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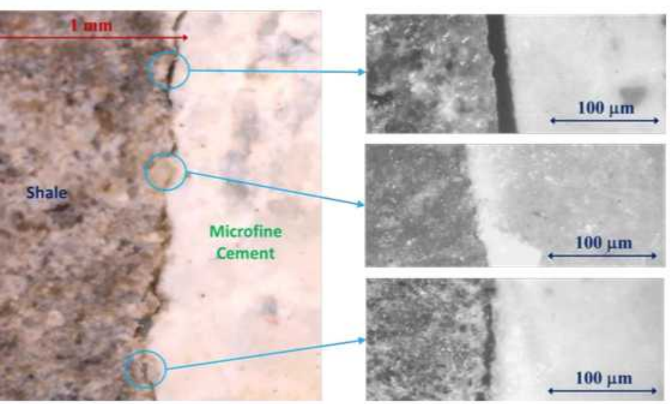
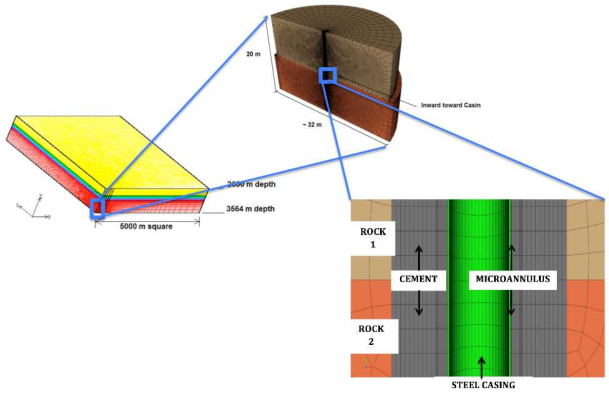
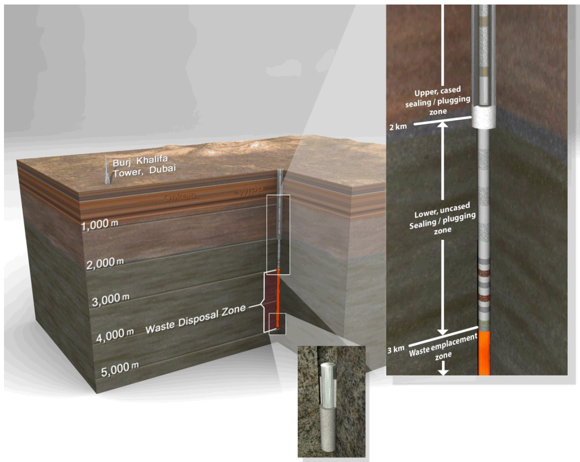






Engineered Seals and Barriers in Subsurface Service Environments

Ed Matteo

Sandia National Laboratories

April 7, 2017

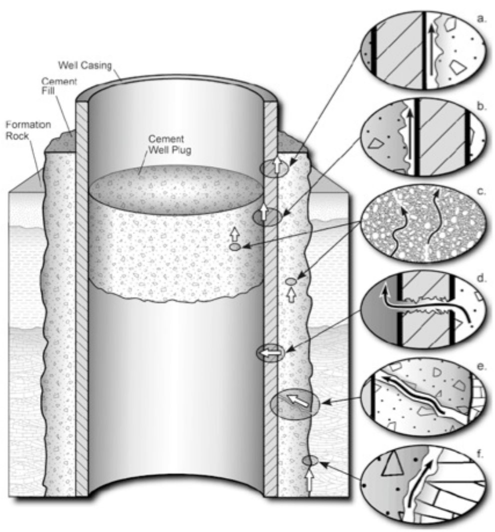
Acknowledgements

- Peter Swift, Pat Brady, David Sassani, Geoff Freeze, Kris Kuhlman (SNL – DBH Team)
- Tom Dewers, Steve Gomez, Steve Sobolik (SNL – Wellbore Integrity Team)
- John Stormont, Mahmoud Taha, Moneeb Genedy (University of New Mexico - Wellbore Integrity Team)

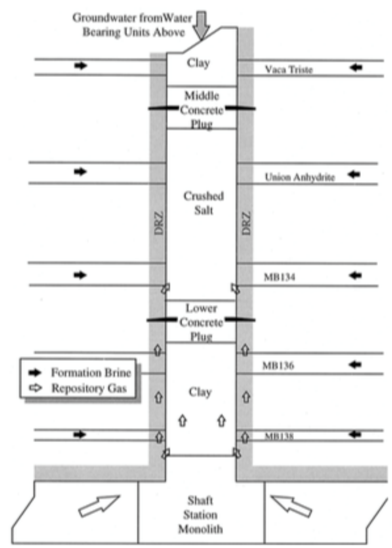
Overview

- Intro and Background
  - Types of Seals – materials and functions
  - Seals fail, Pt. 1 – so what?
  - Seals fail, Pt. 2 – why?
- Case Studies
  - Nuclear Waste Disposal
    - Background on waste inventory and disposal concepts
    - Deep Borehole Disposal Concept and Field Test
    - Evaluating seal performance via THC modelling
  - Wellbore Integrity during Geologic Storage of CO_2
    - Geomechanical modelling to predict *in situ* stress and strain
    - Microannulus evolution and permeability
    - Seal repair development and performance
- Conclusions, ongoing, and future work

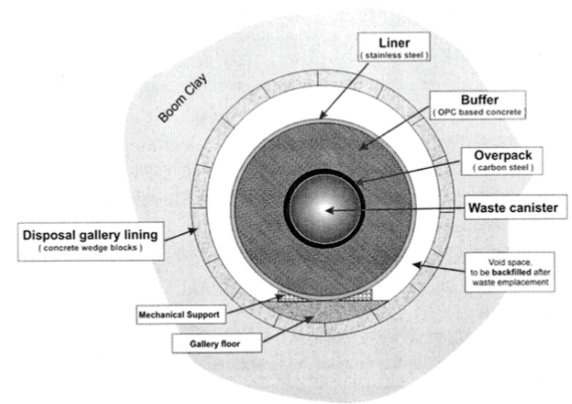
Seals are guardians of conduits that pass through stratigraphy – without seals there is potential for direct communication between subsurface, hydrogeologic units, and the surface



Wellbore Seals



Shaft and Drift Seals



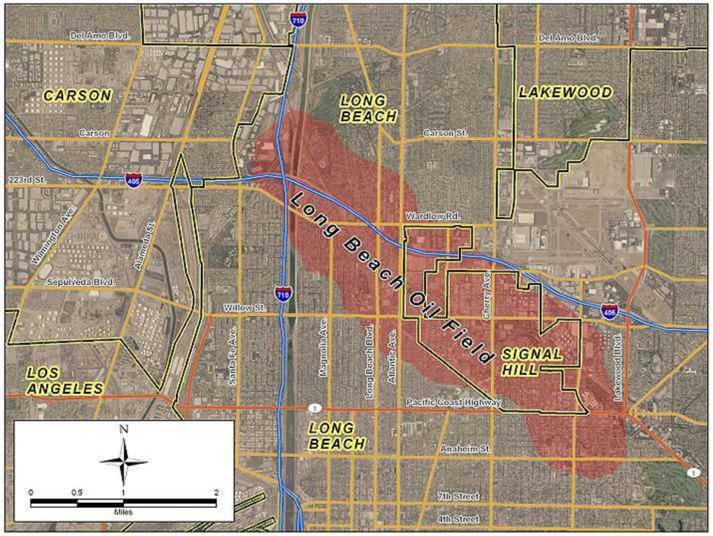
Engineered Barrier System Components

Seals are typically composed of:

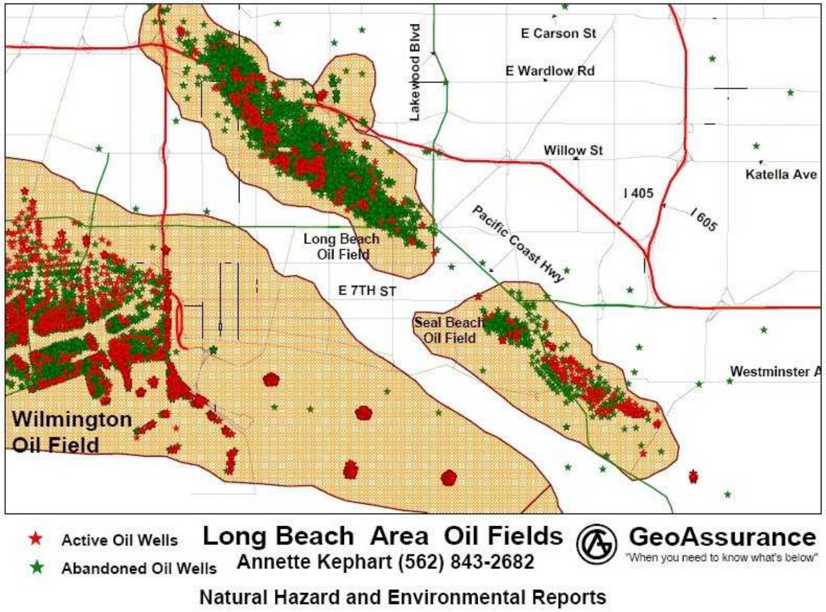
- Cementitious materials (cement, concrete, shotcrete)
  - Class G or Class H wellbore cement
  - Low pH Portland cement (pozzolans to achieve pore sol’n pH < 12)
- Bentonite
  - primarily smectite
  - Swells when wetted
  - Cation getter
- Backfill
  - Compatible with and/or composed of host rock
- Other getters
  - Anionic getters, zeolites

There can be many, many seals!

Typically, there are thousands of (known) abandoned wells in a field (Re-completion is prohibitively expensive).

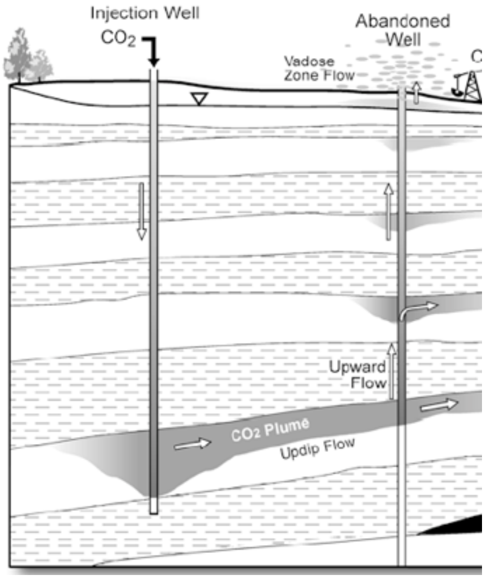


http://en.wikipedia.org/wiki/Long_Beach_Oil_Field



http://en.wikipedia.org/wiki/Long_Beach_Oil_Field

Seals can FAIL! .. but can also fail quietly



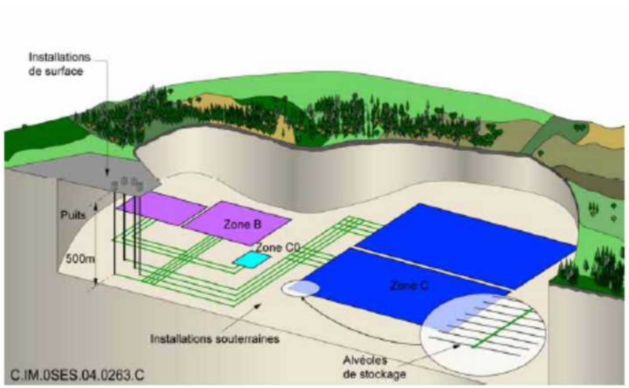
- In many cases (O&G), finding a bad seal is like finding a needle in a haystack
- Field scale models are essential to predicting seal behavior and identifying those with failure risk

Case Study #1 – Deep Borehole Disposal of Nuclear Waste

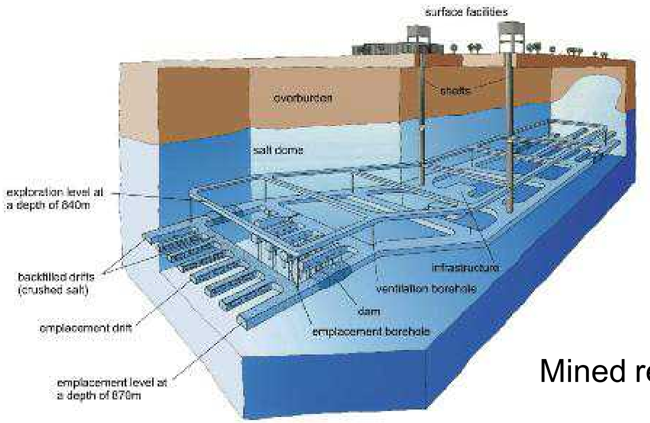
Nuclear Waste Overview

- 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)

Disposal Concepts

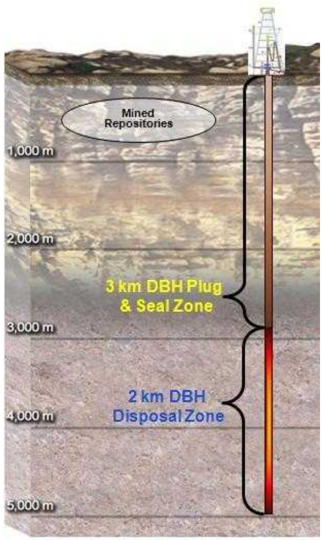


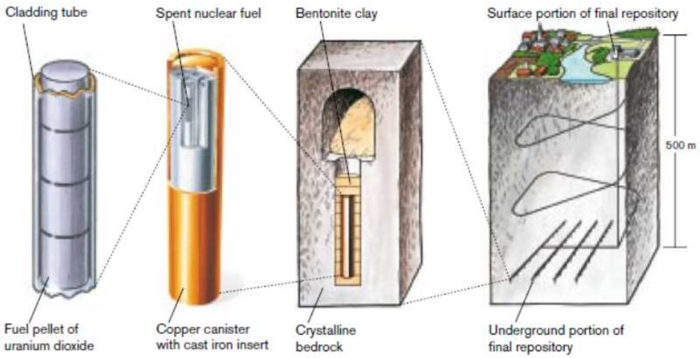
Mined repositories in clay/shale



Mined repositories in salt

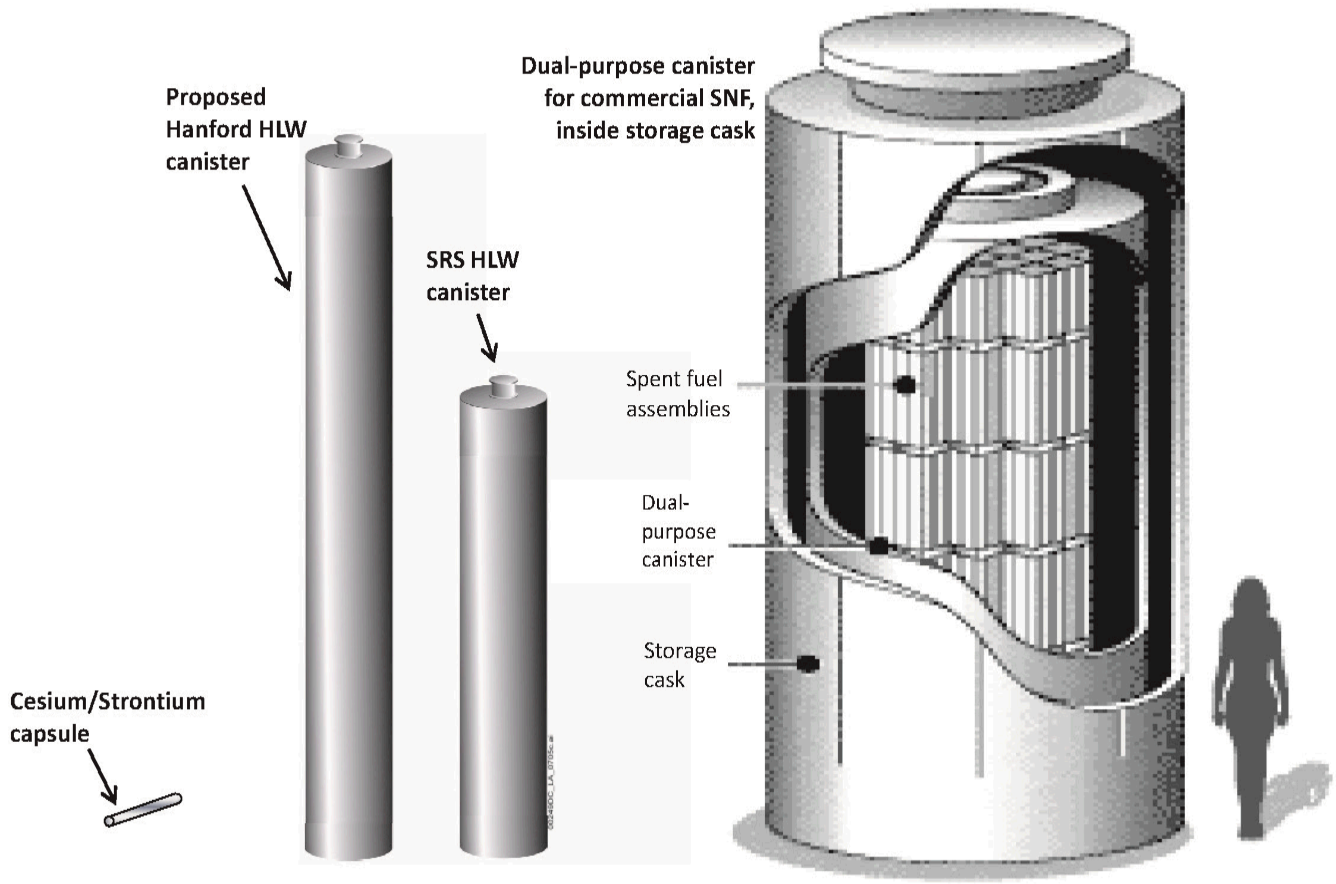
Deep boreholes in crystalline rock





Mined repositories in crystalline rock

Relative Size of Waste Packaging May Have an Impact on Disposal Options



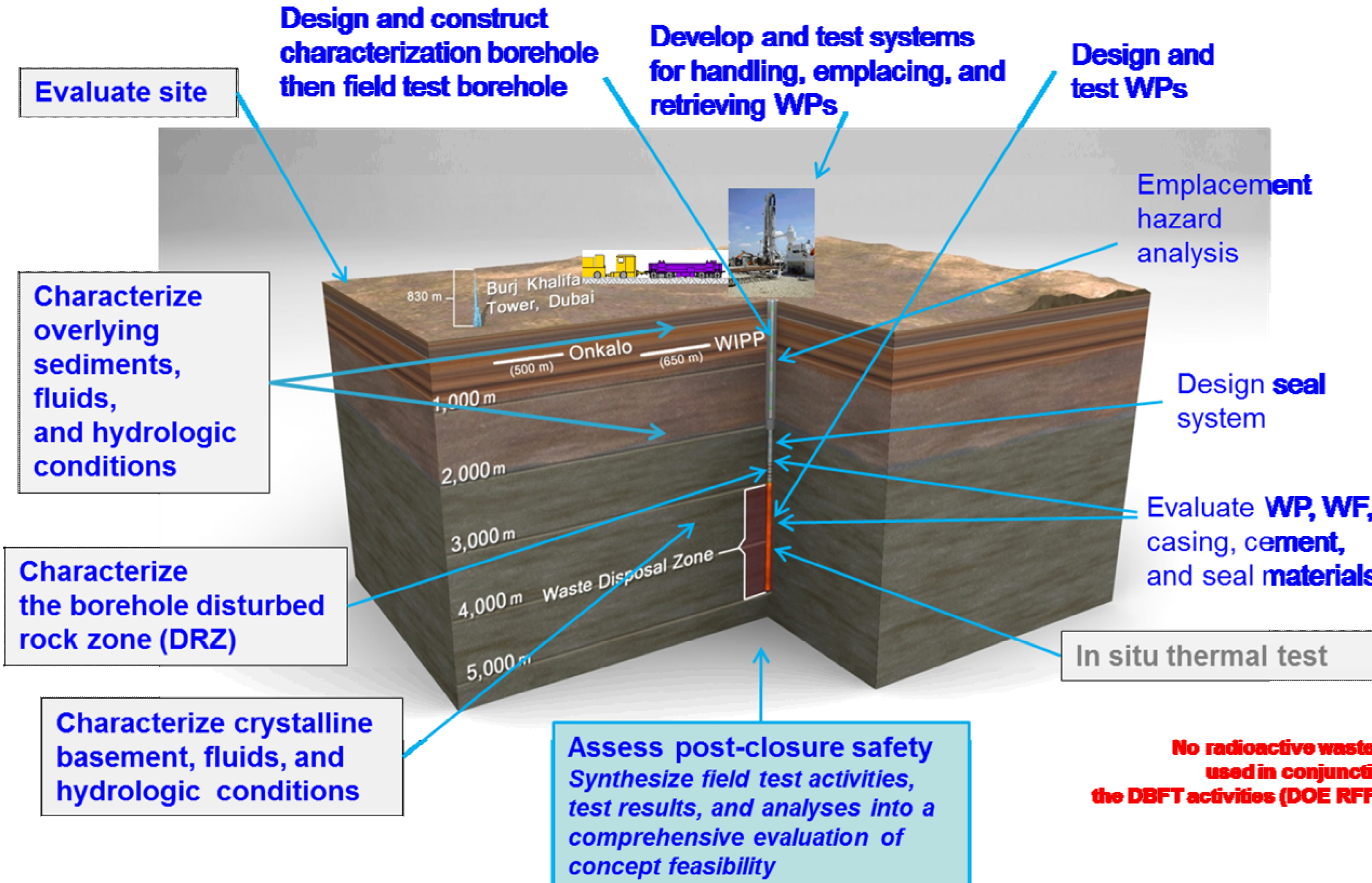
The smallest forms of HLW and SNF that can fit into small diameter canisters could be candidates for deep borehole disposal

Approximate Scale

Deep Borehole Disposal Concept

- ≤17” hole to 5 km
- Straightforward Construction
- Robust Isolation from Biosphere
- Conditions at Depth
  - Low permeability
  - Stable fluid density gradient
  - Reducing fluid chemistry
  - Old groundwater

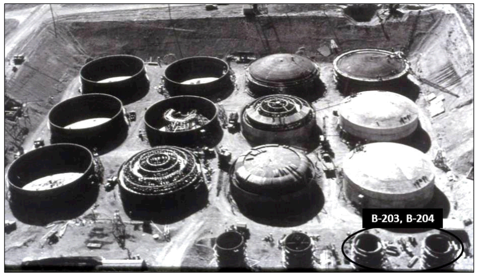
Deep Borehole Field Test Objectives



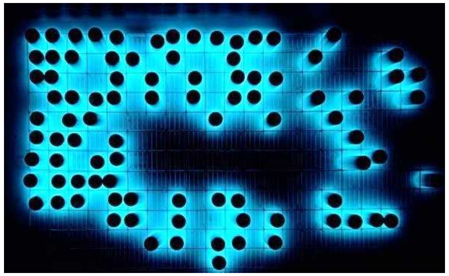
No radioactive waste will be used in conjunction with the DBFT activities (DOE RFP 2016).

Radioactive Waste Forms Specific to the DBH Concept

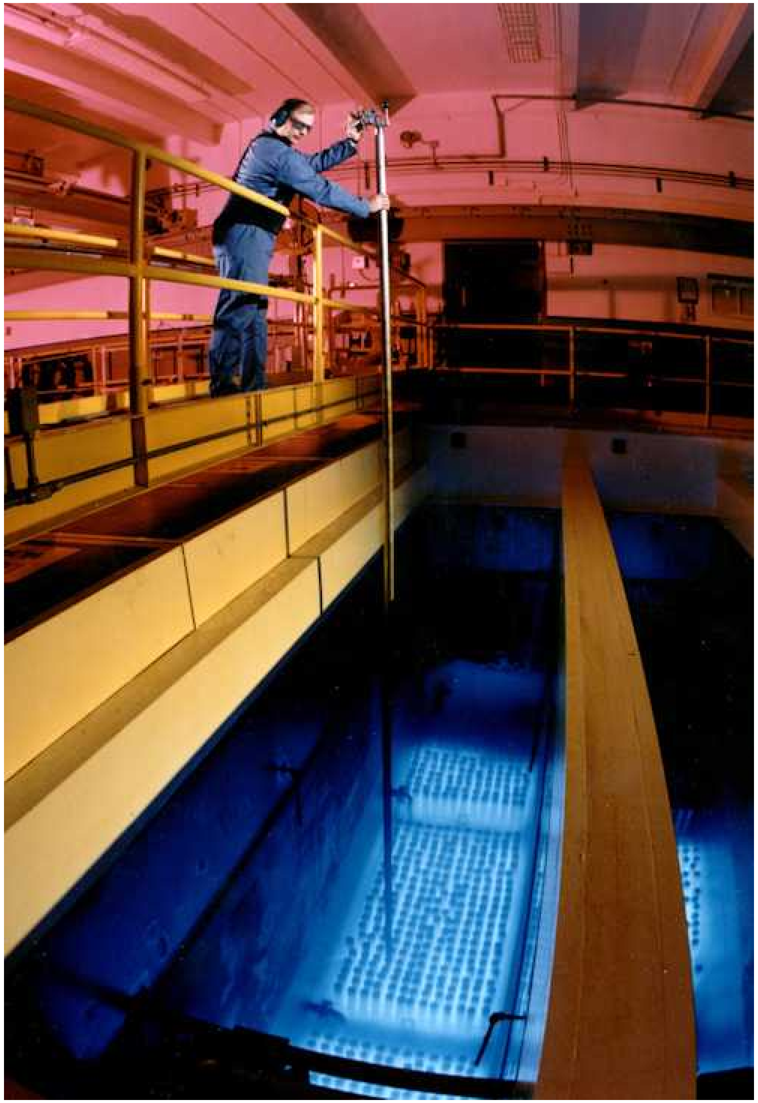
- **Waste Properties**
  - Thermal output
  - Physical size
  - Waste total volume
- **Primary Waste Forms**
  - DOE-managed high-level waste
    - Liquid reprocessing wastes:
      - Borosilicate glass logs
      - Cs-137/Sr-90 capsules
      - Calcine powder



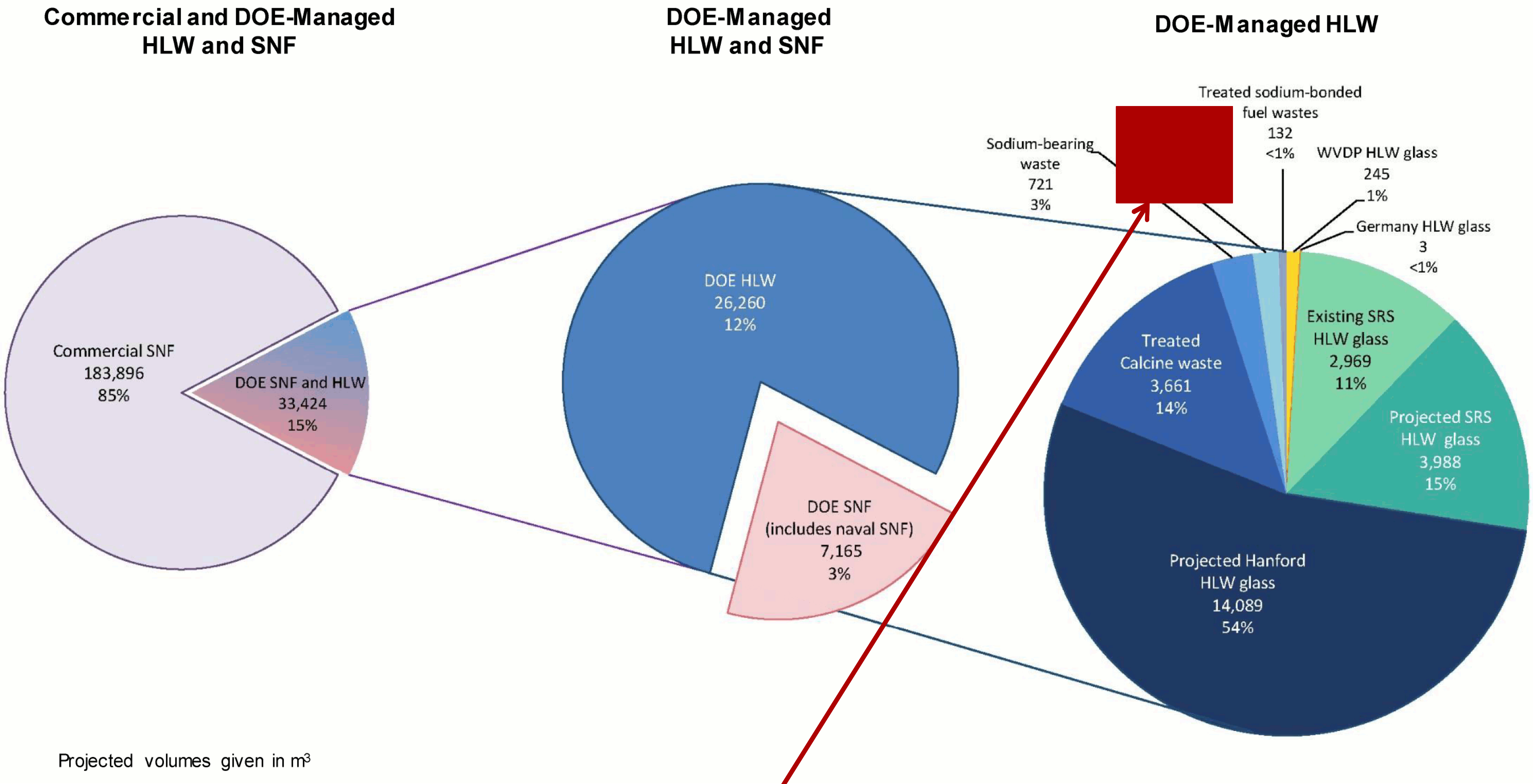
Hanford tank farm



2,000 Cs/Sr Capsules [≈3” diam.]



Radioactive Waste Volumes

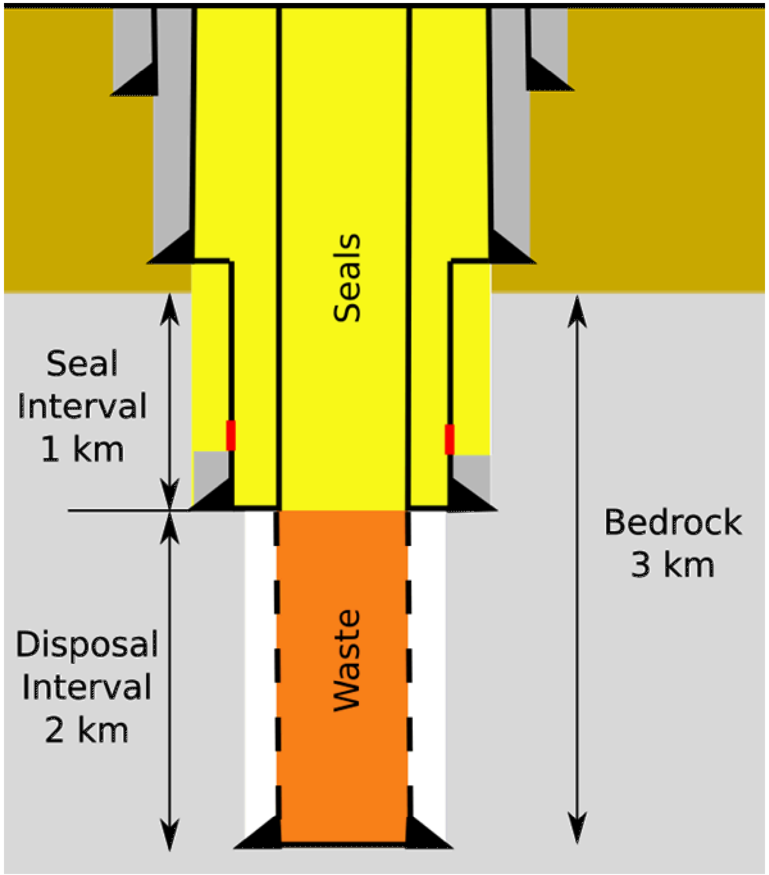


HLW = High-Level Waste
SNF = Spent Nuclear Fuel

≈ 30% total curies of radioactivity at Hanford

Disposal Concept vs. Field Test

- **Deep Borehole Disposal (DBD)**
  - Boreholes in crystalline rock to 5 km TD
  - 3 km basement / 2 km overburden
  - 1 km basement seal
  - 2 km disposal zone
  - Single borehole or grid

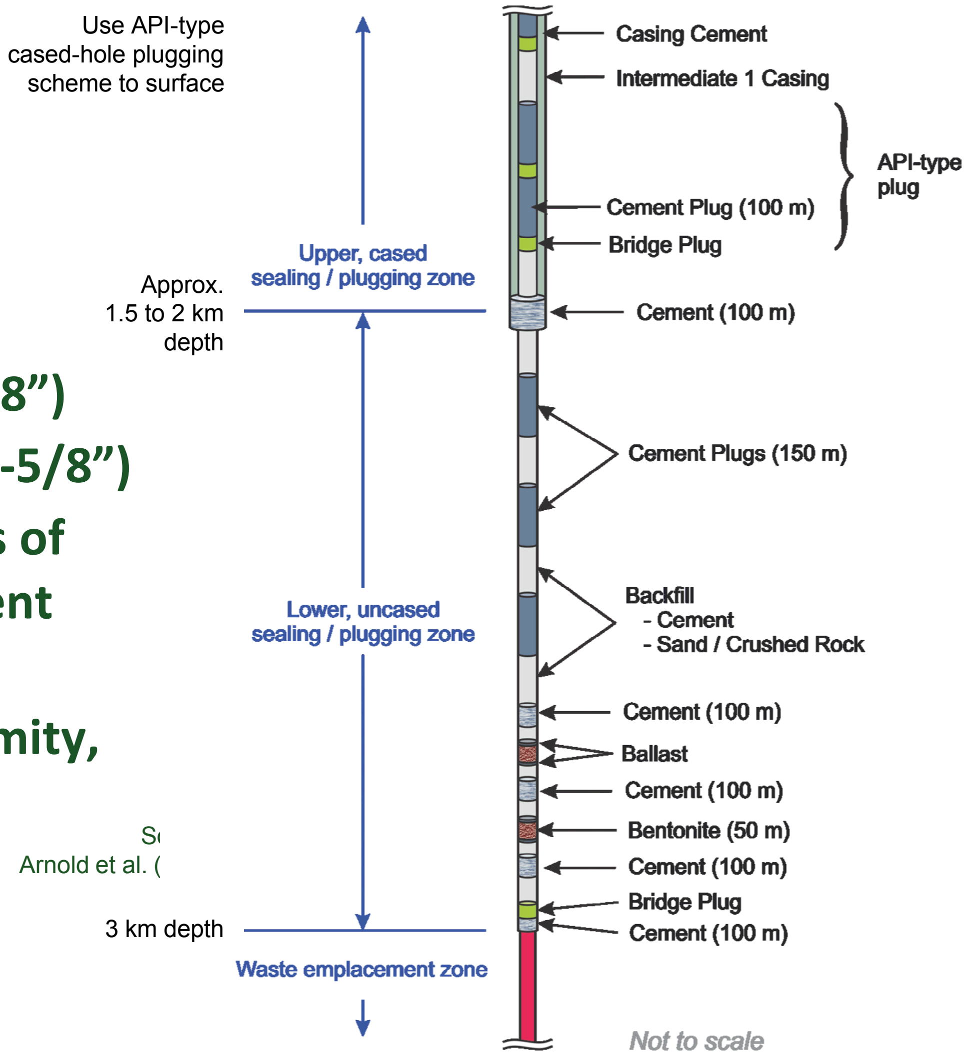


- **Deep Borehole Field Test (DBFT)**
  - Department of Energy – Office of Nuclear Energy (DOE-NE)
  - FY 2017-2021 project
  - Two boreholes to 5 km TD
  - Science and engineering demonstration

Reference Concept for Disposal Borehole Completion and Sealing

- Disposal Zone
  - Cemented guidance casing
  - Emplacement fluid
  - Bridge plugs
- Sealing/Plugging Zone
  - Remove guidance tieback (13-3/8")
  - Remove intermediate casing (18-5/8")
  - Seal/plug with alternating layers of compacted bentonite clay, cement plugs, and cemented backfill
  - Extend upward across unconformity, into the overburden
- Overburden Interval
  - API* type plug, fully cemented

*American Petroleum Institute

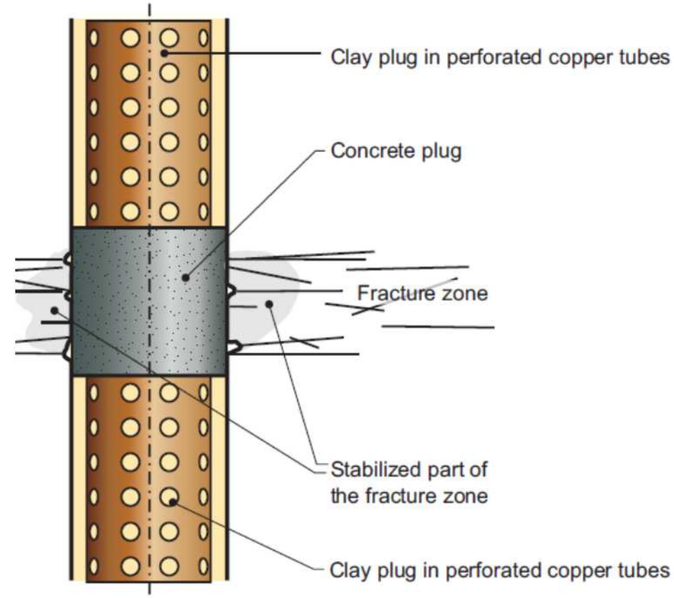


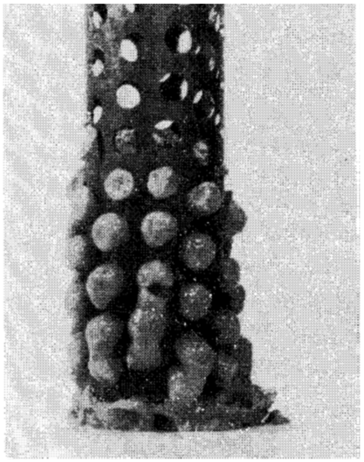
Arnold et al. (

Sealing Materials and Methods

- Sealing *
  - Smectites, illites, zeolites
  - Emplacement methods
- Cement *
  - Material properties and longevity
  - Emplacement methods and setting time
- Fused Borehole Plug
- Rock Melting
  - Low permeability plug
  - Controlled annealing of host rock

Following 35+ years R&D for sealing investigation boreholes and repository shafts





Laboratory immersion 24 hr

(Pusch, R. Borehole sealing with highly compacted Na bentonite. SKB TR-81-09)

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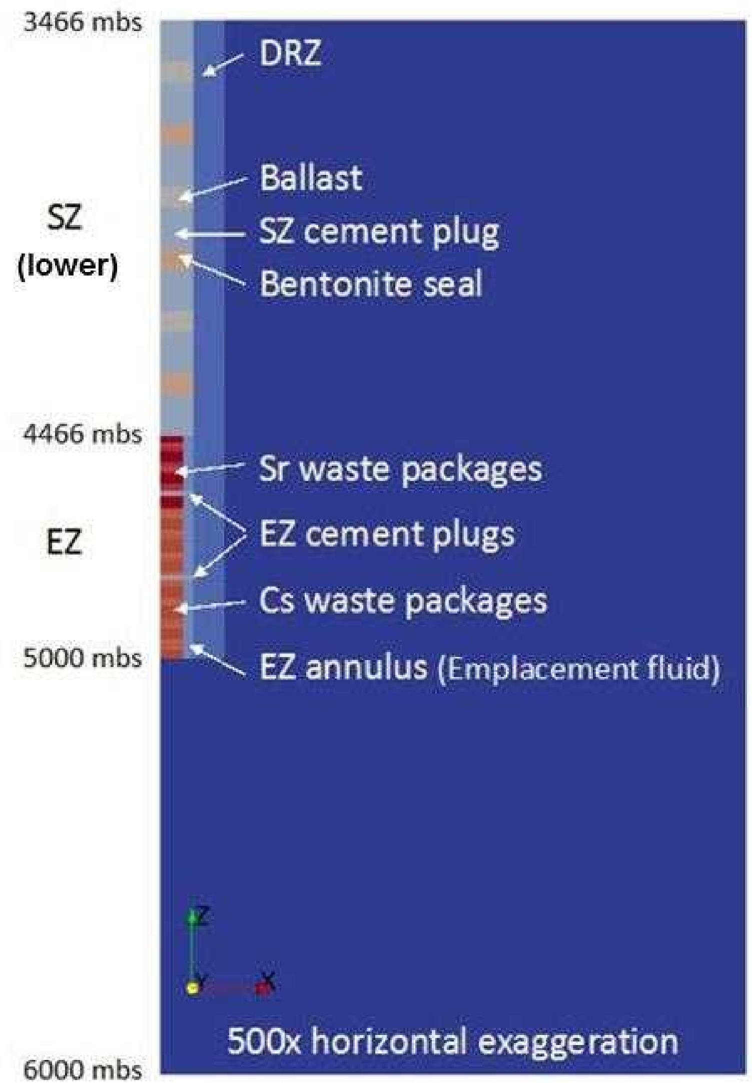
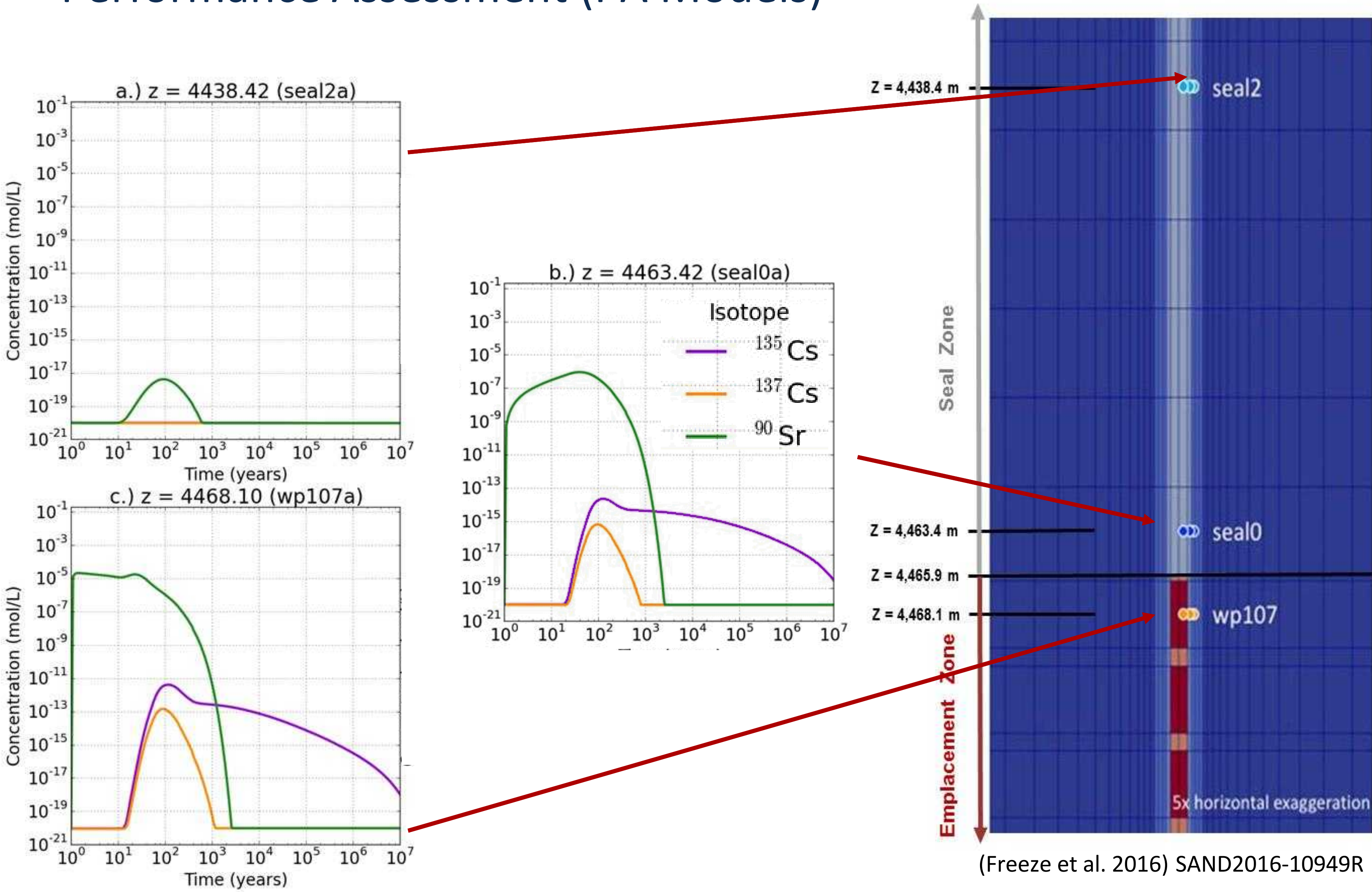
- **Performance Assessment (PA) Modeling**
  - Use standard reference:
    - geology
    - borehole design
  - Assume single boreholes Cs/Sr
  - Assess long-term post-closure safety
  - Thermal-hydrological-chemical processes simulated via PFLOTRAN

PFLOTRAN



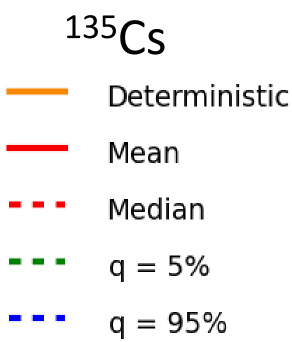
(Freeze et al. 2016) SAND2016-10949R
Deep Borehole Disposal Safety Analysis

Performance Assessment (PA Models)

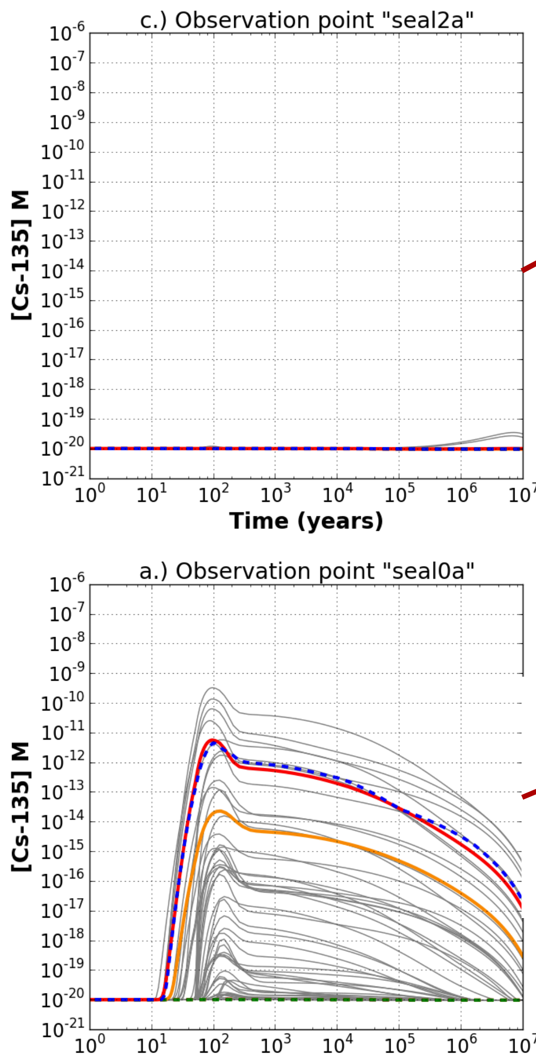


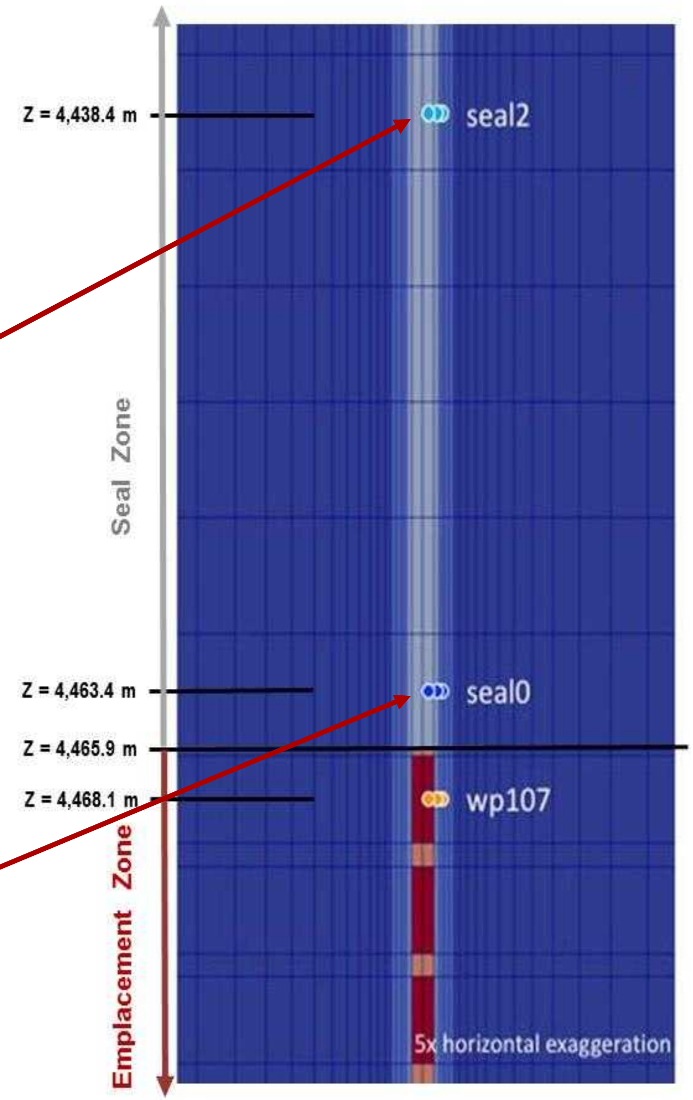
(Freeze et al. 2016) SAND2016-10949R

Performance Assessment (PA Models)



Parameter	Range	Units
Bentonite k	$10^{-20} – 10^{-16}$	m^2
Cement k	$10^{-20} – 10^{-16}$	m^2
DRZ k	$10^{-18} – 10^{-15}$	m^2
WP τ	0.01 – 1.0	--
Bentonite ϕ	0.40 – 0.50	--
Cement ϕ	0.15 – 0.20	--
WP Breach Time	1 – 100	yr
Cs K_d bentonite	120 – 1000	L/kg
Sr K_d bentonite	50 – 3000	L/kg
Cs K_d crystalline	5 – 40	L/kg
Sr K_d crystalline	0.4 – 3	L/kg
Cs K_d DRZ	5 – 40	L/kg
Sr K_d DRZ	0.4 – 3	L/kg





(Freeze et al. 2016) SAND2016-10949R

- For more information, search OSTI (www.osti.gov) for “ Deep Borehole Field Test Conceptual Design Report”

Deep Borehole Field Test Conceptual Design Report

Fuel Cycle Research & Development

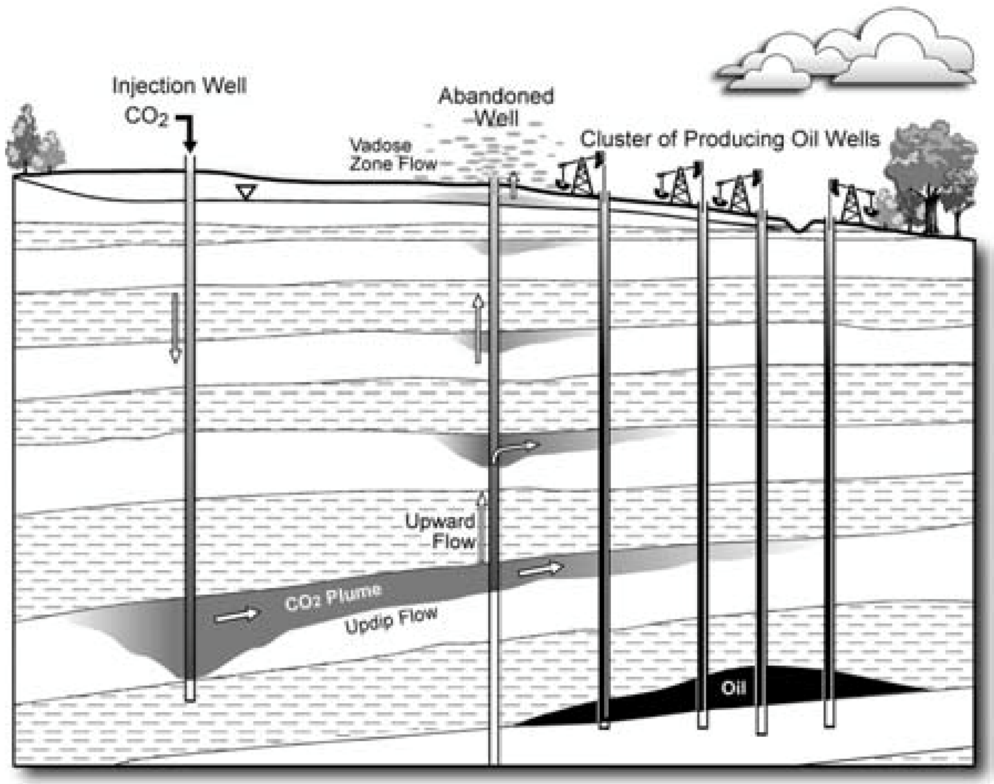
Prepared for the
U.S. Department of Energy
Used Fuel Disposition Campaign

Sandia National Laboratories
Albuquerque, New Mexico
June, 2016
FCRD-UFD-2016-000070 Rev. 0

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

Carbon Dioxide Capture and Sequestration (CCS)

- Emerging technology for reducing greenhouse gases in the atmosphere
- Injecting into porous subsurface media, saline aquifers or depleted O&G formations
- Isolation compromised by abandoned wells that have developed preferential flow paths (leaks)
- Leaks may be cracks in cement; or interface degradation at steel-cement-host rock interfaces



Understanding wellbore leakage

- What are the stress and displacement conditions at the casing-cement interface?
  - What are the conditions in the field?
  - What conditions can be replicated in the laboratory?
- What is the hydraulic aperture relation to mechanical stiffness?
- 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)?

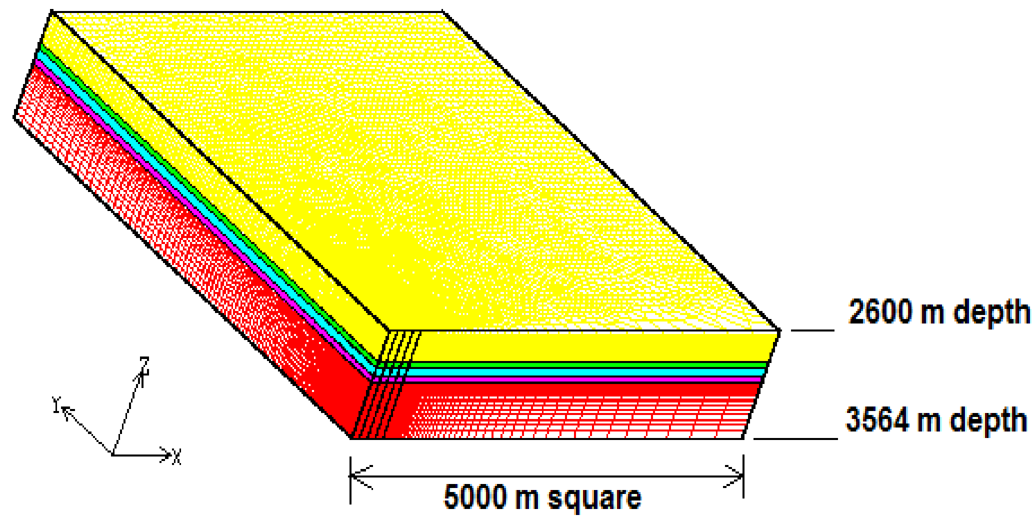
Joint Sandia/UNM research program

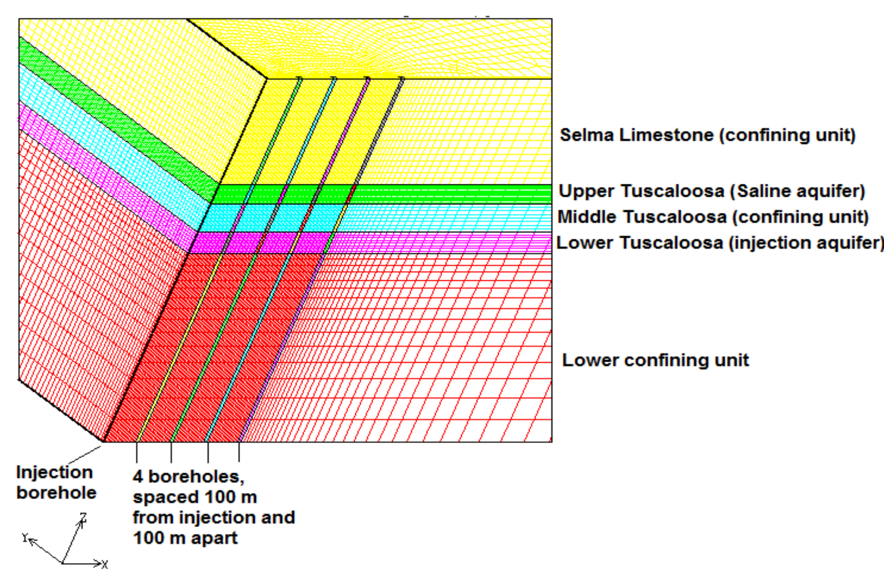
Goal is to develop nanocomposite materials to repair wellbore seals in CO2-injection environments

- 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

Field-Scale Model

- Field-Scale computational model for Cranfield, MS CCS site
  - 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
  - Preliminary coupled THM calculation have been completed



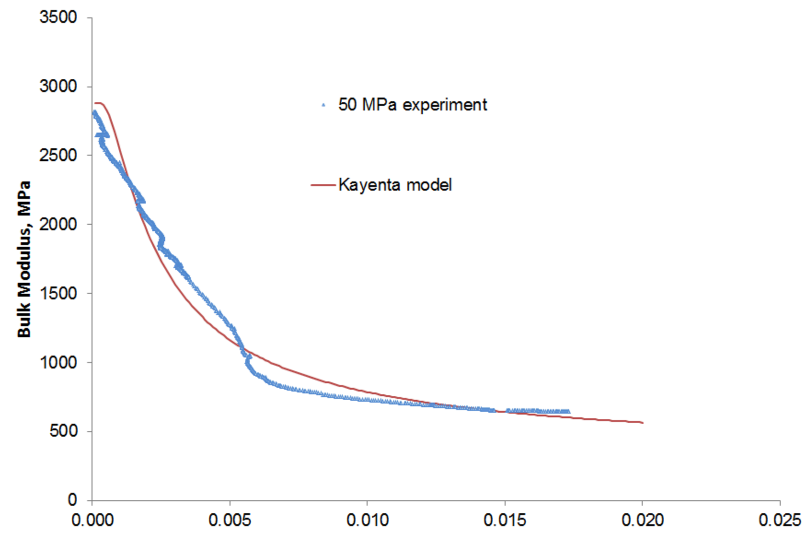


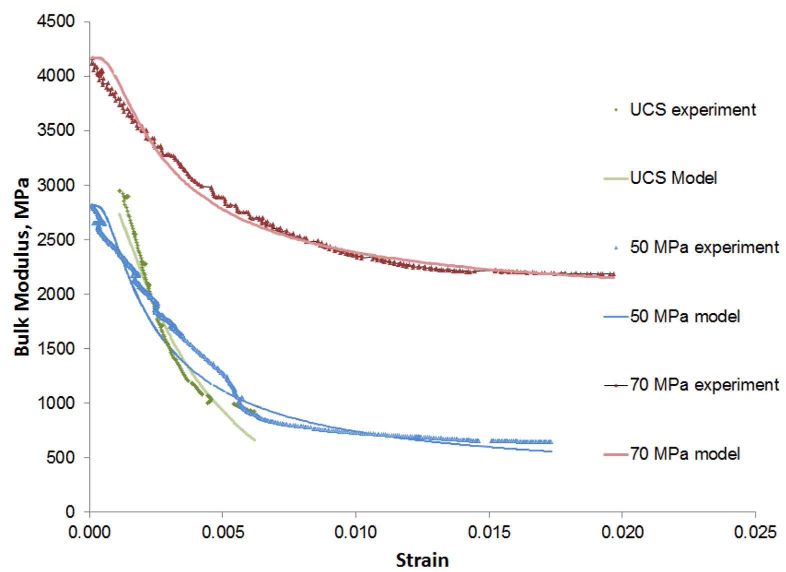
Mechanical Properties of Injection Layer

- Laboratory experiments with Lower Tuscaloosa sandstone (UCS, 50MPa, 70 MPA confining) (Rinehart & Dewers, 2015)
  - Strains measured as axial stress increases
  - Kayenta – generalized plasticity model that includes yield surface, generalized to include inelastic material response including microcrack growth and pore collapse
  - Bulk, shear moduli calculated from stress/strain data as functions of first and second stress tensor invariants, plastic strain:

$$K = f_K\left\{\left[b_0 + b_1\exp\left(-\frac{b_2}{|I_1|}\right)\right] - b_3\exp\left(-\frac{b_4}{|\varepsilon_v^p|}\right)\right\}$$

$$G = f_G\left\{g_0\left[\frac{1 - g_1\exp\left(-g_2 J_2^{1/2}\right)}{1 - g_1}\right] - g_3\exp\left(-\frac{g_4}{|\gamma_v^p|}\right)\right\}$$





Yield Properties of Injection Layer

- Kayenta defines a yield function *F* in stress space such that elastic states satisfy $F < 0$
- Yield surface parameters for Lower Tuscaloosa also derived from laboratory tests (Rinehart and Dewers, 2015)

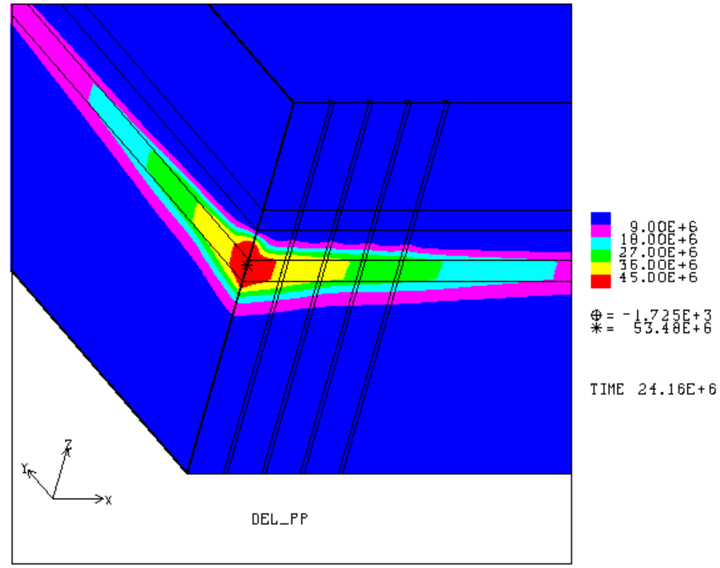
$$F_f(I_1) = a_1 - a_3 e^{-a_2 I_1} + a_4 I_1$$

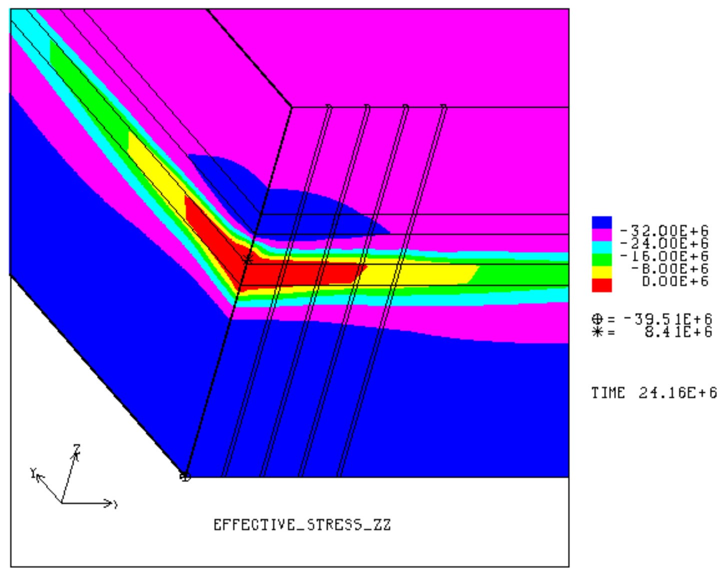
Kayenta parameter values for Lower Tuscaloosa sandstone

Parameter, units	Value
B0, MPa	2846
B1, MPa	100
B2, MPa	150
B3, MPa	2561
B4, dimensionless	0.0020
G0, MPa	1200
G1, dimensionless	0.01
G2, 1/MPa	0.0002
G3, MPa	1080
G4, dimensionless	0.0030
a1, MPa	26.5
a2, 1/MPa	0.03
a3, MPa	6.51
a4, dimensionless	0.210

Field-Scale Model Results

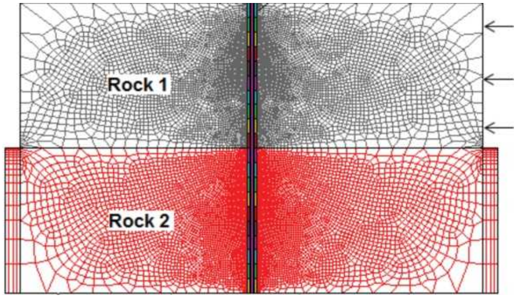
- Field-Scale computational model for Cranfield, MS CCS site – 9 months of CO_2 injection
  - CO_2 injection plume extend significantly past 400m borehole
  - Effective vertical stress along casings can be made tensile by CO_2 injection

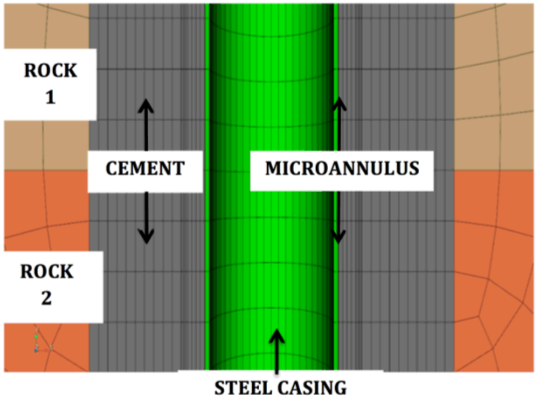


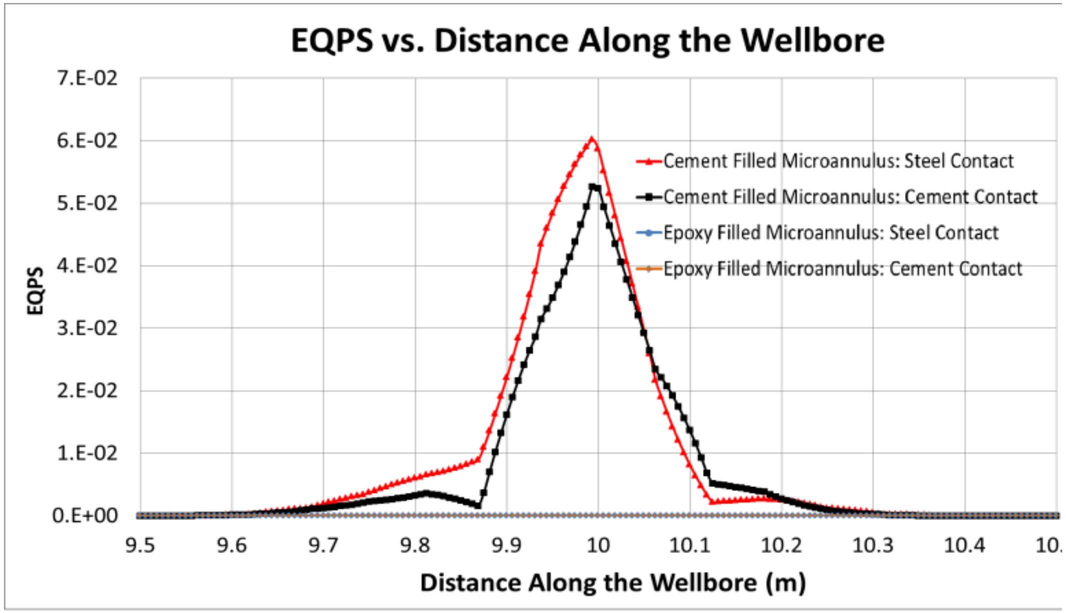


Wellbore-Scale Model – Shear

- Calculations of effect of shear at rock interface on casing materials completed
- Epoxy microannulus ideally would experience no plastic strain under shear conditions that would cause plastic strain, cracking in cement
- Results from testing, modeling of nanomaterial epoxies indicate such epoxies can be formulated (e.g. Novolac, low modulus polysulfide-siloxane epoxies; nanomaterials include multiwall carbon nanotubes (MWCNTs), nanoclay, nanosilica, and nanoalumina particles)

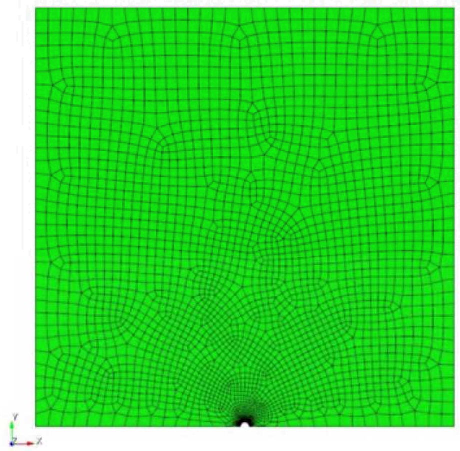






Wellbore-Scale Model – CO2 Injection

- 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



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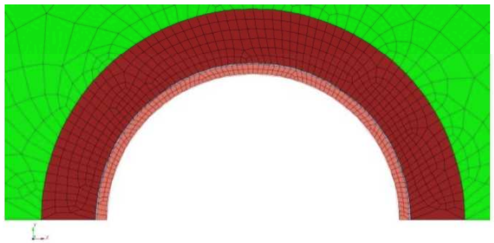

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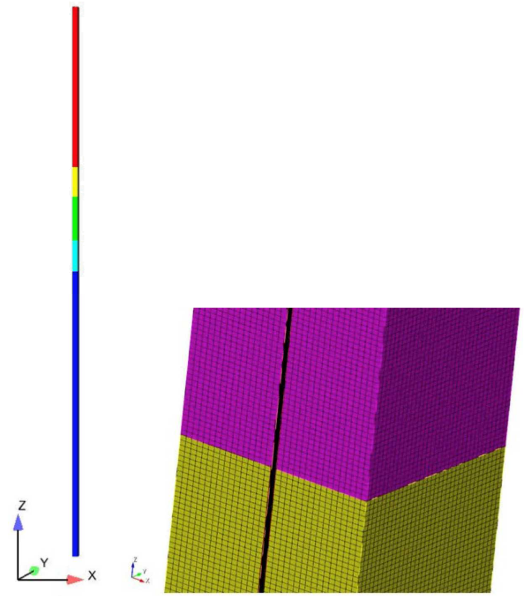
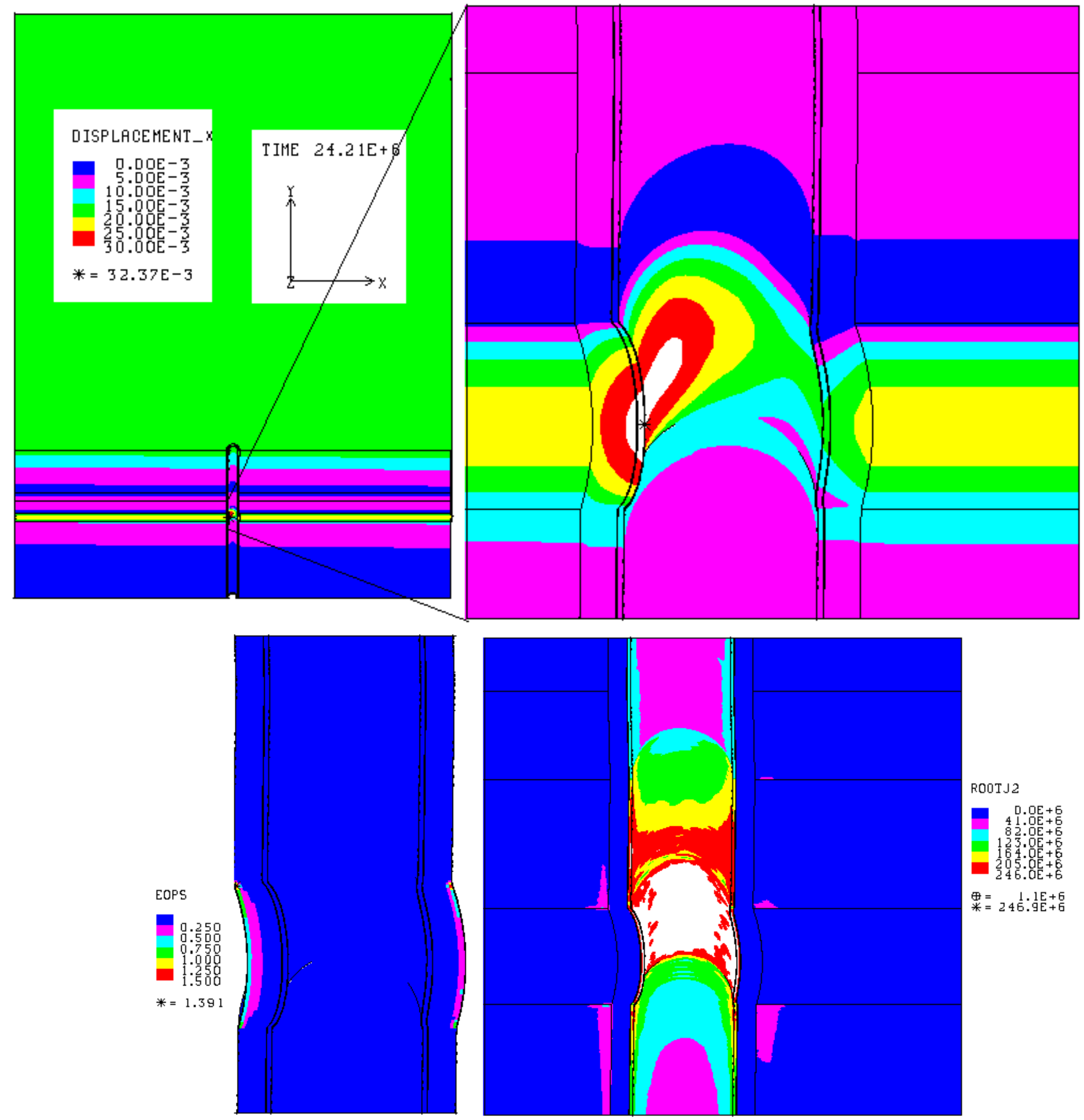


Wellbore-Scale Model – CO_2 Injection

- 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



Field Scale Modeling of Relevant Problems Needs Chemistry

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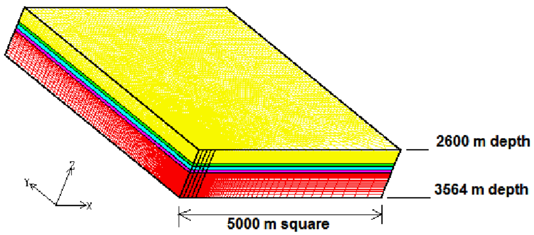
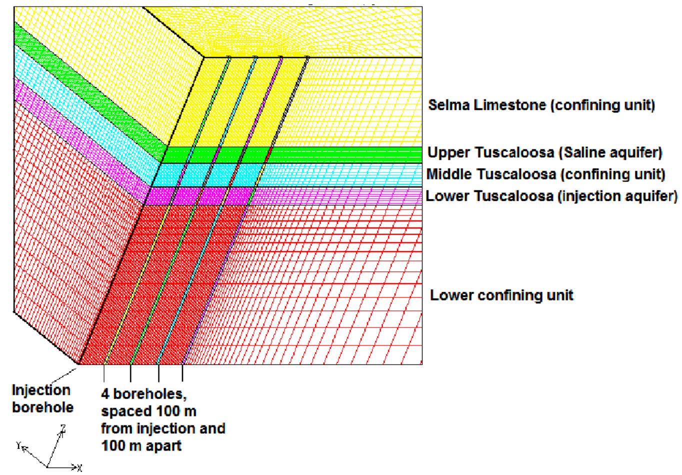
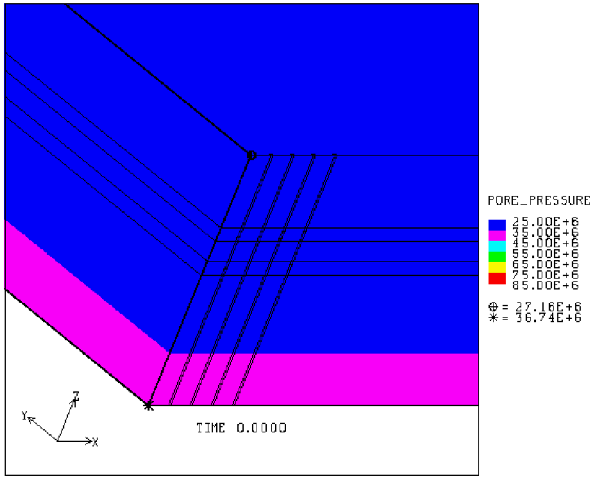
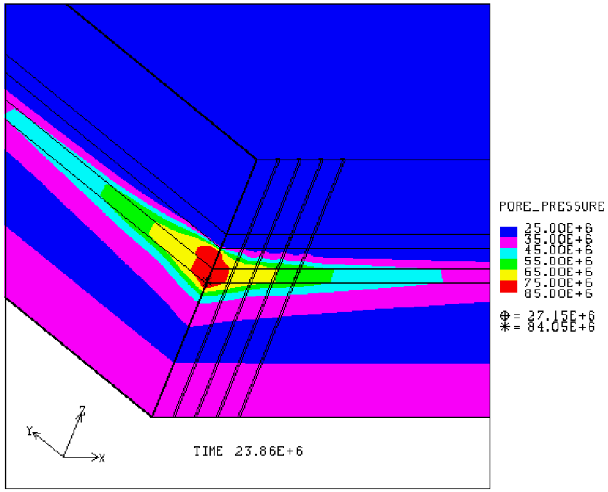


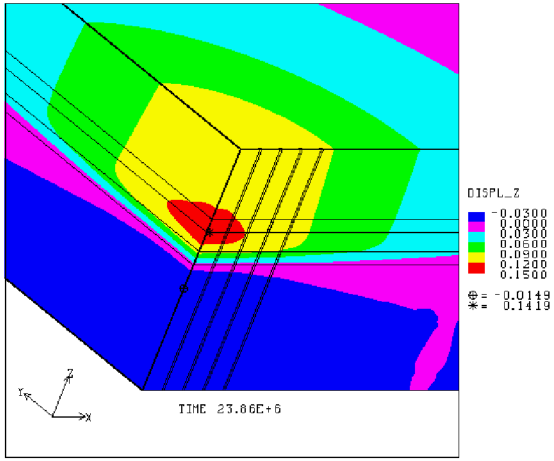




Pore pressure, time = zero



Pore pressure, time = 270 days

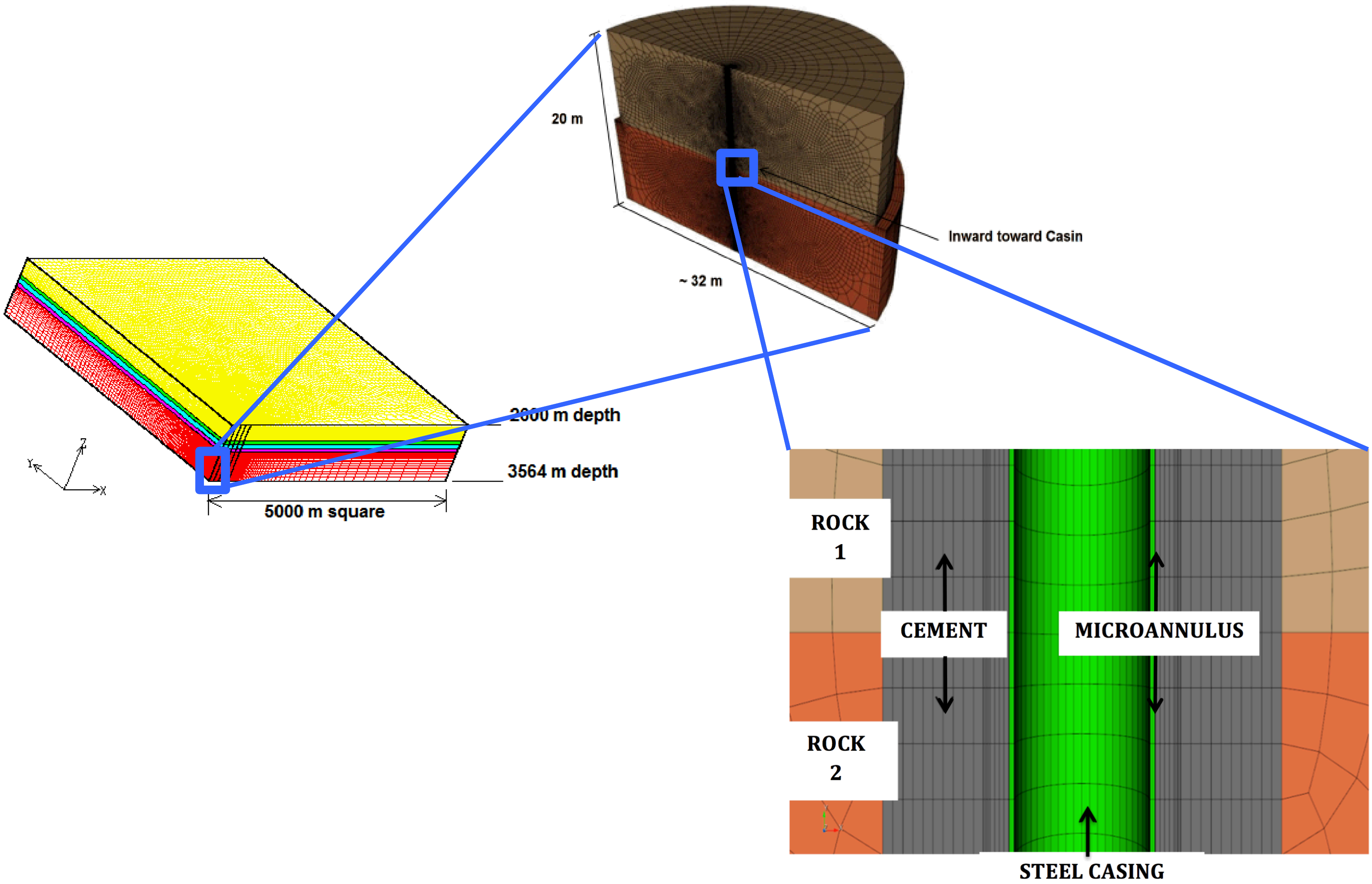


Vertical displacement, time = 270 days

Why is Chemistry important?

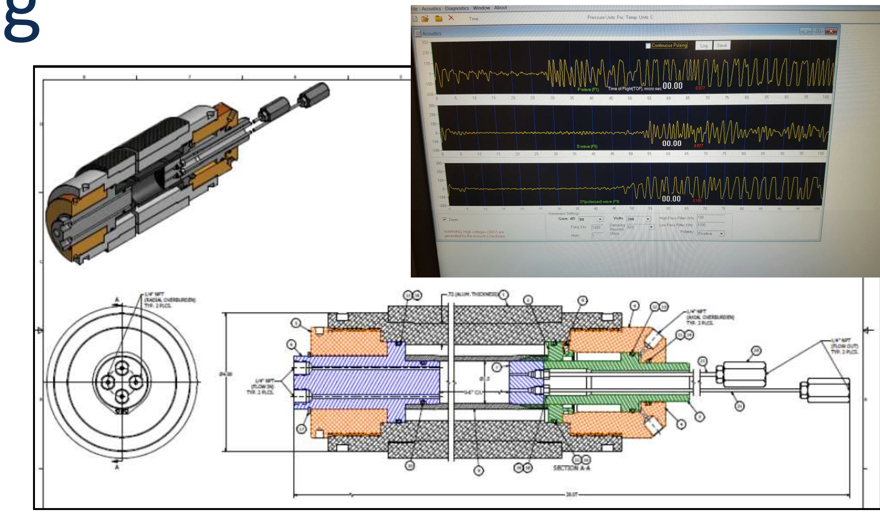
- Cement, despite its ubiquity, is a complex and dynamic material
  - Complex mineral phase assemblage
    - C-S-H (chains of calcium silica hydrate, act as binder)
    - Portlandite (calcium hydroxide)
    - Afm, Aft, etc.
  - High surface area
  - Porous media, saturated (at equilibrium)
  - Pore solution is alklaine (pH ~11 - low pH cement) to extremely alkaline (pH ~ 13 - OPC)
- Not at chemical equilibrium in most subsurface environments

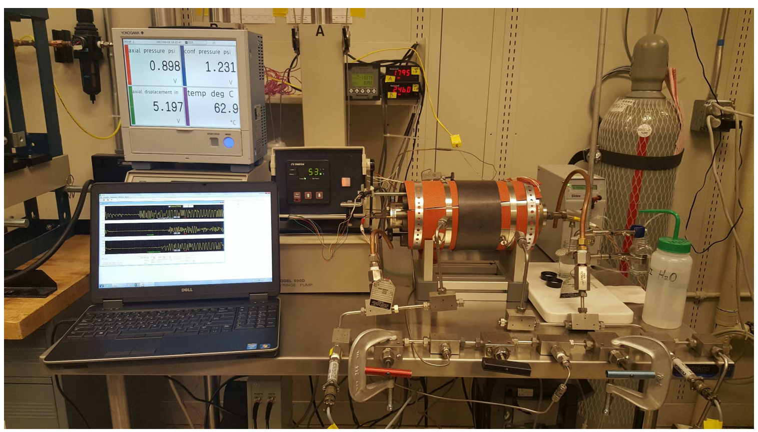
Multi-scale Geomechanics + chemistry – towards coupled chemo-mechanics for predicting seal integrity

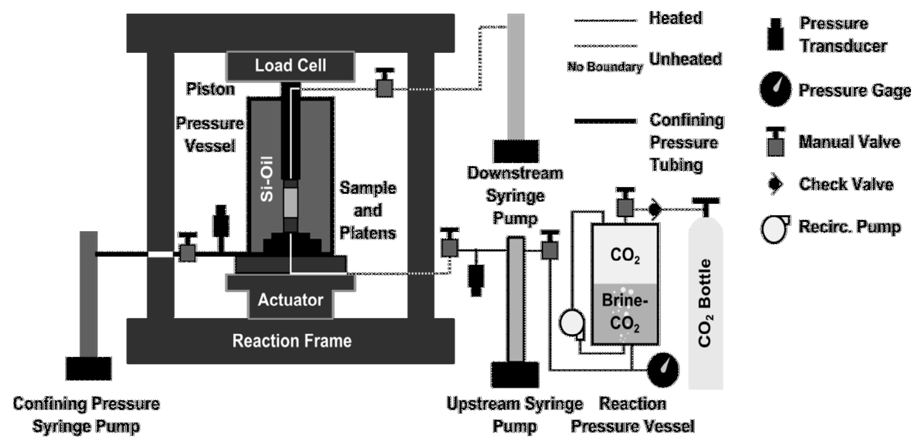


Ongoing and Future Work-Chemo-mechanic coupling

- microCT, SEM-EDS, TEM-EDS, nano-indentation, optical/Laser Confocal/AFM profilometry, and MAS-NMR





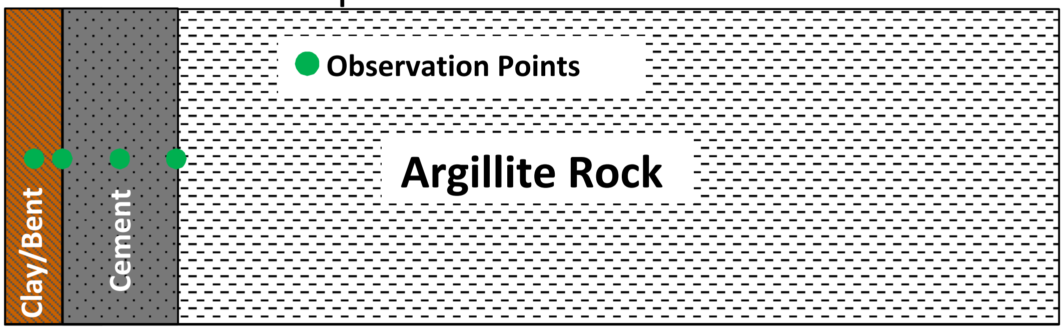


Compression Test System Brine-CO_2 Equilibration System

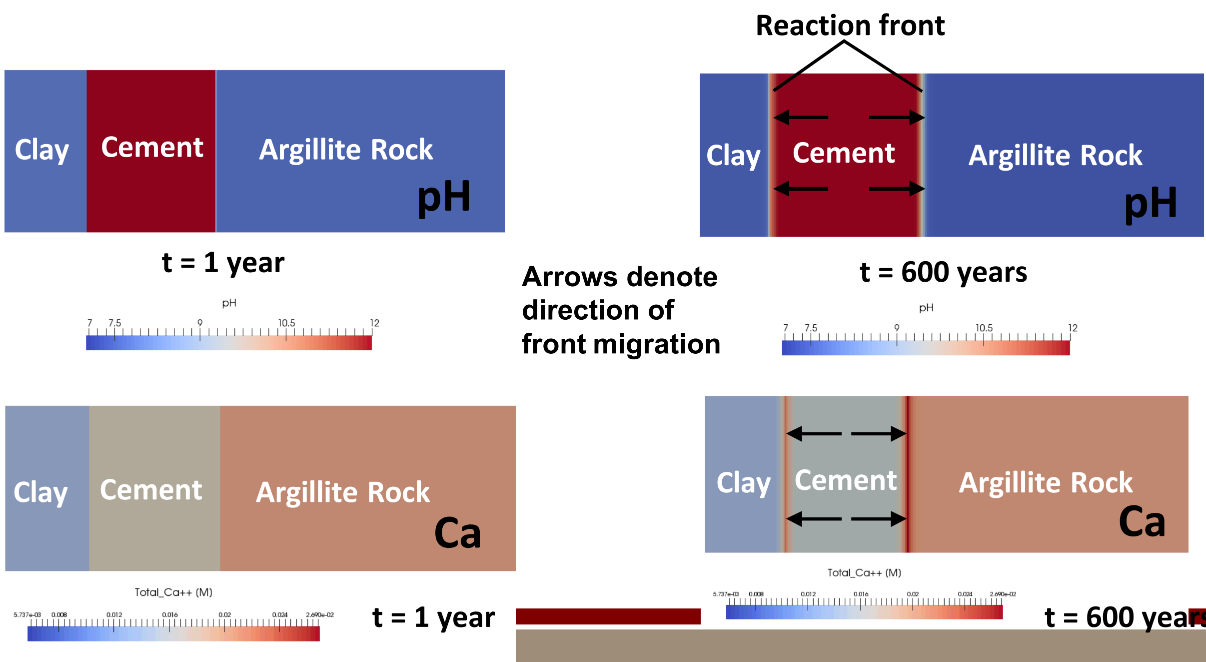
PFLOTRAN: Problem Setup & Preliminary Results

Sandia National Laboratories

Schematic representation of modeled domain



Preliminary Results



1D reactive-transport (RT) PFLOTRAN simulations:

- Simulate development of reaction front between cement and interfacing materials
- 3 material domains: clay/bentonite, cement, clay-rock
- 3 distinct pore solution chemistries
- Cement resembling OPC composition: portlandite, CSH(1.6), calcite, and ettringite
- Focus on reactivity at interfaces and reaction front migration
- Next → Interrogate simulation results:
  - Pore solution chemistry
  - Secondary phases
  - Influence on porosity

The Endgame – fit-for purpose seal materials

Sandia National Laboratories

1) Use an integrated modeling and experimental approach to fundamentally understand failure mechanism at cement-geomaterial interfaces. 2) Use this fundamental knowledge as a design basis for a fit-for-purpose seal repair material

Multi-scale Characterization
-micro-CT, velocimetry of interfaces
-post-mortem analysis(SEM, TEM, EDS, AFM)
-PFLOTRAN-Sierra Mechanics modeling

→

Interface failure
-Rate dependencies
-predominant failure modes
-stresses/strains

→

Seal Repair Material
-robust at *in situ* conditions
-ductility
-penetration into flaws
-self-healing

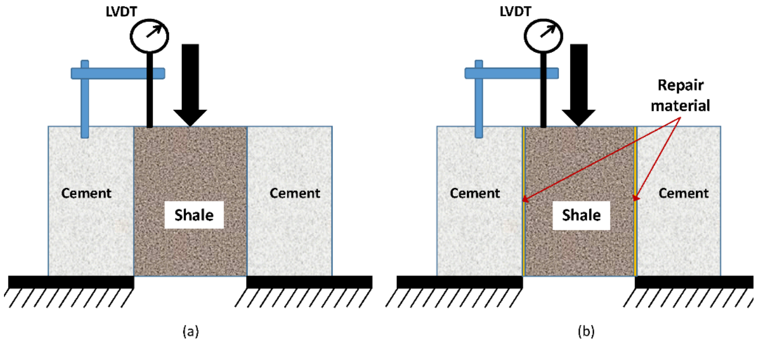
Conclusions

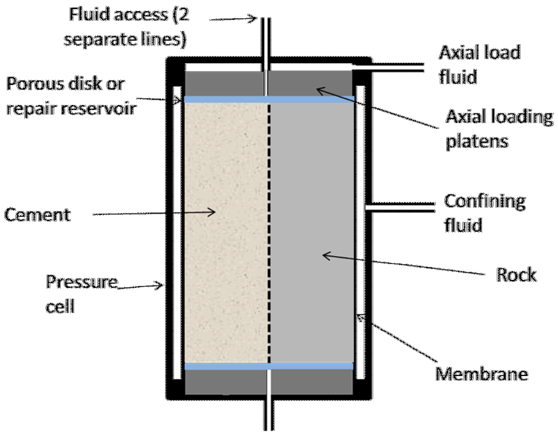
- Laboratory scale experiments have developed data that represents permeability of microannuli, strength of cement and epoxy sealant materials
- Laboratory-scale computational model shown to effectively simulate behavior of materials in lab-scale tests
- Field-scale model predicts stress-strain environment 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 to be investigated
- Model development continues, including eventual comparison of predicted field stresses and displacement to available site data

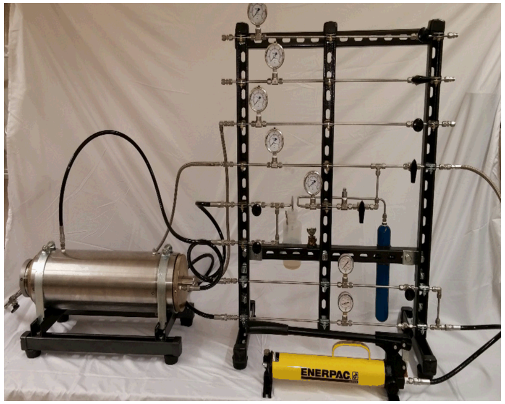
Backup Slides

Seal Repair Design and Evaluation

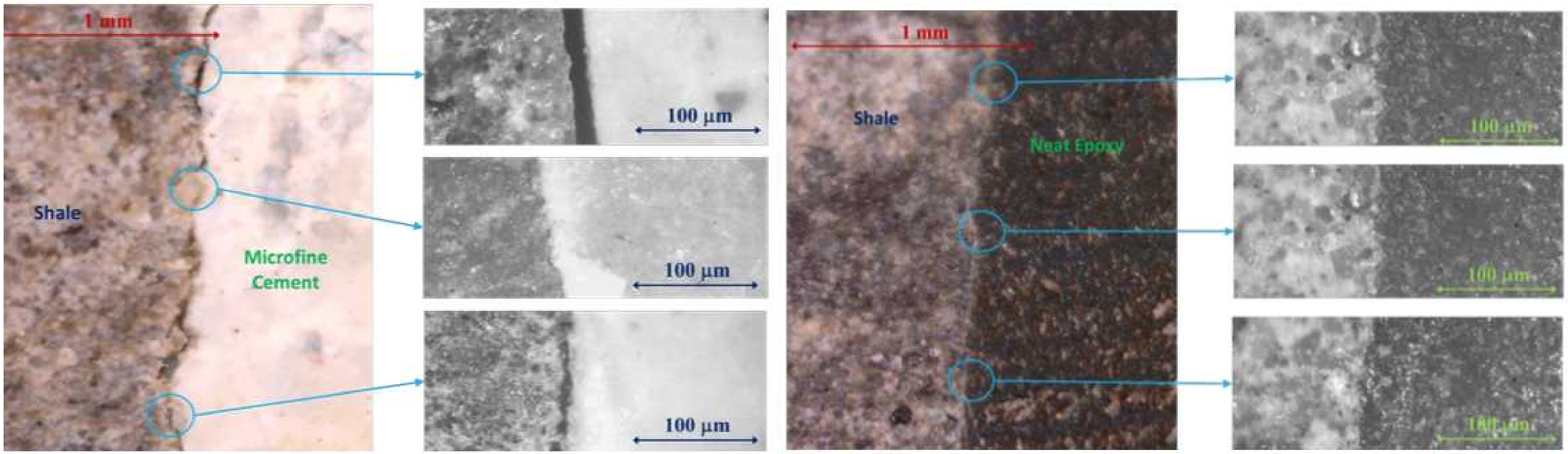
- Synthesis and Characterization
  - Bond strength measurements
  - Rheology measurements
  - Polymer and nanocomposite engineering
- Evaluation
  - Seal mock-up
  - Permeameter for post-repair gas and liquid flow measurements





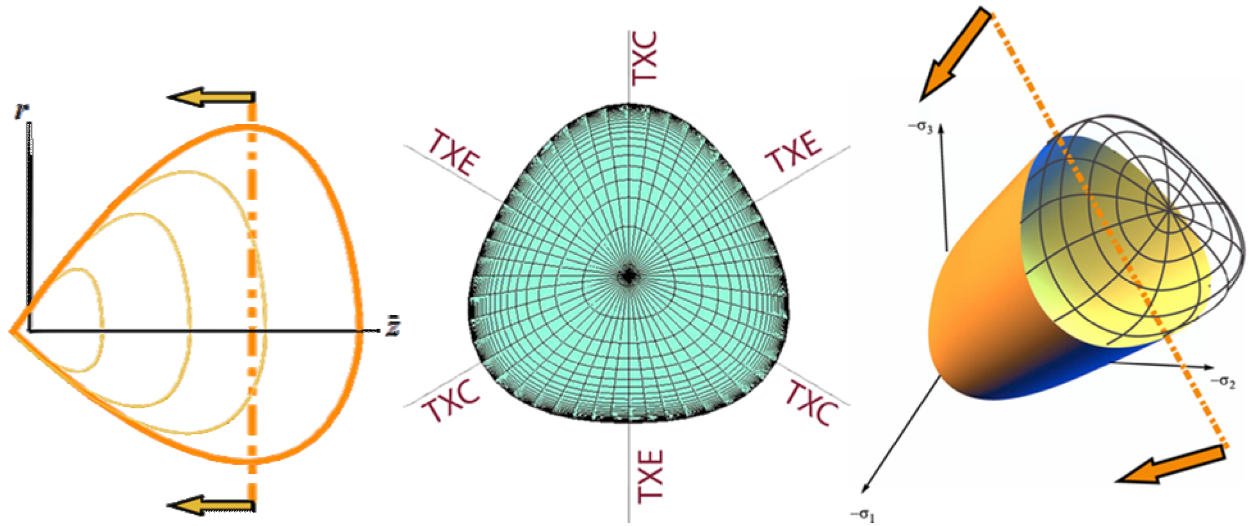


Conventional repair methods vs. Nanocomposite Repair Material



Kayenta

Kayenta is a three-invariant plasticity material model suitable for modeling quasi-brittle materials such as concrete and rock



Activities to date:

1. Kayenta model updated with bug fixes
2. Kayenta model source code migrated to new server
3. Kayenta model source code tests updated to newer test harness
4. Elastic and poro-elastic parameters fit to limited concrete data