Webinars

Welcome!

The program will begin soon.

You will not hear audio until we begin.

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Designing Wells for Carbon Storage Well Integrity: A Friend, Not A Foe

Matteo Loizzo

2022 Nov 7

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Outline of the webinar

- Short intro to CC(U)S
- Wells in CCUS
  - P&A wells and barrier re-rating
- CO_2 injectors' challenges
  - Phase change and injectivity
  - Steel corrosion
  - Cement integrity
    - Microannuli
- Conclusions

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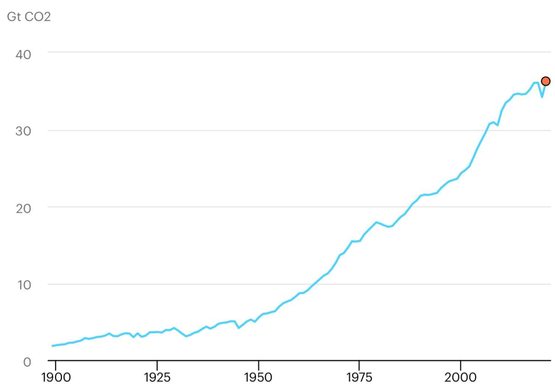
CO_2 – 40 billion (metric) tons of it



Source: IEA 2022; Global Energy Review: CO_2 Emissions in 2021

- Global CO_2 emissions in 2021 → 36.3 Gt
  - +6% post-COVID, with +5.9% GDP
  - CO_2 equals wealth?
    - EU 0.13, US 0.21, China 0.45 tCO_2 per $1,000
- 43% electricity and heat
  - 29% manufacturing & building
  - 22% transport
- Paris agreement
  - Global warming ≤2°C → climate neutral by 2050

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What role can CCUS play?

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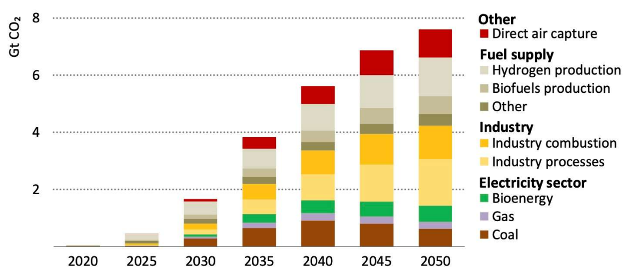

Source: IEA Net Zero by 2050 (Rev.4, 2021)

- IEA Net Zero by 2050
  - 7.6 Gt y^{-1} captured
    - 2.4 Gt y^{-1} from bioenergy use and Direct Air Capture
  - 1.9 Gt y^{-1} stored; rest utilized
    - Half a Socolow ”wedge” → 1 GtC y^{-1} (3.67 $GtCO_2$ y^{-1}) by 2050
- 40 Mt y^{-1} in 2020
  - 30 commercial project, 75% used for EOR in the US

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Funny units – (Metric) tons per year

- Volume (for a gas) depends on p & T → mass is easier
- CO_2 production from one coal power plant
  - 500MW capacity → 3 Mt y^{-1}
- 2 Gt y^{-1} by 2050 → 35 MBbl d^{-1}
  - World oil production ~100 MBbl d^{-1}
  - World water injection ~200 MBbl d^{-1}
- CO_2 injector → 0.5-1 Mt y^{-1}
  - 5,000 wells by 2050

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Carbon Capture & Storage chain

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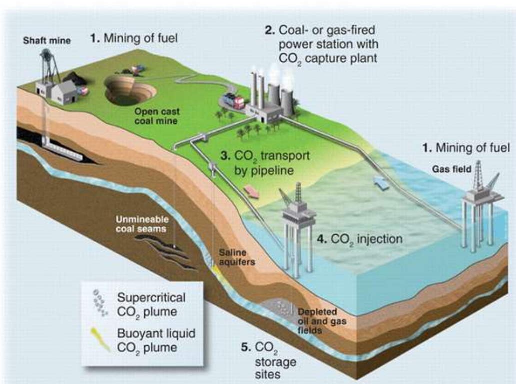

Source: Haszeldine , Carbon Capture and Storage: How Green Can Black Be?, Science (2009)

- Capture → most expensive step
  - Post-combustion
    - Amine, T-swing
- Transport
  - Pipeline
  - Ship
- Storage
  - Deep saline aquifers
  - Depleted O&G reservoirs
  - Plus local quirks
    - Basalt and olivine → Wallula (WA-USA), CarbFix (Iceland)
    - Unmineable coal seams (ECBM)

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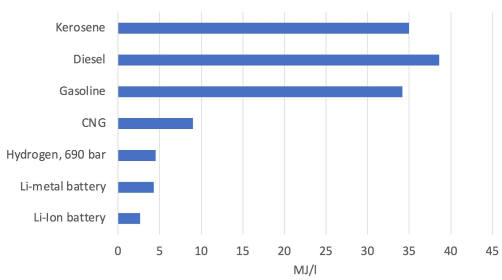
CCUS – Utilization



- Current market → captured and extracted carbon
  - EOR, obviously
  - Urea for fertilizers
  - Fizzy drinks and dry ice
    - "Mineral" water and purity
  - Fire extinguishers, greenhouses, cooling systems…
- Future possibility
  - Building materials → cement carbonation
  - Chemicals and polymers
  - Synthetic fluids
    - Planes and energy density → SpaceX uses kerosene and LNG (Starship)

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CCUS – Performance factors

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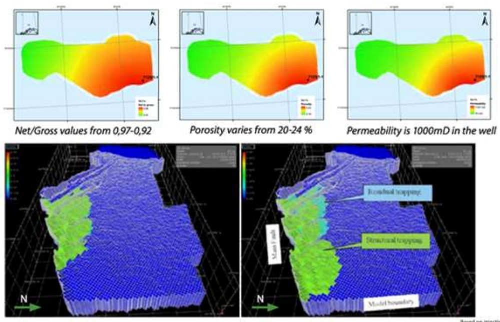
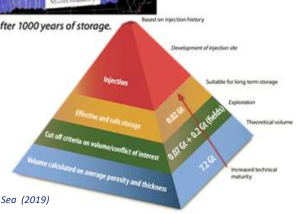


Distribution of injected gas (green) after end of injection (50 years), and after 1000 years of storage. North to the right.



- Capacity
  - Can I fit all my CO_2?
- Injectivity
  - Can I pump it as fast as I produce it?
- Containment, a.k.a. integrity
  - Will it stay there?
  - Geological integrity
    - Caprock and faults
  - Well integrity

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Source: NPD, CO_2 Storage Atlas – Barents Sea (2019)

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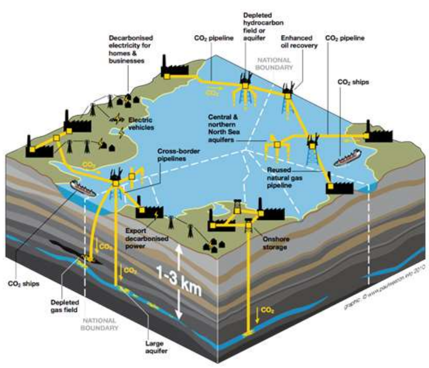
Wells in CCUS



Source: Element Energy (2010), One North Sea (http://www.element-energy.co.uk/2011/01/ccs-potential-in-the-north-sea/)

- Injection wells
  - Thermomechanical stress
    - High p & low T
  - Can use the materials you want
  - Wet CO_2 in case of injection stop
    - Intermittent e.g., boat
- Monitoring wells
  - Cross storage horizon or intermediate aquifer
  - Can be new or reused
  - Wet conditions, possibly CO_2
- Existing wells crossing the storage horizon
  - Active or accessible
  - Permanently abandoned

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P&A wells and CCUS

Source: TexasMonthly, 2022 Jan 12

- Biggest risk, historically
- Properly abandoned or “legacy” wells
  - Grandfathered regulations
  - Little data
- Worst candidates → dry exploration wells
  - Rushed abandonment
    - Saline aquifers? Duh!
    - Sometimes right on top of the anticline
  - No properly qualified barriers, no information on SCP
- Risk-based approach
  - Probability and severity of an event we don’t want to happen
    - Probability of pathways given information (or lack of it) → uncertainty
    - How about severity? Does it matter?

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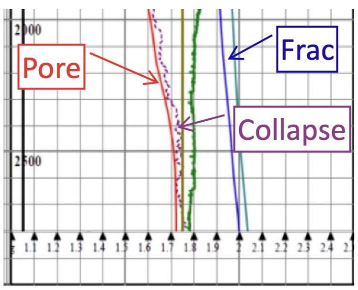
Re-rating abandoned wells' barriers



- Minimum Safe Abandonment Depth
  - Column of fluid (i.e., CO_2) in equilibrium with reservoir meets frac pressure
- Higher pressure, lighter fluid → deeper MSAD
- Failure modes
  - (Hydraulic) fracturing
  - Debonding → open microannulus above closure stress
    - Collapse pressure for shale, σ_h for rock salt

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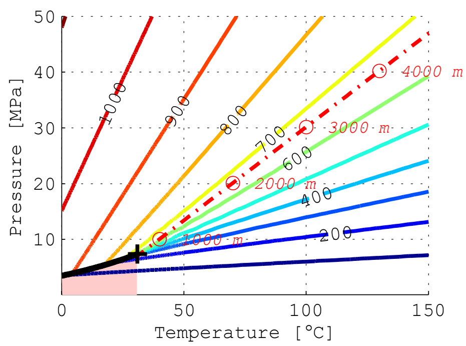
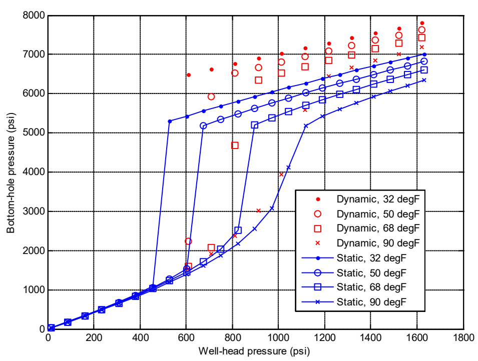
New wells – CO_2 challenges



- Phase change
  - Transported as liquid, stored as supercritical
    - Dense phase
  - Critical point
    - End of the Vapor-Liquid Equilibrium line → T_c=31°C, p_c=7.38 MPa
- Reactivity
  - Soluble in water → 3%-6% by mass
    - Weak acid → sweet steel corrosion
    - Catalytic effect
  - Cement calcination, then carbonation

CO_2 challenges – Injectivity gap



Source: Loizzo et al., SPE 124317 (2010)

- Below Tc, CO_2 can be liquid or vapor at the wellhead
- If reservoir pressure is too low, then either…
  - CO_2 is pumped in vapor phase
    - Loss of efficiency → larger volume for same mass
  - CO_2 is pumped in dense phase
    - Large pressure drop at wellhead or in the formation
- As reservoir pressure increases, will have to switch from vapor to dense phase
  - Injection facility design
- If CO_2 is liquid at the wellhead
  - High bottom hole pressure → fracking
  - Cooling in the near-wellbore
    - Joule-Thomson effect
    - Further reduce the fracture gradient → up to 30% for 20°C
- Big issue with depleted (gas) fields

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CO_2 challenges – J-T effect

Source: Duncan, Ian J., Risk and Monitoring Risk for CO_2 Sequestration in Deep Brine Reservoirs: presented at the 9th International Conference on Greenhouse Gas Control Technologies (GHGT-9), Washington, D.C., November 16-20, 2008. GCCC Digital Publication Series #08-03l

- Joule-Thomson coefficient
  - $\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_H$
- Adiabatic expansion
  - Irreversible → isenthalpic
    - Through orifice, valve or crack → annular leaks and logs
    - Choked flow
  - $\mu_{JT} > 0$, CO_2 cools down
- Large temperature drop
  - Leaks → fog, ice, hydrates, dry ice
    - Safety → poisoning, low visibility, projectiles
  - Expansion at wellhead or reservoir
    - Low temperature completion design

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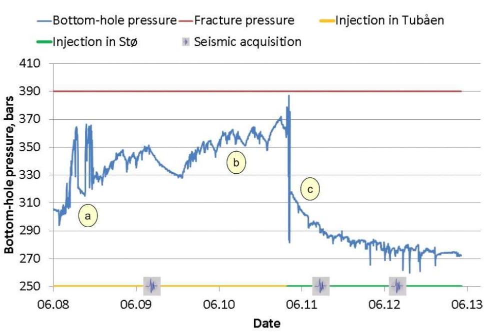
CO_2 challenges – Low temperature

- Thermal shrinkage
  - Vertical → completion sealing and tensile stresses
    - Non-metal to metal seal e.g., packers
  - Radial → cement debonding
- Steel rating for (almost) cryogenic conditions
- Stress cycling
  - May be an issue for 1,000's of cycle and fatigue
- Frac pressure reduction

CO_2 challenges – Skin



Source: Paasch, B., What have we learned?, 2015

- Injectivity → how much CO_2 can be pumped at a given time
  - Number of wells is the cost factor
- Near-wellbore effects
  - Salting out
    - CO_2-water displacement and residual saturation S_{rw}
    - Capillary flow and evaporation of residual water in the plume
  - Geochemistry
    - Carbonate dissolution
    - Scaling → includes hydrates from cooling

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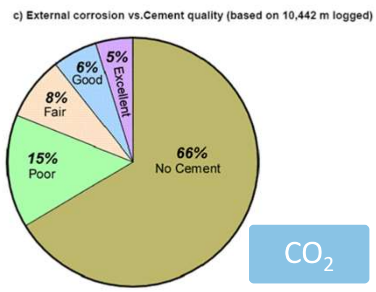
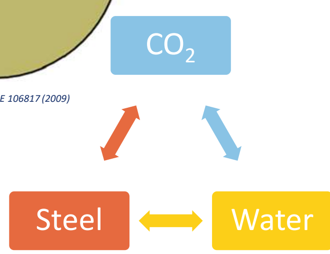
CO_2 challenges – Corrosion



Source: Watson and Bachu, SPE 106817 (2009)



- Weight-loss corrosion
  - Needs water → CO_2 trilemma
    - Worse with oxygen (including NOx!), T, strong acids
  - Higher T, lower [CO_2] but kinetics faster, same effect for cement
- Protection from cement
  - Long-term?
  - Some protection from $FeCO_3$ layer
- Corrosion management
  - Prediction is futile
  - Corrosion-Resistant Alloys
    - Expensive → pipelines are the weak link
    - Plastic coating and Glass-Reinforced Epoxy
- Dehydrating CO_2 → most effective corrosion control
  - 500-750 ppm, above critical pressure
    - Now <50 ppm (e.g., Northern Lights)
  - Injection breaks and formation water flow back
    - CRA in wetted areas? Whole production casing?

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CO_2 challenges – Cement reactivity

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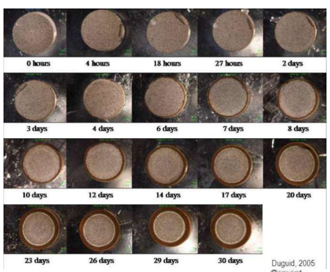
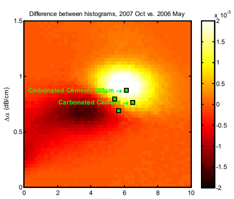


Duguid, 2005



Source: Carey, J.W. et al. Cement with 30 years of CO_2 exposure. Int. J. GHG Control I (2007)

- "Thermodynamically unstable"
  - …like aluminum with oxygen
  - Carbonation then dissolution
- Diffusion-limited reaction → sqrt(t)
  - Fast over 2 cm in the lab
    - 2,000 years for 1 m
  - Sharp fronts with Class G/H
    - Calcite "passivates" cement matrix
    - Subtle role of C-S-H nanostructure → fly ash and EverCRETE
    - Density → porosity and permeability
  - Constrained by transport
    - With enough water and CO_2, cement will leach
- Reaction but no degradation, unless leakage pathway
  - But then, do we care?
  - Mechanical concerns overrated in confined annulus
- "*despite early concerns, a significant body of research suggests that while supercritical CO_2 is reactive with wellbore materials, it does not necessarily lead to a degradation of wellbore integrity*"
  - Pawar et al., 2015

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CO_2 challenges – Cement integrity

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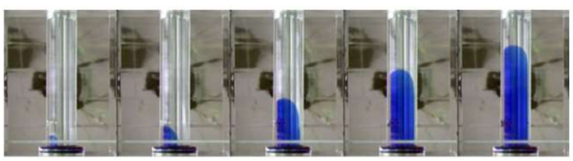

Source: Lecampion, B., Quesada, D., Loizzo, M., Bunger, A., Kear, J., Deremble, L., & Desroches, J. (2011). Interface debonding as a controlling mechanism for loss of well integrity: Importance for CO2 injector wells. Energy Procedia

- Avoid construction defect
  - Losses, mud channels, chimneys
  - Invest in process, not material
- Debonding and microannulus
  - Favored failure mode of solid cement → cracks stay local
  - Hydraulic fracture when pressure > closure stress
    - Inject a high pressure, low temperature fluid
    - Closure stress → creeping formations
  - Other microannulus scenarios
    - Debonding when cement expands or casing contracts → gas on logs, integrity indicator
    - Water layer during cement setting

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CO_2 and microannuli

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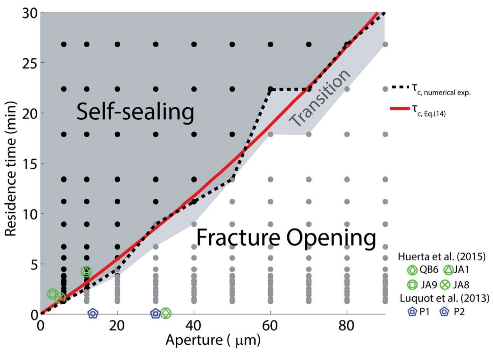

Source: Brunet, J.-P.L. et al. International Journal of Greenhouse Gas Control 47 (2016)

- Bubble flow in microannulus → leading cause of (small) gas leaks, possibly
  - Not only dissolved water, but cement “sweating” from carbonation
- Microannuli and crack experiments
  - Carey, Huerta, Spiers, Walsh, Torsæter…
  - Coupled (T)HMC leak modeling less studied
    - Deremble (2011), Huerta
- Calcite precipitates in the defect, healing it
  - Limescale in kettles
  - Dependence on flow rate and residence time
  - Hints from fault sealing

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Conclusions

- Critical scenarios
  - Low temperature and completion design
  - Sweet corrosion management – in wetted areas
  - Cement debonding
    - Healing possible
    - Use creeping formations
- Cement degradation is a red herring
  - Invest in preventing leakage pathways instead
- Don’t simply “accept” the risk of abandoned wells
  - Lesson painfully learned
- We can make CCUS work
- Thanks to WITS for encouragement and support!

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