CCUS Well Integrity
ARB Carbon Capture and Sequestration Technical Discussion Series: Well Mechanical Integrity

Andrew Duguid, Ph.D., P.E.
Battelle

May 12, 2016
Presentation Outline

• Background / Leakage Pathways
• Well Construction
• Cement
• Examples and measurements
• Summary
Typical abandoned oil well

- Surface casing and cement
- Plug at surface
- Uncemented zone
- Mud, water, or open casing
- Production casing and cement
- Plug in production zone
Potential Avenues for Leakage

- Well plug
- Well casing
- Well cement
- Migrating CO$_2$

LEGEND
- Cement
- Formation
- Drilling mud
- Well casing
- Open casing
- Migrating CO$_2$
Well Construction

- The wells must be designed to function under the expected pressures, temperatures, and volumes. Wells must provide isolation for the life of the project
  - Design for temperature, tensile stress, maximum internal, maximum external, and triaxial loadings.
- Formation Properties
  - Pressure
  - Permeability
  - Gas/fluid chemistry
- Material Properties
  - Steel/Fiberglass
  - Cement
- Drilling Techniques
  - OBM/WBM
  - Mud Removal
- Well Use
  - Injection/Production
Construction: Cement sheath defects

- **Placement defects**
  - Poorly centralized casing can lead to channels that bypass the narrow side of the annulus
  - Mud films can also create pathways and reduce zonal isolation

- **Gas migration during cement hydration may cause channels**
  - Driven by a drop in cement pore pressure during hydration

- **Thermomechanical effects**
  - Cracks caused by cement failure in compression/tension, microannuli caused by debonding at the interfaces with casing and/or rock

These can all lead to direct communication to the casing and may increase transport by establishing a communication path vertically.

Construction practices should minimize the chances for defects. (proper slurry design, WOC, centralizers)
Materials: Casing and Elastomers

• Typical carbon steel casing is vulnerable to degradation by anodic dissolution, exposure to chloride laden waters, and exposure to carbonic acid [Anstice et al, 2005 and Stone et al., 1989]
  ▪ A passive layer is created between the cement and the casing that protects the casing from degradation
  ▪ Lack of cement or degradation of the cement can lead to a breakdown of the passive layer allowing for corrosion of the steel

• Corrosion resistant alloy casing does exist and may be needed in CO$_2$ exposed zones (stainless steel etc.)

• Elastomers can be degraded by CO$_2$. Degradation can include explosive decompression and blistering.
Typical well cement composition

**Unhydrated**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>3CaO•SiO₂</td>
<td>50</td>
</tr>
<tr>
<td>2CaO•SiO₂</td>
<td>30</td>
</tr>
<tr>
<td>3CaO•Al₂O₃</td>
<td>5</td>
</tr>
<tr>
<td>4CaO•Al₂O₃•Fe₃O₃</td>
<td>12</td>
</tr>
</tbody>
</table>

**Hydrated**

<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>

Data from Nelson, 1990
Cement degradation reactions

- **Ca(OH)\(_2\) dissociation**
  \[ \text{Ca(OH)}_2 \leftrightarrow \text{Ca}^{2+} + 2\text{OH}^- \]

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

May open up new porosity

Precipitation of CaCO\(_3\) blocks connected pores and reduces permeability

Opens pores blocked by CaCO\(_3\) precipitation and additional porosity created by the dissolution of cement reaction products
Materials: Reactions At The Cement-Rock Interface--Lab

Neat cement pH 2.4 and 50°C

Sandstone-cement at pH 3 and 20°C
Materials: Reactions At The Cement-Rock Interface--Field

SACROC Field Cement

Carey et al. 2006
Sustained Casing Pressure Analysis

Rate Profiles for SCP Bleed and Build Models for Same Cumulative Gas

Vein Model is not limited by critical pressure ratio (flow at sonic velocity).

Orifice Model is limited to critical flow at asymptote pressure.

Critical Orifice: $q \sim C_{or} \cdot P_1$

Sub-critical Orifice: $q \sim C_{or} \cdot \sqrt{P_1 (P_1 - P_2)}$

Vein (crack): $q \sim C_v \cdot \sqrt{(P_1^2 - P_2^2)}$

Porous (perm): $q \sim C_p \cdot (P_1^2 - P_2^2)$

Orifice and Vein Models both end abruptly.

Porous Model has significantly higher rates in early and late time.
Data Collection

- **Logging Tools**
  - Isolation Scanner* cement evaluation service
  - SCMT* slim cement mapping tool

- **Testing and Sampling Tools**
  - CHDT* cased hole dynamics tester
  - MDT* modular formation dynamics tester
  - MSCT* mechanical sidewall coring tool
EGL7 SCMT (CBL) Well Annulus

<table>
<thead>
<tr>
<th>Discriminated CCL (CCLD)</th>
<th>Transit Time (TT)</th>
<th>B/L ( &gt; 70% ) From B/L to B/L</th>
<th>CBL Amplitude (CBL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 (V) (-2)</td>
<td>400 (US)</td>
<td>200</td>
<td>6 (MV) 100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tension (TENS) (LBF)</th>
<th>Gamma Ray (GR)</th>
<th>Bond Index (BI)</th>
<th>CBL Amplitude (CBL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Min VariableDensity (VDL) 200

Max VariableDensity (VDL) 1200

1000 PSI

Little change

Cement Map Image (0 - 100)

(NoPVT) (MV)

2,255.52 m

No Pressure

1100 psi

2,286 m
Casing Expansion (Lower Bound on Annulus)

Casing expansion = 70.55 μm (0.00278 in)

\[
\sigma_c = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} - \frac{r_i^2 r_o^2 (p_o - p_i)}{r^2 (r_o^2 - r_i^2)}
\]

Where:
- \(\sigma_c\) = Circumferential stress (psi) [23,013 psi]
- \(p_i\) = Pressure in the well (psi) [4,550 psi]
- \(p_o\) = Pressure outside the well (psi) [3,500 psi]
- \(r_i\) = Internal radius of the casing (in) [3.363 in]
- \(r_o\) = Outer radius of the casing (in) [7.000]
- \(r\) = Radius of interest in the casing (in) [7.000]
- \(\varepsilon\) = Strain (in/in) [0.00079]
- \(\sigma\) = Stress (psi) [\(\sigma_c\)]
- \(E\) = Young’s Modulus (psi) [29 x 10^6 psi]
- \(C\) = Circumference (in) [21.99115]

Circumferential Hoop Stress

Hooke’s Law  Definition of Strain  Circumference of a Circle

\[
\varepsilon = \frac{\sigma}{E}
\]

\[
\varepsilon = \frac{\Delta C}{C}
\]

\[
C = 2\pi r
\]
Well Testing – CHDT
CHDT Analysis

$k = 125 \ \mu D$

Curve Fit Results

Fit Type: least squares fit
Coefficient values ± one standard deviation
- $y_0 = 1824.7 \pm 0.497$
- $A = -856.69 \pm 0.873$
- $\tau = 138.71 \pm 0.345$

Constant:
- $X_0 = 5224$
Approximately constant pumping rate
Annulus Size Estimates for EGL 7

- Source at 42 ft from test point
- Source at 90 ft from test point
- Source at 140 ft from test point
- Source 330 ft from test point

Actual Flow Rate Measured
Flow Points
Calculated change in annulus between SCMT runs
EGL7 Isolation Scanner Log Sections from 2008 and 2013 Over CHDT Test Zone Showing Material Removed
Well Testing – MDT

- Perforated zone
- Upper packer
- Lower packer
- Flow path
- MDT measurement point
- Perforated zone
- Pressure equalization line
MDT VIT Model Results

Best-fit model results to VIT data from the 46-TPX-10 (left) and CC1 (right) wells.

- Shown (in red) are the measured MRPA data in blue and the model results obtained from parameter estimation. The uncertainty of the best-fit solution is tied to the PDF of estimated wellbore permeability values produced by a parameter estimation algorithm. The 95% confidence in the best-fit solution is bracketed by the dotted red lines.
Sidewall Cores

CC1 1111.9 m (3648 ft)

46-TPX-10 1223.8 m (4015 ft)

CC1 1051.6 m (3450 ft)

CC1 960.1 m (3150 ft)

46-TPX-10 1220.7 m (4005 ft)
Permeability

Comparison of cement sample and VIT permeability

- **CC1 910.4 m (2987 ft)**
- **CC1 VIT 908.3 - 911.4 m (2980 - 2990 ft)**
- **46-TPX-10 1220.7 m (4005 ft)**
- **46-TPX-10 VIT 1222.2 - 1225.3 m (4010 - 4020 ft)**

![Permeability Chart](image-url)
Summary

• Leakage is more likely at cement interfaces than through the cement pore structure

• Well construction is a key factor and establishing and maintaining well integrity
  ▪ Care should be taken selecting and placing materials
  ▪ Best industry practices should be followed

• Although example zones with poor integrity can be located in many wells a full analysis is needed to establish that well is leaking

• Even a small zone of good cement may keep a well from being a leakage pathway

• Field experience has shown that reactions in the ground are probably much slower than what has been seen in the lab [Duguid et al., 2014, Crow et al., 2010 and Carey et al., 2006] but do occur.

• CO₂ resistant portland cements have been used and are currently available
Collaborators

- Robert Butsch, Schlumberger Carbon Services
- J. William Carey, Los Alamos National Lab
- Mike Celia, Princeton University
- Nikita Chugunov, Schlumberger-Doll Research
- Sarah Gasda, Uni Research
- Boyun Guo, University of Louisiana at Lafayette
- Susan Hovorka, University of Texas at Austin
- Mark Moody, Battelle
- Runar Nygaard, Missouri University of Science and Technology
- T.S. Ramakrishnan, Schlumberger-Doll Research
- Joel Sminchak, Battelle
- Vicki Stamp, True Oil Company
- Rebecca Thingelstad
- James Wang, Princeton University,
References


Thanks!

This work was supported by DOE NETL funding agreements: DE-FE-0026585, DE-FE-0001040 and DE-FE-0009284