Well Integrity and Carbon Storage

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Outline and Summary

• Focus of leakage is on existing and abandoned wells within the project area that penetrate the caprock
  – Purpose built wells will have adequate construction and inspection standards
• CO₂ is not inherently deleterious to cement but will rapidly corrode steel that is not protected by cement
• Slow CO₂ leakage processes are, in many instances, self-sealing/self-limiting
• Well integrity statistics show that oil and gas wells experience barrier failures at rates from 1-12% but can be locally much higher
  – Groundwater contamination occurs only when multiple barriers fail
• Groundwater contamination incidents are much lower at 5-12 incidents per 100,000 well-years
• Sustained casing pressure and methane migration provide useful analogs
  – Note: these may be strongly impacted by the presence of shallow gas that is not derived from the reservoir and therefore not directly relevant to CO₂ storage
• Risk assessment methods are available to evaluate potential leakage scenarios (see DOE’s National Risk Assessment Partnership)
What Does Wellbore Integrity Failure Look Like?

Crystal Geyser: CO₂ from abandoned well
http://www.4x4now.com/cg.htm

Aliso Canyon natural gas storage well blowout
(Environmental Defense Fund)

Slow casing leak
Natural gas
Watson and Bachu 2009
Old Wells vs. New Wells

- New wells for carbon storage sites are likely to be purpose-built and may contain novel, \( \text{CO}_2 \)-resistant construction materials
- Old wells were designed for a limited service life (40-50 years)
  - Wells above the storage reservoir could provide a path upward
- The construction practices and abandonment conditions of old wells may be unknown
- Uncertainties with old wells drives some project to areas (or depths) without significant well penetrations
- However, this means giving up on some of the most economically feasible and well studied potential reservoirs
Why do wells leak? Cement & Steel

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-Completion

• Mechanical stress/strain
  – Formation of micro-annulus at casing-cement interface
  – Disruption of cement-formation bond
  – Fracture formation within cement
  – Role of well stimulation (fracking)?
• Geochemical attack
  – Corrosion of steel casing
  – Degradation of Portland cement
    – Carbonation
    – Sulfate attack
    – Acid attack
Field Evidence from Wells for Leakage

Migration of CO$_2$ behind casing has been observed
Magnitude of leakage not quantified (but small?)

Miscible CO$_2$ Flood
Natural CO$_2$ Reservoir
Immiscible CO$_2$ Flood

Carey et al. (2007) IJGGC
Crow et al. (2007) IJGGC
Crow, Carey (unpublished)

These findings were not associated with known groundwater impacts
Experimental Studies:
Conventional wellbore materials can perform in CO₂-rich environments

Cement reacts with CO₂ but does not deteriorate

Steel is corroded by CO₂ but protected by cement

Kutchko et al. (2007)

Carey et al. (2010)
Experimental Studies of Wellbore Integrity: Self-Healing

- Single phase (water+CO$_2$, water+HCl), multiphase (water+scCO$_2$, water +ethane)
- Diffusive carbonation of cement; no carbonate in interfaces
- Formation of leached layers of silica or other amorphous silicate
- Channelized fluid flow
- Migration of cement fines

Newell and Carey (ES&T 2013)
Huerta et al. (ES&T 2013)
Wolterbeek et al. (GETE2013)
Walsh et al. (Rock Mech. Rock Eng. 2013)
Do Well Defects Self-Heal?

(Carey 2013; Carroll et al. 2013)

• Field and experimental observations show reduced permeability at interfaces and in defects (Carey et al. 2007, 2010; Bachu and Bennion 2009; Huerta et al. 2013; Walsh et al. 2013; Luquot et al. 2013; Cao et al. 2013; Brunet et al. 2016)

• Cement deformation may close annuli and defects (Liteanu and Spiers 2011; Walsh et al. 2013; unpublished data)

• Corrosion may be limited by iron-carbonate precipitation (Carey et al. 2010; Han et al. 2011)

• A few studies have found enhanced permeability (Yalcinkaya et al. 2011; Luquot et al. 2013; Cao et al. 2013)

• Weak caprock can seal the external annulus (Williams et al. 2009; Ardila et al. 2009)
Leakage to the atmosphere

- Sustained casing pressure (leakage in an annulus)
  - 4% of wells in Alberta (Watson and Bachu 2009), 12% of offshore Gulf of Mexico (Bourgoyne et al. 2000), some fields as high as 75% (Davies et al. 2014)
  - Estimated analog flow rates of 0.08 to 1000 kg-CO$_2$/day in Gulf of Mexico (Tao et al., 2010)

- (Natural) Gas migration found in soil
  - Lloydminster Canada: heavy oil production, 23% of wells with soil gas from 0.007-134 kg-CH$_4$/day (Erno and Schmitz 1996)
  - Abandoned oil and gas wells in Pennsylvania: 42 wells with mean flow rate of 0.27 kg-CH$_4$/day (Kang et al. 2014)
  - Alberta oil and gas wells: 0.6% of wells had known soil CH$_4$ migration (Watson and Bachu 2009)
  - Abandoned wells in the UK: 30% with elevated CH$_4$ with flow rate of 1 kg-CH$_4$/day

- Regulatory failure rates: 1.9% of O&G wells in Pennsylvania (Ingraffea et al. 2014); 1-10% of EPA class 1 and 2 wells in state-by-state survey (Lustgarten 2012)
- Crystal geyser: 30,000 kg-CO$_2$/day (Gouveia and Friedman 2006)
- Aliso Canyon: 97,000 metric tonnes CH$_4$ released or 875,000 kg/day over 111 day period (Wikipedia)
Do Leaking Wells Impact Groundwater?

- A small fraction of well “violations” impact groundwater
  - see King and King (2013) on concept of multiple barriers
- Ohio (65,000 wells): 185 groundwater events in 25 years (12 per 100,000 well-years) from Kell (2011)
  - 14 related to failure of subsurface well elements during production or injection (primarily corrosion)
  - 41 due to orphaned wells
- Texas (250,000 wells): 211 groundwater events in 16 years (5 per 100,000 well years) from Kell (2011)
  - 7 related to well integrity failure
  - 28 due to orphaned wells
- Nationwide EPA reported 22 water contamination incidents from 2008-2010 for 150,000 class 2 wells (note 12 of these were in California!; 5 per 100,000 well-years; Lustgarten 2012)
- Majority of groundwater incidents are not well integrity related
- Significant reductions in incidents with time
Risk Assessment of Well Leakage

- National Risk Assessment Partnership (DOE) has developed tools for calculating leakage risk from wells and faults (Viswanathan et al. 2008; Jordan et al. 2015; Harp et al. 2016)

- Long-term risk of wells is poorly constrained (Carey and Torsæter 2016)
  - However creep of rock and various chemical processes provide mechanisms to limit potential leakage
Questions

- Materials: Proper construction and verification are more important than CO$_2$-resistant materials
- MIT: External mechanical tests are the only direct measures of leakage (acoustic, temperature, radioactive tracer)
- Monitoring: I would develop a soil monitoring program for abandoned wells
- Plugging: Evaluate adequacy of plugging of existing abandoned wells
- Leak remediation: requires re-entering wells with various methods of injecting sealants; otherwise abandoning the well
- Factors for well integrity: Initial construction crucial; later thermal and mechanical processes can result in damaged materials (review well operational history)
- Legacy well evaluation: a known history of good performance (and even effectively remediated) may be very helpful
- Biggest concern are abandoned wells as they are difficult to remediate
Conclusions

• There is abundant evidence that well integrity problems are real and can lead to atmospheric leakage and groundwater impacts
• The rate of problems is small
  – Lustgarten’s (2012) summary of UIC Class II violations finds 22 alleged groundwater incidents in 2008-2010 (150,000 wells nationally; rate = 5 per 100,000 well years).
• Regulations, standards and testing can play a key role in minimizing impacts
• Geology (depth, natural fracture systems), density of old wells, and the character of USDW are clearly important to risk assessment
• Most groundwater impacts are related to surface oil and gas activities
• Experimental and field work suggest that most well integrity problems originate in the pre-production stage rather than stress-induced damage (e.g., Jordan and Carey 2016)
  – Self-healing may limit stress-induced damage
References

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References


