Carbon Dioxide Capture and Storage in Deep Geological Formations

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Science and technology for a low GHG emission world.
Topics

• CCS overview
• World-wide potential and status report
• Storage security
• Long term liability
• Conclusions
CO₂ Emissions from Fossil Fuels

> 50% of U.S. electricity comes from coal-fired power plants

60% of global fossil fuel emissions come from large stationary sources

40.5% of global emissions come from coal... this is not expected to change any time soon.

CO₂ Emissions (Mt/year)

Global Emissions 27,136 Mt (2005)
Carbon Dioxide Capture and Geologic Storage
Options for CO₂ Capture

• Post-combustion
  – Established technology

• Pre-combustion
  – Established technology for other applications
  – Not demonstrated for power production

• Oxygen combustion
  – Not demonstrated for power production
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
CCS Could Make a Large Contribution to Reducing CO₂ Emissions

*Expected contributions to GHG emissions with carbon prices in the range of $20 to $100/tCO₂-eq.*

From IPCC, 2007:WG III
“It is likely that the technical potential for geological storage is sufficient to cover the high end of the economic potential range (2200 GtCO$_2$), but for specific regions, this may not be true.”
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• CCS Overview
• World-wide status report
• Storage security
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World-Wide Status Report

- Three industrial-scale projects continuing successfully
  - Sleipner, Off-shore Norway
  - Weyburn, Canada
  - In Salah, Algeria
  - 21 years of collective operating experience
- Snohvit CCS project expected to begin soon
- Many announced planning studies for industrial-scale projects
- High capital costs have been a deterrent to wider application

"...combating global warming after pledging to undertake the first large scale carbon dioxide geosequestration project in Australia... will be larger than any other geosequestration scheme currently contemplated or in production... The energy giant cleared the final stage of the approvals process for the mammoth liquefied natural gas (LNG) Gorgon project. The Age, September 7, 2007"
CO₂ Pre-Combustion Capture Projects

- **Dakota SNG Plant**
- **Draugen**
- **FutureGen**
- **EC HYPOGEN (TBD)**
- **GE IGCC Demo**
- **Siemen IGCC Demo**
- **E.On**
- **Centrica/PEL**
- **PowerFuel**
- **E.On**
- **Nuon Magnum**
- **RWE**
- **GreenGen**
- **ZeroGen**
- **BP DF2**
- **Indiana SNG Plant**
- **EPCOR/CCPC**
- **NRG**
- **FutureGen**
- **EPCOR/CCPC**
- **DF3**
- **Source: IEA Greenhouse Gas Technology Programme**
CO$_2$ Injection and Storage Activities

Source: IEA Greenhouse Gas Technology Programme
World-Wide Status Report

- Increasing government investment in CCS R&D
  - e.g. FutureGen and Regional Sequestration Partnerships
- Cost, regulatory framework and institutional issues at the forefront
- Growing press coverage and public awareness

Otway Basin Pilot Project: Australia
Start: Fall 2007

U.S. DOE Regional Sequestration Partnership Program: Pilot Tests
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“Observations from engineered and natural analogues as well as models suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely* to exceed 99% over 100 years and 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.”

* "Very likely" is a probability between 90 and 99%.
** Likely is a probability between 66 and 90%.
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
Sleipner Project, North Sea

- 1996 to present
- 1 Mt CO$_2$ injection/yr
- Seismic monitoring

Picture compliments of Statoil
Weyburn CO₂-EOR and Storage Project

• 2000 to present
• 1-2 Mt/year CO₂ injection
• CO₂ 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
“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
Phase Diagram for Carbon Dioxide

- CO₂ Solid
- CO₂ Liquid
- CO₂ Gas

Triple Point: (-56.6°C, 0.51 MPa)
Critical Point: (31.1°C, 7.38 MPa)

Typical Storage Conditions

Pressures (MPa):
- 0.0001
- 0.001
- 0.01
- 0.1
- 1
- 10
- 100
- 1000

Temperatures (°C):
- -140
- -100
- -60
- -20
- 20
- 60
- 100
Variation with Depth and Geothermal Regime of Carbon Dioxide Density

Storage at depths greater than ~1 km

(Bachu, 2003)
Storage Mechanisms

- Injected at depths of 1 km or deeper into rocks with tiny pore spaces
- Primary trapping
  - Beneath seals of low permeability rocks
- Secondary trapping
  - CO$_2$ dissolves in water
  - CO$_2$ is trapped by capillary forces
  - CO$_2$ converts to solid minerals
  - CO$_2$ adsorbs to coal

Fundamental Storage and Leakage Mechanisms

Diagram showing layers of sandstone, shale, sandstone, and a layer labeled Shale or Evaporite (seal) and Sandstone or Carbonate (storage formation).
CO$_2$ Migration Processes and Trapping

- Viscous and capillary forces
- Heterogeneity
- Gravity
- Structure
X-ray Micro-tomography at the Advanced Light Source

Micro-tomography Beamline

Image of Rock with CO$_2$

- CO$_2$
- Water
- Mineral grain

2 mm
Comparison to Theoretical Distribution

Measured Distribution

Calculated Distribution at 40% Saturation

From Benson et al., 2006
Multi-phase Flow and Capillary Trapping

High Pressure Pumps

Core Holder In Scanner

Differential Pressure Transducer

Pressure Data Acquisition

CO₂, Brine

38 mm, 75 mm
Small-scale CO₂ Saturation Variations

Sub-corescale saturation variations generally overlooked in relative permeability measurements.
Simulated CO₂ Saturations
Variable P_c Produces Small-scale CO₂ Saturation Variations

<table>
<thead>
<tr>
<th>CO₂ Saturations</th>
<th>Lab Data</th>
<th>Variable Φ, k Simulations</th>
<th>Variable P_c Simulations</th>
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<tbody>
<tr>
<td>10% CO₂</td>
<td>![Image]</td>
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<tr>
<td>90% CO₂</td>
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<tr>
<td>100% CO₂</td>
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CO₂ Saturation: 0% - 70%
Capillary Trapping During Water Injection

Residual saturation of 22%
Effect of Dip Angle on Capillary trapping

From Hesse et al., 2007
Small Amounts of Dip Enhance Trapping

Rel Perm Hysteresis, No $P_c$, $N_{gv} = 55.6$, Homogeneous

Tilting the reservoir enhances trapping efficiency (amount and rate)

From Hesse at el., 2007
Storage Capacity and Trapping Mechanisms

Geological Model

Computational Grid

Reservoir Simulation
Sealing Active and Abandoned Wells

From IPCC, 2005
Well Blowouts in Region IV, California

- 50,277 active wells
- 18,660 shut-in wells
- 36,940 abandoned wells
Blowout Frequency in District 4
Monitoring Needs for CCS Projects

Requirements for Geologic Storage

Worker and Public Safety
Local Environmental Impacts to Groundwater and Ecosystems
GHG Mitigation Effectiveness

Monitoring Program
Monitoring Methods

- 3-D Seismic
- Walk Away VSP
- Flux Tower
- Flux Accumulation Chamber

- Injection Rate
- Wellhead Pressure
- Annulus Pressure
- Casing Logs
- CO₂ Sensors

- Cross-Well Seismic
- Active Source Thermal Sensors

- Pressure Transducer

**Diagram Elements:**
- Injection Well
- Monitoring Well
Seismic Monitoring Data from Sleipner

From Andy Chadwick, 2004
An Alternative Approach: Real-Time Seismic Monitoring

CO₂ Plume

Source Well

Receiver Well

Receiver Well
An Alternative Approach: Real-Time Seismic Monitoring
An Alternative Approach: Real-Time Seismic Monitoring
Proof of Concept:
Real-Time Seismic Monitoring

Real-Time CO₂ Tracking

Cross Well Data Match

- Delta t (ms) vs. time (days)
- Graph showing data points for different distances and depths
- Markers and lines indicating measured data at various times

Top Seal: 2.4 days
Bottom Seal: 0.6 days
0.2 days
1.4 days
Surface Monitoring

Detection Verification Facility
(Montana State University)

80 m

Field Site

Horizontal Injection Well

Flow Controllers

Flux Tower

Hyperspectral Imaging of Vegetation

Soil Gas

Flux accumulation chamber
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Widespread Deployment of CCS

- Unresolved institutional issues create investment risk for CCS
- Cost recovery for CO₂ capture
- Regulatory framework for CO₂ storage
- Pore-space ownership
- Long term financial responsibility
  - Monitoring
  - Remediation

IPCC, 2005
Risk Profile for CO$_2$ Storage

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

- Environmental Risk Profile
- Monitor
  - Calibrate & Validate Models
- Model
  - Calibrate & Validate Models

Pressure recovery
Secondary trapping mechanisms
Confidence in predictive models
Conclusions

• CCS is an important part of the portfolio of technologies for reducing greenhouse gas emissions
• Progress on CCS proceeding on all fronts
  – Industrial-scale projects
  – Demonstration plants
  – R&D
• Technology is sufficiently mature for large scale demonstration projects
• Research is needed to support deployment at scale
  – Capture: Reduce costs and improve reliability
  – Storage: Improve confidence in storage security
• Institutional issues need to be resolved to support widespread deployment