Safety and Monitoring of CO₂ Storage Projects

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Outline

• Fundamentals of storage safety and security
  – Natural analogs
    • Oil and gas reservoirs
    • CO₂ reservoirs
  – Industrial analogues
    • Natural gas storage
    • CO₂ enhanced oil recovery
  – Existing projects
• Environmental risks of geological storage
• Risk management and mitigation
  – Storage security pyramid
  – Monitoring
• CCS development pathway
“… 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.”
What Keeps the CO$_2$ 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
  - CO$_2$ dissolves in water
  - CO$_2$ is trapped by capillary forces
  - CO$_2$ converts to solid minerals
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
Natural Gas Storage

- Seasonal storage to meet winter loads
- Storage formations
  - Depleted oil and gas reservoirs
  - Aquifers
  - Caverns
Role of Natural and Industrial Analogs

• Natural analogues
  – Proof that long term storage of buoyant fluids is possible
  – Identification of geological formations that can store CO₂
  – Understanding of geochemical interactions between CO₂ and rocks
  – Identification of features that cause leakage

• Industrial analogues
  – Demonstrated ability to extract and inject fluids
  – Health, safety and environmental performance
  – Injection technology
  – Modeling and monitoring technology

Proof that storage is possible.
Demonstration of how to do it.
What Does a Good Storage Project Look Like?

• Three examples
  – Sleipner, off-shore Norway
  – Weyburn, Canada
  – In Salah, Algeria
• $CO_2$ remains in the storage reservoir
• Formation pressures remain below the fracture gradient
• Wellbore integrity is maintained
• Monitoring demonstrates satisfactory performance
• No serious accidents

Sleipner Saline Aquifer Storage Project
Weyburn CO$_2$-EOR and Storage Project

- 2000 to present
- 1-2 Mt/year CO$_2$ injection
- CO$_2$ from the Dakota Gasification Plant in the U.S.

Photo's and map courtesy of PTRC and Encana
In Salah Gas Project
- Krechba, Algeria
Gas Purification
- Amine Extraction
1 Mt/year CO₂ Injection
Operations Commence - June, 2004

Gas Processing and CO₂ Separation Facility

Courtesy of BP
What Could Go Wrong?

Potential Consequences

1. Worker safety
   - Industrial operations accidents
   - \( \text{CO}_2 \) exposure due to leakage from surface and subsurface facilities

2. Groundwater quality degradation
   - \( \text{CO}_2 \) and geochemical reaction products
   - Brine or gas displacement, including dissolved or separate phase hydrocarbons

3. Resource damage
   - Migration to oil and gas fields
   - Migration to minable coal

4. Ecosystem degradation
   - Terrestrial plants and animals
   - Aquatic plants and animals

5. Public safety
   - \( \text{CO}_2 \) exposure due to leakage from surface and subsurface facilities

6. Structural damage
   - Induced seismicity
   - Differential land surface subsidence or inflation

7. Release to atmosphere

Potential Release Pathways

- Well leakage (injection and abandoned wells)
- Poor site characterization (undetected faults)
- Excessive pressure buildup damages seal
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IPCC, 2005

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Primary and Secondary Trapping Mechanisms

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

% Trapping contribution

Time since injection stops (years)

- Structural & stratigraphic trapping
- Residual phase trapping
- Increasing Storage Security
- Solubility trapping
- Mineral trapping
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Site Characterization and Site Selection

Status of Sedimentary Basins in California

LEGEND:
- Excluded from further consideration
- Included for further investigation
- Undetermined (not yet evaluated)

Other Layers:
- Natural Gas Field
- Oil Field
- County Boundary
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IPCC, 2005
Increasing Injectivity with Long Reach Horizontal Wells

Krechba 503
1500 metres of horizontal section

Average reservoir permeability ~ 5 md

Courtesy of BP
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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
Conclusions from Safety Analysis

- Industrial analogues suggest that CCS activities will have
  - Accident rates less than overall industry average
  - When accidents occur, they are more likely to result in days away from work than the industry average
  - Fatality rates typical of heavy industry
  - Well blowouts are rare events

*Risks of CCS will be comparable to many workplace activities taking place today.*
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Seismic Monitoring Data from Sleipner

Sleipner Aquifer Storage Project

From Andy Chadwick, 2004

Photo and image, courtesy of Statoil
Surface Monitoring

Flux Tower

Detection Verification Facility (Montana State University)

80 m

Flow Controllers

Field Site

Horizontal Injection Well

Hyperspectral Imaging of Vegetation

Soil Gas
Seismic Monitoring Data from Sleipner

Monitoring Methods

- Monitoring Well
- Injection Well
- Pressure Transducer
- Flux Tower
- Flux Accumulation Chamber
- Walk Away VSP
- Injection Rate
- Wellhead Pressure
- Annulus Pressure
- Casing Logs
- CO₂ Sensors
- Geophones
- Active Source Thermal Sensors
- GCEP
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IPCC, 2005
Reliable Remediation Methods Needed for Each Leakage Scenario

Source: IPCC, 2005
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Geological Storage Safety and Security Pyramid

1. Fundamental Storage and Leakage Mechanisms
2. Site Characterization and Selection
3. Storage Engineering
4. Safe Operations
5. Monitoring
6. Remediation
7. Regulatory Oversight
8. Financial Responsibility

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Regulatory Oversight

- Oversight of due diligence
  - Site selection
  - Operational parameters
  - Monitoring
  - Remediation plans
  - Site closure
- Transparency
- Confidence building

The regulatory regime for CCS is being considered. Long term stewardship needs to be resolved

From IPCC, 2005
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Risk Profile of a Storage Project

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

Risk Profile:
- Pressure recovery
- Secondary trapping mechanisms
- Confidence in predictive models

Monitor & Model:
- Calibrate & Validate Models
- Calibrate & Validate Models
Phased Approach to Financial Responsibility

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

- **Private Sector Instruments**
- **Public Sector Instruments**
  - Bond or trust funds

- **Risk Profile**

- **Monitor**
  - Calibrate & Validate Models

- **Model**
  - Calibrate & Validate Models
Integrated Technology Development Pathway

- Basic and Applied Research
  - Fundamental Understanding
  - Technical Needs
  - Technology
    - Fundamental Understanding
  - Pilot and Demonstration Projects
    - Industrial Scale Projects