Carbon Sequestration Risks and Hazards: What we know and what we don’t know

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Conclusions

Current knowledge strongly supports carbon sequestration as a successful technology to dramatically reduce CO₂ emissions.

“We know enough to site a project, operate it, monitor it, and close it safely and effectively. We do not yet know enough for a full national or worldwide deployment.”

The hazards of CO₂ sequestration are well defined and the associated risks appear small and manageable.

Site characterization, monitoring, and hazard assessment & management are keys to safe and successful deployment.
Geological carbon sequestration is the deep injection of CO₂ to avoid atmospheric release.

CO₂ can be stored in deep geological formations as a pore-filling fluid:

- **Saline Formations:**
  - largest capacity (>2200 Gt)

- **Depleted Oil & Gas**
  - potential for enhanced oil and natural gas recovery

- **Deep Coal Seams:**
  - potential for enhanced gas recovery as well

*Scientific American, 2005*
What empirical evidence is there that transport & geological storage of CO₂ can be done safely?

- Nature has stored oil and natural gas in underground formations over geologic timeframes, i.e. millions of years
- Gas and pipeline companies are today storing natural gas in underground formations (>10,000 facility-years experience)
- Naturally occurring CO₂ reservoirs have stored CO2-rich gas underground for millions of year, including large volumes in the US (WY, CO, TX, UT, NM, MS, WV)
- Almost 3,000 miles of CO₂ pipelines are operate in N. America, carrying over 30 million tons of CO₂ annually
- Well over 100 million tons of CO₂ have already been injected into oil reservoirs for EOR as well as into deep saline aquifers (over 80 projects have been implemented worldwide)
- Three commercial sequestration projects have demonstrably sequestered CO2 at injection rates ~ 1 million t CO₂/y for years across a wide range of geological settings
There are tremendous available resources, applicable learnings, works in progress

- IPCC Special Report
  - 2004 snapshot
  - High level of technical detail
- CO₂ Monography (SPE)
- MIT Report: Future of Coal
- IOGCC draft guidelines (2007)
- NAS study (in progress)
- WRI CCS draft guidelines
- EPA draft regulations
- Many DOE documents
  - N. America CO₂ Atlas
  - Annual Roadmap
  - FutureGen selection criteria
The crust is well configured to trap large CO$_2$ volumes indefinitely. Because of multiple storage mechanisms working at multiple length and time scale, the shallow crust should attenuate mobile free-phase CO$_2$ plumes, trap them residually, & ultimately dissolve them. This means that over time risk decreases and permanence increases.
Several large projects exist, with many pending. The projects, especially the three commercial sequestration projects, demonstrate the high chance of success for CCS.

This experience base contributes to our knowledge regarding what is known about possible leakage hazards and risks.
Deployment efforts have brought focus to CCS operations life-cycle and its key issues.

Regulators and decision makers will make decisions at key junctures, only some of which are well understood technically.

Operators have to make choices that affect capital deployment and actions on the ground.
Site characterization is the MOST important step in storage project preparation.

**Injectivity**
- Rate of volume injection
- Must be sustainable (months – yrs)

**Retention**
- Ability for a site to store CO₂
- Long beyond the lifetime of the project
- Most difficult to define or defend

**Capacity**
- Bulk (integrated) property
- Total volume estimate
- Sensitive to process

Gasda et al., 2005
Monitoring and verification (M&V) is required, but has also been demonstrated in many settings.

MMV serves these key roles:
- Understand key features, effects, & processes
- Injection management
- Delineate and identify leakage risk and leakage
- Provide early warnings of failure
- Verify storage for accounting and crediting

Currently, there are abundant viable tools and methods; however, only a handful of parameters are key.

Demonstrated at:
- Sleipner, In Salah, Weyburn
- Frio Brine Pilot (S. Hovorka’s presentation)
- Otway basin (Aus), Ketzin (Germ), Nagaoka (Japan)

Monitoring and verification improves the operation, safety, and economic value of CCS projects.
Examples of monitored projects

Sleipner Project, N. Sea
Time-lapse seismic

In Salah, Algeria
InSAR

2006 - 1994 difference

CO2 Capture project, 2009

Wright et al., 2008
Overview Of Hazard and Risk Issues
Some basic considerations relevant to the nature and magnitude of CO₂-related risks

- CO₂ is not flammable or explosive
- CO₂ is not a dangerous gas except in very high concentrations (> 15,000 ppm)
  - Not to be confused with carbon monoxide (CO)
  - We inhale and exhale CO₂ with every breath
  - We drink carbonated (CO₂ containing) beverages
  - We buy “frozen” CO₂ for cooling (dry ice)
- We have successfully plugged and abandoned CO₂ injection wells, even badly damaged and failed wells
- Where human, animal or plant mortality has been attributable to CO₂ is due to volcanic releases in large quantities (e.g. Cameroon, Africa) or pooled in depressions or pits (Mammoth Mountain, California)
Wells represent the main hazard to GCS site integrity

We have some understanding of well failure modes

We can properly design CO₂ wells and plug failed wells

Managing and maintaining well integrity is important to avoiding failure and risk minimization

We can identify and recomplete lost wells
Crystal Geyser, UT represents an analog for well leakage, fault leakage, & soil leakage.

Drilled in 1936 to 801-m depth initiated CO₂ geysering.

CO₂ flows from Aztec sandstone (high P&P saline aquifer)

Oct. 2004, LLNL collected flux data
- Temperature data
- Meteorological data
  - Low wind (<2 m/s)
- 5 eruptions over 48 hrs
- Four eruptions and one pre-eruption event sampled
The risks of leakage appear to be both small and manageable. Wells present a challenge to integrity and monitoring which could be resolved through technology application & regulation.
There have been other CO2 well failures with larger release rates

<table>
<thead>
<tr>
<th>Location</th>
<th>CO₂ release rate (original units)</th>
<th>CO₂ release rate (kg/sec (t/d))</th>
<th>Date</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wyoming</td>
<td>100 million cubic feet/day</td>
<td>60 (~5000)</td>
<td></td>
<td>S. Stinson, personal comm. 2007</td>
</tr>
<tr>
<td>Sheep Mt., CO</td>
<td>At least 200x10⁶ scf/day</td>
<td>120 (~10,000)</td>
<td>March 17-April 3, 1982</td>
<td>Lynch et al. (1985)</td>
</tr>
<tr>
<td>Torre Alfina geothermal field, Italy</td>
<td>300 tons/hour</td>
<td>76 (~6500)</td>
<td>1973</td>
<td>Lewicki, Birkholzer, Tsang (2007)</td>
</tr>
<tr>
<td>Travale geothermal field, Italy</td>
<td>450 t fluid/hr</td>
<td>113</td>
<td>Jan. 7, 1972</td>
<td>Geothermics Lewicki et al. (2007)</td>
</tr>
<tr>
<td>Leroy Gas Storage, WY</td>
<td>3e6 m³/year</td>
<td>0.2</td>
<td>1976-1981</td>
<td>Lewicki et al. (2007)</td>
</tr>
<tr>
<td>Edmund Trust #1-33, Kingfisher, OK</td>
<td>45 million cubic feet of gas/month</td>
<td>0.9</td>
<td>Dec. 2005-Jan. 2006</td>
<td>Lewicki et al. (2007)</td>
</tr>
<tr>
<td>Crystal Geyser, UT</td>
<td>2.6 to 5.8 kg/sec</td>
<td>2.6 to 5.8</td>
<td>Continuing</td>
<td>Gouveia &amp; Friedmann (2006)</td>
</tr>
</tbody>
</table>

*These events were detected quickly and stopped*
Simulations of the largest hypothetical event suggest leakage appears to be manageable.

Max. CO₂ flow rate: 7” inside diameter well

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Flow rate (kg/s)</th>
<th>Flow rate (ton/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5036</td>
<td>225</td>
<td>1944</td>
</tr>
<tr>
<td>4614</td>
<td>217</td>
<td>1875</td>
</tr>
<tr>
<td>5102</td>
<td>226</td>
<td>1952</td>
</tr>
<tr>
<td>4882</td>
<td>224</td>
<td>1935</td>
</tr>
</tbody>
</table>

Simulated hypothetical Max. flow rate event

Great plains: no wind

~2x Sheep Mt. event
~50x Crystal Geyser

Simulated hypothetical Max. flow rate event

Great plains: average wind

The HSE consequences from catastrophic well failure do not appear to present an undue or unmanageable risk.
The Lake Nyos event is not analogous to possible CCS leakage

**The worst CO₂ release event in modern history**

- CO₂ accumulated in lake floor over 100’s of years
- Released all at once: >1000 people died

**Two million tons CO₂ released overnight (probably in an hour)**
- ~1000x bigger than Sheep Mt.
- Several million Crystal Geysers
It is worth noting that the risks at present appear to be very small and manageable.

Analog information abundant
- Oil-gas exploration and production
- Natural gas storage
- Acid gas disposal
- Hazardous waste programs
- Natural and engineered analogs

Operational risks
- No greater than (probably much less than) oil-gas equivalents
- Long experience with tools and methodologies

Leakage risks
- Extremely small for well chosen site
- Actual fluxes likely to be small (HSE consequences also small)
- Mitigation techniques exist

Source: LLNL
Little Grand Wash Fault soil surveys suggest fault leakage flux rates are extremely small

Allis et al. (2005) measured soil flux along the LGW fault zone. Overall, concentrations were <0.1 kg/m²/d.

Integrated over the fault length and area, this is unlikely approach 1 ton/day.

At Crystal Geyser, it is highly likely that all fault-zone leakage is at least two orders of magnitude less than the well. This may be too small to detect with many surface monitoring approaches

Allis et al., 2005
Initial concerns about induced seismicity and associated leakage are likely to be misplaced.

An experiment at Rangely field, CO, attempted to induce earthquakes in 1969-1970. It did so, but only after enormous volumes injected over long times on a weak fault:

- Mean permeability: 1 mD
- Pressure increase: >12 MPa (1750 psi) above original
- Largest earthquake: M3.1

There were no large earthquakes.

The seal worked, even after 35 years of water and CO₂ injection.

Most injection sites are less severe than this one.

This phenomenon can only be studied at scale.
The M6.8 Chuetsu earthquake did not cause leakage at the Nagaoka CO2 injection project.

To identify the earthquake’s impact on the storage site, the conditions of the wells, the reservoir, and the injection facility were inspected and tested.

Following these tests & inspections, the conditions of the wells, reservoir, and facility were found intact after the earthquake, and injection was resumed.

- Oct 23, 2004, 17:56
  Mid-Niigata Chuetsu Earthquake occurred.
- Automatic halt of injection due to loss of power supply
  (Cumulative amount at the time of injection halt: approx. 8,950 t-CO2)

http://www.rite.or.jp/English/lab/geological/demonstration.html
One can also actively manage the reservoir through producing and treating water.

Active CO₂ Reservoir Management provides several benefits:
- Reduces CO₂ plume footprint and increases resource use
- Greatly reduces pressure buildup and attendant risks (e.g., seismicity)
- Allows for Enhanced Water Recovery

Passive CO₂ Reservoir Management

- Extraction ratio = 0
  - Aqueous-phase CO₂ concentration
  - 20-km-radius aquifer

Active CO₂ Reservoir Management

- Extraction ratio = 1
  - Aqueous-phase CO₂ concentration
  - Smaller CO₂ footprint contacting caprock
  - Greater fraction of aquifer utilized for trapping mechanisms
We can produce water at sequestration sites for low cost, reducing environmental footprint and adding value.

Modern 1 GW IGCC plant’s CO₂: 7.5 million m³

How much water are we talking about?
3 million tons = 4 million m³ water
• 3000 acre-feet
• Serve 5000 homes
• Irrigate 1000 acres of crops
• Provide all the cooling water needed for 1000 MW natural gas plant with CCS

1. Produce water from neighboring well
2. Desalinate
3. Reinject the concentrate

Treating 7.5 M m³ of displaced brine to make fresh water could:
▪ Help manage pressure in the saline aquifer
▪ Provide half the plant’s operating fresh water (includes cooling)

Current cost estimate:
$400-600/acre-foot
(1/2 of conventional R/O)

Potential to manage and reduce pressure risk is great; important engineering and reservoir issues must be studied.
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