Wellbore Integrity and Mitigation:

Foamed Cement Interactions with CO_2

Presenter: Dr. Barbara Kutchko

US DOE/ NETL

U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology, Innovation and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

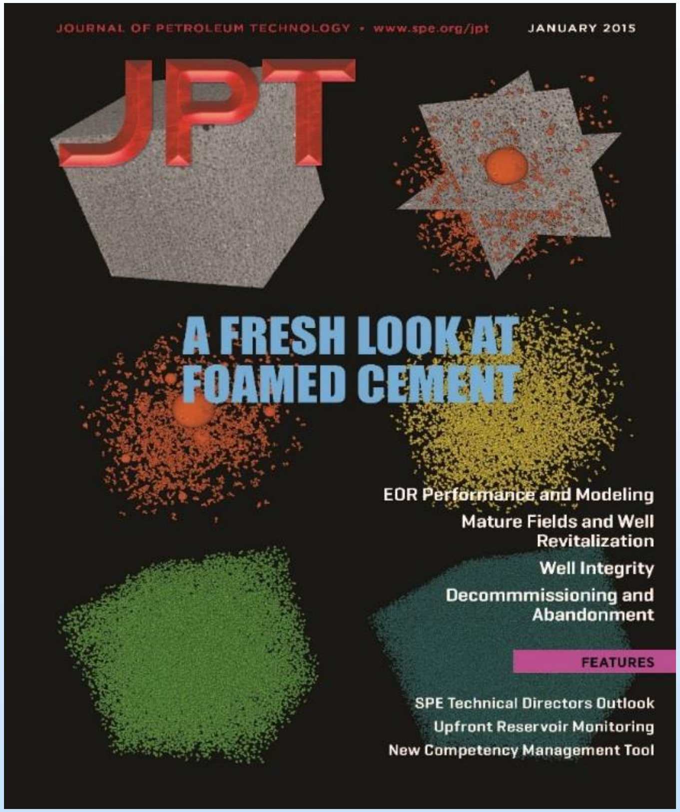
August 16-18, 2016

Benefit to the Program

- As CO_2 storage options are being evaluated in the United States, the possibility of utilizing offshore formations in the GoM is being considered.
- To mitigate shallow hazards in deepwater Gulf of Mexico, foamed cement systems are recommended by the API 65.
- Previous *in situ* experiments show that the cement, host rock and/or casings result in alteration that may compromise wellbore integrity.

What is Foamed Cement?

- Mixture of cement, foaming agents and N_2 gas
- Ultra low-density
- Unique resistance to temperature and pressure-induced stresses
- Minimal shrinkage
- Used in formations that are unable to support the annular hydrostatic pressure exerted by a conventional cement slurry

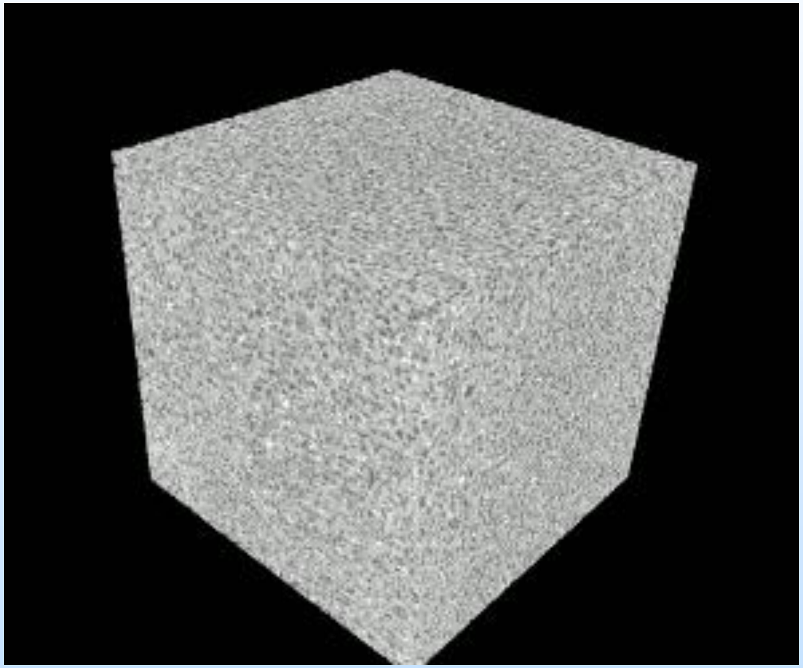


Key Facts:

- ✓ First GoM foam cement job performed in early 90’s
- ✓ Presently, 80 - 90 % of wells drilled in GoM are using foam cement
- ✓ It is often the cement system of choice for shallow flow conditions in the Gulf of Mexico (as outlined in *API RP 65*)

Project Overview: Goals and Objectives

- Evaluate the geochemical and geomechanical impacts of foamed cement due to interactions with CO_2-saturated brine at subsurface conditions typical in the GoM.
- To provide science and guidance on the risk associated with carbon storage in regions of the GoM where foamed cement use is common.



170,000 individual bubbles identified in 1 cm^3 subsample of a 10% Foam Quality cement

Technical Status

Data Sets

1. Generated atmospheric samples using API RP 10 B-4 procedures
   - Class H neat
   - 3 Foam Qualities (10%, 20%, 30%)

In situ Cure & Exposure

1. 28 day cure at atmospheric conditions
2. Exposed to SCCO2 for 7, 14, 28, 56 days

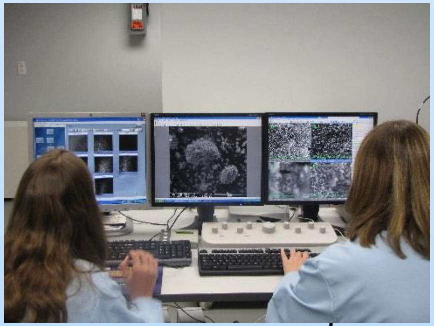
Analysis

Visualization

1. Multi-scale computed tomography scanning
2. Scanning Electron Microscopy

Mechanical testing

1. Porosity, permeability and strength measurements
   - Young's modulus
   - Poisson's ratio



Geochemical

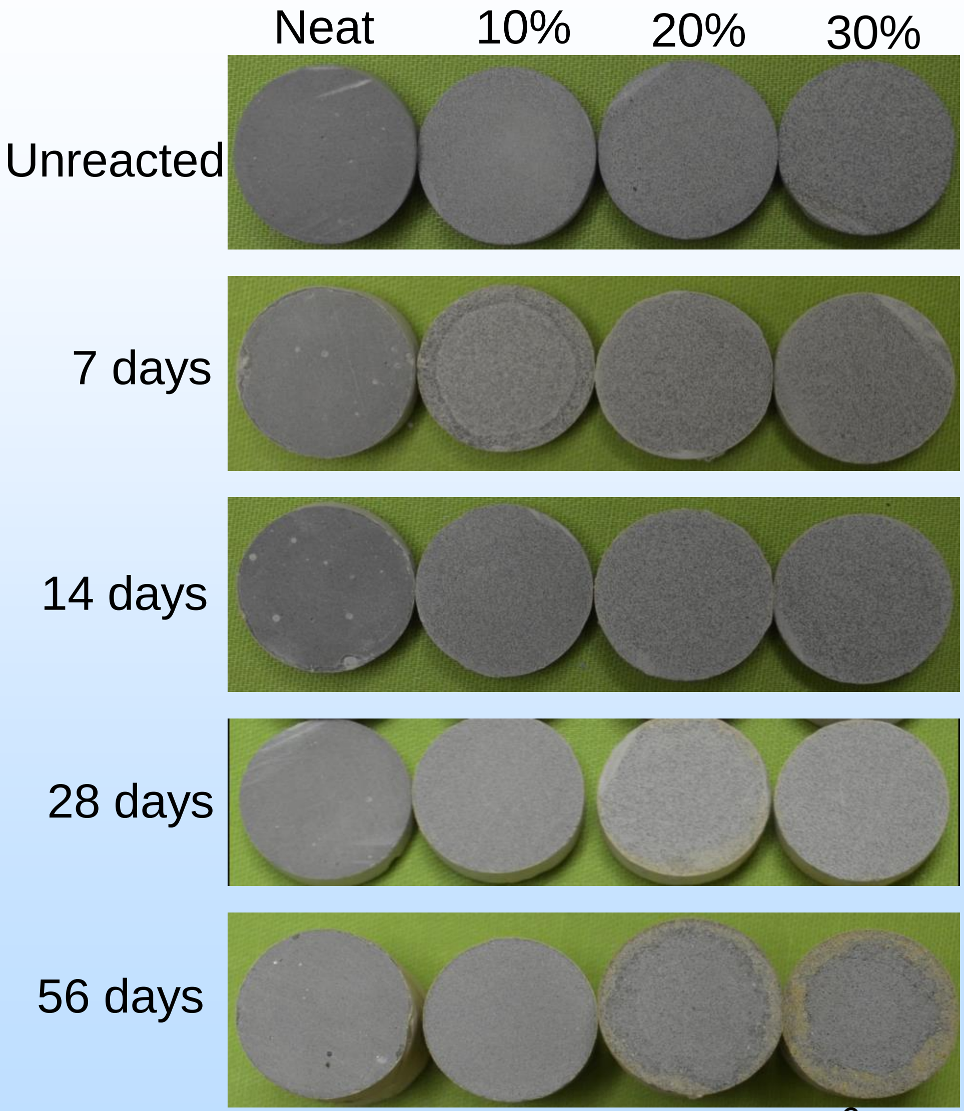
1. XRD
2. ICP-MS/OES
3. SEM-EDS

Experimental Conditions

Standing Parr Autoclaves

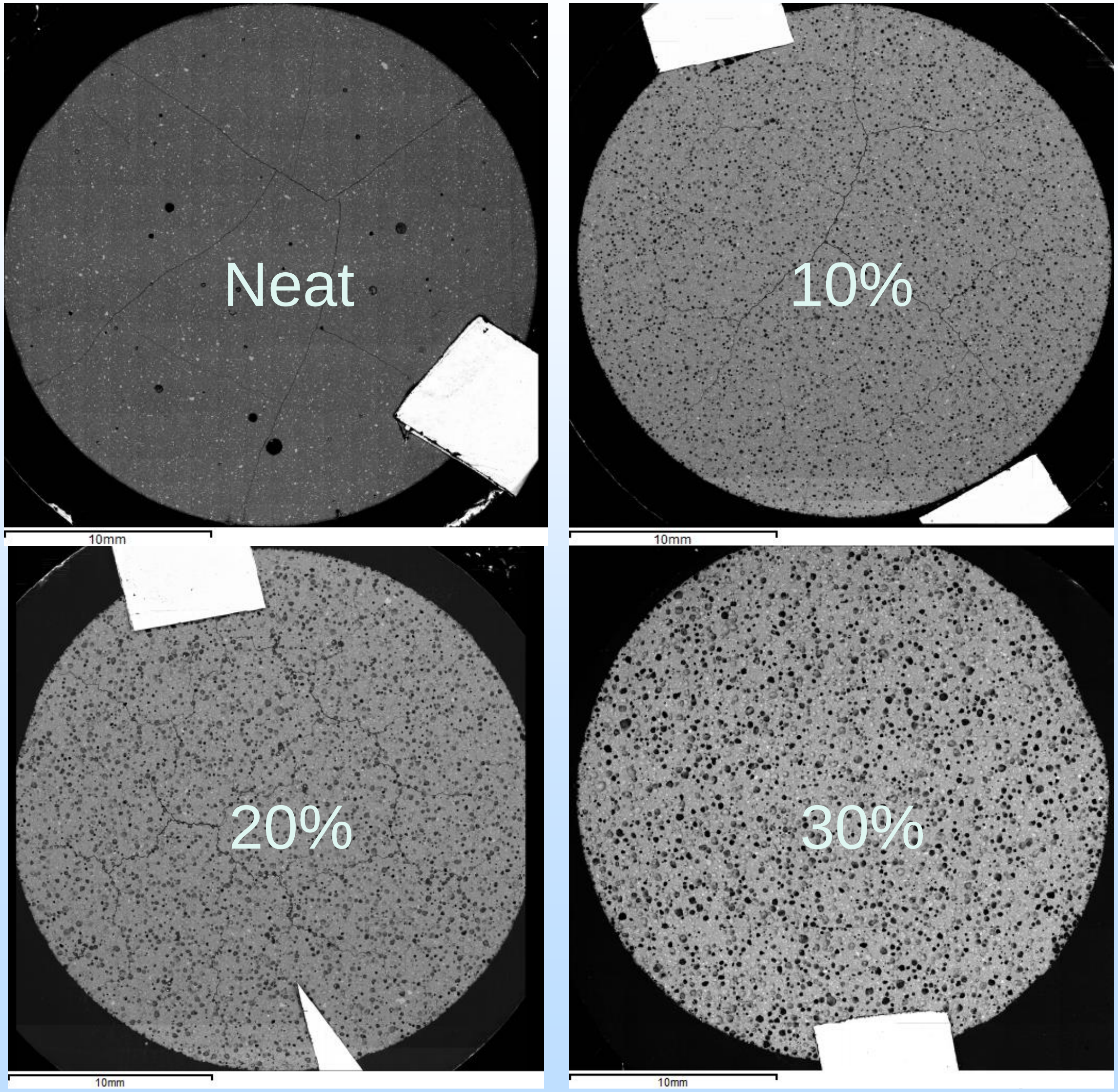
- Static operation
- 4: 1.2-liter C-20 vessels Parr autoclaves
- 4200 psig @ 50˚C
- Samples cured for 28 days
- 7, 14, 28, 56 days of exposure at $SCCO_2$

Determine the potential secondary mineral formation and degradation rates

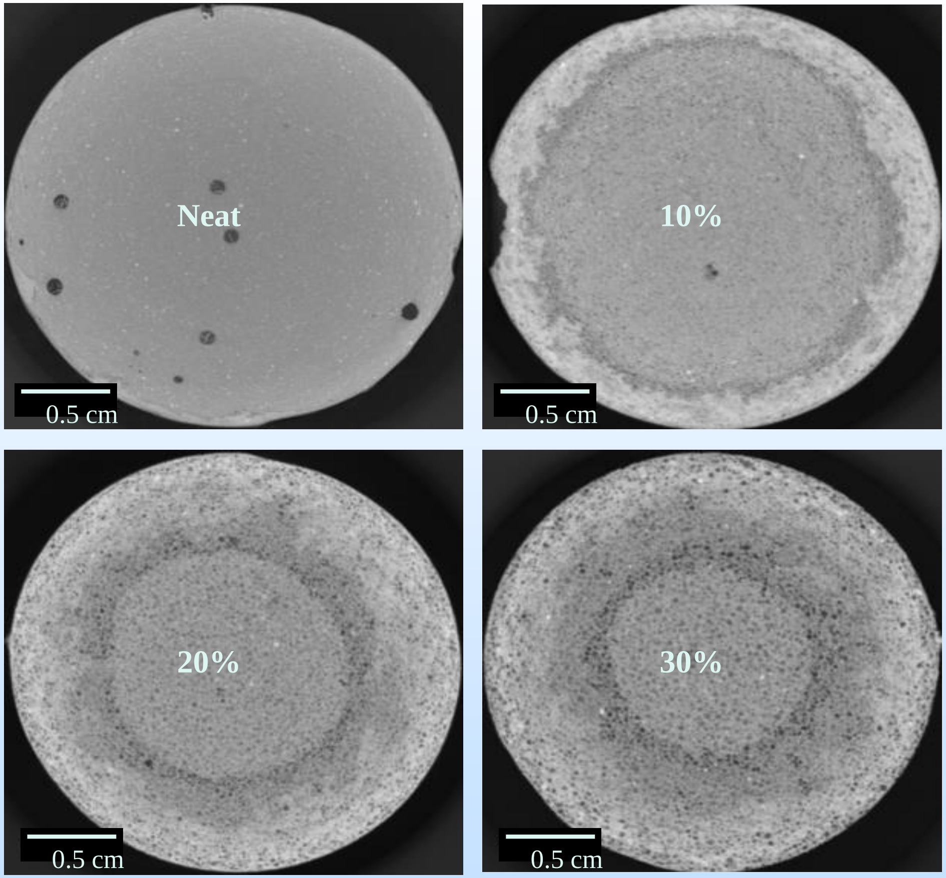


SEM Analysis: Pre-Exposure

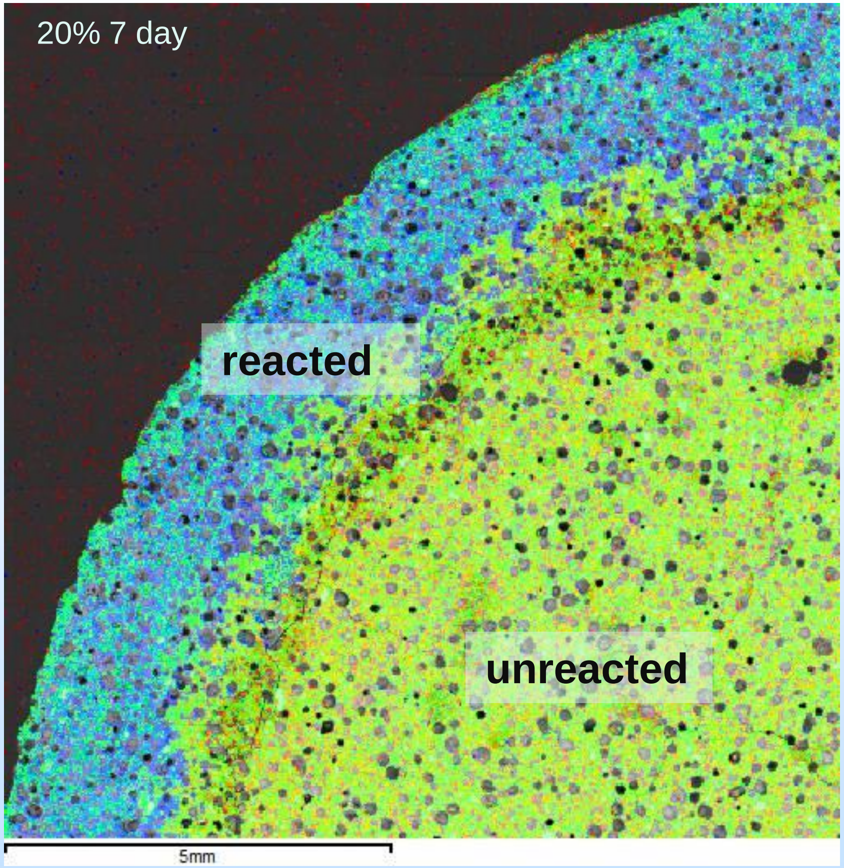
- **Montaged** SEM-BSE images (200x) of unreacted foam cement
- Processing suite ongoing
- Expect bubble size distribution/size analysis



SEM Analysis: Post-Exposure

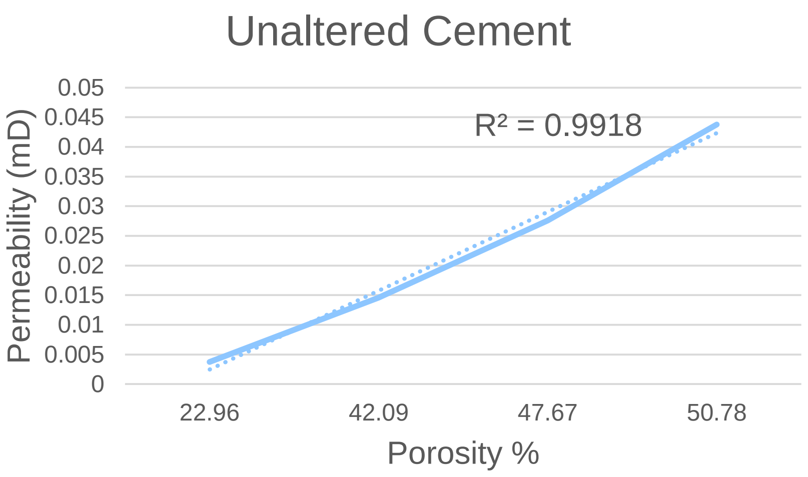


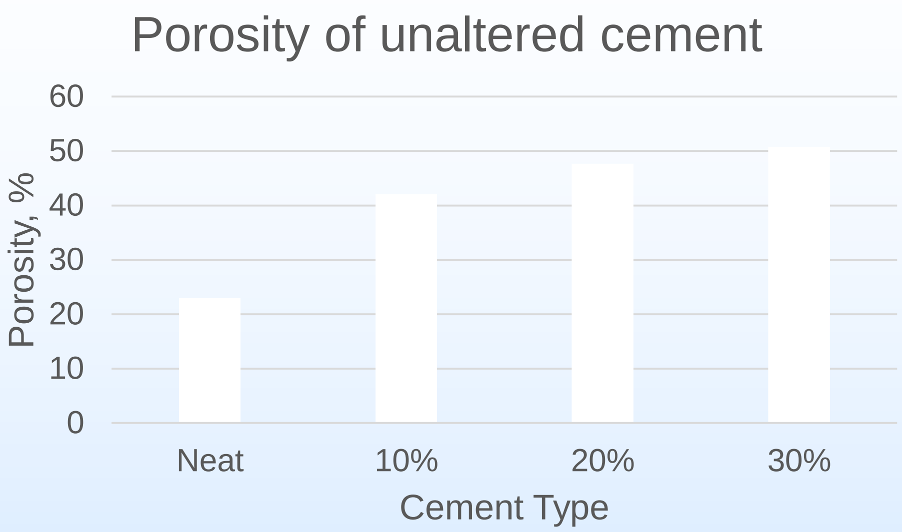
X-ray CT images (slices in Y-direction) of cement cores reacted in CO_2 saturated NaCl brine for **56 days**

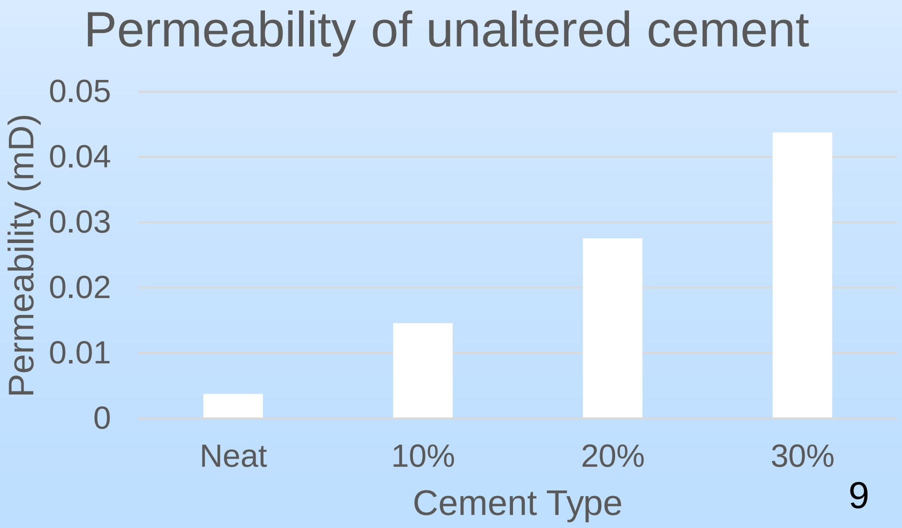


SEM-EDS map of altered cement (20% foam quality) after 7 days.
Green: Cl; Blue: Na; Red: Si

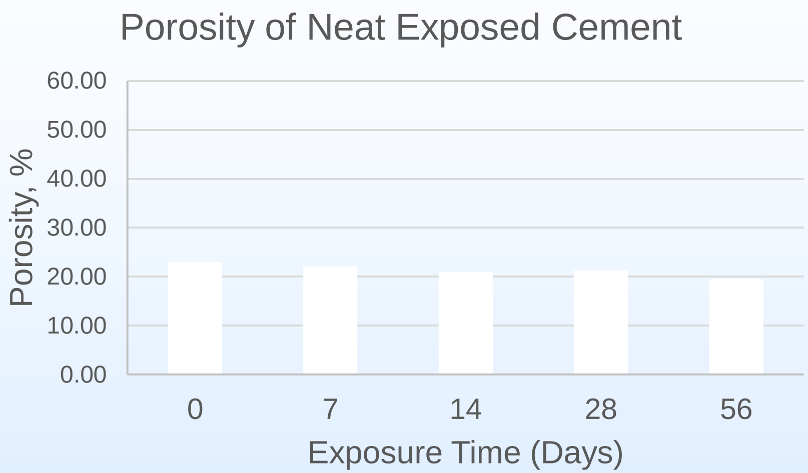
Physical and Mechanical Properties

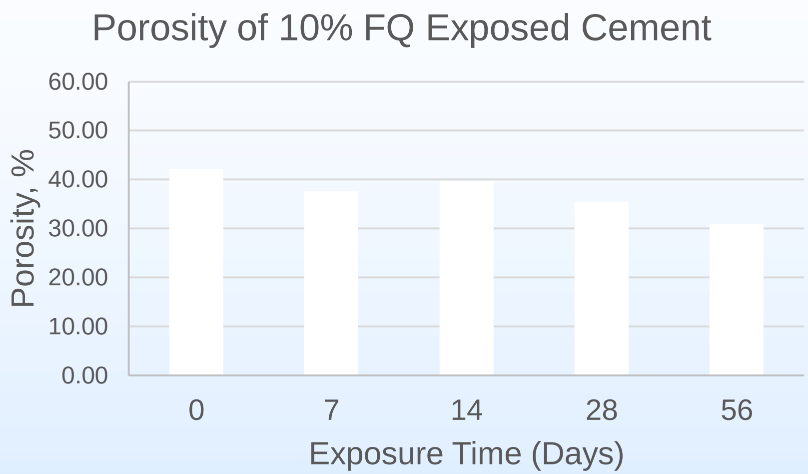


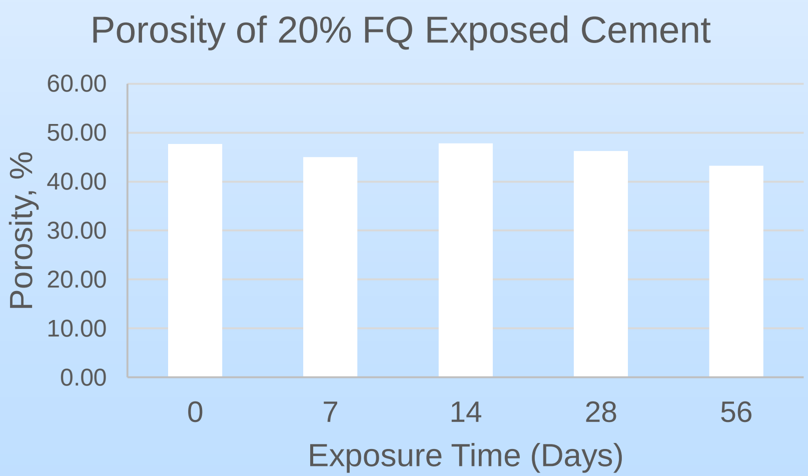


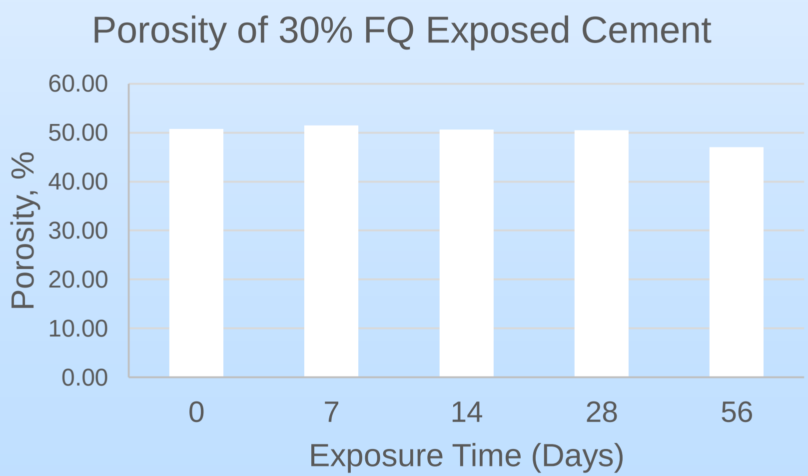


Physical and Mechanical Properties

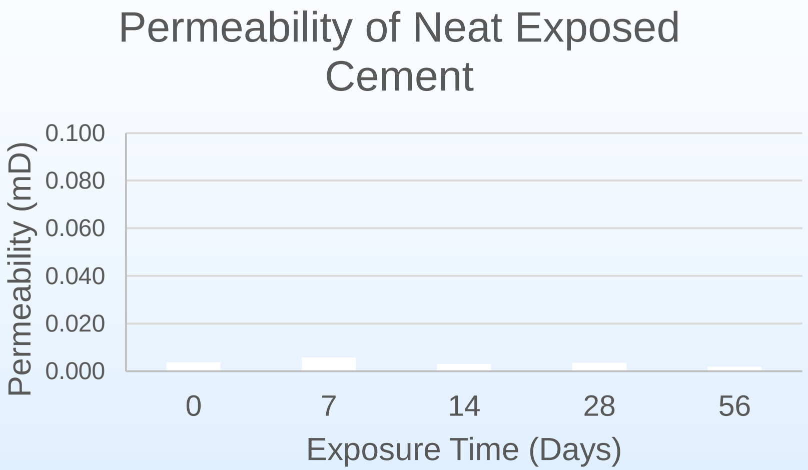


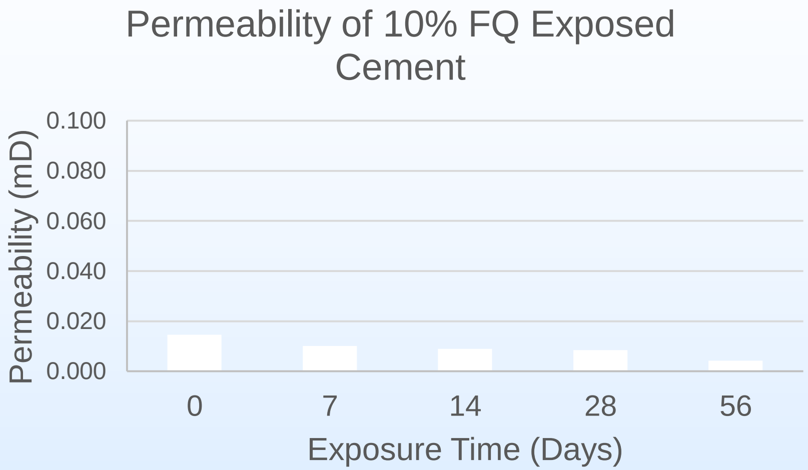


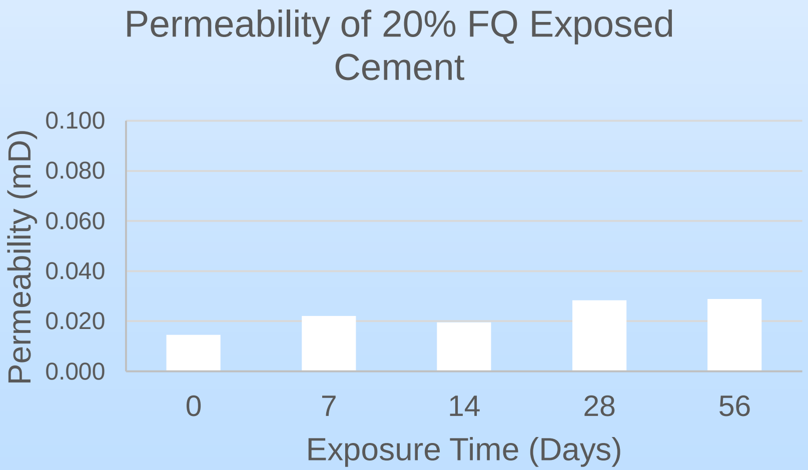


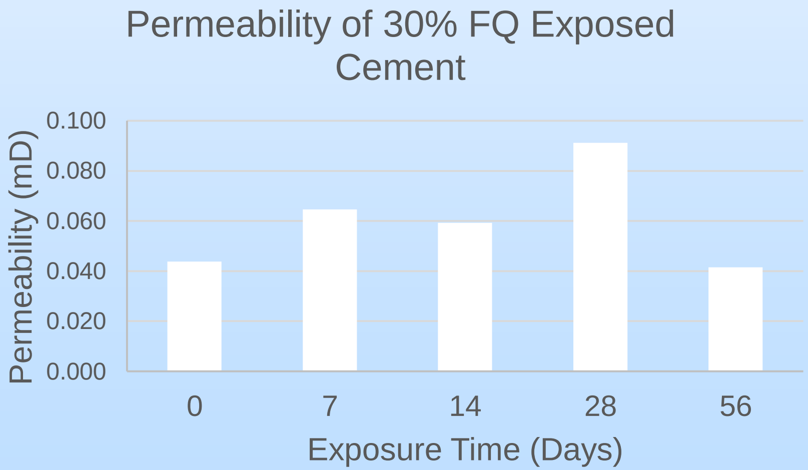


Physical and Mechanical Properties









Physical and Mechanical Properties

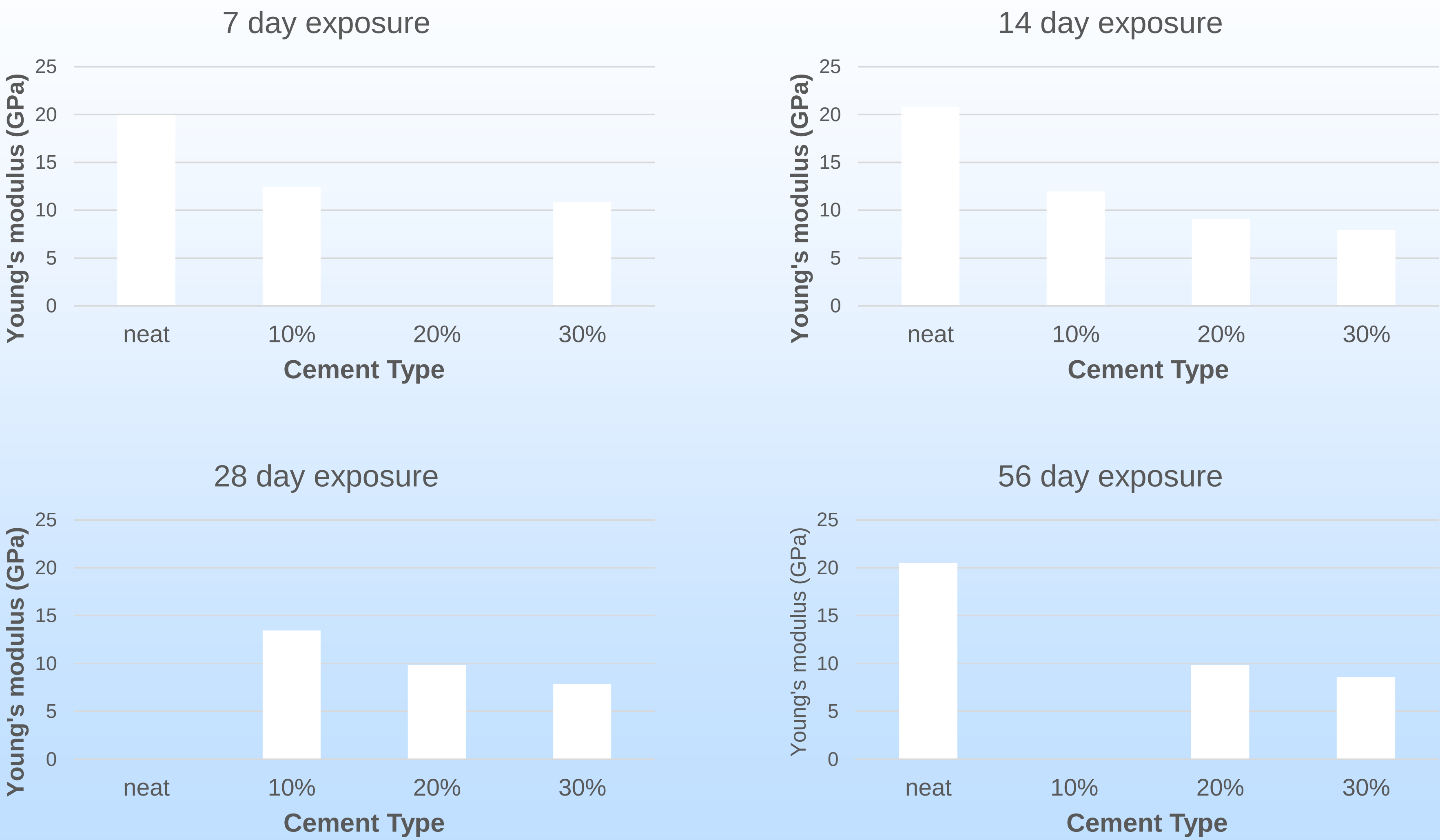
AutoLab 1500 automatic servo hydraulic triaxial system (NER, Inc) simulates in-situ conditions up to 90MPa overburden and 50MPa pore pressure

Dual Purpose Core Holder Assembly (for permeability and sonic velocity measurements)

a) ready to insert to the high pressure vessel

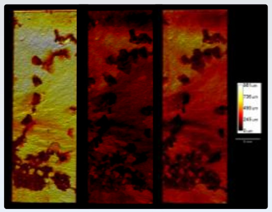
b) disassembled (core between holder heads)

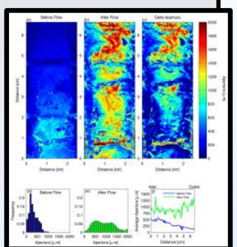
Physical and Mechanical Properties

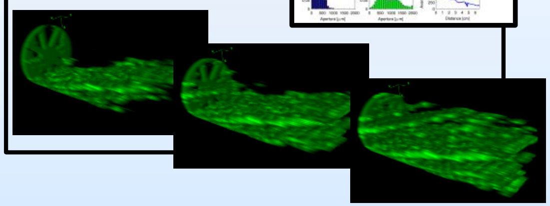


Multi-Scale CT Flow and Imaging Facility

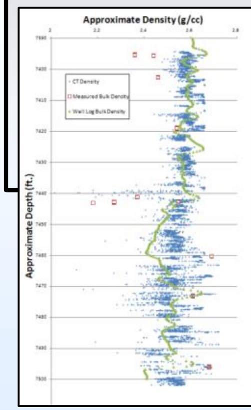
Measuring flow at in situ P, T, stress, and geochemical conditions

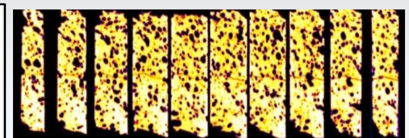


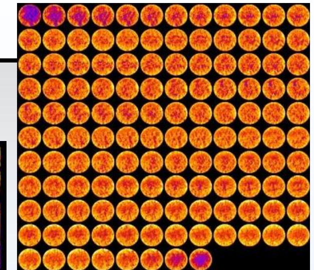




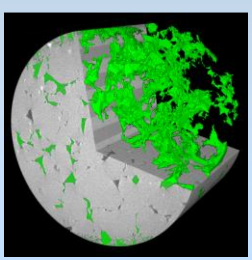
CT/well log comparison

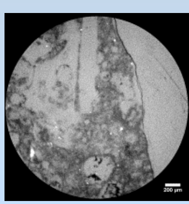






Simulating flow through pore and fracture networks

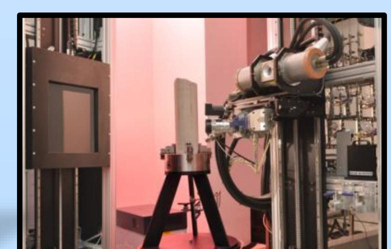


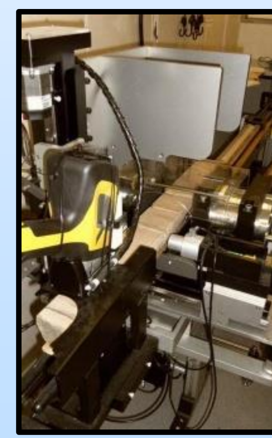


Micro CT Scanner
- Resolution 10^{-6} to 10^{-5} m
- Pore scale

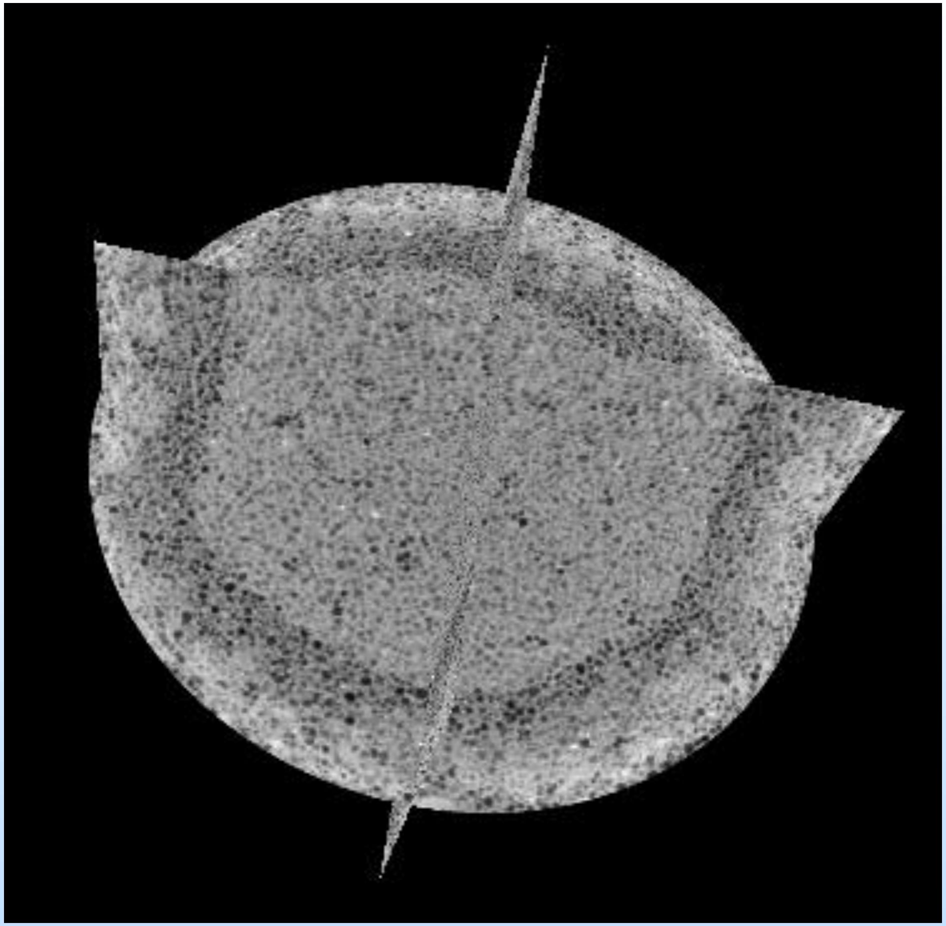
Industrial CT Scanner
- 10^{-6} to 10^{-3} m
- Pore & core scale
- Pressure & flow controls

Medical CT Scanner
- 10^{-4} to 10^{-2} m
- Core scale
- Pressure, temperature, and flow controls



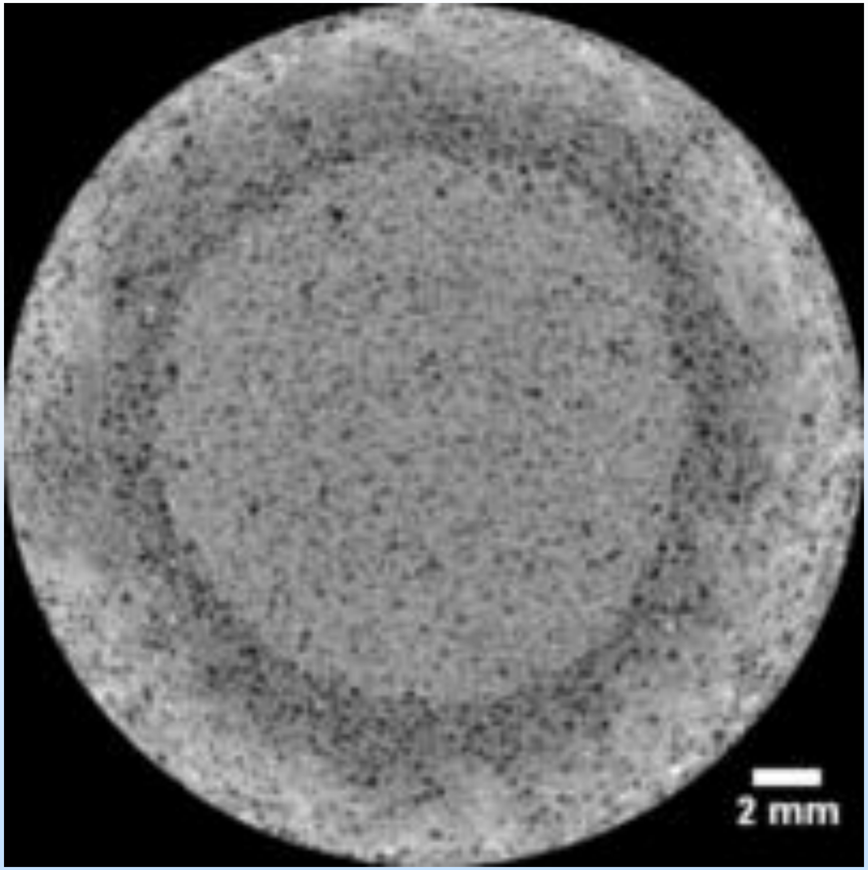


CT Imaging



Small subsection of a 30% Foam Quality cement after 56 days of exposure, shown with an orthogonal view

CT Imaging



30% Foam Quality cement after 56 days of exposure, subsection that scrolls through the core to visualize reactions

Accomplishments to Date

Historical - FY 15	• NA – New task in FY16
Current - FY 16	• Pre- Post physical properties completed • Pre-Post CT scans completed • SEM and CT image analysis ongoing • Mechanical properties continuing
Future - FY 17	• Continued evaluation of the impact of injected CO_2 on the integrity of foamed cement. • Rate extrapolation • Correlation of chemical and mechanical alteration

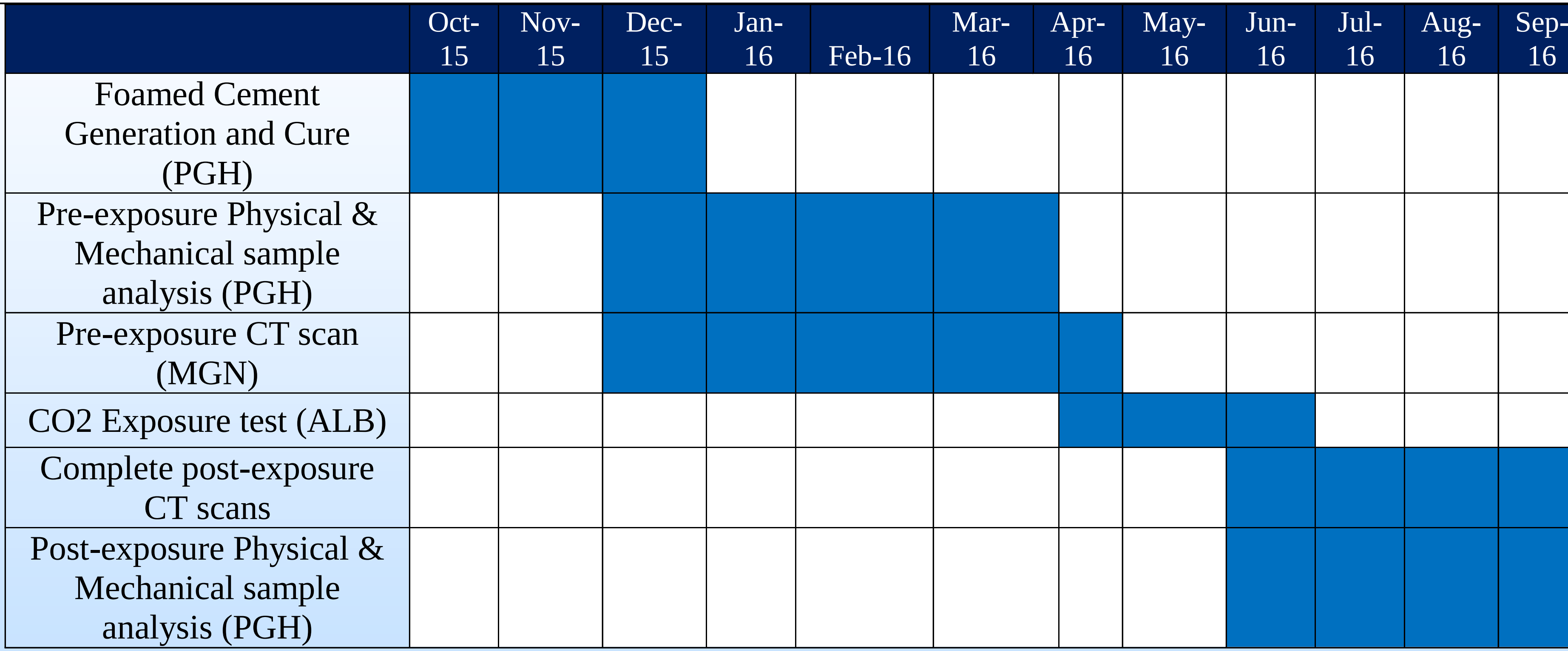
Synergy Opportunities

- Wellbore integrity cross-cuts across all of NETL's portfolios:
  - Offshore
  - Onshore (UNC or otherwise)
  - CO_2 Storage
- Wellbore integrity teams consist of engineers (mechanical, petroleum, environmental), geologists (geophysics, geochemistry), material scientists, fluids specialists, modelers,etc.
- Issues include corrosion (steel components, cement), mechanical, water, cement chemistry, cement mechanics (thermal & pressure cycles), reservoir, etc.
- *Everything we learn from one wellbore integrity project can be applied to the other ongoing projects.*

Organization Chart

Project Participants	NETL Teams	Utilized
• Dr. Circe Verba • Dr. Nik Huerta • Dr. Dustin Crandall • Mr. Rick Spaulding • Dr. Scott Montross • Mr. Jim Fazio • Mr. Bryan Tennant • Dr. Barbara Kutchko	Structural Materials Geophysics Materials Characterization Biogeochemistry Geology & Geospatial	• Pittsburgh Geomechanics Laboratory: Chandler Engineering Waring Blenders (cement generating equipment), AutoLab, He-Porosimeter, and N2-Permeameter, various rock saws, and coring equipment • Morgantown CT scanner laboratory, Image processing techniques (high end computers & software needed for image analysis) • Scanning Electron Microscopes, Sample preparation facilities (i.e. polishing wheels and supplies); X-Ray Diffraction facilities • NETL-Albany High Pressure Immersion and Reactive Transport Laboratory • Scanning Electron Microscopes, Sample preparation facilities (i.e. polishing wheels and supplies); X-Ray Diffraction facilities

Gantt Chart


Oct-15
Nov-15
Dec-15
Jan-16
Feb-16
Mar-16
Apr-16
May-16
Jun-16
Jul-16
Aug-16
Sep-16
Foamed Cement Generation and Cure (PGH)
Pre-exposure Physical & Mechanical sample analysis (PGH)
Pre-exposure CT scan (MGN)
CO2 Exposure test (ALB)
Complete post-exposure CT scans
Post-exposure Physical & Mechanical sample analysis (PGH)

NETL Research Presentations and Posters

TUESDAY, AUGUST 16, 2016

- **12:40 PM** Monitoring Groundwater Impacts - Christina Lopano
- **1:55 PM** Multi Variate Examination of the Cause of Increasing Induced Seismicity – Kelly Rose
- **4:00 PM** Exploring the Behavior of Shales as Seals and Storage Reservoirs for CO_2 – Ernest Lindner
- **5:05 PM** Risk Assessment for Offshore Systems – Kelly Rose
- **5:30 PM** Metal-based systems in Extreme Environments – Jeff Hawk
- 6:15 p.m. **Poster Session**
  - Kelly Rose - Developing a carbon storage resource assessment methodology for offshore systems
  - Doug Kauffman - Catalytic Conversion of CO2 to Ind. Chem. And eval. Of CO2 Use and Re-Use
  - Liwel Zhang - Numerical simulation of pressure and CO2 saturation above an imperfect seal as a result of CO2 injection: implications for CO2 migration detection

WEDNESDAY, AUGUST 17, 2016

- **12:30 PM** MVA Field Activities – Hank Edenborn
- **2:35 PM** Resource Assessment – Angela Goodman
- **2:35 PM** Understanding Impacts to Air Quality from Unconventional Natural Gas – Natalie Pekney
- **4:05 PM** Improving Science-Base for Wellbore Integrity, Barrier Interface Performance – Nik Huerta
- **5:20 PM** Wellbore Integrity and Mitigation – Barbara Kutchko

THURSDAY, AUGUST 18, 2016

- **1:00 PM** Advances in Data Discovery, Mining, & Integration for Energy (EDX) – Kelly Rose
- **1:25 PM** Methods for Locating Legacy Wells – Garrett Veloski
- **2:05 PM** Reservoir Performance – Johnathan Moore
- **3:05 PM** Geochemical Evolution of Hydraulically-Fractured Shales – Ale Hakala

UCR Unconventional Resources

https://edx.netl.doe.gov/carbonstorage/
https://edx.netl.doe.gov/offshore/
https://edx.netl.doe.gov/ucr/

NETL RESEARCH CARBON STORAGE PROGRAM

Appendix

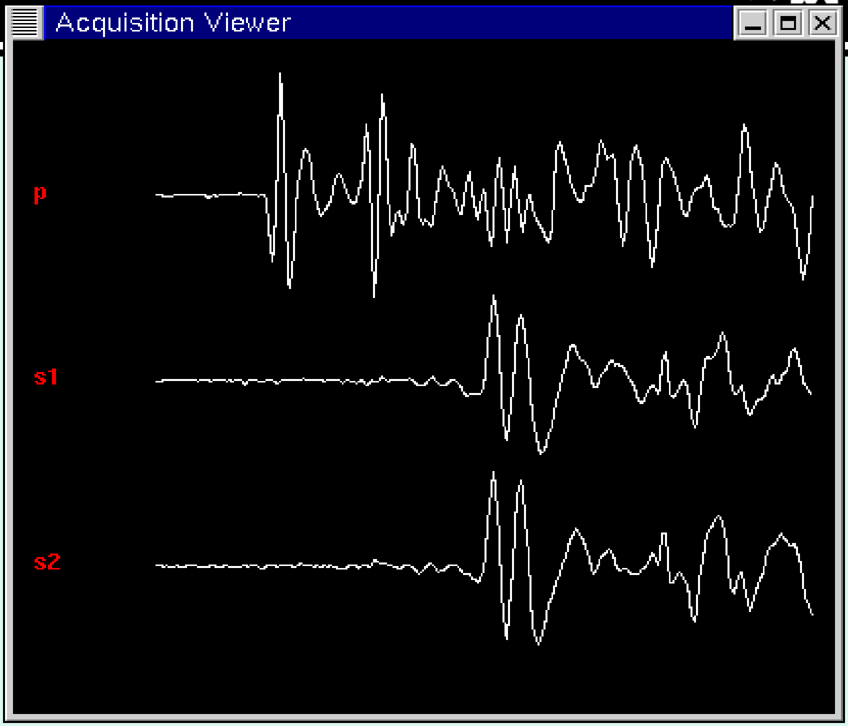
– These slides will not be discussed during the presentation, but are mandatory

Extra Slides

Physical and Mechanical Properties

- Based on sonic information we can calculate stress-strain coefficients

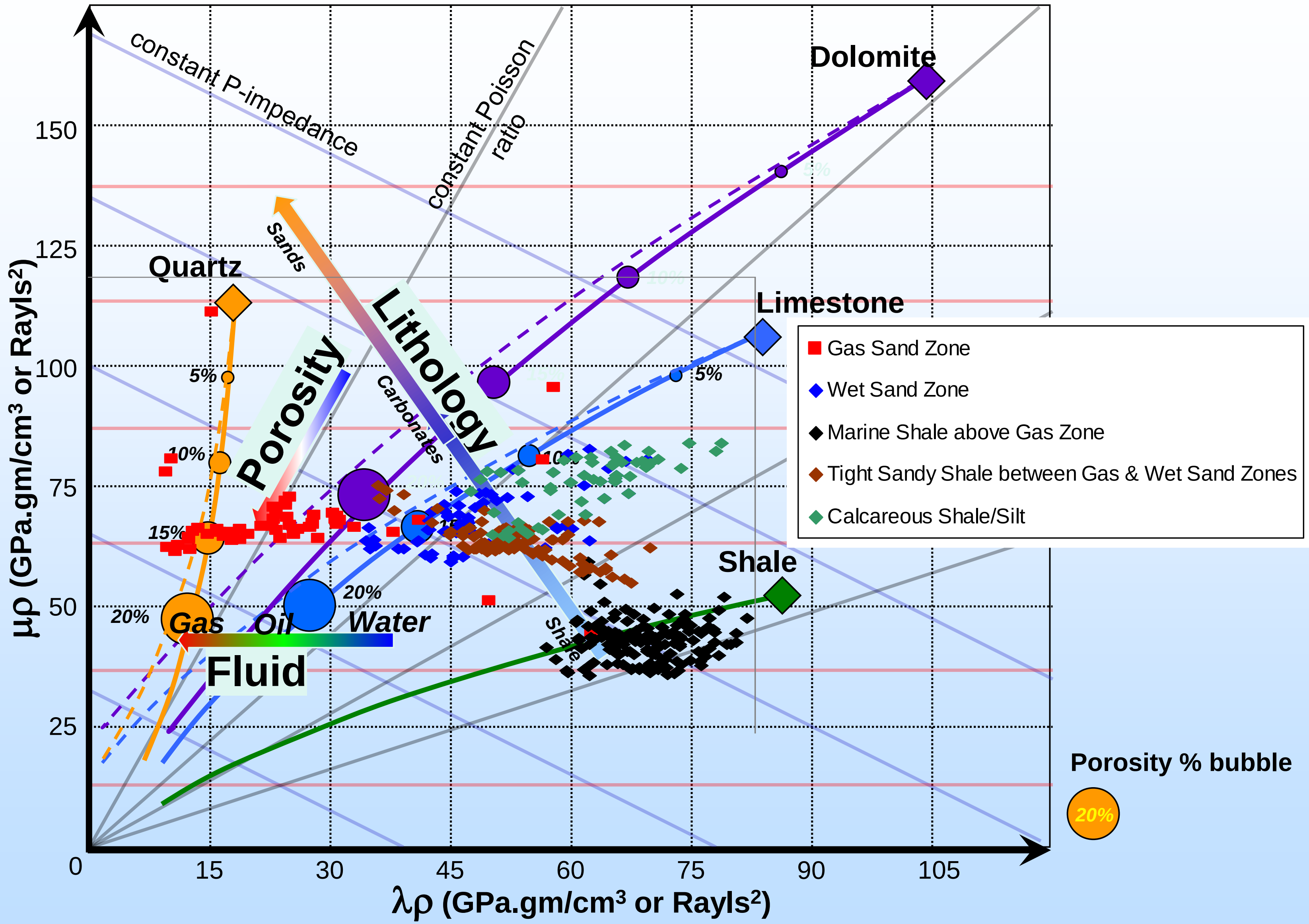
- Velocity of P (compression) waves and S (shear) waves:
  - Lamé Parameters: **Rigidity Mu (μ) and "Pure Incompressibility" Lambda (λ)**
  - Young's Modulus
  - Poisson's Ratio



Common moduli resulting from medium's measurement condition:

"Compressional P-wave Modulus" (Bound uni-axial compression)	$M = \lambda + 2\mu$	
Young's Modulus (Unbound uni-axial compression)	$E = \mu(3\lambda+2\mu)/(\lambda+\mu)$	$E = M - 2\lambda\nu$
Bulk Modulus	$K = \lambda + (2/3)\mu$	$K = M - (4/3)\mu$
Poisson's ratio	$\nu = \lambda/(2\lambda + 2\mu)$	

Fluid, Porosity & Lithology directions in LambdaRho (λρ), MuRho (μρ) space



(Adapted from Hoffe, Perez and Goodway CSEG convention 2008)