Well Integrity Assessment for Two Monitoring Wells at Cranfield Field

Andrew Duguid Ph.D., P.E.

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BACKGROUND
Background: Cranfield Field, Mississippi

- SECARB’s Phase II Gulf Coast Stacked Storage Project

- Monitoring Wells Studied in an EOR Setting
  - CFU 31F-2 and CFU 31F-3, 7 years old

- Injection commenced December 1, 2009 and continued into June 2015. Breakthrough was seen in CFU31F-2 on December 12, 2009 (12 days after injection).
Cranfield CFU31F-2 and CFU31F-3 Construction

- 7-in 26lb N80 to ~10,200ft
- 7 5/8-in Bluebox 2500 from ~10,200 to ~10,700ft
- 7-in 26lb N80 to ~10,700ft to TD (~10,790ft)
- Electrodes and other jewelry in the well
- 12 ¼-inch bit (large cemented annulus)
- Production reservoir ~10,435ft to ~10,518ft (CFU31F-2)

### Cement Slurries

<table>
<thead>
<tr>
<th>Well</th>
<th>Slurry</th>
<th>Cement</th>
<th>Mass (sacks)</th>
<th>Yield (ft³/sack)</th>
<th>Volume (bbls)</th>
<th>Density (ppg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFU31F-2</td>
<td>Lead</td>
<td>35:65:6</td>
<td>565</td>
<td>1.48</td>
<td>148.5</td>
<td>12.8</td>
</tr>
<tr>
<td>CFU31F-2</td>
<td>Tail</td>
<td>Class H + Silica Flour</td>
<td>440</td>
<td>1.91</td>
<td>149.69</td>
<td>16.2</td>
</tr>
<tr>
<td>CFU31F-3</td>
<td>Lead</td>
<td>35:65:6</td>
<td>770</td>
<td>1.48</td>
<td>202.38</td>
<td>12.8</td>
</tr>
<tr>
<td>CFU31F-3</td>
<td>Tail</td>
<td>Class H + Silica Flour</td>
<td>465</td>
<td>1.91</td>
<td>158.19</td>
<td>16.2</td>
</tr>
</tbody>
</table>
Potential Migration Pathways

- Flow through casing defects into the wellbore
- Flow through fractures in cement
- Flow along mud channels
- Flow at the cement-formation interface
- Flow at the casing-cement interface
- Flow through the cement matrix
- Flow through degraded cement

Figure from Duguid et al. [1]
Typical cement

Carbonation Reactions

- **CO₂ dissociation**
  \[ \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3^- \leftrightarrow \text{H}^+ + \text{HCO}_3^- \leftrightarrow 2\text{H}^+ + \text{CO}_3^{2-} \]

- **Cement dissolution**
  - \( \text{Ca(OH)}_2(\text{s}) + 2\text{H}^+ + \text{CO}_3^{2-} \rightarrow \text{CaCO}_3(\text{s}) + 2\text{H}_2\text{O} \)
  - \( \text{Ca}_3\text{Si}_2\text{O}_7\text{H} \cdot 4\text{H}_2\text{O}(\text{s}) + 2\text{H}^+ + \text{CO}_3^{2-} \rightarrow \text{CaCO}_3(\text{s}) + \text{SiO}_x\text{OH}_x(\text{s}) \)
  - \( \text{Ca(OH)}_2(\text{s}) + \text{H}^+ + \text{HCO}_3^- \rightarrow \text{CaCO}_3(\text{s}) + 2\text{H}_2\text{O} \)
  - \( \text{Ca}_3\text{Si}_2\text{O}_7\text{H} \cdot 4\text{H}_2\text{O}(\text{s}) + \text{H}^+ + \text{HCO}_3^- \rightarrow \text{CaCO}_3(\text{s}) + \text{SiO}_x\text{OH}_x(\text{s}) \)

- **Calcium carbonate dissolution**
  - \( \text{CO}_2 + \text{H}_2\text{O} + \text{CaCO}_3(\text{s}) \leftrightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- \)
  - \( 2\text{H}^+ + \text{CaCO}_3(\text{s}) \leftrightarrow \text{CO}_2 + \text{Ca}^{2+} + \text{H}_2\text{O} \)

Precipitation of CaCO₃ blocks connected pores and reduces permeability

Opens pores blocked by CaCO₃ precipitation and additional porosity created by the dissolution of cement reaction products

### Composition

<table>
<thead>
<tr>
<th>Phase</th>
<th>Abbreviation</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca₃Si₂O₇•4H₂O</td>
<td>C-S-H</td>
<td>50-70</td>
</tr>
<tr>
<td>Ca(OH)₂</td>
<td>CH</td>
<td>20-25</td>
</tr>
<tr>
<td>3(3CaO•Al₂O₃•CaSO₄•12H₂O)</td>
<td>AFm</td>
<td>10-15</td>
</tr>
<tr>
<td>4CaO•(Al,Fe₂O₃)•13H₂O</td>
<td>AFt</td>
<td></td>
</tr>
</tbody>
</table>
METHODS
Data Collection

- **Logging Tools**
  - USIT* ultrasonic imager tool (2009)
  - Isolation Scanner* cement evaluation service (2015)
  - DSLT* Digital Sonic Logging Tool (2009)
  - SCMT* slim cement mapping tool (2015)

- **Testing and Sampling Tools**
  - CHDT* cased hole dynamics tester
  - MSCT* mechanical sidewall coring tool

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**LEGEND**
- Perforation for VIT test
- CHDT Sample Point
- Fluid Sample Point
- Point permeability measurement
- Sidewall Core Sample
- VIT Interval
- Wellbore
- Well Cement
- Geologic Formation
Lab Analyses on Core Samples

• Micro Computed Tomography (Micro-CT)
  ▪ Analysis with a TriFoil Imaging eXplore CT 120 Small Animal X-Ray CT Scanner with a Custom generator producing 5 kW peak power. The analyzer had a feature detectability of 4 microns. The energy was between 40–120 kV with a maximum current of 50 mA.

• Laser Ablation Inductively Coupled Plasma Mass Spectroscopy (LA-ICP-MS)
  ▪ Analysis with a Perkin Elmer Nexion 350D ICP-MS and a Photo Machines Excite He1Ex 193nm Laser with a 50 x 50 mm spot size. A NIST 612 standard was used before and after the scans on each sample to account for machine drift. Lines were collected at 20mm/s.

• Environmental Scanning Electron Microscopy (ESEM) with Energy Dispersive X-ray Spectroscopy (EDS)
  ▪ Analysis with a FEI QUANTA 200 SEM in ESEM Mode. The analysis was conducted on portions of the sectioned samples that were polished to 1 micron prior to analysis. Excitation energy ranged from 10 to 20 KV.

• X-ray Diffraction (XRD)
  ▪ Analysis with a Rigaku MiniFlex 600 analyzer. The samples were run using a 40Kv voltage and a 15mA current. The radiation source was an interlock CU tube. Scans were run from 5 to 80 degrees at 1 degree per minute.
Control Line in CFU31F-2

- Control lines visible in the microdebonding image tracks in both wells as a vertical micro-debonded or fluid-filled features

- Not visible in the fiberglass section

- Visible in 2009 and 2015 ultrasonic logs
CFU31F-2 7900 ft

- Crack with visible reaction front perpendicular to the wellbore
- Micro-CT shows filled and unfilled portions of the crack
CFU31F-2 Log Analysis at 7900 ft

- CBLs show a decrease in amplitude (increased bond)
- Ultrasonic logs show a decrease in solid behind the casing
### CFU31F-2 7900-ft XRD

<table>
<thead>
<tr>
<th>Phase name</th>
<th>Zone 1 Weight</th>
<th>Zone 2 Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>20%</td>
<td>42%</td>
</tr>
<tr>
<td>Tilleyite</td>
<td>26%</td>
<td>18%</td>
</tr>
<tr>
<td>Tobermorite M</td>
<td>11%</td>
<td>5.8%</td>
</tr>
<tr>
<td>Calcium Silicate Hydrate</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Brownmillerite, Fe-rich</td>
<td>10%</td>
<td>7.2%</td>
</tr>
<tr>
<td>Calcite</td>
<td>19%</td>
<td>10%</td>
</tr>
<tr>
<td>Halite</td>
<td>4.7%</td>
<td>6%</td>
</tr>
</tbody>
</table>

1 cm
CFU31F-2 9800 ft

- Visible reaction fronts in the casing side of the sample
- Micro-CT shows multiple reaction fronts
CFU31F-2 Log Analysis at 9800 ft

- CBLs show an increase in amplitude (decreased bond)
- Ultrasonic logs show a decrease in solid behind the casing
Reaction Fronts in MSCT sample at 9800 ft
CFU31F-2 9800-ft LA-ICP-MS 2

CFU31F-2 9800 Line 8

- Ca/Si
- Ca/Al
- Ca/Fe

Ratios vs. Distance (microns)

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Traverse City, Michigan, USA
# CFU31F-2 9800-ft XRD

<table>
<thead>
<tr>
<th>Phase name</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight %</td>
<td>Weight %</td>
<td>Weight %</td>
</tr>
<tr>
<td>Tobermorite</td>
<td>2.3</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>Quartz</td>
<td>18.4</td>
<td>25.5</td>
<td>24</td>
</tr>
<tr>
<td>Calcite</td>
<td>63</td>
<td>10.3</td>
<td>22</td>
</tr>
<tr>
<td>Aragonite</td>
<td>11.7</td>
<td>-</td>
<td>-</td>
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<td>Vaterite</td>
<td>0.7</td>
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<td>2</td>
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<tr>
<td>Zeolite UTD-1</td>
<td>2.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Brownmillerite</td>
<td>-</td>
<td>5.6</td>
<td>13</td>
</tr>
<tr>
<td>Tilleyite</td>
<td>-</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>Srebrodolksite</td>
<td>1.4</td>
<td>2.8</td>
<td>-</td>
</tr>
<tr>
<td>Calcium Silicate Hydrate</td>
<td>-</td>
<td>7.3</td>
<td>-</td>
</tr>
<tr>
<td>Gehlenite</td>
<td>-</td>
<td>1.4</td>
<td>-</td>
</tr>
</tbody>
</table>
CFU31F-3 10380 ft

- Cored control line
- Reaction fronts leading away from control line/cement-casing interface
- Micro-CT shows multiple reaction fronts
10380-ft Cement Sectioned

LA-ICP-MS

ESEM

XRD
CFU31F-3 10380-ft LA-ICP-MS

CFU31F-3 10380 ft Line 1

- Ca/Si
- Ca/Al
- Ca/Fe

Ratios vs. Distance (microns)
## CFU31F-3 10380-ft XRD

<table>
<thead>
<tr>
<th>Phase name</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight %</td>
<td>Weight %</td>
<td>Weight %</td>
<td></td>
</tr>
<tr>
<td>Halite</td>
<td>2.3</td>
<td>15</td>
<td>15.2</td>
</tr>
<tr>
<td>Quartz</td>
<td>8.4</td>
<td>10.7</td>
<td>19</td>
</tr>
<tr>
<td>Calcite</td>
<td>84</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>Vaterite</td>
<td>-</td>
<td>19</td>
<td>-</td>
</tr>
<tr>
<td>Faujasite-Ca, dehydrated</td>
<td>-</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Tobermorite M</td>
<td>4.2</td>
<td>-</td>
<td>16.2</td>
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<tr>
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<td>38</td>
<td>-</td>
</tr>
<tr>
<td>Tilleyite</td>
<td>0.4</td>
<td>-</td>
<td>19</td>
</tr>
<tr>
<td>Brownmillerite, Fe-rich</td>
<td>0.1</td>
<td>-</td>
<td>7.1</td>
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<tr>
<td>Wollastonite, ferroan 1A</td>
<td>0.6</td>
<td>-</td>
<td>11</td>
</tr>
</tbody>
</table>

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Zone 1

Zone 2

Zone 3
Fiberglass Casing Degradation
Discussion

• Control lines and hardware are visible as low acoustic impedance features between the CO₂ reservoir at the log top-of-cement indicating that they are not bonded to the casing and could represent a migration pathway.

• Deterioration of the acoustic impedance and CBL signals in the logs is evident over much of the section that was relogged in 2015.

• Each of the cores collected in each well showed carbonation.
  ▪ Both XRD and LA-ICP-MS indicate carbonation occurring at the cement-casing and cement-formation interfaces.
  ▪ LA-ICP-MS shows increases in Ca/Si that are likely calcium carbonate fronts and decreases in Ca/Si near the edges of the sample that indicate calcium depletion.
Discussion

• The core collected at 10380 ft consisted of casing, control line, and cement. The cement portion of the core showed visible reaction fronts moving into the sample from the control line / casing side.
  
  - XRD conducted on the sample show carbonation in each of the zones analyzed.
  - The carbonation is highest adjacent to the control line / casing interface, with 84 percent calcite, and smallest near the formation with 12 percent calcite.

• The degradation of the fiberglass casing in the reservoir CO$_2$ zone can be seen in both the logs and the casing samples collected. The logs show the worst damage in the CO$_2$ zone with less damage above the CO$_2$ zone and the least damage below the CO$_2$ zone.
CONCLUSIONS
CONCLUSIONS

• High carbonation along the interfaces and the geometry of the damage to the fiberglass casing indicate that CO$_2$ is migrating along the casing.
  ▪ buoyant CO$_2$ will migrate up from the reservoir causing more damage above the CO$_2$ zone than below the CO$_2$ zone.

• Time-lapse comparison of cement bond amplitude data and acoustic impedance maps imply a deterioration of cement bond or cement along much of the long-string section.

• Analysis of sidewall cores using XRD and LA-ICP-MS validates the log interpretation by confirming the degradation of cement (carbonation) along the casing-cement interface.
CONCLUSIONS

- The ultrasonic image maps also clearly identify the control lines and monitoring technology attached to the outside of the casing. The sidewall core through the control line at 10380 ft confirms that CO$_2$ is migrating along the control line.

- Study of other wells with external lines should be conducted to see if the results of this study are normal or an exception.
REFERENCES
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Cranfield Field
CFU31F-2 7900-ft LA-ICP-MS

CFU31F-2 7900ft Line 1

- Ca/Si
- Ca/Al
- Ca/Fe

Distance (microns)

Ratio
CFU31F-2 9800-ft LA-ICP-MS 1

CFU31F-2 9800 Line 7

- Ca/Si
- Ca/Al
- Ca/Fe

Ratios vs Distance (microns)
Jewelry and Control Lines (10200 ft)