Security of Geological Storage of CO$_2$: What Do We and Don’t We Know?

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Outline

- What is CO₂ capture and storage—and why it is important
- Expert opinion about the security of geological storage and the evidence to support it
- Storage security pyramid—a concept to frame the issue
  - Highlight some active areas of my research team
- Fundamental research needs and opportunities
Where Do the CO₂ Emissions Come From?

Mt CO₂/year

- Other
- Buildings
- Transport
- Industry
- Transformation
- Power Generation

Source: IEA, 2006
Capture and Geologic Storage of CO$_2$ Avoids Emissions

CO$_2$ Capture and Storage: A Four Step Process

1. Capture
2. Compression
3. Pipeline Transport
4. Underground Injection
Options for Geological Storage

- Oil and gas fields
  - Depleted fields
  - EOR, EGR
- Saline formations
- Unminable coal-seams
- Other
  - Basalt
  - Deep ocean sediments
  - ?

From IPCC Special Report, 2005
What Keeps the CO₂ Underground?

- Injected at depths of 1 km or deeper into rocks with tiny pore spaces

  - Primary trapping
    - Beneath seals made of fine textured rocks that provide a membrane and permeability barrier

  - Secondary trapping
    - CO₂ dissolves in water
    - CO₂ is trapped by capillary forces
    - CO₂ converts to solid minerals
“… the fraction retained in appropriately selected and managed geological reservoirs is likely to exceed 99% over 1,000 years.”

“With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO₂ releases if they arise, the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas.”
Evidence to Support these Conclusions

- **Natural analogs**
  - Oil and gas reservoirs
  - CO₂ reservoirs

- **Performance of industrial analogs**
  - 30+ years experience with CO₂ EOR
  - 100 years experience with natural gas storage
  - Acid gas disposal

- **20+ years of cumulative performance of actual CO₂ storage projects**
  - Sleipner, off-shore Norway, 1996
  - Weyburn, Canada, 2000
  - In Salah, Algeria, 2004

~35 Mt/yr are injected for CO₂-EOR
“With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods…”

IPCC, 2005

“…the fraction retained in appropriately selected and managed geological reservoirs is likely to exceed 99% over 1,000 years.”

IPCC, 2005

Geological Storage Safety and Security Pyramid
“With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods…”

IPCC, 2005

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IPCC, 2005
Some Key Issues for CO₂ Storage in Deep Saline Aquifers

- What fraction of the pore space can be filled with CO₂?
- How big will the CO₂ plume be?
- How much CO₂ will be dissolved?
- How much will capillary trapping immobilize CO₂?
- Can accurate models be developed to predict CO₂ fate and transport?

Answering these questions depends on the complex interplay of viscous, capillary, buoyancy forces and heterogeneity and structure on CO₂ plume migration.

Courtesy of Christine Doughty, LBNL
Core-flood Set-Up for Relative Permeability Measurements

- Brine composition: CO$_2$ saturated brine with 0.5 molar potassium iodide

Room Temperature: 16.5° C

Overburden Pressure: 100 bars

\[ \frac{\mu_w}{\mu_{CO_2}} = 14.3 \]

- Constant Displacement Pumps
- Differential Pressure Transducer
- Pressure Data Acquisition
Core-Scale Imaging of CO₂ Distributions

High Pressure Pumps

Core Holder
In Scanner
Sub-corescale saturation variations generally overlooked in relative permeability measurements.
Simulated CO$_2$ Saturations

Variable P$_c$ Produces Small-scale CO$_2$ Saturation Variations

<table>
<thead>
<tr>
<th>CO$_2$ Saturations</th>
<th>Lab Data</th>
<th>Variable $\phi$, $k$ Simulations</th>
<th>Variable P$_c$ Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% CO$_2$</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
</tr>
<tr>
<td>90% CO$_2$</td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>100% CO$_2$</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
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CO$_2$ Saturation: 0% - 70%
“With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods…”

IPCC, 2005

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Geological Storage Safety and Security Pyramid

- Financial Responsibility
- Regulatory Oversight
- Remediation
- Monitoring
- Safe Operations
- Storage Engineering
- Site Characterization and Selection
- Fundamental Storage and Leakage Mechanisms
Seismic Monitoring Data from Sleipner

Sleipner Aquifer Storage Project

Photo and image, courtesy of Statoil
An Alternative Approach: Real-Time Seismic Monitoring

CO₂ Plume
An Alternative Approach: Real-Time Seismic Monitoring
An Alternative Approach: Real-Time Seismic Monitoring

Plume

Source Well

Receiver Well

Receiver Well
Proof of Concept: Real-Time Seismic Monitoring

Real-Time CO$_2$ Tracking

Cross Well Data Match

Delta t (ms)

0.00 0.50 1.00 1.50 2.00 2.50 3.00

time (days)

1650 1655 1660 1665 1670 1675 1680

Distance (m)

Top Seal

Bottom Seal

0.2 days 0.6 days 1.4 days 2.4 days

1650 Measured 1658 Measured 1666 Measured 1676 Measured

1650 1658 1666 1676

1680 Measured
“With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods…”

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Primary and Secondary Trapping Mechanisms

- Sandstone
- Shale
- Sandstone
- Shale or Evaporite (seal)
- Sandstone or Carbonate (storage formation)

![Diagram showing trapping mechanisms over time](image_url)
Quantifying Secondary Trapping Mechanisms

Geological Model

Computational Grid
Numerical Simulations of Plume Movement and Trapping

From Doughty and Benson, 2006
Simulated Trapping

CO₂ Trapping 30-Years Post Injection
Conceptual Risk Profile for Geological Storage

- Injection begins
- Injection stops
- 2 x injection period
- 3 x injection period
- n x injection period

Health, Safety and Environmental Risk

- Pressure recovery
- Secondary trapping mechanisms
- Confidence in predictive models

Monitor
- Calibrate & Validate Models

Model
- Calibrate & Validate Models
Phased Approach and Hybrid to Financial Responsibility

Private Sector Instruments

- Pressure recovery
- Secondary trapping mechanisms
- Confidence in predictive models

Public Sector Instruments
- Bonds
- Trust fund

Injection begins
Injection stops
2 x injection period
3 x injection period
n x injection period

Health, Safety and Environmental Risk

Monitor
Calibrate & Validate Models
Calibrate & Validate Models

Model

GCEP
### Fundamental Research Needs

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<th>Influence of heterogeneity at all scales on plume migration</th>
<th>Greater confidence in simulation models</th>
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<tr>
<td>Geochemical reactions and kinetics in multi-phase flow systems</td>
<td>Greater confidence in mineral trapping</td>
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<tr>
<td>Dynamic imaging of complex multi-phase flows</td>
<td>Better quality monitoring</td>
</tr>
<tr>
<td>Geomechanical and hydrological effects of large anthropogenic perturbations</td>
<td>Better knowledge of CO₂ leakage and brine migration potential</td>
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<td>Flow and transport properties of seals, faults and fractures</td>
<td>More reliable seal assessment and site selection</td>
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The Scale is Large

- Sleipner Project: ~1 Mt/yr
- 1,000 MW Power Plant with Capture: ~6 to 8 Mt/yr
- All CO₂-EOR in U.S.: ~30 Mt/yr
- U.S. Emissions from Coal-Fired Power Plants: ~2,000 Mt/yr