LANL Sequestration Activities: Long-term Wellbore and Caprock Seal Integrity
FWP FE-715-16-FY17

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Poland and Davis (1969) “Land Subsidence Due to Withdrawal of Fluids"
Outline/Motivation

• Project goal: Quantify possible leakage processes of CO₂ through wellbore and caprock seals

• Geomechanical model of injection-induced damage in wellbore systems
  – Injection/production results in expansion/contraction of the reservoir
  – Shear stress results that has the potential to damage the well-formation interface

• Geomechanical experiments on fracture-permeability behavior of caprock

• Numerical study and summary of geochemical self-sealing processes in wellbore systems
Technical Status

• Completed: “Engineering Prediction of Axial Wellbore Shear Failure due to Reservoir Uplift”

• Modified and enhanced a triaxial direct-shear coreflood system with simultaneous x-ray radiography/tomography

• Completed: experimental study of potential fracture leakage processes in shale as caprock

• Completed: “Hydrated Portland Cement as a Carbonic Cement: The Mechanisms, Dynamics, and Implications of Self-Sealing and CO$_2$ Resistance in Wellbore Cements”
Geomechanical Model of Injection-Induced Damage to Wellbores

- Analytical model that evaluates wellbore integrity in response to reservoir uplift
- Shear and tensile failure at cement interfaces in response to coupled casing-cement-rock poro-mechanics
- Initial state of stress of cement a key component of analysis
- Verified with Abaqus numerical model
Problem Set-up

Effective Stress Changes

\[ \sigma' = \sigma - \alpha p \]

Uplift function of elastic properties

\[ \Delta \varepsilon_z = \frac{\Delta \sigma'_z}{E} \left(1 - \frac{2v^2}{1-v} \right) \]
Shear Criteria at Well Interface

Stress Diagram of Well

Shear Criteria

\[ 0 = \left( R_o^2 - R_i^2 \right) d\sigma_z' - 2dzR_o\tau \]

\[ \tau_{\text{max}} = \sigma_n' \tan \phi + c_c \]

\[ L = \frac{\left( R_o^2 - R_i^2 \right) \Delta \sigma_z'}{2R_o \left( \sigma_n' \tan \phi + C \right)} \]

Tensile Criteria

(Percolation)

\[ \tau \leq \sigma_n' - (p_W - \alpha p_P) \]
### Parameters for Base Case

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Injection overpressure, MPa ($\Delta p$)</td>
<td>6.000*</td>
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</tbody>
</table>

- **Non-percolating**: Injection fluids do not enter damaged annulus
- **Percolating**: Injection fluids enter damaged annulus
Sensitivity to Friction Angle

N.P. = Non-percolating
P. = Percolating
C.S. = Cement-steel
C.R. = Cement-reservoir
Sensitivity to Cement Density

N.P. = Non-percolating
P. = Percolating
C.S. = Cement-steel
C.R. = Cement-reservoir

Base case
Sensitivity to Injection Pressure

N.P. = Non-percolating
P. = Percolating
C.S. = Cement-steel
C.R. = Cement-reservoir
Sensitivity to Depth

N.P. = Non-percolating
P. = Percolating
C.S. = Cement-steel
C.R. = Cement-reservoir

Base case
Numerical Validation

Stress Distributions

Radial

Vertical

Cross

Failure Length

(a) 

(b) 

(c)
Conclusions for Well Geomechanics

- We developed a system of analytical equations that allows calculation of stress and failure in wellbore systems subject to changing reservoir pressures.
- Shear failure and fluid percolation are most sensitive to cement density, injection pressure, and depth of the reservoir.
- The equations provide a rapid and effective way of designing wells for planned injection operations.
- The equations provide a rapid and effective way of evaluating whether wells in the Region of Interest are subject to potential injection-induced shear failure and leakage.

Frash and Carey (submitted) SPE Journal
Hydrated Portland Cement as a Carbonic Cement: The Mechanisms, Dynamics, and Implications of Self-Sealing and CO$_2$ Resistance in Wellbore Cements

- Newly developed model of self-sealing behavior in cement associated with CO$_2$ and brine flow
- See poster by George Guthrie et al. for details
- Self-sealing conditions arise for large range in cement and reservoir properties
- For constant flow conditions, self-sealing conditions migrate at velocity proportional to fluid velocity and maintain precipitation-dominated for sealing-favorable periods of time
- CO$_2$-reacted Portland cement is a “carbonic cement” in the same sense that H$_2$O-reacted Portland cement is a hydraulic cement
Accomplishments to Date

• Published reviews of wellbore integrity (Carey 2013; Carroll, Carey et al. (2016))

• Developed field evidence (Carey et al. 2007), experimental evidence (Carey et al. 2010; Newell and Carey 2013) and computational models (Guthrie et al. 2017) of self-sealing behavior

• Developed and demonstrated a protocol for characterizing leakage behavior in caprock as a function of stress conditions (Carey et al. 2015; Frash et al. 2016, 2017)

• Determined a threshold change in leakage potential in caprock as effective stress increases (Frash et al. 2016, 2017)

• Developed an analytical geomechanical model for analysis of stress and failure in wellbore systems (Frash and Carey, submitted)
Lessons Learned

• Portland cement is a carbonic cement with self-sealing properties; it is far more resilient than originally thought
  – Coupled casing corrosion and cement carbonation is not yet understood
  – Experimental geomechanics of wellbore systems is just beginning
• Caprock integrity characterization involves more than determining low permeability; fracture-permeability behavior is key to understanding risk of leakage
  – Much work remains to understanding resilience and breakdown of caprock systems as function of lithology and subsurface conditions
• Difficulties
  – Coupled processes are technically challenging both experimentally and computationally
  – Field observations of well and caprock failure processes are extremely limited
• Excellent opportunities to collaborate on geomechanics and induced seismicity of storage reservoir systems
  – Penn State study of rheology of fracture slip (D. Elsworth)
  – UT-Austin study of reservoir seal geomechanics (P. Eichhubl)
  – LBL study of \textit{in situ} fault slip (J. Birkholzer)

• Excellent opportunities to collaborate on well integrity problems
  – Clemson study of strain/stress measurement in wells (L. Murchoch)
  – LLNL study of thermal stresses in wells (J. Morris/P. Roy)
  – NETL studies of well integrity (N. Huerta/B. Kutchko)
  – LLNL studies of cement deformation and sealing (Carroll, Iyer, Walsh)

• Many other projects are closely allied to work here (reservoir geomechanics, well integrity studies, etc.)
Project Summary

• One key to reducing risk of leakage is through observation and measurement of self-healing properties of cement and caprock.

• We have shown that leakage is mitigated under some conditions:
  – Wellbore integrity is better understood and mitigation appears to be bounded by the size and continuity of the defect.
  – Understanding mitigation of caprock leakage has just started.

• Understanding fracture-permeability behavior of caprock is an effective means of addressing potential impact of induced-seismicity.

• A complete treatment of the geomechanics of wellbore systems is limited by lack of understanding of in situ stress conditions in cement:
  – A framework for analysis has been established but awaits additional characterization of full implementation.
Benefit to the Program

• Develop long-term predictive models for use in risk-based analyses of carbon storage systems
• Determine the consequences of stress-induced damage to wellbore and caprock seals?
• Develop and validate technologies to ensure 99% storage permanence.
Project Overview
Goals and Objectives

• Impact of stress (mechanical and chemical) on wellbore and caprock integrity focused on role of CO$_2$-water
  – Experimental studies of the impact of mechanical stress on leakage processes
  – Experimental studies of the impact of CO$_2$ flow and geochemical reactions on leakage
  – Field studies of cement-steel-caprock samples obtained from CO$_2$-containing reservoirs
  – Numerical models to predict damage and leakage in wellbore and caprock seals
Rajesh Pawar  
(Project Lead)

Task 1: Wellbore and Seal Integrity  
(Bill Carey PI)

Task 2: Novel Methods to Detect Small Leaks  
(Andrew Delorey PI)

Task 3: Unconventional Utilization of CO₂  
(Rajesh Pawar PI)

Task 4: Monitoring of Faults  
(Paul Johnson PI)

Triaxial Coreflood Experiments  
Bill Carey

Fracture-Flow Processes  
Bill Carey

Post-doc  
Luke Frash

Post-doc  
Phong Nguyen
<table>
<thead>
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<th>Task</th>
<th>SubTask</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
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<td>1.2 Experimental Study of Fracture-Permeability Behavior of Seal Materials</td>
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<tr>
<td></td>
<td>1.2.1 Development of theoretical framework</td>
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<td>1.2.2 Fracture-permeability behavior of caprock</td>
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<td>1.2.3 Fracture-permeability behavior of wellbore materials</td>
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<td>1.3 Computational Study of Fluid Flow through Pre-existing Flow Pathways</td>
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- **40%** completion by FY17
- **60%** completion by FY17
- **30%** completion by FY17
- **20%** completion by FY17
Appendix: Publications 2015/2017

Supported in total or in part by this project

Appendix: Publications 2015/2017 (cont.)

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