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Well Integrity and Carbon Storage

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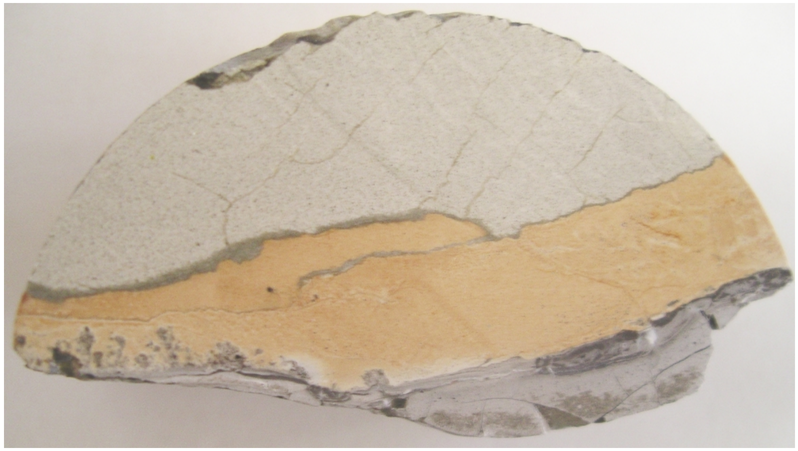

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Outline and Summary

- 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
- CO_2 is not inherently deleterious to cement but will rapidly corrode steel that is not protected by cement
- Slow CO_2 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 CO_2 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: CO_2 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, 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

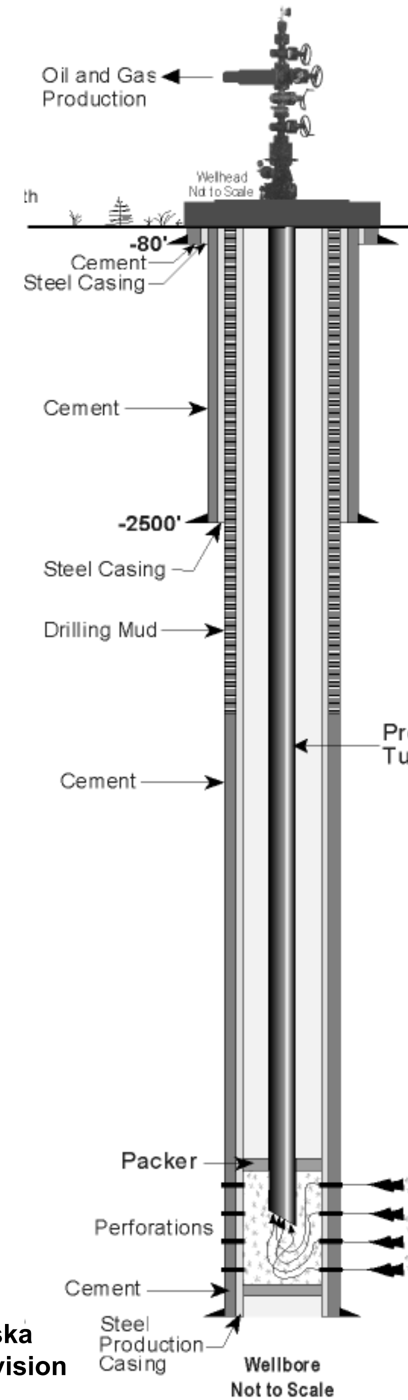
Why do wells leak? Cement & Steel

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



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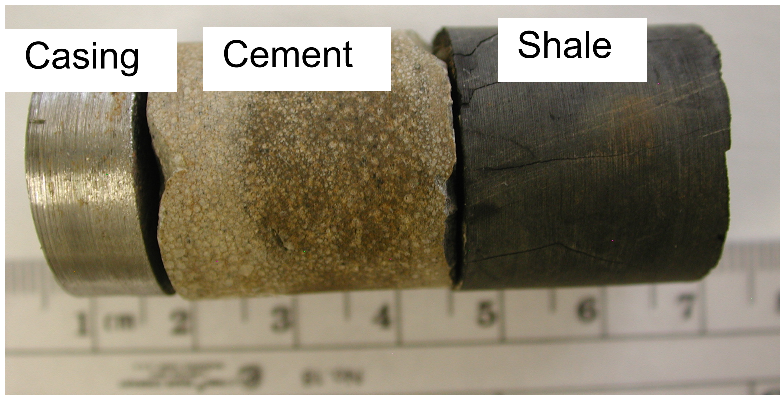
Field Evidence from Wells for Leakage

Migration of CO_2 behind casing has been observed
Magnitude of leakage not quantified (but small?)

Miscible CO_2 Flood

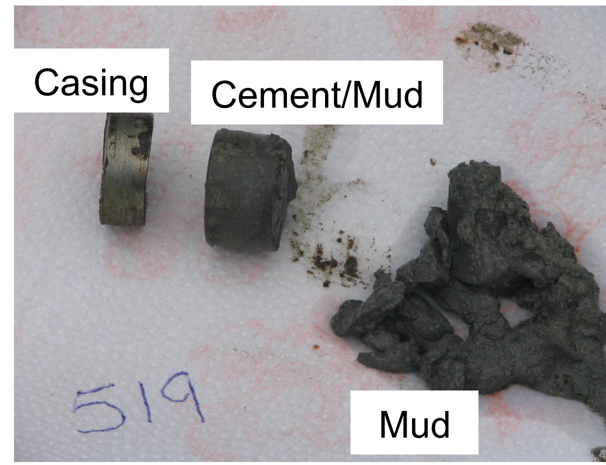
Carey et al. (2007) IJGGC

Natural CO_2 Reservoir



Crow et al. (2007) IJGGC

Immiscible CO_2 Flood



Crow, Carey (unpublished)

Duguid et al. (2014)

These findings were not associated with known groundwater impacts

Experimental Studies:

Conventional wellbore materials can perform in CO_2-rich environments

Cement reacts with CO_2 but does not deteriorate

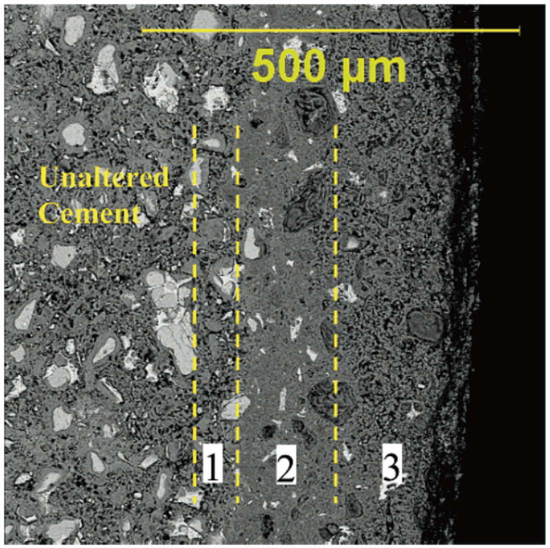
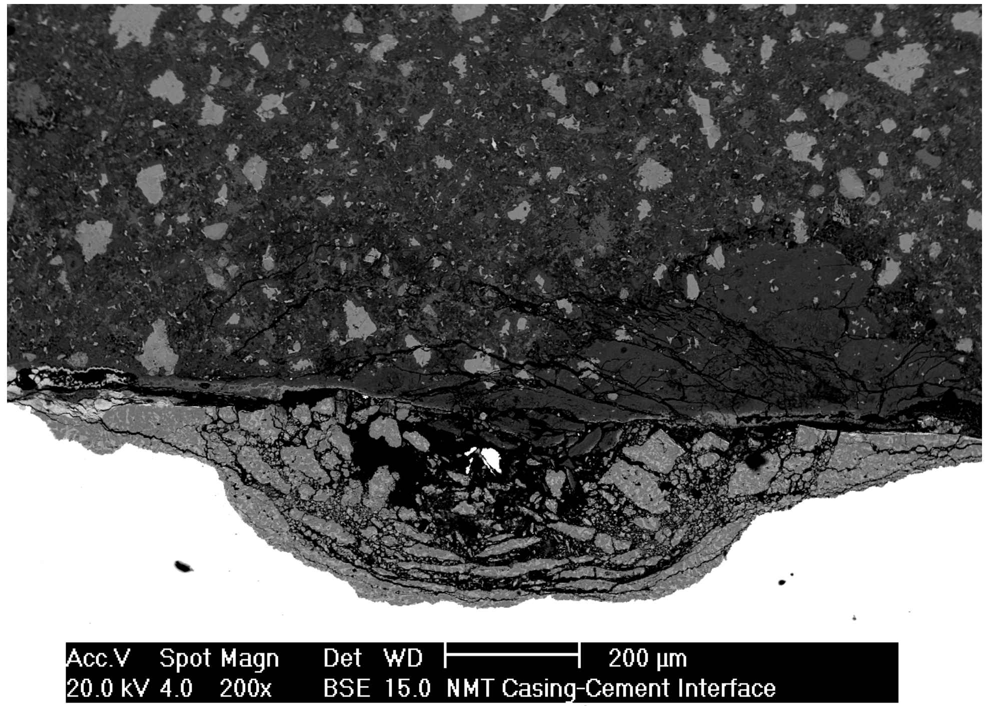


FIGURE 2. SEM-BSE image of cement cured for 28 days at 50 °C and 30.3 MPa and exposed 9 days to aqueous CO_2 at 50 °C and 30.3 MPa. This figure illustrates typical degradation observed. The degraded region can be divided into three distinct zones that are described in detail in the text.

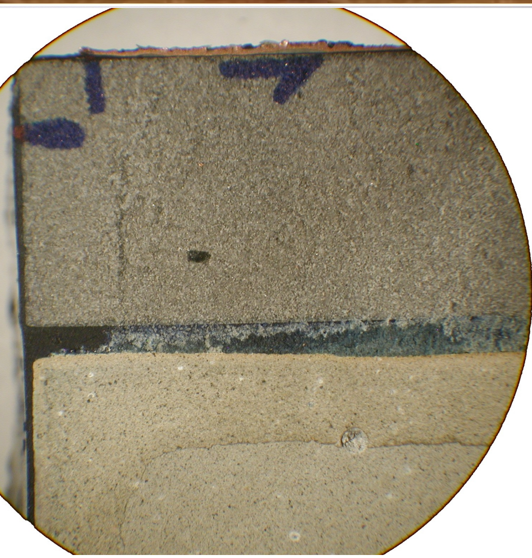
Kutchko et al. (2007)

Steel is corroded by CO_2 but protected by cement

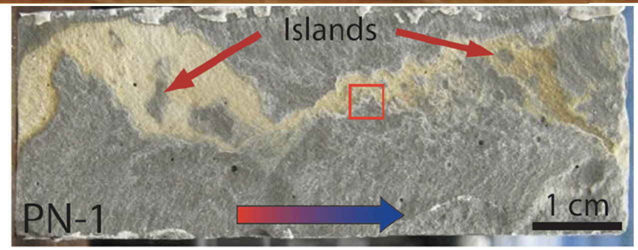


Carey et al. (2010)

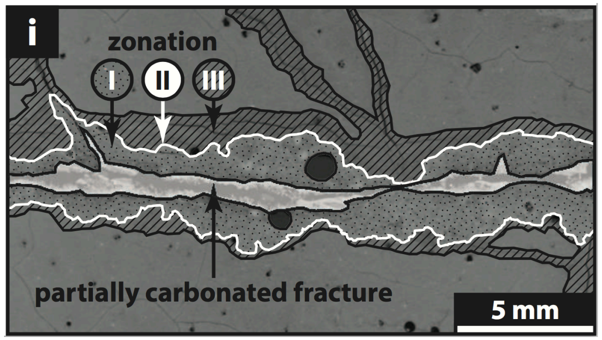
Experimental Studies of Wellbore Integrity: Self-Healing



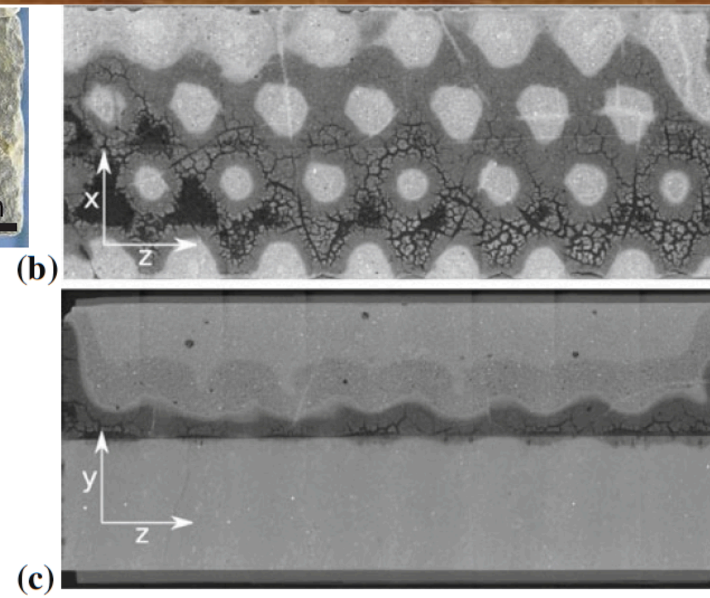
Newell and Carey (ES&T 2013)



Huerta et al. (ES&T 2013)



Wolterbeek et al. (GETE2013)



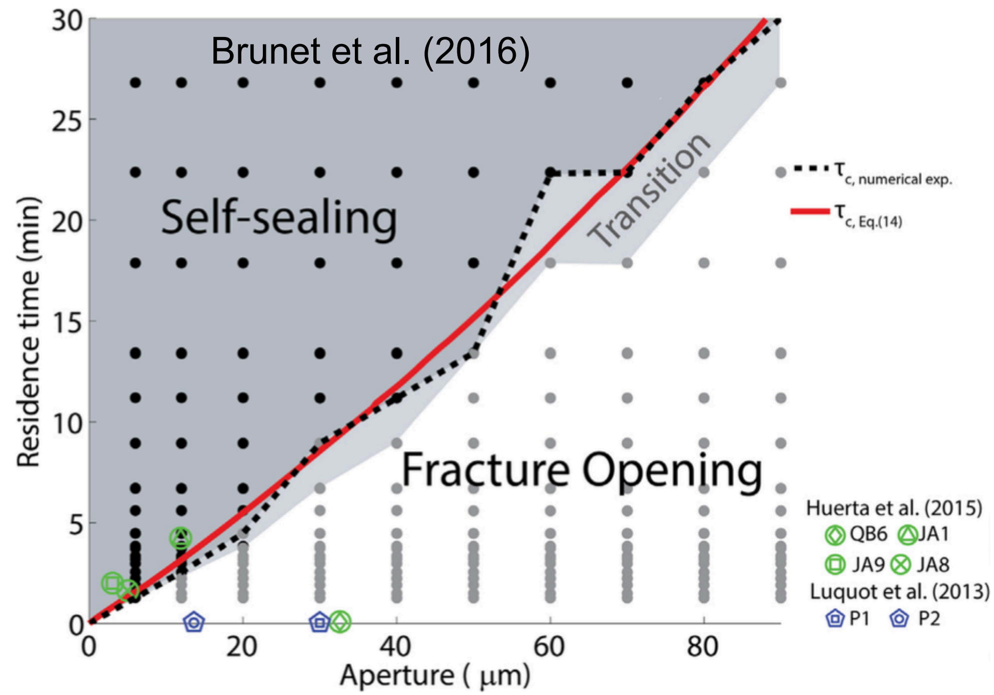
Walsh et al. (Rock Mech. Rock Eng. 2013)

- **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**

Do Well Defects Self-Heal?

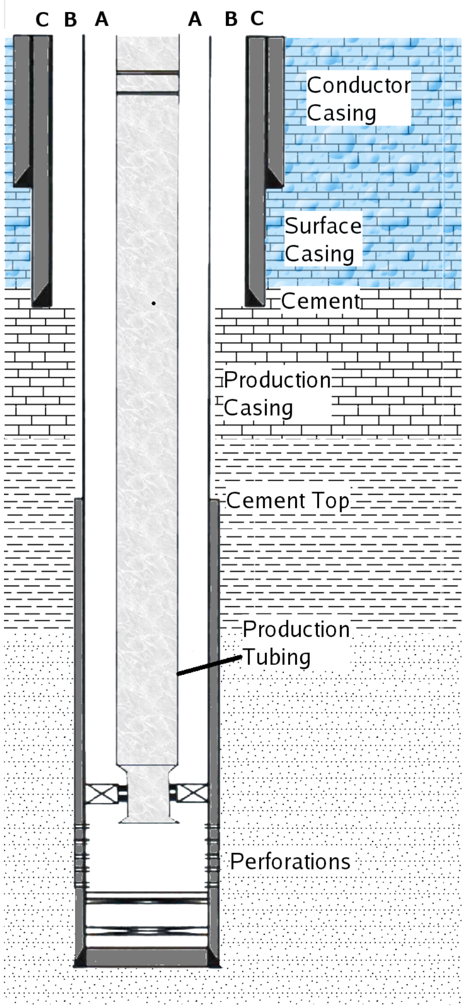
(Carey 2013; Carroll et al. 2013)

- 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)**

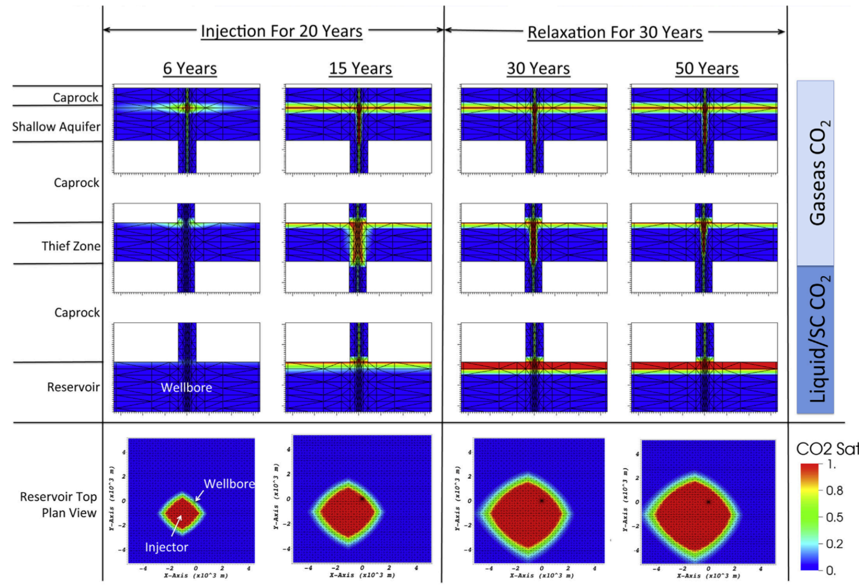


Do Leaking Wells Impact Groundwater?

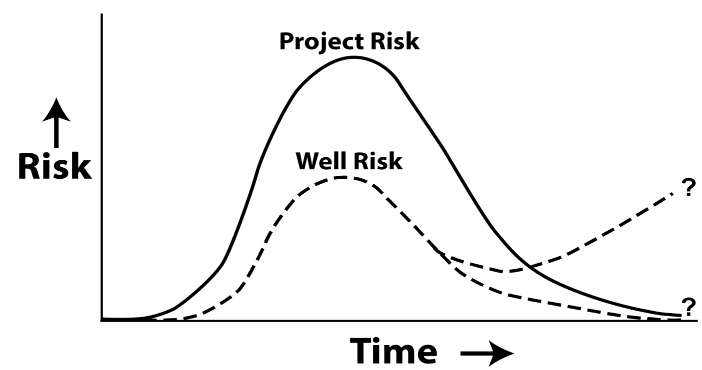
- A small fraction of well "violations" impact groundwater
  - see King and King (2013) on concept of multiple barriers
- Ohio (65,000 wells): 185 groundwater events in 25 years (12 per 100,000 well-years) from Kell (2011)
  - 14 related to failure of subsurface well elements during production or injection (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**



Harp et al. (2016)



Carey and Torsæter et al.(2016)

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

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