evolution and permeability
    - Geomechanical modelling to predict *in situ* stress and strain
- Conclusions, ongoing, and future work

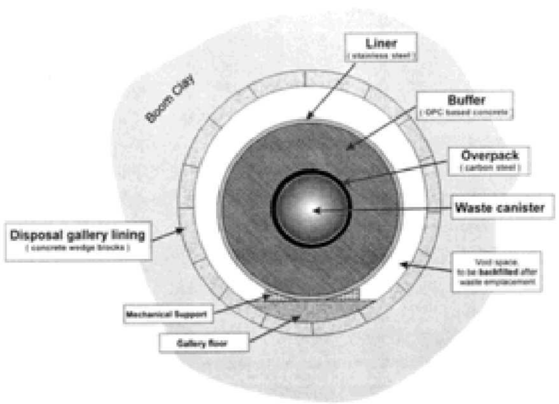
Seals are guardians of conduits that pass through stratigraphy – without seals there is potential for direct communication between subsurface, hydrogeologic units, and the surface



Wellbore Seals



Shaft and Drift Seals



Engineered Barrier System Components

Seals are typically composed of:

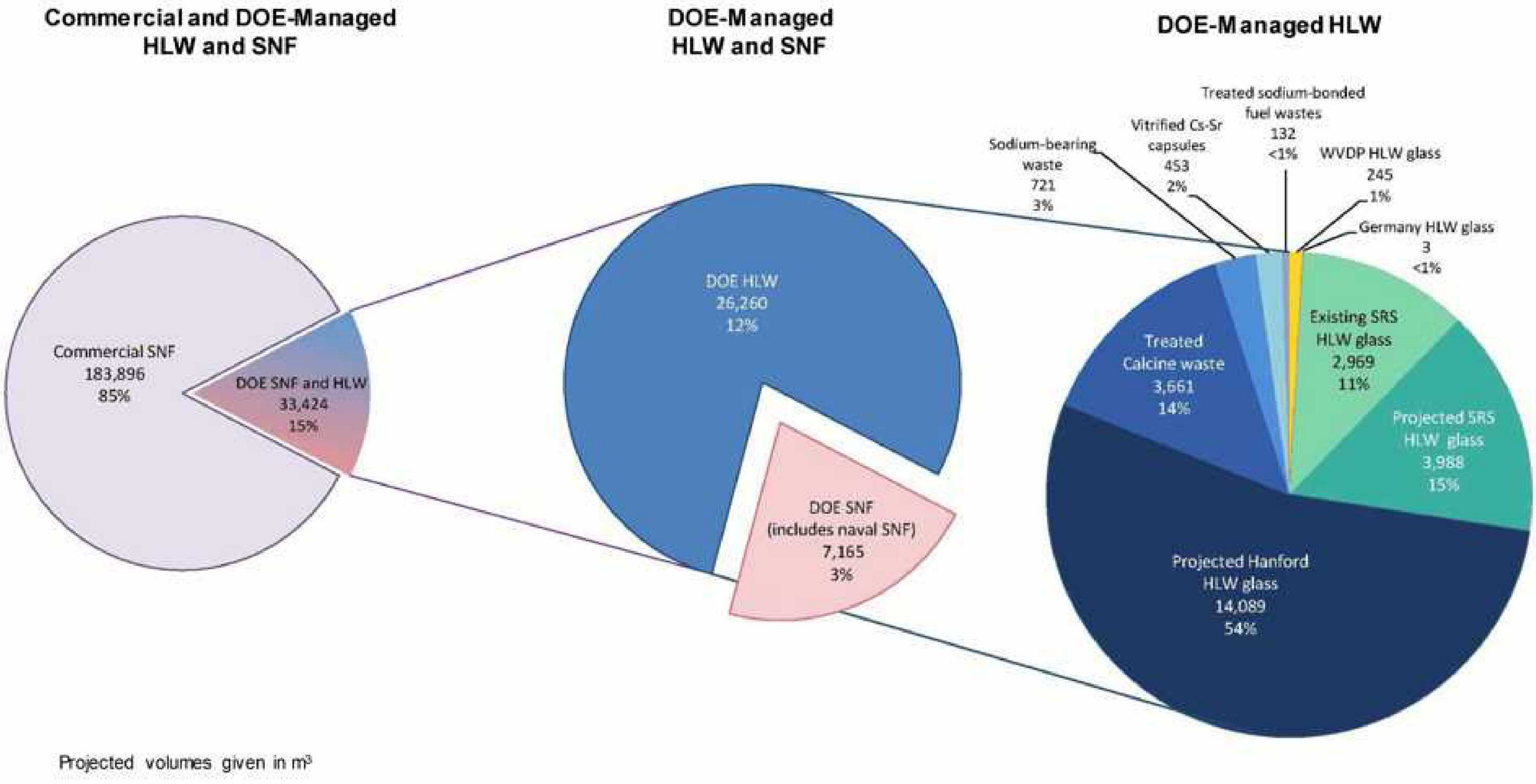
- Cementitious materials (cement, concrete, shotcrete)
  - Class G or Class H wellbore cement
  - Low pH Portland cement (pozzolans to achieve pore sol'n $pH < 12$)
- Bentonite
  - primarily smectite
  - Swells when wetted
  - Cation getter
- Backfill
  - Compatible with and/or composed of host rock, as well as hydrogeologic units along the stratigraphy of a shaft seal
- Other getters
  - Anionic getters, zeolites

Case Study #1 – Shaft and Drift Seal Designs for Disposal of Nuclear Waste

Nuclear Waste Background

- Broadly speaking, there are two “types” of waste:
  - Spent Nuclear Fuel (SNF) – Fuel rods from the reactor
    - Commercial SNF – CSNF compromises >95% (by mass) of SNF waste
    - Defense SNF – DSNF
  - High Level Waste (HLW) – products from processing materials associated with US Defense-related activities
    - Vitrified Glass
- Typically, waste is classified according to the activity from which it was produced:
  - Commercial (CSNF)
  - Defense (HLW and DSNF)

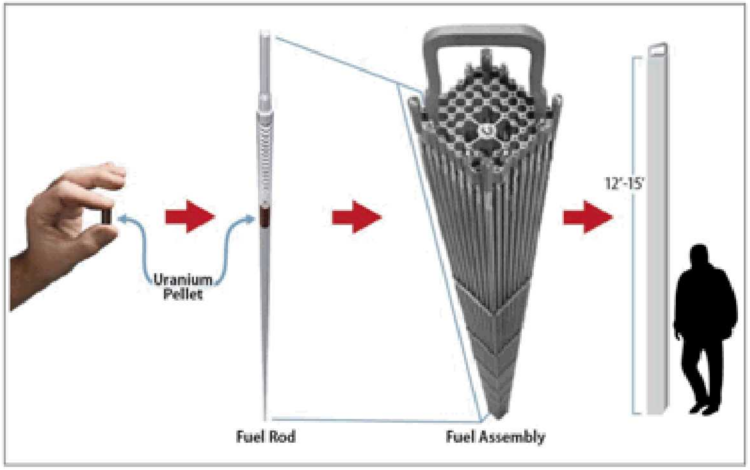
Radioactive Waste Volumes



HLW = High-Level Waste
SNF = Spent Nuclear Fuel

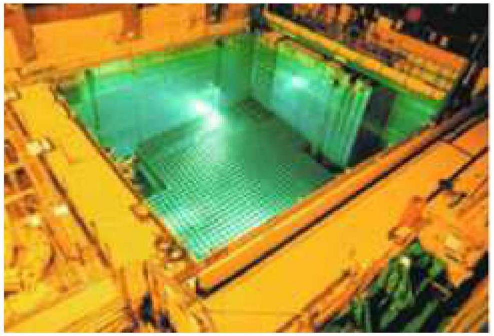
What is Spent Fuel?

- Wet vs. dry storage
  - ~75% in wet storage
  - Post-Fukushima, the rate of transfer from wet to dry storage has increased



From Werner 2012

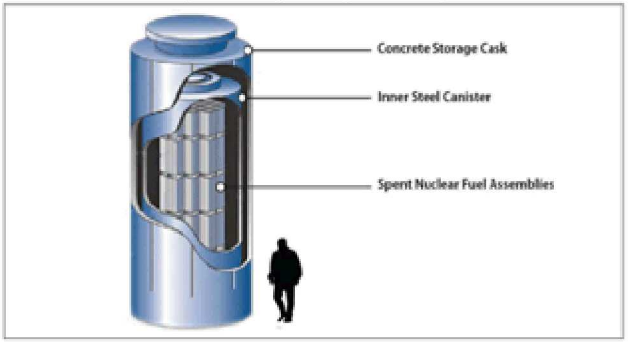
Pool Storage



from nrc.gov

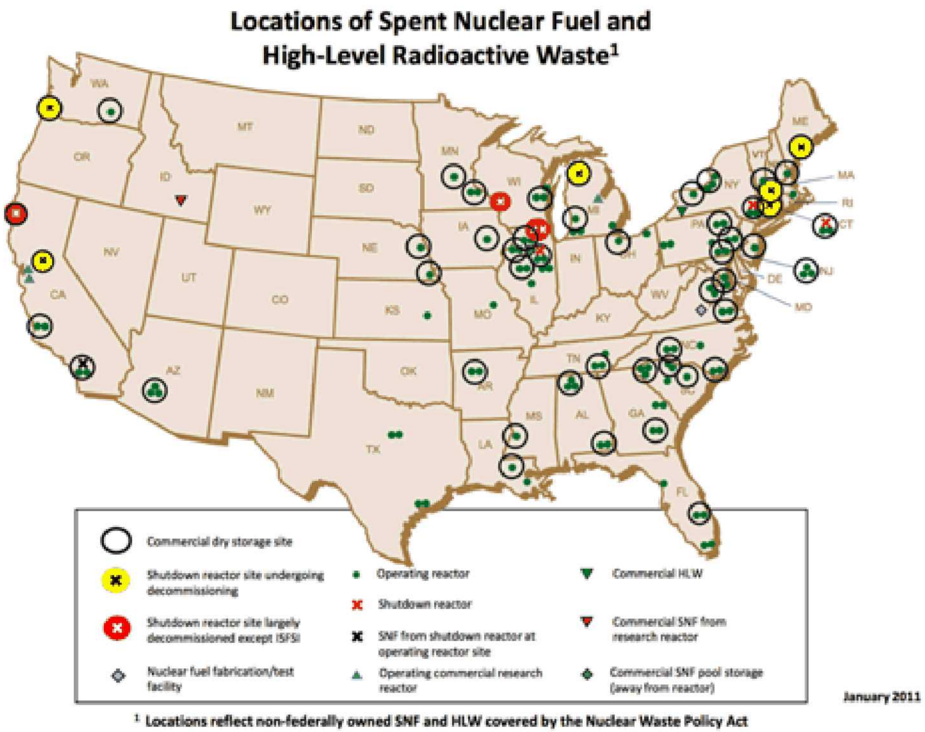
Dry Storage

from connyankee.com

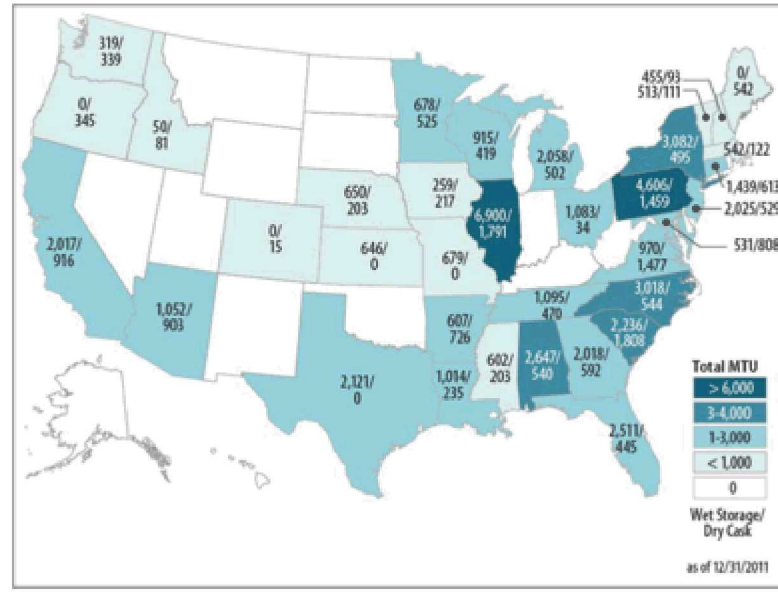


From Werner 2012

Where is Spent Fuel located?



From energy.gov



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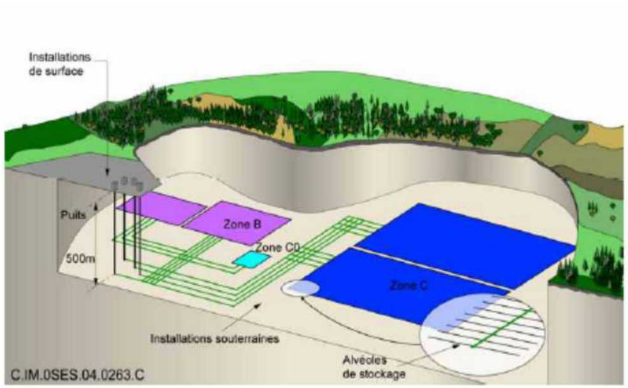
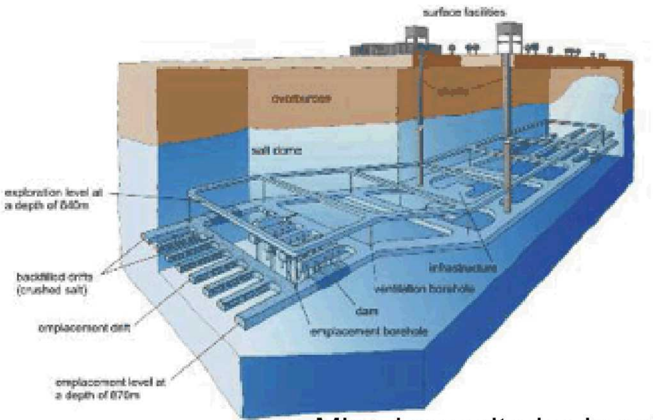
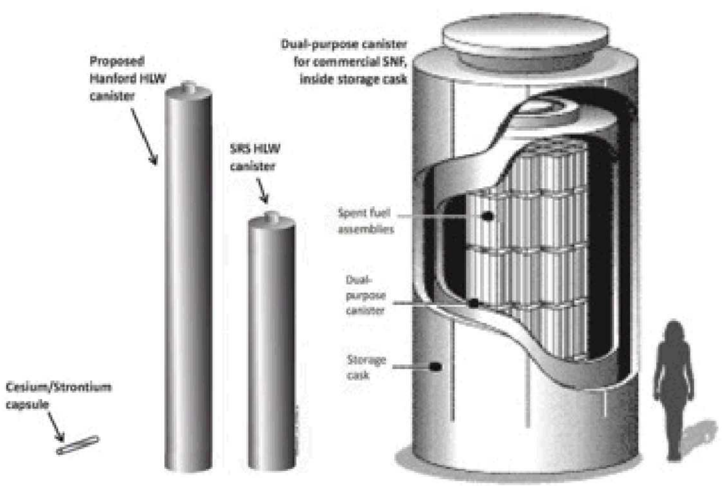
Disposal Concepts

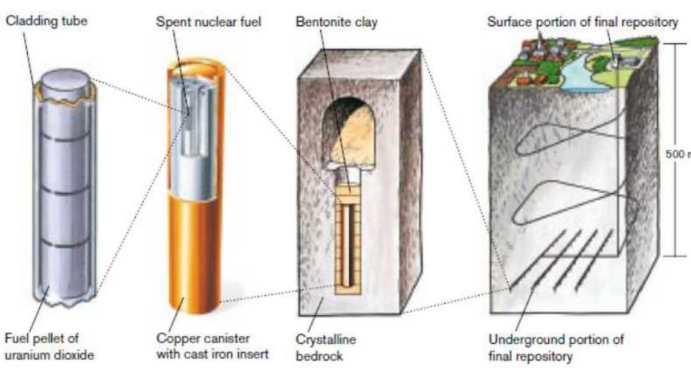


Mined repositories in clay/shale (ANDRA 2005)



Mined repositories in salt (BMWi 2008)

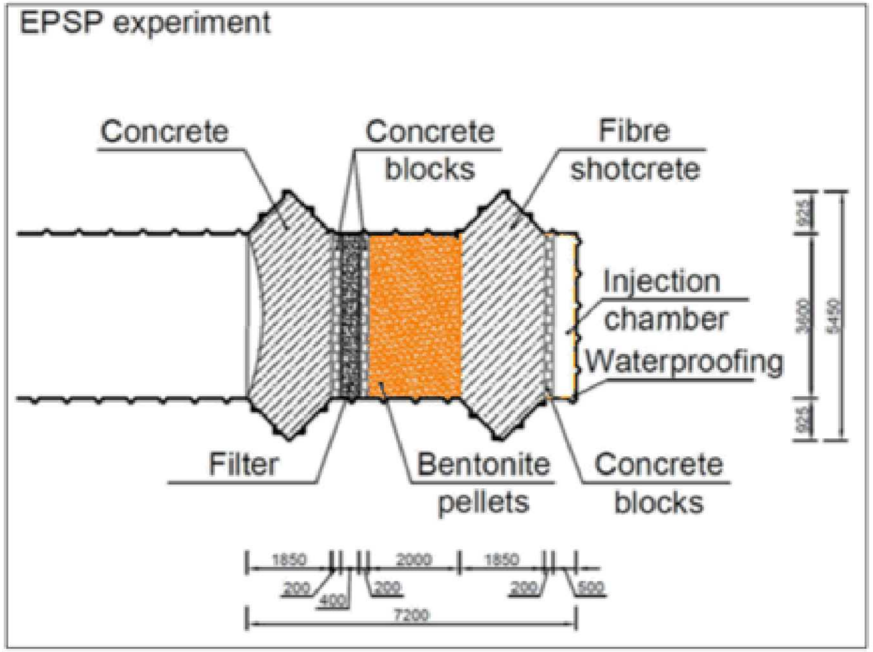




Mined repositories in crystalline rock (SKB 2011)

Seal functions and challenges the repository environment

- The seal blocks potential preferential flow pathways, created by excavation of tunnels, shafts , and drifts
- Needs account for the excavation damage zone (EDZ), e.g. design will have break-outs to seal pathways in the EDZ
- Achieve both short-term an long-term isolation needs
  - Cement
    - Short term hydraulic barrier, easy to emplace, setting shrinkage
  - Clay long-term stability, sorption, swelling



From J. Hansen et al. 2016
From DOPAS 2016

Challenges to Seal Durability/Integrity

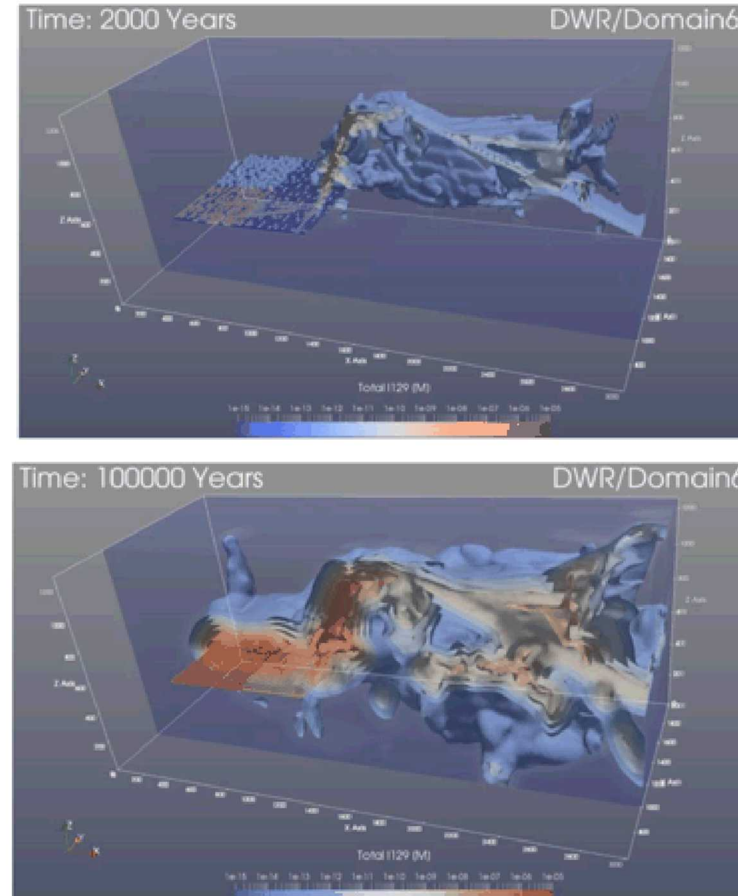
- Thermal
  - Spent fuel generates A LOT of heat (~ kW)
- Chemical durability
  - Complex near field chemical environment (connate brine, evolving geochemical milieu, long timescales, subsurface heterogeneity)
  - Waste form degradation, waste package corrosion, complex chemistry/geochemistry
- Mechanical durability
  - Convergence of excavations
  - Weight of waste packages
  - Discontinuous mechanical processes, e.g., roof-fall
- And, oh yeah, the above can lead to … Coupled processes!!!
  - Introduces a considerable amount of uncertainty

Performance Assessment (PA Models)

- **Performance Assessment (PA) Modeling**
  - Use standard reference:
    - geology
    - Repository design
  - Assess long-term post-closure safety
  - Thermal-hydrological-chemical processes simulated via PFLOTRAN

PFLOTRAN

I-129 concentrations

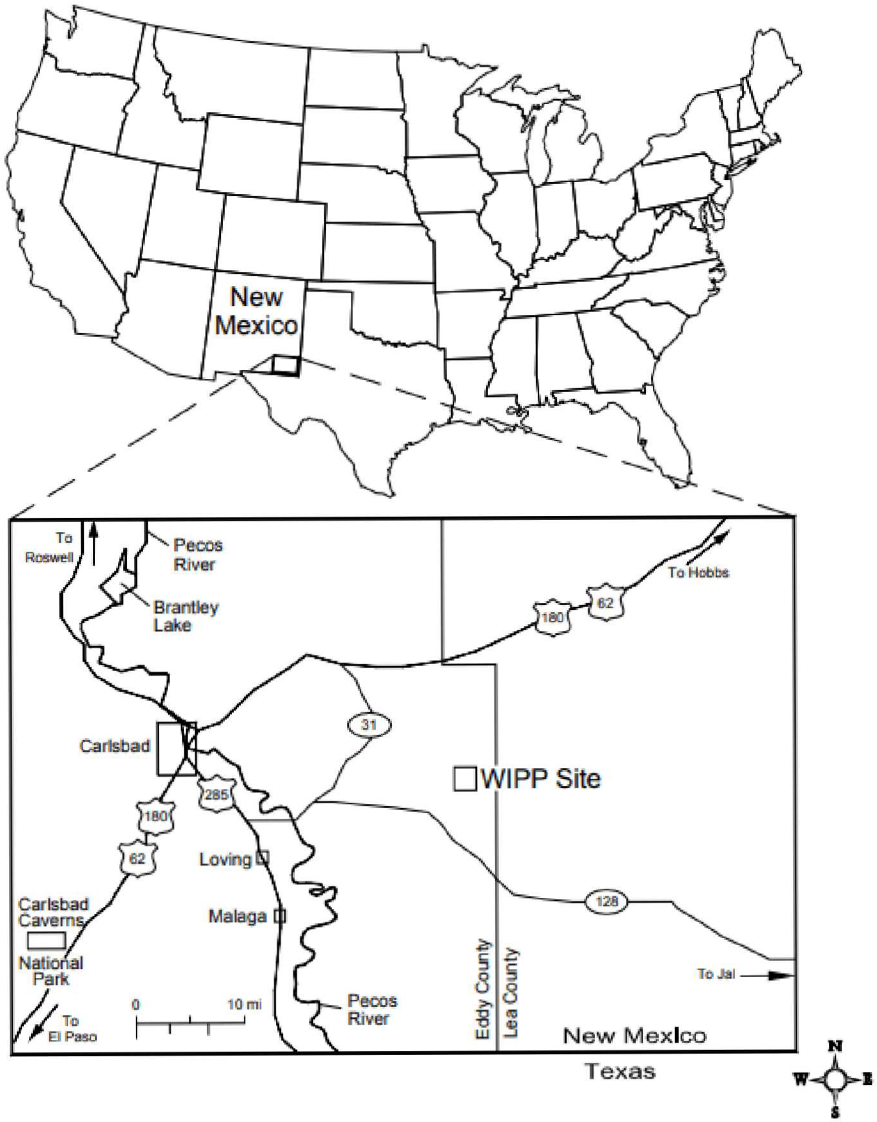


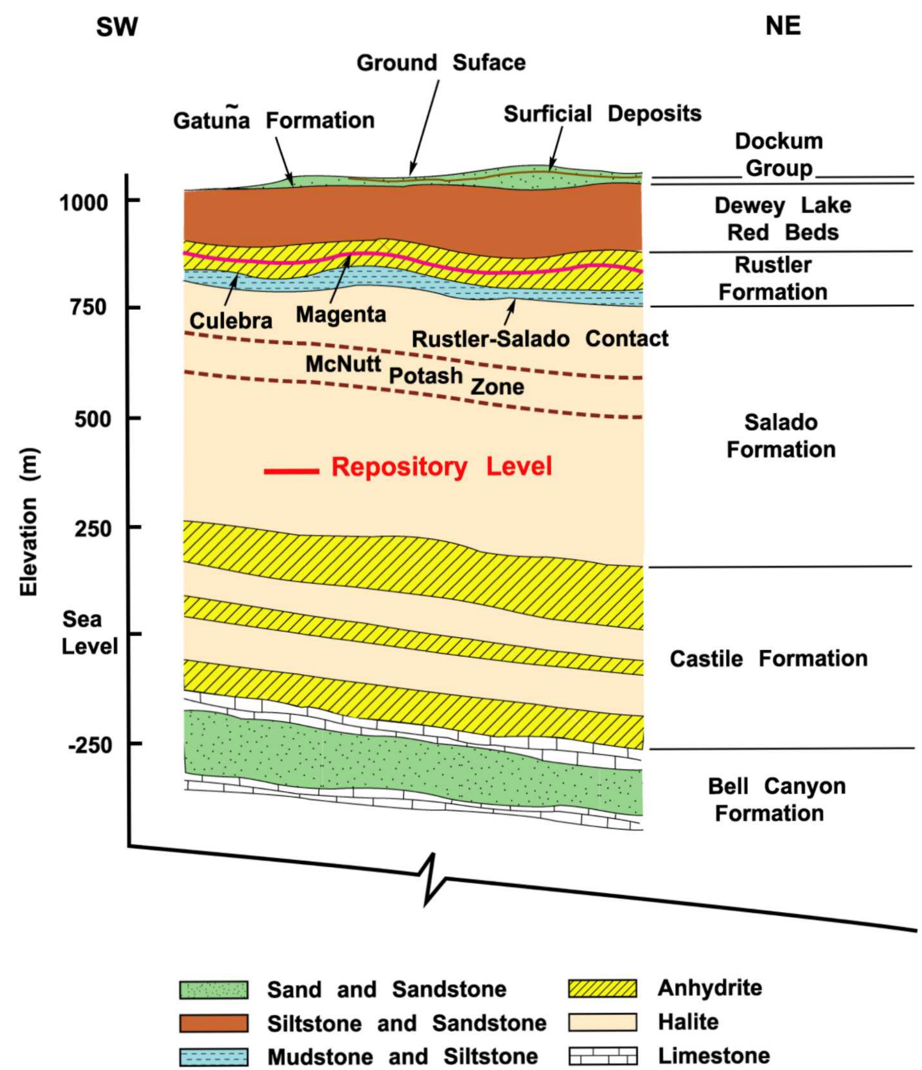
Sevougian et al. 2016

Case Study #1 - Outline

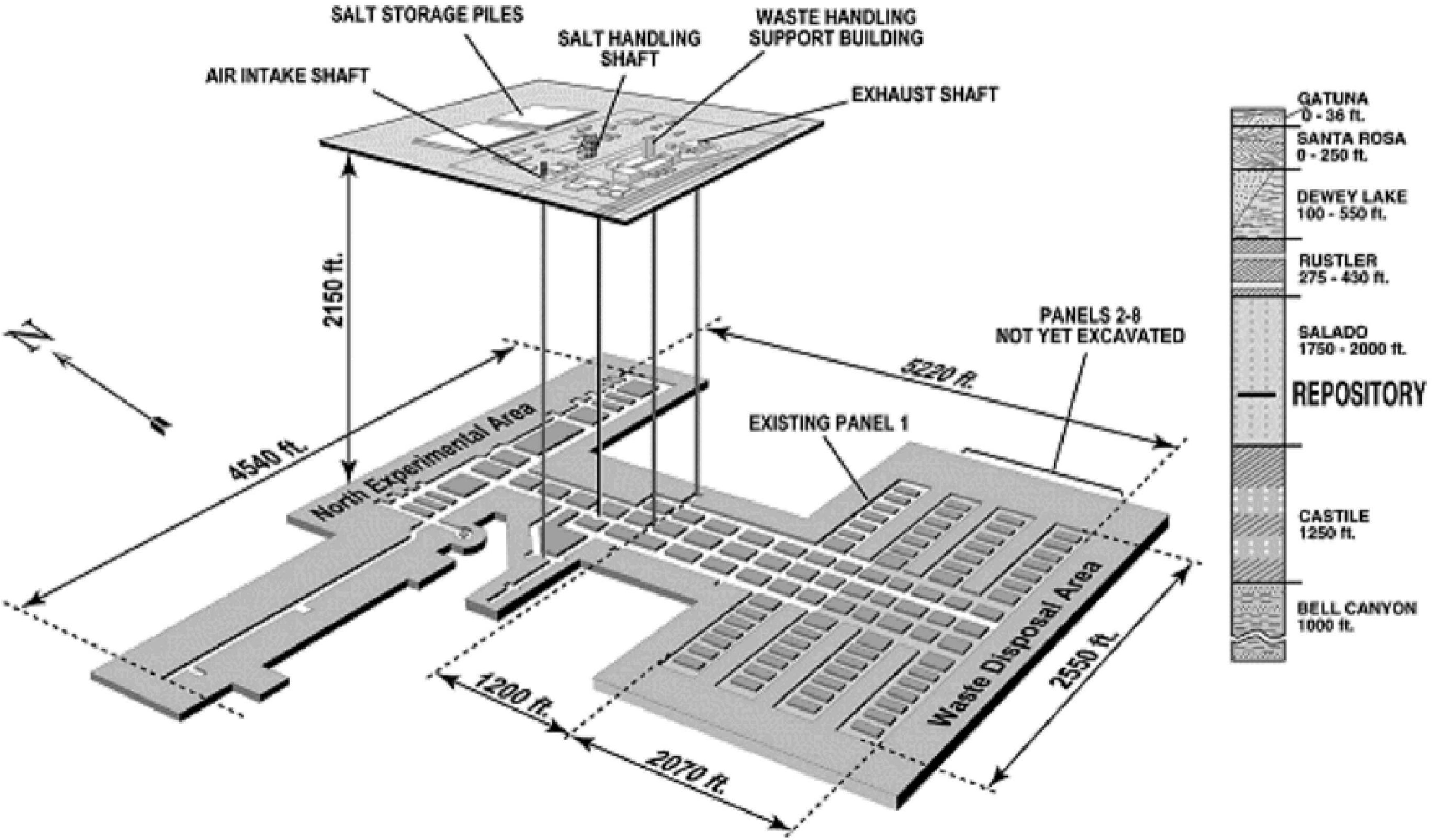
- Seals for a Salt Repository
    - Salt backfill
    - Compacted salt, Clay, Asphalt
    - Salt concrete, Ultrafine grout
- History of Seal Tests in the US
  - WIPP Borehole Plugging Program
    - Predecessor - Salt Vault Program (early 1970's)
    - ERDA No. 10 (1977)
    - Bell Canyon Test (1979)
    - Waterways Experiment Station (WES) Grout Studies (70's and 80's)
  - Small-Scale Seal Performance Tests (at WIPP)
- WIPP Seal Design vs. Salt HLW Repository

Waste Isolation Pilot Plant (WIPP) Background



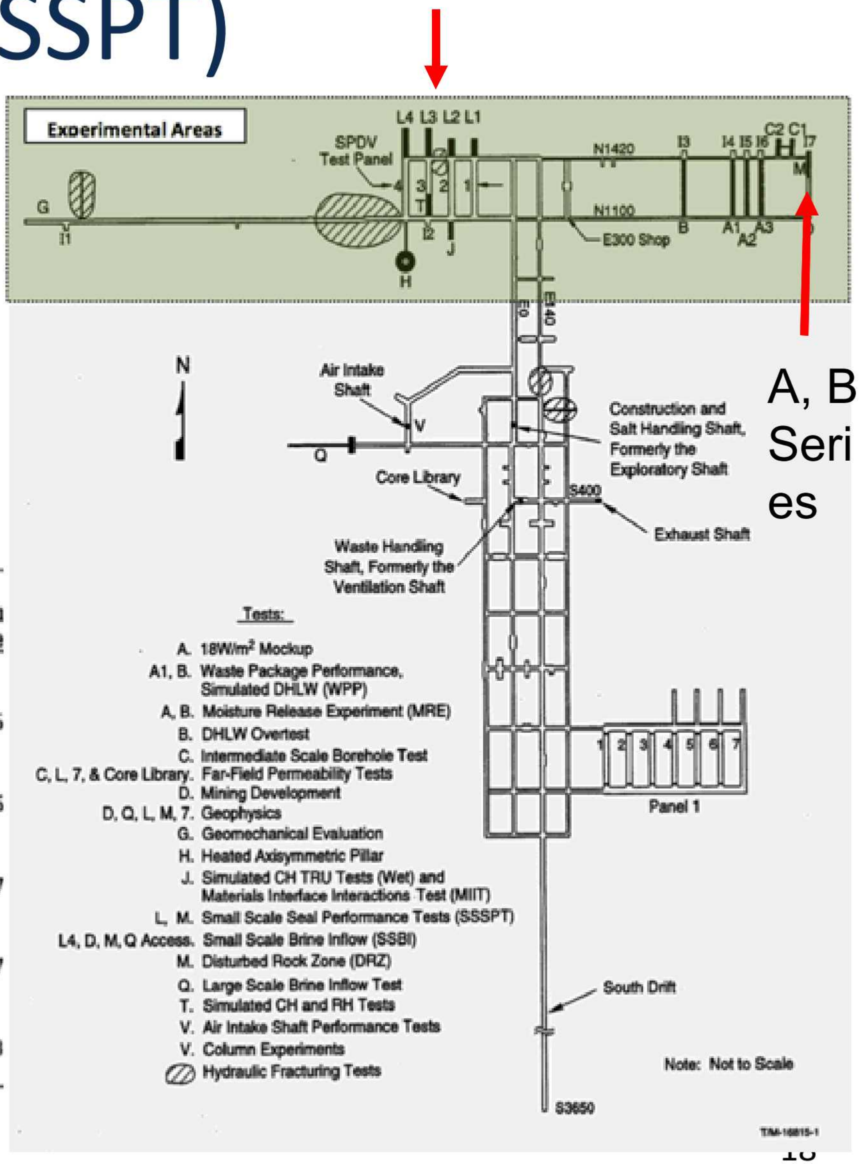


WIPP Facility and Stratigraphic Sequence



Small-Scale Seal Performance Tests (SSSPT)

- WIPP Experimental Area - Rooms L, M
- Vertical and horizontal boreholes
- Expansive Salt Concrete (ESC), Salt blocks, salt/bentonite blocks and backfill, ultrafine grout (F series)



Test Series Schedule

Test Series	Seal Material	Direction	Schedu Emplace
A	Salt-based concrete	Vertical	7/85
B	Salt-based concrete	Horizontal	2/86
C	Salt and bentonite block and mortar	Horizontal	3/87
D	Salt and bentonite backfill	Vertical	9/87
E	Salt-based concrete	Vertical (thru Marker Bed 139)	3/88

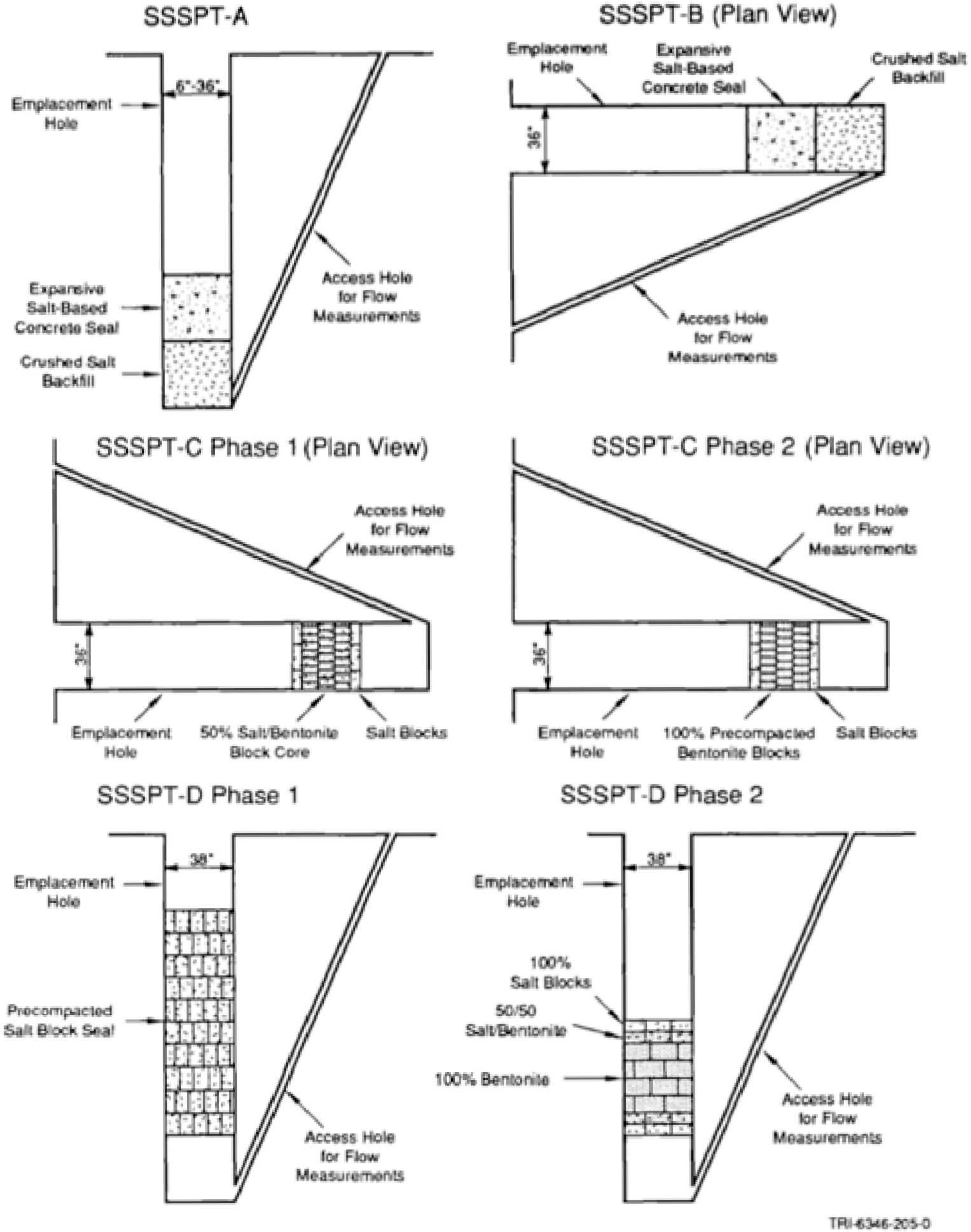
From Stormont 1987

SSSPT Configurations

Test Series	Seal Material	Seal Emplacement Orientation	Emplacement Date	Measurements*
A	Salt-Based Concrete	Vertical	7/85	Seal Pressure; Displacement and Temperature; Gas and Brine Flow
B	Salt-Based Concrete	Horizontal	2/86	Seal Pressure; Gas and Brine Flow
C Phase 1	Salt and 50/50% Salt/Bentonite Block	Horizontal	9/86	Seal Pressure; Brine Flow
C Phase 2	Bentonite Block	Horizontal	12/90	Seal Pressure; Brine flow
D Phase 1	Salt Block	Vertical	1/88	Seal Pressure; Hole Closure; Floor Heave; Gas Flow
D Phase 2	Bentonite Block (short-term)	Vertical	9/89	Seal Pressure; Brine Flow

TABLE 1. TEST SERIES CURRENTLY PLANNED FOR SSSPT

* Note: Instruments include strain gages, stress meters, thermocouples, pressure cells, borehole displacement gages, Multiple Point Borehole Extensometers (MPBX), and the Four Packer Fracture Flow Tool (FPFFT) for fluid flow measurements.



From Finley et al. 1992

SSSPT Highlights, 1/2

- SSSPT Tests provide confidence to Performance Asessment in the form of *in situ* data on permeability and mechanical performance

Table III. Summary of SSSPT Seal System Permeabilities

Test Fluid	Concrete Permeability (m^2)	Concrete Permeability (m^2)	50%/50% Salt/bentonite Permeability (m^2)	100% Bentonite Permeability (m^2)
Test Period	(1985-1987)	(1993-1995)	(1986-1990)	(1988-1995)
Gas	$10^{-17} - 10^{-20}$	$10^{-19} - 10^{-23}$	–	see Figure 3
Brine	$\sim 10^{-19}$	$10^{-19} - 10^{-22}$	$\sim 10^{-16}$	$\sim 10^{-19}$

From Knowles and Howard 1995

SSSPT Highlights, 2/2

- Expansive Salt Concrete Seals
  - Exhibited sub-microdarcy permeability for both gas and brine (9 seals tested)
  - Flow path decreased within a year of emplacement (tracer test)
  - Emplaced using commercial equipment
  - AND optimized for key operational attributes including:
    - slump, limited bleed, segregation, limited air entrainment, self-leveling behavior, and workability
  - BUT…, in the late 80's the expansive agent became commercially unavailable (enter Salado Mass Concrete)
- Lessons learned with respect to cement formulations (from Wakeley 1987)
  - Simpler is better … for prediction, batching, sourcing, etc.
  - Working time is a critical property
  - By the late 80's, it became evident that **concrete** (not grout) would play a central role at WIPP as components in the sealing system for bulkheads and drift, panel, and shaft seals - as opposed to the primary seal
    - Lifetime requirements on the order of 100 years instead of 10,000 years

Cementitious Seals Test 1/2

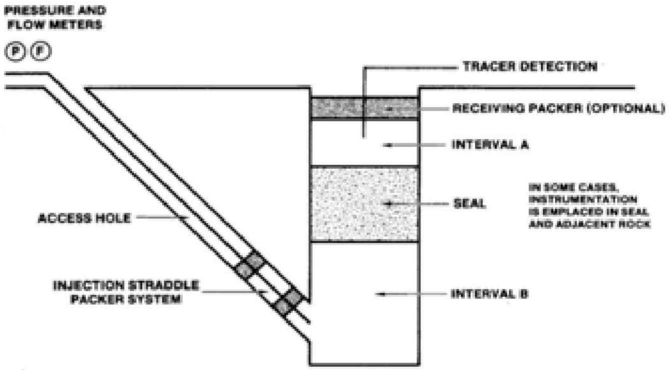
- Key issues for Cementitious Seal Performance Evaluation
  - Autogenous shrinkage of seal (during setting)
    - Gap formation at cement/salt interface
    - Crack formation in cement plug
  - Heat output of mass concretes
    - Crack formation in cement plug
  - Material selection (i.e., Sorel cement, salt concrete, low pH?)
  - Effects of salt host closure on the seal
- Why do a field-scale test of seals in bedded salt
  - Most recent field tests have been in domal salt (saltcrete, Sorel)
  - Bedded salt tests at WIPP - Small Scale Seal Performance Tests Series A, B, C
    - Used a very specific formulation of "Expansive Salt Concrete"
    - Key ingredients are unavailable and potential difficult to reproduce

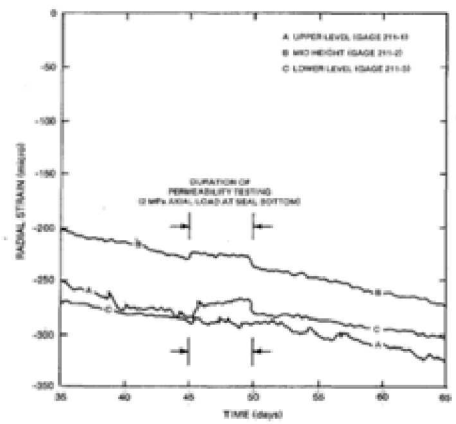
Cementitious Seals Test 2/2

- Relevant Tests in Domal Salt
  - Lab-scale Tests for DOPAS (Czaikowski et al. 2016)
  - ERAM Test Seal - salt concrete
  - Asse tests - Sorel cement and salt concrete

From Czaikowski et al. 2016

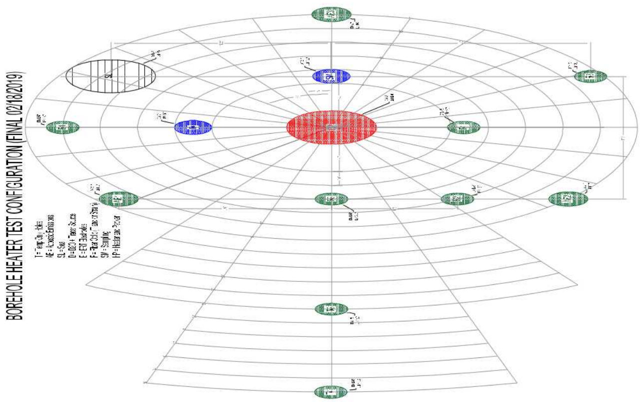
- Create a seal test at WIPP with the concept of a potential HLW Salt Repository in mind (with relevance to some generic, bedded salt site)
  - Measure borehole closure and permeability of the seal

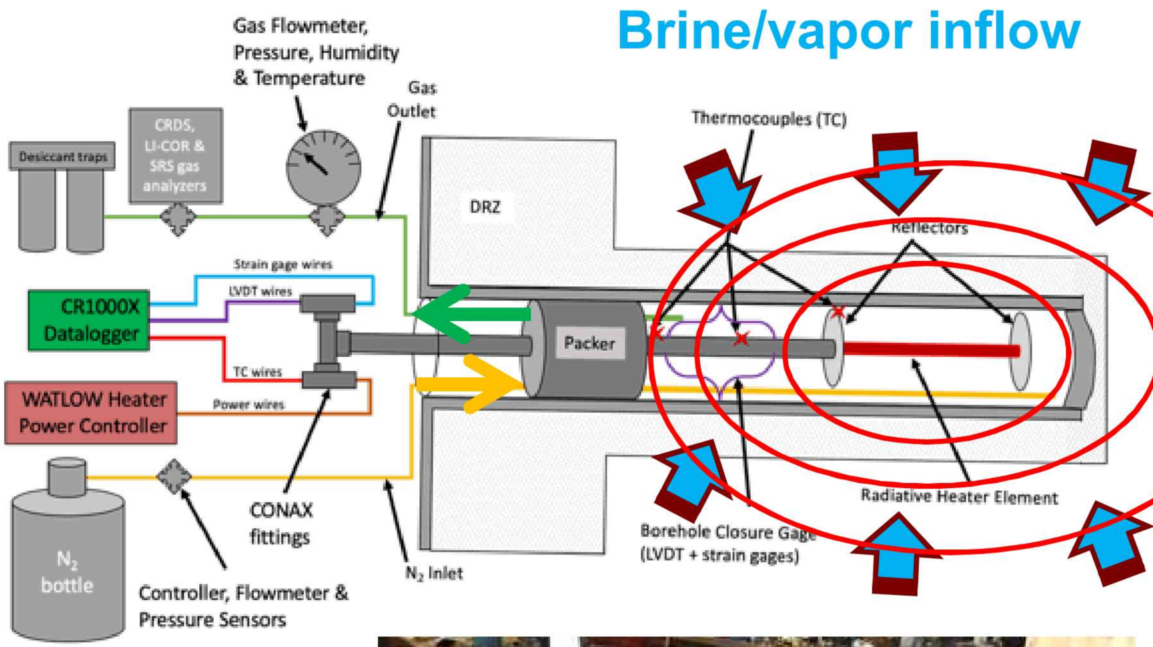




From Stormont 1987

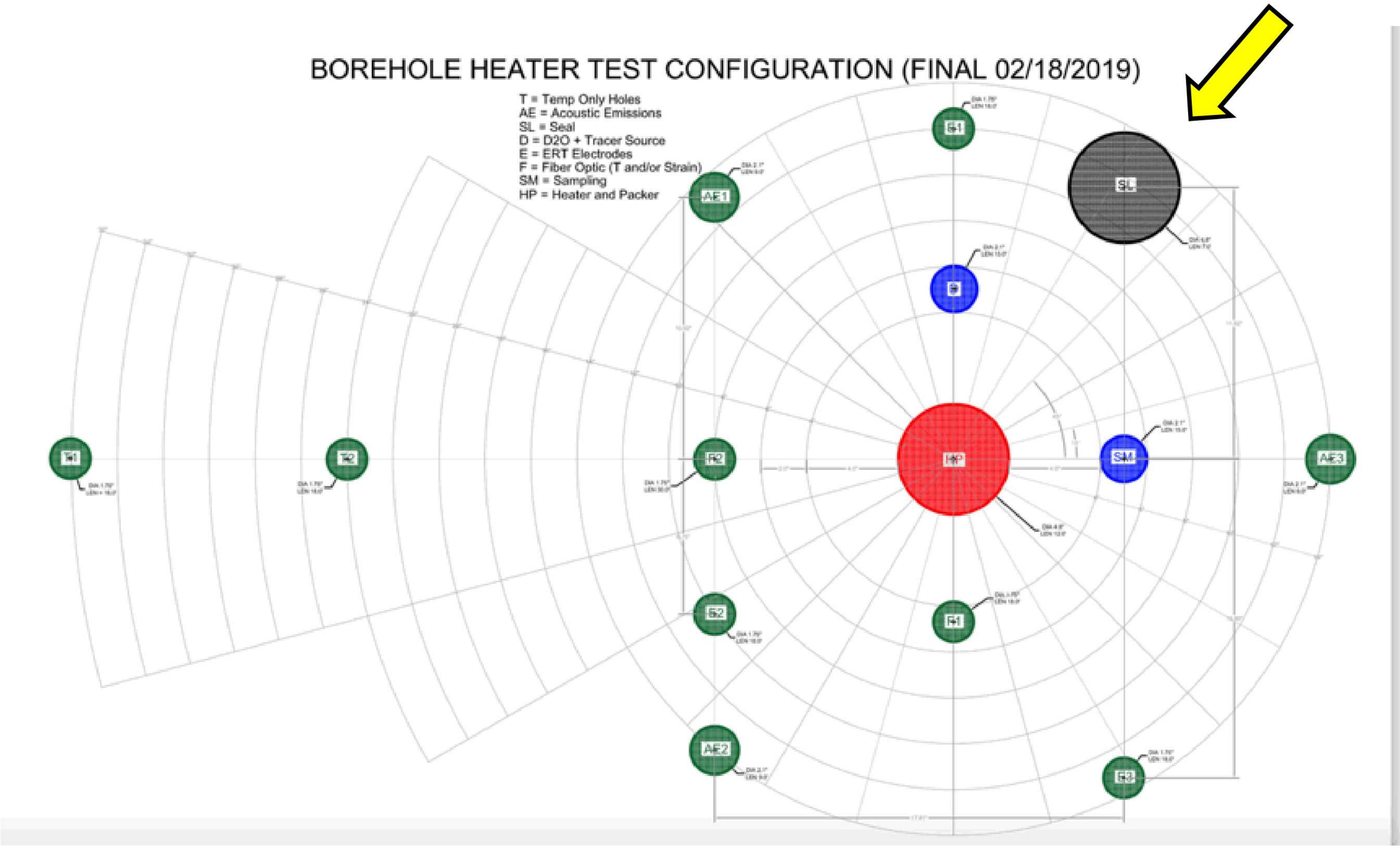
BATS Test Instrumentation





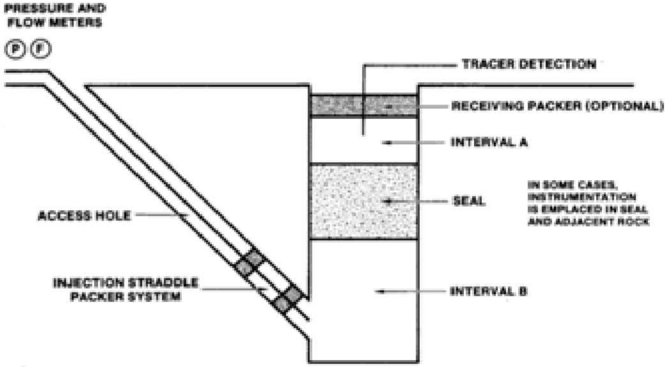
- Two identical arrays
  - Heated (120 C) and Unheated
- Behind HP packer (right)
  - Circulate dry N_2
  - Quartz lamp heater (750 W)
  - Borehole closure gage
  - Gas permeability before / after
- Samples / Analyses
  - Cores (X-ray CT and fluorescence at NETL)
  - Gas stream (natural / applied tracers, humidity and isotopes)
  - Liquid brine (natural chemistry and natural / applied tracers)
- Geophysics
  - 3 × Electrical resistivity tomography (ERT)
  - 3 × Acoustic emissions (AE) / ultrasonic travel-time tomography
  - 2 × Fiber optic distributed strain (DSS) / temperature (DTS) sensing
  - +100 thermocouples

BATS Borehole Layout, SL = Seal Borehole



Preliminary Seal Test in BATS

- Seal materials to test
  - Salt concrete
  - Sorel cement
  - OPC?
- Embedded strain gauges
- Thermocouples
- Post-test overcore and characterization
- Ultimately, would also eant to measure seal permeability *in situ,* as done in SSSPT



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Backup Slides

Case Study #2 – Wellbore Integrity during Geologic Storage of CO_2

Case #2- CO_2 Storage Project Overview

Goals: Predict/characterize Wellbore Integrity Evolution and Develop nanocomposite materials to repair wellbore seals in CO_2-injection environments

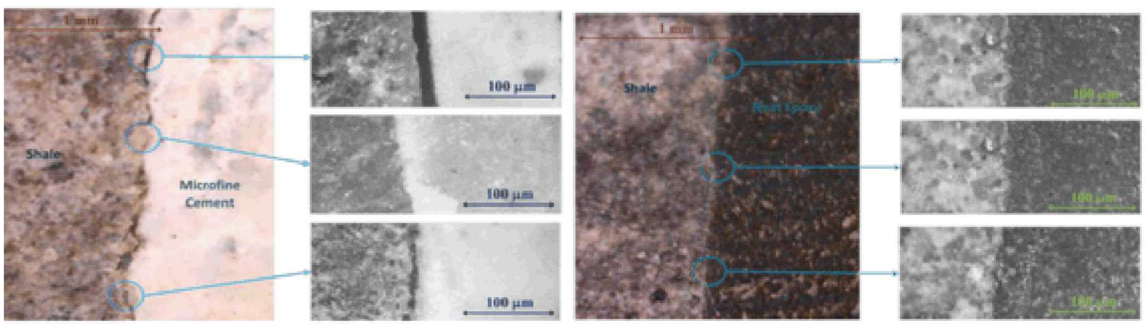
- Experimental component
  - Bench-top experiments of integrated seal system in an idealized scaled wellbore mock-up to test candidate seal repair materials
- Computational component
  - Bench-scale numerical models to identify and evaluate the essential hydrologic and mechanical properties of candidate sealants; gain understanding of wellbore microannulus compressibility and permeability
  - Field-scale model of a pilot CO_2 injection operation to develop a stress-strain history for wellbore locations
  - Wellbore-scale model examines the impacts of various loading scenarios on a casing structure

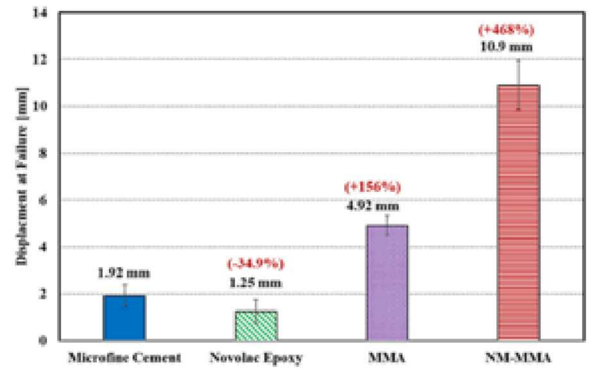
Understanding wellbore leakage

- What materials are available to repair existing wellbore leakage?
  - What is the strength of these materials in comparison to cement?
  - How effectively can they seal existing leaks?
  - How easily can they be delivered to flow paths (specifically, flaws or microannuli in the steel/cement interface)?
- What is the hydraulic aperture relation to mechanical stiffness?
- What are the stress and displacement conditions at the casing-cement interface?
  - What are the conditions in the field? (can vary with stratigraphy)
  - What conditions can be replicated in the laboratory?

Well Integrity Project Highlights (1/3)

- Novel repair materials that are more robust and have superior penetrability into cement-casing microannuli





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A new polymer nanocomposite repair material for restoring wellbore seal integrity

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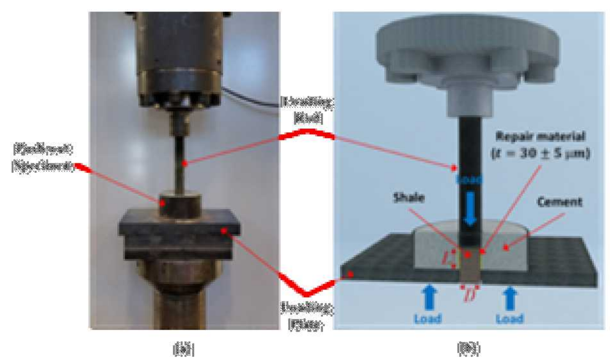
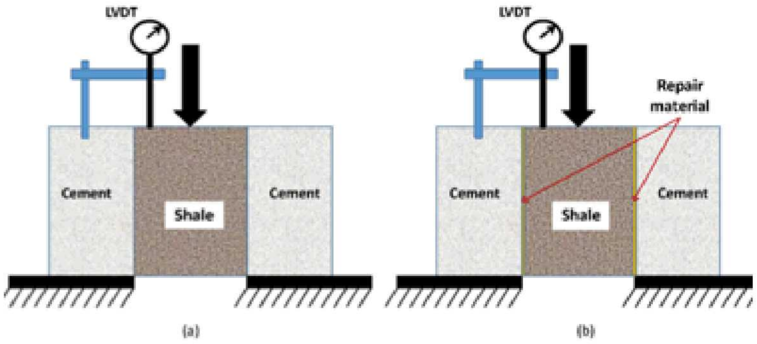
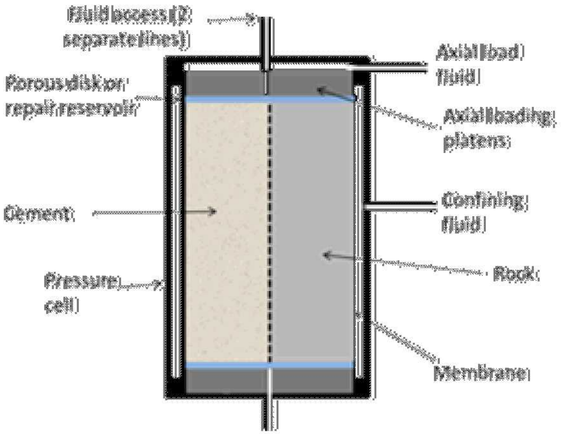
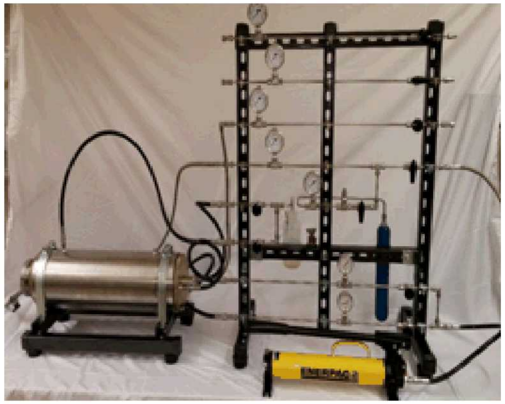


Seal Repair Design and Evaluation

- Synthesis and Characterization
  - Bond strength measurements
  - Rheology measurements
  - Polymer and nanocomposite engineering
- Evaluation
  - Seal mock-up
  - Permeameter for post-repair gas and liquid flow measurements

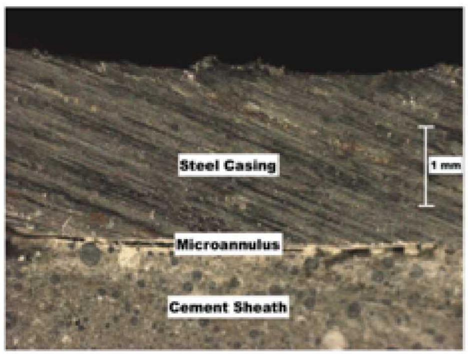


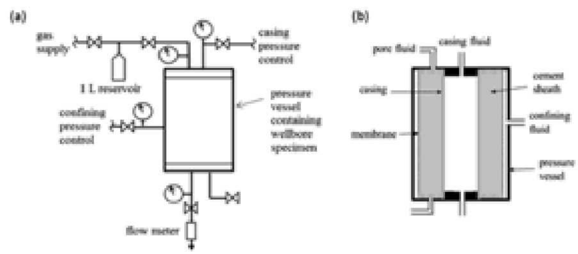


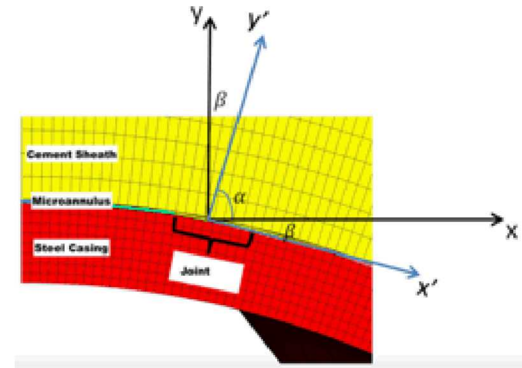


Well Integrity Project Highlights (2/3)

- Critical insights into the complexity of the microannuli contact surfaces, esp. understanding how microannuli repsond to deformations







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Gas flow through cement-casing microannuli under varying stress conditions

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Research Paper

Investigation of wellbore microannulus permeability under stress via experimental wellbore mock-up and finite element modeling

Steven P. Gomez [a,b,*], Steve R. Sobolik [b], Edward N. Matteo [b], Mahmoud Reda Taha [a], John C. Stormont [a]

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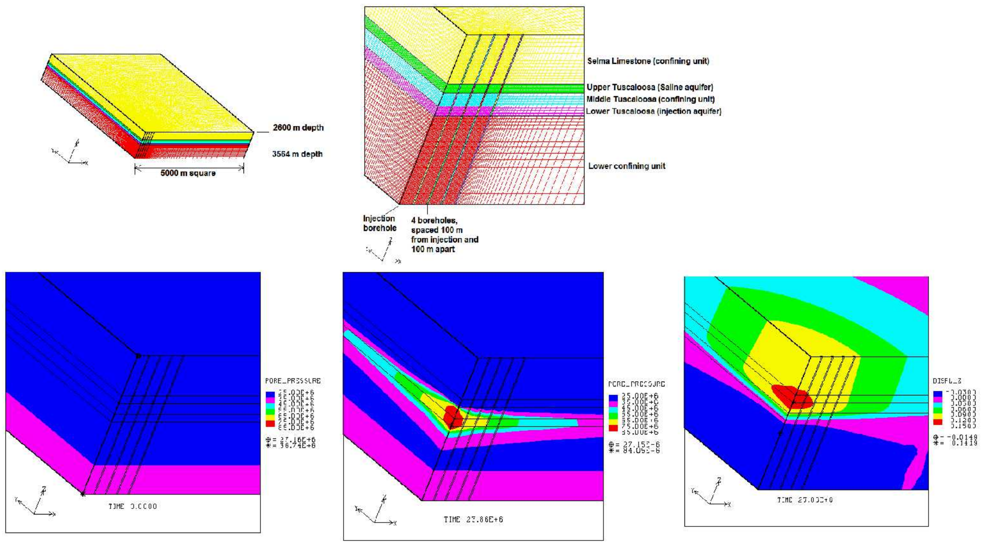
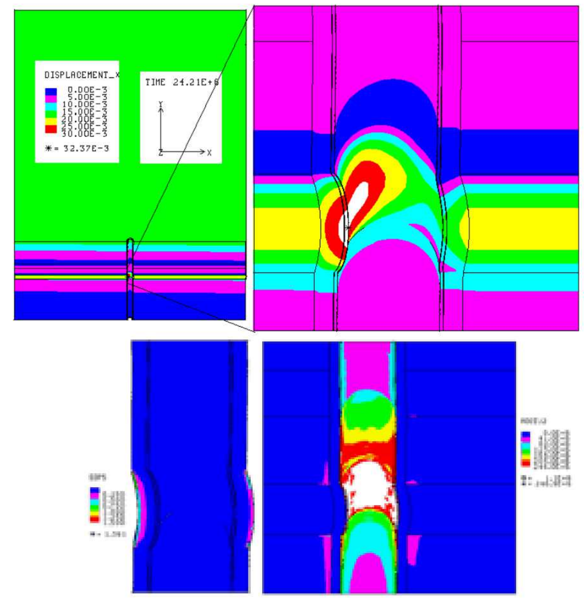
Well Integrity Project Highlights (3/3)

- Wellbore models coupled to field scale models of injection to predict wellbore deformations





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International Journal of Greenhouse Gas Control

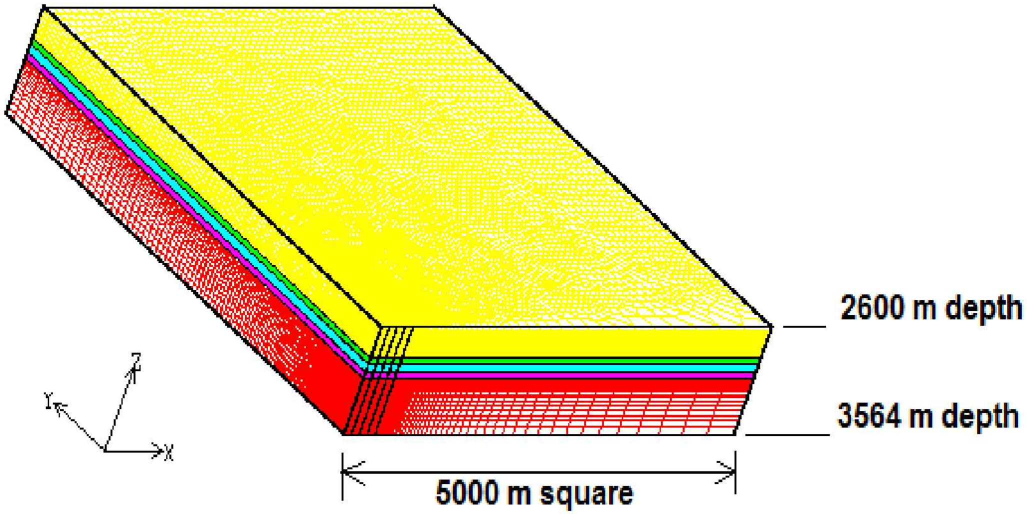
journal homepage: www.elsevier.com/locate/ijggc

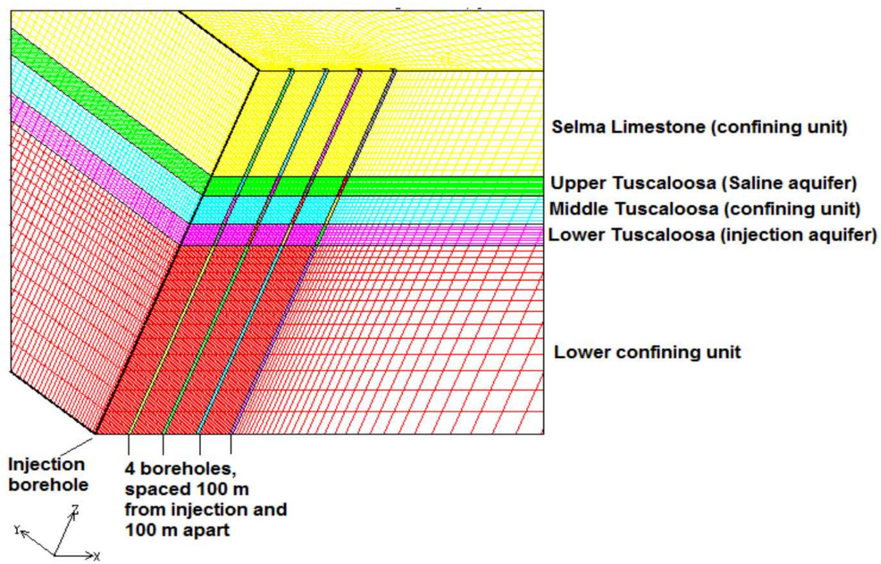
Heterogeneity, pore pressure, and injectate chemistry: Control measures for geologic carbon storage

Thomas Dewers[a,*], Peter Eichhubl[b], Ben Ganis[c], Steven Gomez[d], Jason Heath[a], Mohamad Jammoul[c], Peter Kobos[e], Ruijie Liu[f], Jonathan Major[b], Ed Matteo[g], Pania Newell[h], Alex Rinehart[i], Steven Sobolik[a], John Stormont[j], Mahmoud Reda Taha[j], Mary Wheeler[c], Deandra White[c]

Field-Scale Model

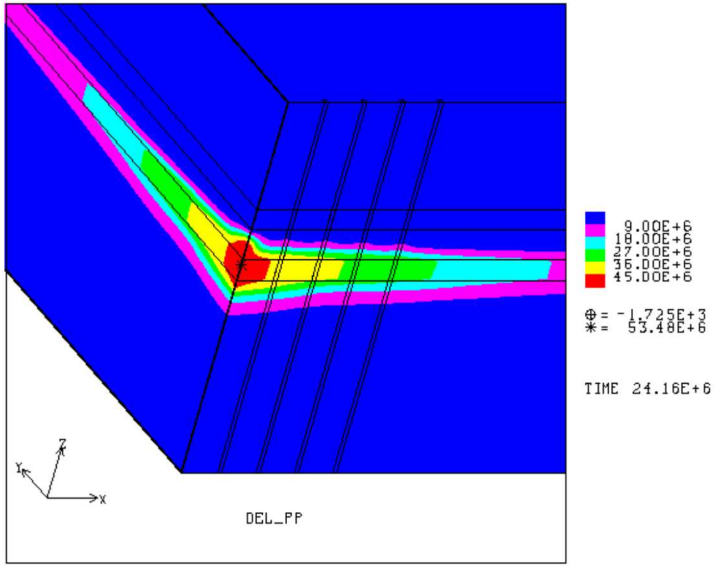
- Field-Scale computational model for Cranfield, MS CCS injection site (1.5 Mt over 1.5 yrs)
  - Thermally active reservoir coupled with pore pressure caused by dynamic CO_2 injection
  - Mechanical properties (Kayenta porous media plasticity model) of injection layer obtained from lab tests
  - Coupled THM calculations

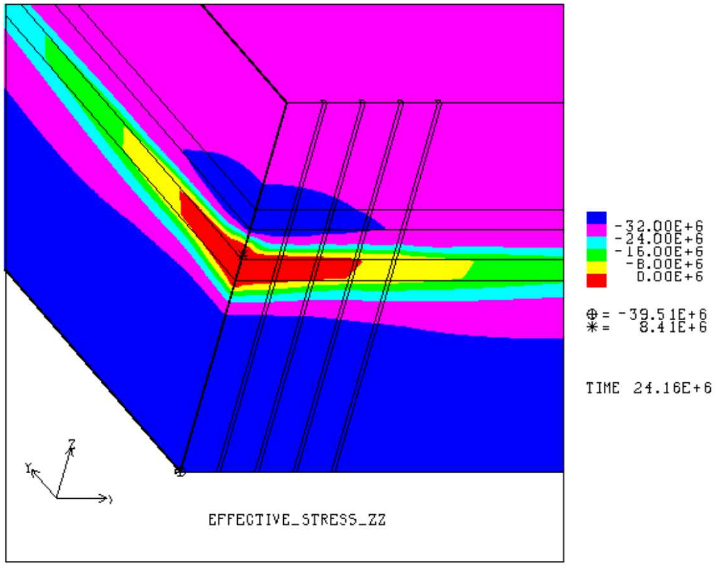




Field-Scale Model Results

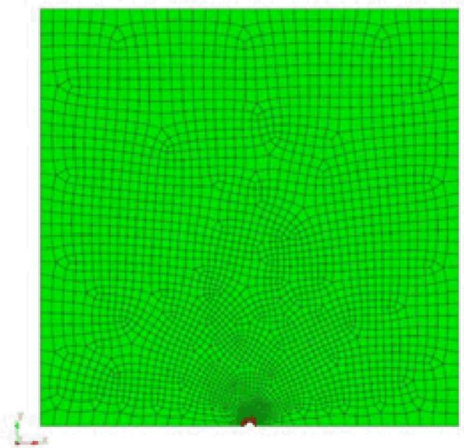
- Field-Scale computational model for Cranfield, MS CCS site – 9 months of CO_2 injection
  - CO_2 injection plume extend significantly past 400m borehole
  - Effective vertical stress along casings can be made tensile by CO_2 injection



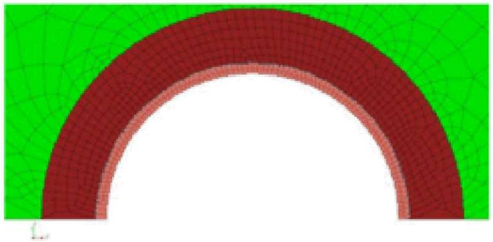


Wellbore-Scale Model – CO_2 Injection

- Pore pressures, host rock strains from field-scale model applied to wellbore scale with steel and cement liners, epoxy annulus
- Intent is to apply stresses/strain environment induced from injection process to microannuli of different materials, evaluate applicability under field conditions



(a)



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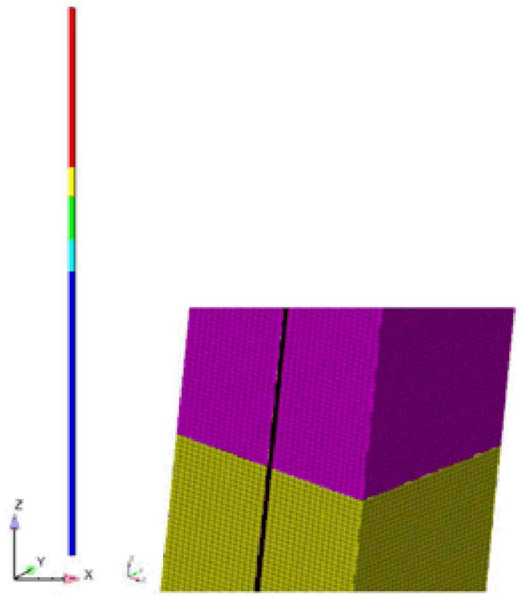
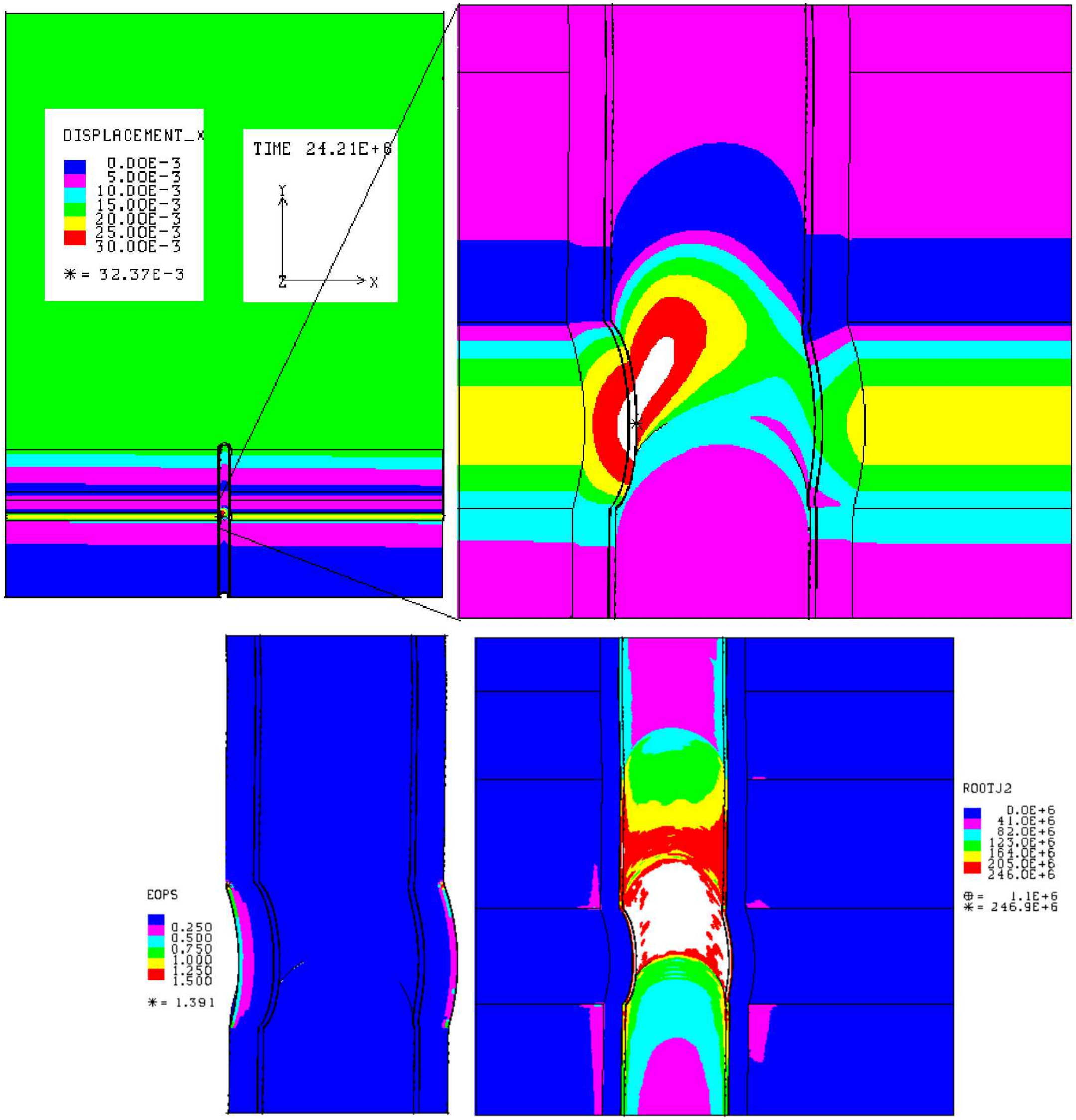


Wellbore-Scale Model – CO_2 Injection

- CO_2 injection causes significant porous expansion in Lower Tuscaloosa, inducing large lateral deformation in borehole casing (~3 cm)
- Significant plastic strain in cement, shear stress in steel casing
- Epoxy microannulus material would experience significant strain, transmit shear stress to casing; epoxies evaluated thus far not yet tested to this magnitude of deformation



Conclusions

- Laboratory scale experiments have developed data that represents permeability of microannuli, strength of cement and epoxy sealant materials
- Field-scale model predicts stress-strain environment under which epoxy will be subjected
- Wellbore model can predict effect of field environment on sealants
- Ability of epoxy to be effectively injected into microannuli investigated
- Model development continues, including eventual comparison of predicted field stresses and displacement to available site data