Well Integrity and Long-Term Well Performance Assessment
(Insights from work on CO$_2$ Sequestration)

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How Is Wellbore Integrity Achieved?

- **Operational measures**
  - Adequate weight drilling mud
  - Monitoring pressure for gas intrusion (“gas kick”)
  - Blowout preventers

- **Design measures**
  - Steel
  - Portland cement

- **Guidelines:** API HF1 (hydraulic fracturing), www.theoildrum.com
Why do wells leak?

Pre-Production

- Formation damage during drilling (caving)
- Casing centralization (incomplete cementing)
- Adequate drilling mud removal
- Incomplete cement placement (pockets)
- Inadequate cement-formation, cement-casing bond
- Insufficient cement coverage of well length
- Cement shrinkage
- Contamination of cement by mud or formation fluids

Post-Production

- Mechanical or thermal stress/strain
  - Formation of micro-annulus at casing-cement interface
  - Disruption of cement-formation bond
  - Fracture formation within cement
- Geochemical attack
  - Corrosion of steel casing
  - Degradation of Portland cement
    - Carbonation
    - Hydrogen sulfide
    - Sulfate attack
    - Acid attack
Field Observations: Role of Interfaces

<table>
<thead>
<tr>
<th>Casing</th>
<th>Cement with Rind</th>
<th>Cement with Vein</th>
<th>Cement Orange Zone Shale Fragment Zone</th>
<th>Shale Fragment Zone and Shale</th>
</tr>
</thead>
</table>

- Evidence for CO₂ migration at cement-caprock interface (carbonate deposit)
- Evidence for CO₂ migration at casing-cement interface (orange, carbonated cement)
- Steel not corroded (but cathodic protection)
- Healed fractures in cement
- SACROC, West Texas: CO₂-EOR, 55-year old well, 30 years exposure

Carey et al. IJGGC (2007)
### SACROC—Cement-\(\text{CO}_2\) reactions

#### Fracture Permeability

<table>
<thead>
<tr>
<th>Phase</th>
<th>Gray Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amorphous</td>
<td>Major</td>
</tr>
<tr>
<td>Portlandite</td>
<td>15-58%</td>
</tr>
<tr>
<td>Calcite</td>
<td>0-28%</td>
</tr>
<tr>
<td>Katoite</td>
<td>22-26%</td>
</tr>
<tr>
<td>Brucite</td>
<td>3-9%</td>
</tr>
<tr>
<td>Ettringite</td>
<td>3-4%</td>
</tr>
<tr>
<td>Friedel’s Salt</td>
<td>2-4%</td>
</tr>
<tr>
<td>Halite</td>
<td>9-32%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase</th>
<th>Orange Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcite</td>
<td>44%</td>
</tr>
<tr>
<td>Aragonite</td>
<td>8%</td>
</tr>
<tr>
<td>Vaterite</td>
<td>33%</td>
</tr>
<tr>
<td>Halite</td>
<td>13%</td>
</tr>
</tbody>
</table>

Carey et al. IJGGC (2007)
Simulation of SACROC: Accurate account of cement mineralogy

Carey and Lichtner (2007)
Experimental studies: Permeability of Cement-Caprock Interfaces

- Class G fly-ash Portland cement - fine grain quartz sandstone composite
- Interface of crushed sandstone (80%) and cured cement (20%): 125-250 µm
- 1500 psi pore (~10 Mpa), ~2600 psi confining (~18 Mpa), 60°C
- Brine flow (I = 0.04 M): 0.15 to 0.25 ml/min
- scCO₂ flow: 0.048 to 0.08 ml/min
- Fractional flow CO₂ = 0.24;
Permeability and pH: Self-healing

- Permeability of SS-Cement interface
  - Assumes flow only along interface
- 1461 ml brine; 460 ml CO₂ (~140 g)
- ~890 interface pore volumes
- Steady state perm: ~500 pore volumes
- In situ pH calculated (Newell et al., 2008)
Coreflood experiments: Self-Healing Behavior in Cement-Cement Interfaces

Huerta et al. (ES&T 2013)

Wigand et al. (Chem. Geol. 2009)

Walsh et al. (Rock Mech. 2012)
Experimental Studies of Corrosion at the Steel-Cement Interface

- Flow-through experiments
  - 50:50 CO₂-Brine (30,000 ppm, NaCl-rich) mixture (41,000 PV)
  - 20 ml/hour for 274 hours; 10 ml/hour for 120 hours; 6200 ml total
  - 40 °C; 14 MPa inlet pressure; 28 MPa confining pressure
- ~10 cm Limestone against ~6 cm Portland Cement

Carey et al. (2010) Int. J. Greenhouse Gas Control
Extensive corrosion at inlet
Backscatter Electron Images of Cement-Casing Interface

Steel: uniform brightness

Cement: spotted

Carbonation front

Empty channel

FeCO₃

Acc.V  Spot  Magn  Det  WD
20.0 kV  3.0  200x  BSE  15.0  NMT Casing-Cement Interface
Geomechanical Behavior of Wells

- Critical in hydraulic fracturing
- Casing expands and stresses cement
- Cement behaves plastically at elevated confining pressure (Liteanu et al. 2009)
- What does hydraulic fracture pressure do to cement bond, cement?
- Can hydraulic fracture pressures communicate with older wells?

Carey et al. (2012) GHGT-11
Short-Term Versus Long-Term Risk

- Wells are an important part of project risk at early stages
- Late-stage risk is assumed to decrease
- What happens to the wellbore over long times?
Conclusions

• Wellbore systems are susceptible to flow at interfaces (cement-steel, cement-caprock, cement fractures)
• Experiments and field observations have demonstrated some degree of self-limiting permeability at interfaces (at least with CO$_2$; Carey, Huerta, Walsh et al.)
• Cement deforms plastically at elevated depths and its geomechanical behavior is critical to assessing potential damage
• Steel response to hydraulic pressure key to assessing damage to isolation
• Coupled mechanical and hydrologic field observations, experiments and models will help resolve threats to zonal isolation
Future Work

- What are the limits (in terms of flow-rate) of self-healing behavior?
- Does carbonated cement protect steel?
- What are the hydrologic and mechanical consequences of cement carbonation?
- Are special formulations of cement and stainless steel necessary in CO$_2$ sequestration projects?
- Coupled mechanical and chemical experiments and models are needed
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