Technical Challenges to Geological Carbon Sequestration

Science, risks, and getting to yes

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Conclusions

Current knowledge strongly supports carbon sequestration as a successful technology to dramatically reduce CO$_2$ emissions.

*Current science and technology gaps appear resolvable at scale*

Deployment issues, including regulatory, legal, and operational concerns can be advised by science IN LARGE PROJECTS

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

Site characterization, monitoring, and hazard assessment & management are keys to commercial success
Carbon dioxide can be stored in deep geological formations as a dense, pore-filling fluid

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

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

*Scientific American, 2005*
CO$_2$ Capture & Sequestration (CCS) can provide 15-50% of global GHG reductions

- A key portfolio component (w/ cons., effic., nuclear, renew.)
- Cost competitive to other carbon-free options (enables others, like hydrogen)
- Uses proven technology
- Applies to existing and new plants
- Room for cost reductions (50-80%)

**Econ. value of 1 wedge ~ $11 T**

R. Socolow, 2007
A Simple View of CCS economics

<table>
<thead>
<tr>
<th>Current Cost of Production</th>
<th>Carbon Capture and Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA: 5-6¢ per KWHr</td>
<td>3-5¢ per KWHr</td>
</tr>
</tbody>
</table>

- Additional value of reduced carbon emission product
- Value of CO2 used as commodity
- Value of offsets sold to others

We must both **reduce costs** and **increase value** for CCS to be profitable.

Probably too big and certainly uncertain!
High purity (>95%) CO\textsubscript{2} streams are required for storage

Three technology pathways can capture and separate large volumes of CO\textsubscript{2}:

- **Post combustion**
  - Coal
  - Gas
  - Biomass
  - Power & Heat
  - CO\textsubscript{2} Separation
  - N\textsubscript{2} O\textsubscript{2}

- **Pre combustion**
  - Gasification
  - Gas, Oil
  - Reformer + CO\textsubscript{2} Sep
  - H\textsubscript{2}
  - Power & Heat
  - N\textsubscript{2} O\textsubscript{2}

- **Oxyfuel**
  - Coal
  - Gas
  - Biomass
  - Power & Heat
  - CO\textsubscript{2}

These costs can and will go down

After IPCC SRCCS, 2005
Storage mechanisms are sufficiently well understood to be confident of effectiveness.

Physical trapping
- Impermeable cap rock
- Either geometric or hydrodynamic stability

Residual phase trapping
- Capillary forces immobilized fluids
- Sensitive to pore geometry (<25% pore vol.)

Solution/Mineral Trapping
- Slow kinetics
- High permanence

Gas adsorption
- For organic minerals only (coals, oil shales)
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.
The true scope of large-scale CCS deployment is the primary challenge

Let’s suggest that by 2020, all new coal plants will be fitted for CO₂ capture and storage *(watch this space)*. The scope and scale of injection from a single plant must be considered.

One 1000 MW coal plant, 85% c.f., 90% capture:
- 5-8 MM t CO₂/yr
- 120,000-200,000 bbl/d (as supercritical phase)
- After 60 year, 2.8-4 G bbls
- CO₂ plume at 10y, ~10 km radius: at 50 yrs, ~30 km
- Many hundreds of wells
- Likely injection into many stacked targets

Sites must receive large volumes of CO₂ at a high rate and contain them for long periods
We need large projects to give the technical basis regulation and legal frameworks. The projects demonstrate the high chance of success for CCS. Sites of note: Pending, CO₂-EOR. Large projects must be the CCS engines of discovery.
Large projects in the US are announced from many parties in many regions.

These projects are proceeding with real understanding of uncertainties.
The drive to deployment has brought focus on the life-cycle of CCS operations 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.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site screening and early characterization</td>
<td></td>
</tr>
<tr>
<td>Site selection</td>
<td></td>
</tr>
<tr>
<td>Continued characterization pre-injection</td>
<td></td>
</tr>
<tr>
<td>Project permitting and approval</td>
<td></td>
</tr>
<tr>
<td>Baseline monitoring and characterization</td>
<td></td>
</tr>
<tr>
<td>Injection begins</td>
<td></td>
</tr>
<tr>
<td>Operational injection and monitoring</td>
<td></td>
</tr>
<tr>
<td>Injection ends</td>
<td></td>
</tr>
<tr>
<td>Project decommissioning</td>
<td></td>
</tr>
<tr>
<td>Post-injection monitoring</td>
<td></td>
</tr>
<tr>
<td>Site activity ceases</td>
<td></td>
</tr>
</tbody>
</table>
Site selection due diligence requires characterization & validation of ICE

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

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

**Effectiveness**
- Ability for a site to store CO$_2$
- Long beyond the lifetime of the project
- Most difficult to define or defend

Gasda et. al, 2005
A lot of conventional (and new) technology exists to characterize ICE

Injectivity
- Pump/injection tests
- Conventional P&P analyses
- Conventional reservoir mapping
- Fm. parting pressure tests

Capacity
- Conventional reservoir mapping
- Residual phase core measurement
- Conventional simulation or RTM

Effectiveness
- Orphaned/abandoned well detection
- Conventional geological mapping
- Geomechanical analyses
- Capillary entry pressure tests
Assessments represent the lowest cost, highest impact step in CCS

**Expected Costs of CCS Technology Elements**

- **Capture:** $40-80/t CO₂
- **Storage:** $3-8/t CO₂
- **M&V:** $0.2-$1.0/t CO₂
- **Assessment:** <$0.01/t CO₂

*IN GENERAL TERMS, CCS is cost competitive with new nuclear and wind.*

Locally, this will vary considerably.

For any large injection volume, local assessment is extremely low in cost and can be executed with conventional technology.
Leakage risks remain a primary concern

1) High CO₂ concentrations (>15,000 ppm) can harm environment & human health.
2) There are other potential risks to groundwater, environment
3) Concern about the effectiveness & potential impact of widespread CO₂ injection
4) Economic risks flow from uncertainty in subsurface, liability, and regulations

Elements of risk can be prioritized
• Understanding high-permeability conduits (wells and faults)
• Predicting high-impact effects (asphyxiation, water poisoning)
• Characterizing improbable, high-impact events (potential catastrophic cases)
The focus for CO$_2$ storage operations should be HAZARDS first, RISKS second.

HAZARDS are easily mapped & understood, providing a concrete basis for action.

*RISK = Probability * consequence*

RISKS are often difficult to determine
- Hard to get probability or consequence from first principles
- Current dearth of large, well-studied projects prevents empirical constraint
Because of local nature of hazards, prioritization (triage) is possible for any case.

Hypothetical Case: Texas GOM coast

<table>
<thead>
<tr>
<th>Atmospheric release hazards</th>
<th>Groundwater degradation hazard</th>
<th>Crustal deformation hazards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well leakage</td>
<td>Well leakage</td>
<td>Well failure</td>
</tr>
<tr>
<td>Fault leakage</td>
<td>Fault leakage</td>
<td>Fault slip/leakage</td>
</tr>
<tr>
<td>Caprock leakage</td>
<td>Caprock leakage</td>
<td>Caprock failure</td>
</tr>
<tr>
<td>Pipeline/ops leakage</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pink = highest priority
Orange = high priority
Yellow = moderate priority

Part of protocol design is to provide a basis for this kind of local prioritization for a small number of classes/cases.
Wells represent the main hazard to GCS site integrity

We have some understanding of well failure modes

We can properly design CO$_2$ wells and plug failed wells

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

We can identify and recompletelost wells

Gasda et al., 2005

Reddick et al. 2006
Crystal Geyser, UT represents an analog for well leakage, fault leakage, & soil leakage

Drilled in 1936 to 801-m depth initiated CO$_2$ geysering.

CO$_2$ 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
There have been other CO₂ well failures with large 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 200x10^6 scf/day</td>
<td>120 (~10,000)</td>
<td>March 17-April 3, 1982</td>
<td>Lynch <em>et al.</em> (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 <em>et al.</em> (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>

Almost all these events were detected quickly and stopped.
Simulations of the largest hypothetical event suggest leakage appears to be manageable.

The HSE consequences from catastrophic well failure do not appear to present an undue or unmanageable risk.

<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>

Max. CO₂ flow rate: 7” inside diameter well

**~2x Sheep Mt. event**

**~50x Crystal Geyser**

Simulated hypothetical Max. flow rate event

Great plains: no wind

Simulated hypothetical Max. flow rate event

Great plains: average wind
Managing leakage hazards should be FAST
Flexible, Actionable, Simple, and Transparent

Wells present a challenge to integrity and monitoring which could be resolved through technology application & regulation.
Teapot Dome case illustrates ability to constrain and manage hazards (L. Chiaramonte, Stanford)

Time structure map 2nd Wall Creek Fm
(after McCutcheon, 2003)
Once injection begins, monitoring & verification (M&V) is required

M&V 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
- Direct fluid sampling via monitoring wells (e.g., U-tube)
- T, P, pH at all wells (e.g., Bragg fiberoptic grating)
- CO$_2$ distribution in space: various proxy measures (Time-lapse seismic clear best in most cases)
- CO$_2$ saturation (ERT, EMIT likely best)
- Surface CO$_2$ changes, direct or proxy (atmospheric eddy towers best direct; LIDAR may surpass) (perfluorocarbon tracing or noble gas tracing best proxies)
- Stress changes (tri-axial tensiometers)
### Many tools exist to monitor & verify CO₂ plumes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best tool</th>
<th>Other tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid composition</td>
<td>Direct sample</td>
<td>(Surface sampling + simulation)</td>
</tr>
<tr>
<td>T, P fieldwide</td>
<td>Thermocouples &amp; pres. sensors</td>
<td>Fiberoptic Bragg grating</td>
</tr>
<tr>
<td>Subsurface pH monitoring</td>
<td>pH sensors</td>
<td></td>
</tr>
<tr>
<td>CO₂ distribution</td>
<td>Time-lapse seismic</td>
<td>(microseismic, tilt, VSP, electrical methods)</td>
</tr>
<tr>
<td>CO₂ saturation</td>
<td>Electrical methods (ERT)</td>
<td>(advanced seismic)</td>
</tr>
<tr>
<td>Surface detection</td>
<td>Soil gas, PFC tracing</td>
<td>(Atmos. eddy towers, FTIRS, LIDAR, hyperspectral)</td>
</tr>
<tr>
<td>Stress/strain changes</td>
<td>(Tri-axial tensiometers)</td>
<td>Bragg grating, tilt, InSAR</td>
</tr>
</tbody>
</table>
The goals & metrics of a large sequestration demo are not exclusively commercial

**CCS is substantively a new enterprise**

Profitability is not the only substantive metric, TECOP not the only framework. Regulatory & legal frameworks are coming together now.

Politics shifting rapidly
- EPA proposal by July 2008
- CDM may/may not accept CCS
- Warner-Lieberman; 5 others

Legal issues outstanding
- Ownership (WY, others)
- Post-closure liability

Public perception unformed
- EOR is NOT CCS
- Concern over property values, groundwater

No technical basis for minimal req.; due diligence

*If you’re not at the table, you’re on the menu*

Conceptual Risk Profile

Courtesy S. Benson, Stanford
Ultimately, more experience is needed through targeted study of large projects.

The costs of this effort are small compared to the projected cost of plants, pipelines, or global warming impacts.
Outline of large-scale demonstration and experimental projects using low-cost CO₂

Basic requirements for a successful large-scale project include both the logistical and scientific aspects, for ~ 8 years.

Detailed pre-drill assessment $3-10 M
Injection (1-2) & monitoring wells (3-8) $3-12 M
CO₂ (500,000 – 1,000,000 t/y) $3-20 M/y
Compression $5-10 M/y
Monitoring (multiple methods) $3-8 M/y
Analysis and modeling $5-9 M/y
Post-injection sampling/recompletion $3-10 M
Total $89– 267M
Annual $11 – 34 M

In places where the CO₂ and wells are already expensed, the scientific component of a research program is only $49–117M

Large projects must be the CCS engines of discovery.
The Western Region is at the center of national action and interest in carbon management

CA’s SB1368 prohibits long-term power purchase agreements with emissions greater than natural gas plants: other states considering

CA’s AB32 targets cannot be met with efficiency and renewable improvements alone; AB1240 (LCFS) will be difficult using current refineries and carbon loads

WGA’s carbon markets initiative

AB1925, New Mexico executive orders look to find incentives for CCS deployment

New WY law (March 2008) on ownership rights for CO2 injection.

BAAQMD will fine CO\textsubscript{2} emissions ($0.044/t)
Conclusions

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

Current science and technology gaps appear resolvable at scale

Deployment issues, including regulatory, legal, and operational concerns can be advised by science in large projects.

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

Site characterization, monitoring, and hazard assessment & management are keys to commercial success.
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.
China capacity & opportunities can be quickly assessed and pursued

These basins lie near large, concentrated CO₂ sources and contain a relevant range of geology. Assessments, short pipelines, and wells could be completed at low cost.

China is geologically very complex, requiring a long, large-scale effort at capacity assessment.

However, only a few of basins matter the most due to source proximity. These could be assessed fairly quickly and easily given proper cooperation and data access:

- Songliao
- Bohainan-Liaodong
- Sichuan
- Jianghan
- Ordos
- Subei
CO2 storage in the Ordos basin provides unique opportunities and challenges

Many target reservoirs
- Majiagou Fm. (Ord. carbonates)
- Taiyuan Fm. (Carb. sandstones)
- Xiashihenzi Fm. (Perm. sandstones)
- Yanchange Fm (Jurassic sandstones)

Low permeability in general
- Must characterize injectivity carefully
- Can be augmented (deviated wells)
- Improved residual phase trapping
- Many stacked potential targets

Structural complexity modest
- Compression and extension
- Not isotropic in-situ stress

Demonstrated effectiveness
- Substantial oil & gas seals (>5MPa capillary entry pressures)

Some monitoring challenges
- Fast velocity – seismic limitations
- InSAR, tilt, microseismic strong

Newlands & Langford, 2005
The next generation of simulators is needed to capture all key processes in subsurface:

- Fracture/flow response
- Mineral kinetics
- Distribution of dissolution and precipitation
- $CO_2$ equations of state

modified from Norton (1984)