Impact of Thermal Stress on Wellbore Integrity

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Kamila Gawel, Jelena Todorovic, Malin Torsæter (SINTEF)
Impact of thermal stresses caused by injection of cold CO₂ into warmer storage reservoirs on wellbore integrity

Data from Snohvit CO₂ storage project (White et al., 2014)

Thermal mismatch between the formation and the injected CO₂ is a potential source of leakage risk

(Malin Torsater, BigCCS, 2015)
Project Objective

Assess the impact of thermal stresses caused by injection of CO$_2$ into storage reservoirs

- What is the extent of damage during thermal cycling operations?
- How the thermally induced stresses vary with variation of cooling/heating rates?
- Where the fractures are more likely to appear during thermal cycling operations?
- How to translate the experimental and simulation results into field scale?
Program Goals and Benefits

- This project develops and validates geomechanical computational tools needed to avoid wellbore failure during CO$_2$ injection.

Approach
- GEOS - multi-scale, multi-physics simulator developed at LLNL
- Wellbore Integrity
  - Update key physics to bound the impact of thermal stresses on well integrity (Completed)
  - Constrain simulations against thermal cycling experiments conducted by SINTEF (Focus of this talk)
  - Apply model to physical conditions reflecting CO$_2$ operations (Future work)

- Success is defined as determining temperature ranges that yield minimum damage in the wellbore.
Experimental Setup

SINTEF Thermal cycling setup with liquid nitrogen tank and heating/cooling stage

Technical drawing of the thermal platform
Sample length = 20 cm, diameter = 20 cm
Simulation Specifications

- Thermal and Linear Elastic Solvers
- Variable Temperature at inner radius
- Constant Temperature at outer radius
- Temperature range = -50 – 80 °C
- Heating or cooling rate = 1.0 – 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>
</tr>
<tr>
<td>Thermal Exp. Coeff (m/(mK))</td>
<td>12.0 x 10⁻⁶</td>
<td>7.9 x 10⁻⁶</td>
<td>10.0 x 10⁻⁶</td>
</tr>
<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>Tensile 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>
</tbody>
</table>
Stresses in hollow cylinder assuming plane strain condition

\[ \sigma_r = \frac{R_o^2 \sigma_{ro} - R_w^2 p_w}{R_o^2 - R_w^2} - \frac{R_o^2}{R_o^2 - R_w^2} \frac{R_w^2}{r^2} (\sigma_{ro} - p_w) \]

\[ \sigma_\theta = \frac{R_o^2 \sigma_{ro} - R_w^2 p_w}{R_o^2 - R_w^2} + \frac{R_o^2}{R_o^2 - R_w^2} \frac{R_w^2}{r^2} (\sigma_{ro} - p_w) \]

- Ve = Compressive stress
+ Ve = Tensile stress

Code validation: Stress concentration near the wellbore region
Code validation: Temperature variation across multiple materials

Steady state temperature distribution in a cylindrical disk with constant temperature boundary conditions

Markers: Numerical solution
Solid lines: Analytical solution
Temperature profile during Cooling

Cooling rate = 1 °C/min

Temperature (°C) vs. Radial distance (m)

Temperature (left) variations with time
Radial Stress and Hoop Stress during Cooling

Cooling rate = 1 °C/min

High tensile radial stress at casing-cement interface

High tensile hoop stress in casing

Tensile hoop stress in cement

Thermal Stress: \[ \sigma_T = \frac{E \alpha}{1 - 2 \alpha} (T - T_0) \]

Radial stress (left) and hoop stress (right) variations with time
Temperature profile during Heating

Heating rate = 1 °C/min

Temperature (left) variations with time
Radial stress and Hoop stress in during Heating

Heating rate = 1 °C/min

Radial stress (left) and Hoop stress (right) variations with time

Tensile hoop stress near cement-rock interface and inside rock

High compressive radial stress at casing-cement interface

Thermal Stress:

$$\sigma_T = \frac{E'\epsilon}{1 - 2\nu}(T - T_0)$$
Radial crack initiation during heating
During heating –
Thermal expansion causes radial cracks

Temperature contours

Radial cracks due to high hoop stress

Fracture propagation

Heating rate = 1.8 °C/min.
Displacement 1000x magnified
Fracture width = 5-10 micro meter

Adding confining pressure slows/ prevents fracture propagation
During cooling – Thermal contraction causes interfacial debonding

Temperature contours

Interfacial debonding due to high radial stress

Fracture propagation

Cooling rate = 1.8 °C/min.
Displacement 1000x magnified
Fracture width = 10-20 micro meter

Adding confining pressure slows/prevents fracture propagation
Modeling of the Experiment

Variable thermal conductivity used between copper and casing
Schematic of Experiment: Thermocouple positions
Copper-Casing Interface Temperature

Good agreement with experimental data
Cement-Casing Interface Temperature

Numerical results

Thermocouple readings

Set Temperature

Good agreement with experimental data
Cement-Rock Interface Temperature

Good agreement with experimental data
CT scan results did not show any visible crack

- Resolution of CT Scan: 150-200 micro meter in XY (horizontal) and 1 mm in Z (vertical) direction
- The material properties, especially the tensile strength and modulus of elasticity, might be different
- The CT scan was conducted at room temperature
- De Andrea et al. (2014) and Albwai et al. (2014) experimentally showed that pre-existing cracks can extend upon thermal cycling

Before (Cycle = 0)  
After (Cycle = 20)

Voids within cement – gray  
cement – transparent yellow  
casing – transparent blue
Summary and Future Work

- Radial cracks are likely to occur in cement and/or rock during heating while debonding is likely to occur in cement/casing or cement/rock interfaces during cooling.

- Confinement reduces the tensile stresses and delays/prevents the initiation of fracture.

- Modeled SINTEF Experiments: Good agreement was found between the thermocouple readings and the numerical temperature profiles.

- No visible crack was detected during the experiment. However, numerical simulations showed possibility of failure due to the thermal cycling operations.

- Specifying the in-situ stress state for field scale simulations (on-going work as part of NRAP Phase 2).

- Predict acceptable temperature ranges for safe injection and storage of CO₂ (part of NRAP Phase 2).
Synergy Opportunities

• Collaboration with SINTEF Petroleum Research
  — Provides detailed experimental data to constrain models

• Joint publications: ARMA, GHGT
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
## Project Timeline for FEW0191

<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>
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<td>1-Oct-14 30-Mar-15</td>
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<tr>
<td>1.2</td>
<td>Calibrate NMR Permeability Estimates</td>
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<tr>
<td>1.3</td>
<td>Scale Reactive Transport Simulations from the core to reservoir scale</td>
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<td>1-Jul-15 28-Feb-17</td>
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<td>1.4</td>
<td>Write topical report on CO2 storage potential in carbonate rocks</td>
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<td>2.1</td>
<td>Algorithm development and testing</td>
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<td>2.2</td>
<td>Array design and monitoring recommendations</td>
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<tr>
<td>2.3</td>
<td>Toolset usability and deployment</td>
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<td>3.1</td>
<td>Analysis of monitoring and characterization data available from the In Salah Carbon Sequestration Project</td>
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<td>3.2</td>
<td>Wellbore model development</td>
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<td>3.3</td>
<td>Analysis of the full-scale wellbore integrity experiments</td>
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<td>Refining simulation tools for sharing with industrial partners</td>
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<td>1-Mar-14 30-Sep-15</td>
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</table>

* No fewer than two (2) milestones shall be identified per calendar year per task
Temperature profiles from experiment

Dashed lines represent bottom thermocouple readings
Solid lines represent top thermocouple readings
Comparison with experimental data

Thermocouple readings

Set Temperature

Numerical results

Outer Rock temperature

Lawrence Livermore National Laboratory
Extreme cooling
Operating conditions can be overlaid on the sealing map to guide risk assessment

\[ \Delta p = 1 \text{ MPa, } l = 10 \text{ m} \]

Fracture due to thermal stress

Leakage path

Courtesy: Jaisree Iyer et al. (2016)
Effect of cement hardening: No Expansion of Cement
Effect of cement hardening: 1% Expansion of Cement

![Graph showing radial stress vs. radial distance with markers for steel, cement, and rock. The graph compares stress before and after curing.]