Well Integrity in CCS/CCUS Projects

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by
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Overview of Well Integrity in CO$_2$ Projects
(CO$_2$ Injection for Storage & EOR)

- Well integrity maintained by best practices, e.g.:
  - ~100 yrs. of lessons learned in oil & gas wells
  - ~40% of oil & gas production is sour (CO$_2$ & H$_2$S)
  - API standards, specifications, and recommended practices
  - API technical report on CO$_2$ EOR project design & operations
  - CCP book, esp. chapters on well design & construction
  - CSA Z741 standard for all phases of CCS projects

- CO$_2$ well integrity issues are:
  - Similar to oil & gas wells
  - More severe than sweet oil & gas production
  - Less severe than highly sour production and acid gas injection
  - Low risk in modern wells and in new wells
  - Higher risk in wells drilled without best practices

- Monitoring & Repairing Leaks Restores Well Integrity
Well Integrity in CO₂ Injection Projects

- >18,000 CO₂ EOR wells worldwide (OGJ)
- 95% of CO₂ EOR wells in USA
- Successful environmental protection
  - Wells designed with multiple pressure barriers
    - No failures of all barriers
  - Monitoring and mitigation is routinely practiced
    - Monitoring helps protect USDW
    - Mitigation keeps flows normal
  - Field-wide monitoring gaining acceptance
Abnormal Flows in CO$_2$ Injection Projects

- No evidence of leakage into USDW or air
- Abnormal flows ("leakage") found & fixed by,
  - Mass balance measurements
  - Periodic MIT, flow profile logging, etc.
  - Flow path sealing technologies
- Flows far up-hole are rare (>1 barrier fails)
- BUT, risk and costs can threaten project viability
  – especially offshore
- Frequent flow monitoring can reduce risks
## MIT Results in Injection Wells

(Koplos et al, 2007)

<table>
<thead>
<tr>
<th>Injection Type</th>
<th>Years</th>
<th>Total # of Wells</th>
<th>Total # of Wells with MIT Failure</th>
<th>% Wells with MIT Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>acid gas</td>
<td>pre-1995</td>
<td>568</td>
<td>35</td>
<td>6.2%</td>
</tr>
<tr>
<td></td>
<td>1995-1999</td>
<td>594</td>
<td>9</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td>2000-2005</td>
<td>748</td>
<td>61</td>
<td>8.2%</td>
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<tr>
<td></td>
<td>All Years</td>
<td>752</td>
<td>98</td>
<td>13.0%</td>
</tr>
<tr>
<td>CO₂</td>
<td>pre-1995</td>
<td>3,324</td>
<td>135</td>
<td>4.1%</td>
</tr>
<tr>
<td></td>
<td>1995-1999</td>
<td>3,432</td>
<td>46</td>
<td>1.3%</td>
</tr>
<tr>
<td></td>
<td>2000-2005</td>
<td>3,978</td>
<td>298</td>
<td>7.5%</td>
</tr>
<tr>
<td></td>
<td>All Years</td>
<td>4,105</td>
<td>455</td>
<td>11.1%</td>
</tr>
<tr>
<td>fresh water</td>
<td>pre-1995</td>
<td>5,395</td>
<td>197</td>
<td>3.7%</td>
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<tr>
<td></td>
<td>1995-1999</td>
<td>5,703</td>
<td>57</td>
<td>1.0%</td>
</tr>
<tr>
<td></td>
<td>2000-2005</td>
<td>6,175</td>
<td>359</td>
<td>5.8%</td>
</tr>
<tr>
<td></td>
<td>All Years</td>
<td>6,400</td>
<td>596</td>
<td>9.3%</td>
</tr>
<tr>
<td>brackish water</td>
<td>pre-1995</td>
<td>10,713</td>
<td>483</td>
<td>4.5%</td>
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<tr>
<td></td>
<td>1995-1999</td>
<td>12,715</td>
<td>223</td>
<td>1.8%</td>
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<tr>
<td></td>
<td>2000-2005</td>
<td>14,488</td>
<td>731</td>
<td>5.0%</td>
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<tr>
<td></td>
<td>All Years</td>
<td>16,060</td>
<td>1,366</td>
<td>8.5%</td>
</tr>
</tbody>
</table>
Designing Wells for Integrity Risks  
(CCP Book Chapter 2)

<table>
<thead>
<tr>
<th>Description</th>
<th>Potential Risks and Concerns</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubing Hanger</td>
<td>CO₂ corrosion may be associated with well back-flushing provision and process interruptions.</td>
<td>CRA - Generally high Nickel Content</td>
</tr>
<tr>
<td>Conductor Casing</td>
<td>Some aquifers have a potential external corrosion risk.</td>
<td>Carbon steel - consider external coating.</td>
</tr>
<tr>
<td>Surface Casing</td>
<td></td>
<td>Carbon steel.</td>
</tr>
<tr>
<td>Injection Tubing</td>
<td>Provision for periodic back-flushing and process up-sets may yield water exceeding 8,000 mpy</td>
<td>GRE lined Carbon Steel or CRA.</td>
</tr>
<tr>
<td>Production Casing</td>
<td>Metallurgy in accordance with industry standards for any contaminants in CO₂.</td>
<td>Carbon Steel - Surface to immediately above base of sealing formation.</td>
</tr>
<tr>
<td>Production Liner</td>
<td>Process upsets &amp; provision for back-flushing may result in high water content CO₂ in the injection zone. Also there may be contaminants in the CO₂ such as H₂S.</td>
<td>CRA. Industry standard if required for applicable contaminants.</td>
</tr>
</tbody>
</table>

Abbreviations used: CRA = Corrosion Resistant Alloy; GRE = resin epoxy; NACE = National Association of Corrosion Engineers.
Typical Well Design to Resist Corrosion

**Wellbore Design – Part II**

**Corrosion Control**
- **Cement** (designed on all strings to circulate to surface)
- **Cathodic Protection**
- **Lined Tubulars**
- **Chemical**
  - **Injectors** – “packer fluid” left in tbg-csg annulus
  - **Producers** – batch or continuous circulation

Planning to Prevent Corrosion

- Determine the severity of corrosion conditions
- Get geochemical data from mud logger or cores
- Use corrosion model predictions over life of well
- Run lab tests with predicted pH values
  - Cement core tests in Hassler Cells
  - Coupon tests for metallurgy in tubulars, DH tools & wellheads
  - Chemical barriers in formation core tests
  - Treatments for packer fluids, drilling & completion fluids
  - Elastomer tests for packer & wellhead sealing elements
- Select well materials based on modeling & lab tests
- Prepare contingency plan for remediation
Modeling pH of CO$_2$ in Brine

(Zhu, 2009)
Equilibrium and rate calculations for corrosive brines in rocks & soluble minerals

- Prior to project: design well tubulars, packers, and cements.
- Monitor data: provide in situ conditions during flood for remediation.

<table>
<thead>
<tr>
<th>H2O</th>
<th>OH-</th>
<th>KCl(aq)</th>
<th>smectite-na</th>
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</thead>
<tbody>
<tr>
<td>H+</td>
<td>Al(OH)2+</td>
<td>KSO4-</td>
<td>k-feldspar</td>
</tr>
<tr>
<td>Ca+2</td>
<td>Al(OH)3(aq)</td>
<td>MgCl+</td>
<td>chlorite</td>
</tr>
<tr>
<td>Mg+2</td>
<td>AIOH+2</td>
<td>MgHCO3+</td>
<td>hematite</td>
</tr>
<tr>
<td>Na+</td>
<td>HAI02(aq)</td>
<td>MgSO4(aq)</td>
<td>pyrite-2</td>
</tr>
<tr>
<td>K+</td>
<td>Al+3</td>
<td>NaCl(aq)</td>
<td>smectite-ca</td>
</tr>
<tr>
<td>Fe+2</td>
<td>NaAlO2(aq)</td>
<td>NaCO3-</td>
<td>albite-low</td>
</tr>
<tr>
<td>SiO2(aq)</td>
<td>CaCl+</td>
<td>NaHCO3(aq)</td>
<td>dolomite-2</td>
</tr>
<tr>
<td>HCO3-</td>
<td>CaCl2(aq)</td>
<td>NaHSiO3(aq)</td>
<td>siderite-2</td>
</tr>
<tr>
<td>SO4-2</td>
<td>CaCO3(aq)</td>
<td>NaOH(aq)</td>
<td>ankerite-2</td>
</tr>
<tr>
<td>AIO2-</td>
<td>CaHCO3+</td>
<td>NaSO4-</td>
<td>dawsonite</td>
</tr>
<tr>
<td>Cl-</td>
<td>CaOH+</td>
<td>SO2(aq)</td>
<td></td>
</tr>
<tr>
<td>O2(aq)</td>
<td>CaSO4(aq)</td>
<td>HCl(aq)</td>
<td></td>
</tr>
<tr>
<td>Acetic~Acid(aq)</td>
<td>FeCl+</td>
<td>calcite</td>
<td></td>
</tr>
<tr>
<td>CO2(aq)</td>
<td>FeCl4-2</td>
<td>kerogen-os</td>
<td></td>
</tr>
<tr>
<td>CO3-2</td>
<td>FeCO3(aq)</td>
<td>magnesite</td>
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<tr>
<td>Fe+3</td>
<td>FeHCO3+</td>
<td>quartz</td>
<td></td>
</tr>
<tr>
<td>H2(aq)</td>
<td>H2S(aq)</td>
<td>kaolinite</td>
<td></td>
</tr>
<tr>
<td>HS-</td>
<td>H3SiO4-</td>
<td>illite</td>
<td></td>
</tr>
<tr>
<td>CH4(aq)</td>
<td>HSO3-</td>
<td>oligoclase</td>
<td></td>
</tr>
</tbody>
</table>
Cements & CWD Prevent Corrosion

- **Challenge:** Corrosion prevention and mitigation methods
  - May occur in old and new wells
- **Solutions:**
  - CO\(_2\) resistant, self-sealing cements (Portland based when pH >4.0)
  - CWD chemical barriers in the rock

**Self-sealing CO\(_2\) cement**

**Conformance While Drilling**
Protects CO\(_2\) Well Integrity by Blocking Rock Permeability

**Hassler Cell Core Test conditions:**
- BHST: 220°F
- CO\(_2\) pressure: 500 psi (water std@RT)
- Confined press: 2000psi
- Duration: 2 hours
- Initial Flow: ~3.4 std cc/min
- Final Flow: non-detectable
- Time to STOP flow ~6min

**Graph:**
- Y-axis: Gas Flow (std cc/min) Range: 0 to 5
- X-axis: Time (4:48:00 to 9:36:00)

**Chart:**
- CO\(_2\) injection time
- Data points show a decrease in gas flow over time.
Self-Sealing CO\textsubscript{2} Cement after Stress Cracking

- Dynamic CO\textsubscript{2} flow test
  - Pre-cracked Cement Core Specimen
  - Core flow test using Hassler sleeve
Stress Cracks Sealed by Self-Sealing CO\textsubscript{2} Cement

Typical un-cracked sample

Cracked sample (arrows show the healed crack)
Monitoring, Inspection, Modeling Tools

- Annular pressure monitoring (API RP 90-1 & 90-2)
- Slick-line casing/tubing inspection (impression block, camera, etc)
- Wireline-conveyed logging tools (CBL, calipers, spinners, etc)
- Seismic array surveys & imaging
- Downhole pressure/temperature (P/T) data modeling
- Well flow meters, tracers & P/T gauges for mass balance data analysis
- Micro-deformation measurements & imaging
  - Surface & downhole tiltmeters
  - Satellite-based InSAR (interferometric synthetic aperture radar)
- Fiber optic sensing
  - DAS (Distributed Acoustic Sensing)
  - DTS (Distributed Temperature Sensing)
  - DSS (Distributed Stress Sensing)
- CO₂ flow predictions via reservoir engineering models
  - Benchmarked and calibrated by monitoring data
  - Periodically verified by monitoring data
Find Abandoned Wells and Field-wide Monitoring

- Magnetometer surveys locate old/unrecorded wellbores
  - Know when CO₂ flow approaches looks abnormal
  - Compare plume flow to old well locations
- Barrier wells use water injection
  - Control plume movement to AOR
  - Help protect old wells from corrosion
  - Prevent flow under sensitive sites

Long Term Monitoring for Decades:
- Maximum displacement corrected by GPS and/or Tilt
- Exceptional spatial range of InSAR allows the identification of motions not anticipated outside of Immediate Region of Interest

3D Perspective of Magnetic Survey
Sealants to Repair Well integrity

- Primary cements formulated for remedial jobs
  - Profile Control Treatments (SPE Monograph, etc)
  - Squeeze annular & out-of-zone flows (SPE103044)
  - Plug-backs
- In-situ cross-linked polymers
- In-situ polymerized monomers (SPE 70068)
- Latex-resin systems externally activated
- Internally or externally catalyzed silicates
- Crystallized copolymer (SPE 101701, etc)
- Rubber cement squeezes (SPE 26572)
- Resin Systems

Longevity:....all sealant types must maintain sealing indefinitely
Brine Leak Remediation via Horizontal Well Drilled into Leak Flowpath Created by CO₂ Injection into Saline Aquifer

- Longstring casing
- Sealant placed in leak flowpath
- Annular injection of safe fluid
- Logging detector
- Reacted sealant interface
- Caprock
- CO₂ injection
- Brine
- Brine leak flowpath
Repairing Well Integrity

• Challenge: Re-Plugging old wells
  • Old P&A standards may not meet needs for CO₂ EOR or CCS

• Solution:
  • Standard wellbores: re-enter, drill out old plugs, clean wellbore to adequate depth, MIT & diagnostic logs, re-plug with cement, re-test each
  • Non-standard (sub-grade pipe, cement, etc) wellbores: re-enter, drill out old plugs, clean wellbore to required depth, MIT + logs, run wireline pipe inspection, mill out damaged casing in required intervals, plug cement at milled-out intervals & those in regulations, re-test each (bottoms up)
Repairing Well Integrity

• Challenge: Tubing and Casing Leaks
  – May occur in old and new wells

• Solution:
  – Diagnostics to pinpoint detection: pressure communications, MIT, pipe inspection logs, pulsed neutron or other logs, downhole camera, etc
  – Repair: pull/replace-or-repair/re-run/re-test pipe or squeeze
    • Pipe-repair: casing patches, expandable liners, pipe connections, etc
    • CO₂ resistant cement squeezes
    • Chemical sealants: CO₂ resistant gels, resin systems, etc
  – P&A liner section, drill sidetrack, run new completion
  – Repeat diagnostics to confirm sealing integrity: MIT, logs, etc

Leaking pipe retrieved

![Diagram showing in-situ polymerizing monomers solution for pinhole casing leaks]
Repairing Well Integrity

• **Challenge: Behind casing flow**
  – May occur in old and new wells

• **Solution:**
  – Apply diagnostic tools to pinpoint leak flow path
  – Design/Execute
    • Perforating into leak path
    • Treatments (squeeze sealants)
      – \( \text{CO}_2 \) resistant cement squeezes
      – \( \text{CO}_2 \) resistant chemical sealants: gels, resin systems, etc
  – Repeat diagnostics to validate success
Repairing Well Integrity

- **Challenge:** Caprock Seal Integrity Failure
  - Leaks via fractures and unsealed faults may occur in some reservoirs

- **Solution:**
  - Apply diagnostic tools (WL logs, seismic, micro-deformation, etc)
    - Pinpoint leak flow path in fracture or fault between wells
  - Design/Execute
    - If needed, coil-tubing drilling into leak path
    - Treatments (squeeze sealants)
      - \( \text{CO}_2 \) resistant cement squeezes or gel-cement stages squeezed
      - \( \text{CO}_2 \) resistant chemical sealants: gels, resins, etc
  - Repeat diagnostics to validate success: sealed leak for \( \text{CO}_2 \) sweep & containment

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Inter-well communication outside the injection pattern due to fractures
Repairing Well Integrity

• Challenge:
  – Injection/production perforation-flow profile control (improve sweep & stop losses)

• Solution:
  – Apply diagnostic tools (modeling, seismic, micro-deformation, WL logs, etc)
  – Design/Execute:
    • Treatments (squeeze sealants)
      – CO₂ resistant cement squeezes to seal perf tunnels
      – CO₂ resistant chemical sealants (gels, resins, etc) to seal perm
    • Mechanical devices: flow control valves, etc to control flow into perfs
  – Repeat diagnostic monitoring to confirm success

[Diagram showing CO₂ breakthrough and gel system shutting off]
Repairing Well Integrity

- Cased-Hole Liner (CHL) to patch casing
- Provide cost-effective repairs to any length of casing
- Specialized CR13 expandable liner systems
Thank you

Questions or Comments?