Implications of Stress State Uncertainty on Caprock and Well Integrity (FEW0191)

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Project Objectives

Task 3.1– Improve assessment of thermal-hydraulic fracturing risk during CO$_2$ injection

Task 3.2 – Illustrate modes of well failure caused by heating and cooling
Program Goals and Benefits

- This project meets the Carbon Storage Program goals to develop and validate technologies to ensure 99% storage permanence.

- This project develops and validates geomechanical computational tools needed to avoid caprock and wellbore failure during CO₂ injection.

Approach
- GEOS - multi-scale, multi-physics simulator developed at LLNL
- Caprock Integrity
  - Update key physics to bound operational practices that might fracture the caprock during CO₂ injection
  - Test simulation results against data from the In Salah CO₂ demonstration
- Wellbore Integrity
  - Update key physics to bound the impact of thermal stresses on well integrity
  - Constrain simulations against thermal cycling experiments conducted by SINTEF
  - Apply model to physical conditions reflecting CO₂ operations

Success is defined as a methodology to define
- pressure thresholds to maintain caprock integrity and
- temperature ranges that yield minimum damage in the wellbore.
Task 3.1 – Improve assessment of thermal-hydraulic fracturing risk during CO₂ injection

Motivation: Injection of cold CO₂ at high pressure can potentially fracture reservoir rocks and caprock seals.

In Salah Case Study: Bottom hole pressure and estimated fracture pressure range at KB-502.
Task 3.1 – Improve assessment of thermal-hydraulic fracturing risk during CO₂ injection

In Salah Case Study: Velocity anomalies seen in 3D/4D seismic. Features run perpendicular to minimum horizontal stress, and may indicate fracturing in the reservoir and lowermost caprock [White et al. 2014].
New modeling approach to allows arbitrarily oriented fractures to be embedded in a standard reservoir simulator.

We solve for fracture pressure, fracture aperture, matrix pressure, and matrix displacement in a tightly-coupled fashion.
New modeling approach allows arbitrarily oriented fractures to be embedded in a standard reservoir mesh.

Simple test problem with a pressurized crack on a fixed background mesh. Computed response is independent of crack orientation, as expected.
Task Status – We are currently calibrating an In Salah model, using available data as constraints.

“Static” fracture model used to calibrate rock properties against surface deformation data. Next step will use a propagating fracture to look at the time-evolution of the system.

<table>
<thead>
<tr>
<th>Constraint 1: InSAR data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constraint 2: pressure data</td>
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<tr>
<td>Constraint 3: 4D seismic</td>
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</table>
Goal is to understand the importance of key uncertainties on the fracturing process:

- Layered in situ stress profile
- Fluid leakoff to reservoir / caprock
- Thermal perturbations
- Single fracture vs. multiple interacting fractures

Spectrum of fracture behavior, from single mode-I fracture to a complex multi-fracture environment

In Salah leak off test and formation integrity test data.
Task 3.2 – Assess the impact of thermal stresses caused by injection of cold CO\textsubscript{2} into warmer storage reservoirs on wellbore integrity

![Graphical representation of thermal stresses and CO\textsubscript{2} injection rates with temperature variations over time.]

**Snohvit, Tubåen Fm. (Phil Ringrose, Statoil)**

**CO\textsubscript{2} injected**

**Gauge Temperature**
Task 3.2 – Experimental Setup at SINTEF
Simulation Specifications

- Thermal and Linear Elastic Solvers
- Variable Temperature at inner radius
- Constant Temperature at outer radius
- Temperature range = 6 – 106 °C
- Heating or cooling rate = 1.5 – 2 °C/min

- Fail Strength
  - Steel-Cement interface = 1.0 Mpa
  - Cement-Rock interface = 1.5 MPa

<table>
<thead>
<tr>
<th>Properties/ Material</th>
<th>Steel</th>
<th>Cement</th>
<th>Rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>8000</td>
<td>2300</td>
<td>2500</td>
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<tr>
<td>Thermal Exp. Coeff (K⁻¹)</td>
<td>12.0 x 10⁻⁶</td>
<td>7.9 x 10⁻⁶</td>
<td>10.0 x 10⁻⁶</td>
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<tr>
<td>Thermal Conductivity (W/m/K)</td>
<td>50</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>Specific Heat (J/kg/K)</td>
<td>450</td>
<td>1600</td>
<td>2000</td>
</tr>
<tr>
<td>Fail Strength (MPa)</td>
<td>200</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Fracture Toughness (Mpa.m¹/²)</td>
<td>40</td>
<td>1</td>
<td>2.5</td>
</tr>
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</table>
During cooling – Thermal contraction causes interfacial debonding.

Adding confining pressure slows fracture propagation.
During heating – Thermal expansion causes radial cracks

Adding confining pressure slows fracture propagation
Summary and Future Work

3.1 – Caprock Integrity
- Implementation of an embedded fracture model in a continuum geomechanics / flow simulator
- Future model improvements, including:
  - Multiphase effects
  - Non-isothermal conditions
- Finalize the In Salah case study

3.2 – Successfully modeled modes of deformation of wellbore upon heating and cooling separately
- Update model to account for thermal cycling

3.3 Model SINTEF experiments (on – going)

3.4 Refine simulation tools for sharing with industrial partners

3.4 Development of best practices for risk management
Synergy Opportunities

- Collaboration with SINTEF and In Salah JIP
  - Provides detailed field and experimental data to constrain models
  - Provides strong ties with industry to identify real and practical questions from an operators point of view
Appendix
Fuel Cycles Innovations (Roger Aines)

Carbon Management (Susan Carroll)

LLNL Carbon Sequestration Program

Task 1. Carbonates

Task 2. Induced Seismicity

Task 3. Caprock & Well Integrity

Task 4. Industrial Partnerships

Technical Staff

Carroll, Hao, Smith

Matzel, Templeton, White

Carroll, Hao, Iyer, Morris, Roy, Walsh, Wang, White

Carroll, White

Expertise

Subsurface Hydrology

Computational Geomechanics

Experimental and Theoretical Geochemistry

Seismology
<table>
<thead>
<tr>
<th>Task</th>
<th>Milestone Description*</th>
<th>Project Duration</th>
<th>Start : Oct 1, 2014</th>
<th>End: Sept 30, 2017</th>
<th>Planned Start Date</th>
<th>Planned End Date</th>
<th>Actual Start Date</th>
<th>Actual End Date</th>
<th>Comment (notes, explanation of deviation from plan)</th>
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<tr>
<td>1.1</td>
<td>Calibrate Reactive Transport Model</td>
<td>Project Year (PY) 1</td>
<td>Q1 Q2 Q3 Q4 Q5 Q6 Q7 Q8 Q9 Q10 Q11 Q12</td>
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<td>1-Oct-14</td>
<td>30-Mar-15</td>
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<tr>
<td>1.2</td>
<td>Calibrate NMR Permeability Estimates</td>
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<td>1-Oct-14</td>
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<td>1.3</td>
<td>Scale Reactive Transport Simulations from the core to reservoir scale</td>
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<td>1-Jul-15</td>
<td>28-Feb-17</td>
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<tr>
<td>1.4</td>
<td>Write topical report on CO2 storage potential in carbonate rocks</td>
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<td>1-Dec-16</td>
<td>30-Sep-17</td>
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<td>2.1</td>
<td>Algorithm development and testing</td>
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<td>Array design and monitoring recommendations</td>
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<td>30-Sep-16</td>
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<td>3.4</td>
<td>Refining simulation tools for sharing with industrial partners</td>
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<td>4.1</td>
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<td>4.2</td>
<td>Develop work scope with industrial partners</td>
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<td>30-Sep-15</td>
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* No fewer than two (2) milestones shall be identified per calendar year per task