Area of Interest 2,
Geomechanics of CO$_2$
Reservoir Seals
DE-FE0023316

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Presentation Outline

• Benefit
• Problem Statement
• Project Overview
• Methodology
• Accomplishments to Date
  – Fracture mechanics experiments
  – Fracture & leakage modeling
• Summary
Benefit to the Program

- **Program goals:** Develop characterization tools, technologies, and/or methodologies that improve the ability to predict geologic storage capacity within ±30%, improve the utilization of the reservoir by understanding how faults and fractures in a reservoir affect the flow of CO$_2$, and ensure storage permanence.
  - Area of Interest 2 – Fractured Reservoir and Seal Behavior: Develop tools and techniques to increase the accuracy and reduce the costs of assessing subsurface seal containment and the seal/reservoir interface, including the measurement of in-situ rock properties in order to develop a better understanding of seal behavior when CO$_2$ is injected into a reservoir.

- **Project is designed to**
  - *Provide calibrated and validated numerical predictive tools for long-term prediction of reservoir seal integrity beyond the engineering (injection) time scale.*
  - *Contribute toward technology ensuring 99% storage permanence in the injection zone for 1000 years.*
Problem Statement

• Sealing efficiency of CO$_2$ reservoirs has to exceed 99%.
• Design criteria are needed that establish the long term sealing capacity of CO$_2$ reservoirs and to model leakage risk.
• Top and fault seal risk assessment well established in oil & gas exploration, but:
  • scCO$_2$ and CO$_2$ brine potentially interact physically & chemically with top seal.
• Seal risk assessment criteria taking these interactions into account are needed for CO$_2$ systems.
Project Overview: Goals and Objectives

• **Perform laboratory fracture mechanics testing** to
  – gain fundamental understanding into fracture processes in chemically reactive systems and to
  – provide input parameters on fracture constitutive behavior, fracture rate and geometry, and deformation and transport processes involved in subcritical chemically assisted fracture growth for relevant top seal lithologies.

• **Derive predictive and validated numerical models** for fracture growth in chemically reactive environments relevant to CCUS top seal lithologies.

• **Validate** numerical & laboratory observations **against microstructural and textural observations** on fractures from natural CO$_2$ seeps.

• **Perform upscaled numerical simulations** that are informed by field and lab results toward predictive tools **for top seal integrity analysis**, top seal mechanical failure, and impact on CO$_2$ leakage in CCUS applications.
Fractures in CO$_2$ caprocks

Crystal Geyser field analog site

Active on $10^2$ - $10^5$ year time scales
Natural fracture networks

Mancos Shale at Crystal Geyser

10 m from CO$_2$ conduit

> 300 m away from CO$_2$ conduit
Methodology

• Experimental measurement of subcritical fracture propagation in various shale lithologies
  – Double torsion test, unconfined conditions
  – Short-rod test, confined conditions (scCO₂)

• Textural and compositional characterization
  – Shale material used for fracture testing
  – Fractures & CO₂ alteration in natural systems
  – Post-mortem analysis of lab test specimens

• Numerical modeling of fracture propagation in top seals
  – Fracture network modeling using JOINTS
  – Upscaled modeling for top seal deformation using Sierra Mechanics
Double torsion fracture mechanics testing

\[ V = A \left( \frac{K_I}{K_{IC}} \right)^n \]

- **V**: fracture propagation velocity
- **K_I**: mode-I stress intensity factor
- **K_{IC}**: mode-I fracture toughness
- **A**: pre-exponential constant
- **n**: velocity exponent, subcritical crack index (SCI)

**Sample geometry**

After Atkinson, 1984

**K_{IC} = fracture toughness**

**K^* = stress corrosion limit**

Rijken, 2005
Material characterization

Marcellus Shale (carbonate-rich)
- Carbonate & clay
- Minor amounts of quartz and pyrite

Woodford Shale
- Quartz & clay
- Minor amounts of carbonate and feldspar
Woodford: dry-air-water

- Strong reduction of $K_{IC}$ (48%) and SCI (75%) from ambient air to DI water
- Fracturing strongly facilitated in $H_2O$ saturated conditions
- K-V curves obey power-law, indicating fracturing @ stress-corrosion regime (I)
- Load relaxation technique (lines) match constant loading rate method (squares)
- H-treatment restricts water-sample interaction to the fracture tip
- H-treatment protects $K_{IC}$ from large weakening in DI water
- H-treatment has little effect on long-term SCI both in ambient air and DI water
- $K_{IC}$, SCI not obviously dependent on pH
- Non-power-law $K$-$V$ curves for H-treated sample
- SCI begin > SCI Untreated > SCI end
- H-treatment protects $K_{IC}$ from strong weakening
Woodford: effect of salinity

- $K_{IC}$ dependency on salinity: Untreated: $K_{IC}$ ↓ as salinity ↑.
  H-treated: $K_{IC}$ ↑ as salinity ↑.
- Non-power-law K-V curves for H-treated samples.
- SCI begin > SCI Untreated > SCI end.
Woodford: large drop of $K_{IC}$ and SCI between ambient to aqueous solutions.
Glass and Marcellus: less change in $K_{IC}$ and SCI.
Results fracture mechanics testing

- $K_{ic}$ and SCI lower in water compared to dry tests
  - Dry tests of limited applicability for aqueous subsurface systems
  - Dry tests potentially applicable to scCO$_2$ systems
- Effect of varying water chemistry minor in current tests
- Dry-out by scCO$_2$ injection could strengthen caprock
- Water increases inelastic behavior, impedes fracture growth
  - Decreased inelastic behavior under dry CO2 conditions could favor fracture growth
JOINTS fracture network model

- Boundary element code
- Linear elastic
- Pseudo-3D, accounts for elastic interaction
  - Opening-mode and mixed-mode fracture propagation
- Allows simulation of subcritical fracture propagation as function of
  - Subcritical index SCI
  - Elastic material properties
  - Distribution of nucleation sites (seed fractures)
  - For applied displacement or stress boundary conditions
Effect of var SCI, constant $K_{lc} = 1$ MPa·m$^{1/2}$
JOINTS models for Woodford
Plan view; Fractures initiate internally

KIC = 0.81
SCI = 68

KIC = 0.59
SCI = 63

KIC = 0.32
SCI = 14

KIC = 0.24
SCI = 14

KIC = 0.21
SCI = 11

KIC = 0.28
SCI = 11
JOINTS models of caprock failure

- Vertical section in shale caprock
- Fractures initiate at base
- Best fracture connectivity with DI water
- Decreased fracture connectivity in dry CO$_2$ gas

**Woodford: Dry CO2**

KIC = 0.81  
SCI = 68

**Woodford: Ambient**

KIC = 0.59  
SCI = 63

**Woodford: DI water**

KIC = 0.32  
SCI = 14
Caprock Integrity Sierra Mechanics


Test for effect of:
- wellbore orientation: vertical, horizontal
- injection rate: 3 Mt/yr, 5 Mt/yr for 30 years
- caprock/reservoir thickness: 50 m, 100 m, 200 m

on leakage across caprock with/without pre-existing fractures (implicit continuum scale)
Pore pressure within reservoir

- Lower pressure in horizontal wellbore cases
- Even for horizontal well, fractures can be reactivated causing leakage

Reservoir, cap: 100 m
Maximum saturation of CO$_2$ on top of seal

- Leakage for higher injection rates even in horizontal wellbore
- Long-term: same leakage for horizontal & vertical well @ 5 Mt/yr; later onset of leakage for horizontal well

Reservoir, cap: 100 m
Effect of layer thickness

Vertical well

- Thick reservoir is safer
- For given reservoir thickness, thicker caprock is safer
- Reservoir thickness is more important than caprock thickness

Horizontal well

- Combined reservoir & caprock thickness ($h_{\text{total}}$) controls leakage amount of to the top layer
- High total thickness is safer
Summary

• Wide range in fracture properties for different caprock lithologies
• Distinct stress corrosion effect observed in DT tests in water w/ varying composition
• Shale less fracture prone in dry CO$_2$ gas environment
• Fractures most transmissive at intermediate SCI
• Horizontal wells, thick reservoir & seal favor caprock integrity
  – Vertical well: Reservoir thickness most important
Accomplishments to Date

• Fracture mechanics testing on caprock lithologies in dry & aqueous environments of varying composition
• Conducted numerical simulations on fracture network evolution by chemically aided fracture growth
• Simulated caprock leakage behavior using in Sierra Mechanics continuum models for varying well/reservoir/caprock geometry
Next steps

• DT and short-rod fracture testing under
  – varying temperature
  – water composition
  – pressure
  – scCO$_2$
• Integration of continuum & fracture network modeling
  – Effects of varying $K_{ic}$ & SCI included into Sierra Mechanics
• Validation of fracture network models with field fracture network observations
Synergy Opportunities

• Fracture mechanics analysis of Cranfield and FutureGen II core material
• Coordination with EFRC research on reservoir rock geomechanics
• Integration of lab results with fracture network modeling (phase-field, cohesive end-zone, peridynamics)
• Integration with hydraulic fracture research
Appendix
Organization Chart/Communication Plan

- Established Sandia-UT collaboration
  - Olson – Schultz – Eichhubl on joint industry projects
  - Dewers – Newell – Eichhubl on joint EFRC
Team

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### Gantt Chart

<table>
<thead>
<tr>
<th>Task/Subtask</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
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<tbody>
<tr>
<td>1. Project Management and Planning</td>
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<td>2.1. Short rod fracture toughness tests</td>
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<td>2.2. Double torsion tests</td>
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<td>2.3. Fracturing in water-bearing supercritical CO2</td>
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<td>3.1. Field fracture characterization</td>
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<td>3.2. Textural and compositional fracture imaging</td>
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<td>4.1. Discrete fracture modeling using Sierra Mechanics</td>
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<td>4.2. Fracture network modeling using JOINTS</td>
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<td>4.3. Upscaled modeling using Kayenta</td>
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<td>5. Model validation and integration</td>
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* Short rod tests (task 2.1) are being performed under task 2.3 under confined conditions.
• **Journal, multiple authors:**