Geological storage of CO$_2$ in saline aquifers

by

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Capture and storage of CO$_2$ provide a way to avoid emitting CO$_2$ into the atmosphere by capturing CO$_2$ from major stationary sources, transporting it usually by pipeline, and storing it.

Various CO$_2$ storage options are considered at present, namely geological, ocean and mineral storage. Among these geological storage has achieved most attention and development, reaching a stage at which large deployments are foreseeable.

(Source: Schiermeier, 2006)
Introduction

Content:

• Storage mechanisms and security
• Storage formations and capacity
• Characterization and performance prediction
• Monitoring and verification
• Risk management
• Legal issues
• Summary and conclusions

The main source of information:

Introduction

Options for geological storage  (Source: Cook, 1999)

Numerous CO₂ storage projects already exist and are planned in Algeria, Canada, China, Japan, Netherlands, Norway, UK, USA, etc.
Introduction

Sleipner Project, Norway (Source: IPPC, 2005)
Introduction

In Shalah Gas project (Source: IPPC, 2005)
• Main CO2 Storage Pilot/Demo

Starting operation
– Shenhua 100,000 t/a CCS demonstration, Inner Mongolia

• Features:

  **Technologies:** CO2 chemical source capture + saline aquifer storage
  **Injection scale:** 10,000-100,000 tons per year
  **Injection life:** for Phase I, 3 years
  **Target Layer:** Deep saline aquifers
  **Expected Depth:** 1000-2500 m
  **Number of wells:** 1 injection well, 2 monitoring well
  **Implementation Period:** On-site injection started in 2010
  **CO2 Source:** Captured from coal liquefaction plant
Shenhua 100,000 t/a CCS demonstration site and site analysis
Storage mechanisms and security

Injection of CO₂ into deep geological formations is achieved by pumping it down into a well.

It is typically in super-critical state.

Source: Sasaki et al. (2008)
Injection of CO₂ into deep geological formations is achieved by pumping fluids down into a well.

Transport mechanisms in the subsurface:

- **Advection** in response to pressure gradients due to injection or to natural pressure gradients
- **Buoyancy** due to density difference between CO₂ and formation fluid
- Molecular **diffusion**
- **Dispersion** and fingering due to formation heterogeneities and mobility contrast between CO₂ and formation fluid
- **Dissolution** into formation fluid
- **Mineralisation**
- Pore space trapping (**residual trapping**)  
- **Adsorption** of CO₂ onto organic material
Storage mechanisms and security

Experimental investigation of CO₂ migration in porous media
Courtesy of Profs Pei-Xue Jang and Ruina Xu, Tsinghua University, Beijing

Parameter of Core
Berea Stone
• Diameter: 24.73mm
• Length: 50mm
• Porosity: 22.1%
• Permeability: 650mD
NMR images
Courtesy of Profs Pei-Xue Jang and Ruina Xu, Tsinghua University, Beijing

Saturated Water

Irreducible Water

CO₂:H₂O=1:1

CO₂:H₂O=1:3
Simulation models can be used to predict migration of CO$_2$.

**Pore scale** – usually research

**Aquifer (reservoir) scale** – real world engineering problems or research. Available commercial simulators: ECLIPSE, TOUGH, NUFT, MOFAT etc.
Storage mechanisms and security

Input data for pore scale models:
• Pore geometry
• Initial and boundary conditions

(Source: Tashman et al. 2003)

(Source: Lin et al. 2010)
Storage mechanisms and security

Simulation of fluid flow in Ottawa sand

(Source: Tashman et al. 2003)
Storage mechanisms and security

Simulation of two-phase flow in a packed bed of sand particles.

(Source: Lin et al. 2010)
Storage mechanisms and security

Input data for aquifer scale models

• Saturated permeability for each phase
• Relative permeability curves
• Porosity
• Simulation domain
• Initial and boundary conditions

(Source: Sasaki et al. 2008)
Storage mechanisms and security

Distribution of CO$_2$ after two years of injection simulated using TOUGH code

(Source: Doughty and Pruess, 2004)
Storage mechanisms and security

2D radial model of CO$_2$ injection into homogeneous 100m thick formation

(Source: Ennis-King and Paterson, 2003)
Simulation of 50 years of CO$_2$ into the base of a saline formation

(Source: Kumar, 2005)
Storage mechanisms and security

$CO_2$ storage mechanisms in geological formations

(Source: IPCC, 2005)
Potential CO$_2$ storage sites  (Source: IPCC, 2005)
Storage formations

Storage sites should have
• Adequate capacity and injectivity
• Satisfactory sealing caprock or confining unit
• Sufficiently stable geological environment to avoid compromising integrity of the storage site

Criteria for site selection
• Basin characteristics (tectonic activity, sediment type, geothermal and hydrodynamic regimes);
• Basin resources (hydrocarbons, coal, salt),
• Industry maturity and infrastructure
• Societal issues (level of development, economy, environmental concerns, public education and attitudes)
Efficiency of CO\textsubscript{2} storage in geological media = amount of CO\textsubscript{2} stored per unit volume. Important parameters are:

- **CO\textsubscript{2} density** (for efficiency and safety)
  Increases with depth while CO\textsubscript{2} is in gaseous phase, but levels off when it is supercritical or liquid. Decreases with temperature, so ‘cold’ sedimentary basins are favourable – CO\textsubscript{2} attains higher density at shallower depth (Bachu, 2003)

- Formation **porosity** and thickness (for storage capacity)

- Formation **permeability** (for injectivity)
Storage formations

Possible sites
• **Oil & gas:**
  - Abandoned oil and gas fields
  - Enhanced oil recovery
  - Enhanced gas recovery

(Source: IPCC, 2005)
Storage formations

- **Saline formations**

(Source: IPCC, 2005)
Storage formations

• **Coal seams**. CO$_2$ trapping not well understood.
  Screening criteria:
  - adequate permeability,
  - geometry (a few thick seams),
  - simple structure (minimal faulting and folding),
  - homogeneous, laterally continuous and vertically isolated seams,
  - adequate depth,
  - suitable gas saturation,
  - ability to dewater the formation
  - coal rank

• Other geological media
  - Basalts
  - Oil or gas rich shale
  - Salt caverns
  - Abandoned mines
Capacity of storage sites is evaluated, depending on the trapping mechanism, as:

- **Volumetric** trapping: product of available volume and CO\textsubscript{2} density at \textit{in situ} temperature
- **Solubility** trapping: amount of CO\textsubscript{2} that can be dissolved in formation fluid
- **Adsorption** trapping: product of coal volume and its capacity for adsorbing CO\textsubscript{2}
- **Mineral** trapping: based on available minerals for carbonate precipitation and the amount of CO\textsubscript{2} that will be used in these reactions

Scale of evaluation:

- Global capacity – simplifying assumptions
- Country-, region- or basin- specific estimate
Storage formations

Global storage capacity (Source: IPCC, 2005)

<table>
<thead>
<tr>
<th>Reservoir type</th>
<th>Lower estimate GtCO₂</th>
<th>Upper estimate GtCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil &amp; gas fields</td>
<td>675</td>
<td>900</td>
</tr>
<tr>
<td>Unminable coal seams</td>
<td>3-15</td>
<td>200</td>
</tr>
<tr>
<td>Deep saline formations</td>
<td>1000</td>
<td>Uncertain, possibly 10,000</td>
</tr>
</tbody>
</table>
Evaluation of storage in deep saline formations is a challenge for the following reasons:

• **Multiple mechanisms** for storage
• Mechanisms operate both simultaneously and on different **time scales**
• Relations between various mechanisms are very **complex**, evolve with time and are highly dependent on local conditions
• There is no single consistent and broadly available **methodology**
• Limited **data**

(Source: IPCC, 2005)
Storage formations

Matching of CO₂ sources and geological storage sites.

Examples of regional studies:

• **Canada** (Bachu, 2003)
  - Oil & gas several GtCO₂,
  - Deep saline formations 100 to 1000 times more
  - Most emitters have potential storage sites close

• **Australia**
  - Total capacity 740 GtCO₂ (= 1600 years);
  - Realistic capacity 100-115 Mt CO₂/year
  - ‘Cost curve’ capacity 20 – 180 Mt CO₂/year
Criteria for selection and matching of sites

- Volume, purity and rate of the CO$_2$ stream;
- **Suitability** of the storage sites including the seal;
- **Proximity** of the source and storage sites;
- **Infrastructure** for the capture and delivery of CO$_2$;
- Existence of a **large number** of storage sites to allow diversification;
- Known or undiscovered energy, mineral or groundwater **resources** that might be compromised;
- Existing wells and **infrastructure**;
- **Injection strategies** and (for EOR and ECBM) also production strategies which affect the number of wells and their spacing;
- **Terrain** and right of way;
- Location of **population** centres;
- Local **expertise**;
- Overall **costs** and economics.
Identified sites

Data required for site characterisation

- **Seismic** profiles;
- **Structure contour maps** of reservoirs, seals and aquifers;
- Detailed maps of the structural **boundaries**;
- Maps of the predicted **CO$_2$ pathways** from the point of injection;
- Documentation and maps of **faults**;
- **Facies** maps
- Core and drill cuttings **samples**;
- **Well logs** (geological, geophysical and engineering logs);
- **Fluid** analyses and tests from downhole sampling;
- Oil and gas **production data** (if a hydrocarbon field);
- Reservoir and seal **permeability**;
- ...
Data required for site characterisation continued:

- ... 
- **Petrophysical** data: porosity, mineralogy, seal capacity, pressure, temperature, salinity, rock strength; 
- **In situ stress** analysis to determine the maximum sustainable pore fluid pressure during injection (for reservoir, seal, faults) 
- **Hydrodynamic** analysis to identify the magnitude and direction of water flow, hydraulic interconnectivity of formations and pressure decrease associated with hydrocarbon production; 
- **Seismological** data, geomorphological data and tectonic investigations to indicate neotectonic activity
Factors affecting site integrity:

- **Stratigraphic** (capacity of a seal rock to hold back fluids)
- **Geomechanical** (to prevent reservoir or seal rock deformation)
- **Geochemical** (change of pore water pH affects CO2 solubility – more acid – less soluble; chemical reactions with minerals in the rock, borehole cements and seals may cause mineral dissolution, hence breakdown of the rock matrix or mineral precipitation, hence plugging of the pore system)
- **Anthropogenic** (active or abandoned wells and mine shafts can provide short circuits)
**Performance prediction** and optimisation rely heavily on simulation models.

A **code intercomparison study** was conducted (Pruess et al. 2004) to evaluate the capabilities and accuracy of numerical simulators. The test problems addressed CO2 storage in saline formations and oil & gas reservoirs. Comparison is overall encouraging but there are areas with only fair agreement or even discrepancies. The disagreements were mainly due to the description of fluid properties.

The main source of uncertainty in field applications is in the **data interpretation** and **sparse data sets**.
CO$_2$ injection well is very similar to gas injection well in an oil field or natural gas storage project. Number of wells depends on a number of factors.

(Source: IPCC, 2005)
Well technology

Well abandonment  (Source: IPCC, 2005)

(a) Cased abandoned well
(b) Uncased abandoned well
Injectivity of CO₂ is significantly greater than brine injectivity. However, it can be less than predicted and it may decline with time.

Injection pressure must be higher than formation pressure. Safe injection pressure is site-specific. It is determined based on the measurements of in situ formation stresses and pore fluid pressure.

Relationship for the maximum safe injection pressure (Van der Meer, 1996):

• 1.35 x hydrostatic pressure for depth down to 1000m
• 2.4 x hydrostatic pressure for depths 1-5km.

The maximum pressure gradients for natural gas stored in an aquifer are different in different countries.
Injection rates for selected CO$_2$ storage projects
(Source: IPCC, 2005)
Monitoring

Monitoring is used to:

- Ensure **effective injection** and well control
- Verify the **quantity** of injected CO$_2$
- **Optimise** the efficiency of the storage project
- Demonstrate that CO$_2$ remains **contained** in the intended formation
- **Detect leakage** and provide an early warning

The following needs to be monitored:

- Injection rates and pressures
- **Subsurface distribution of CO$_2$**
- Well integrity
- Local environmental effects
## Monitoring

<table>
<thead>
<tr>
<th>Technique</th>
<th>Measured quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracers</td>
<td>Travel time&lt;br&gt;Partitioning of CO₂ into brine or oil&lt;br&gt;Identification sources of CO₂</td>
</tr>
<tr>
<td>Water composition</td>
<td>CO₂, HCO₃⁻, CO₃²⁻&lt;br&gt;Major ions&lt;br&gt;Trace elements&lt;br&gt;Salinity</td>
</tr>
<tr>
<td>Pressure</td>
<td>Subsurface pressure&lt;br&gt;Formation pressure&lt;br&gt;Annulus pressure&lt;br&gt;Groundwater aquifer pressure</td>
</tr>
<tr>
<td>Well logs</td>
<td>Brine salinity&lt;br&gt;Sonic velocity&lt;br&gt;CO₂ saturation</td>
</tr>
<tr>
<td>Time-lapse 3D seismic imaging</td>
<td>P and S wave velocity&lt;br&gt;Reflection horizons&lt;br&gt;Seismic amplitude attenuation</td>
</tr>
<tr>
<td>Vertical seismic profiling and crosswell seismic imaging</td>
<td>P and S wave velocity&lt;br&gt;Reflection horizons&lt;br&gt;Seismic amplitude attenuation</td>
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(Source: IPCC, 2005)
## Monitoring

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<tbody>
<tr>
<td>Passive seismic monitoring</td>
<td>Location, magnitude and source characteristics of seismic events</td>
</tr>
</tbody>
</table>
| Electrical and electromagnetic techniques     | Formation conductivity  
Electromagnetic induction                                                                   |
| Time-lapse gravity measurements              | Density changes caused by fluid displacement                                        |
| Land surface deformation                      | Tilt  
Vertical and horizontal displacement using interferometry and GPS                |
| Visible and infrared imaging from satellite or planes | Hyperspectral imaging of land surface                                                   |
| CO₂ land surface flux monitoring using flux chambers or eddy covariance | CO₂ fluxes between the land surface and atmosphere                                      |
| Soil gas sampling                             | Soil gas composition  
Isotopic analysis of CO₂                                                            |

(Source: IPCC, 2005)
Monitoring

Produced water chemistry at Weyburn (Source: Perkins et al., 2005)
The environmental impacts arise from release of stored CO$_2$ into the atmosphere. They into two broad categories:

- **Global** – uncertainty in the effectiveness of storage
- **Local** – health, safety and environmental hazards arising from:
  - Direct effect of the elevated CO$_2$ concentrations
  - Effects of dissolved CO$_2$ on groundwater chemistry
  - Effect arising from the displacement of fluids by the injected CO$_2$

Pathways for release of CO$_2$ from geological storage sites:

- Through the **pore system** in low-permeability caprocks
- Through **openings** in the caprock or **fractures** and **faults**
- Through **man-made** structures
Risk management

Potential escape routes for CO$_2$ injected into saline formations
(Source: IPPC, 2005)
Risk management

Possible leakage pathways in an abandoned well
(Source: Gasda et al., 2004)
Risk management

**Probability of release** from geological storage sites:

- No systematic study exists, but rough evaluations can be made based on:
  - data on natural systems
  - data on engineered systems such as natural gas storage
  - fundamental processes
  - numerical modelling and
  - data from current storage projects

- For large-scale operational CO$_2$ project, assuming that they are well selected, designed, operated and monitored, the available evidence suggests that
  - 99% of CO$_2$ is **very likely** to remain retained over first 100 years
  - 99% of CO$_2$ is **likely** to remain retained over first 1000 years
Possible local and regional **hazards**:
- Human health and safety
- Groundwater quality from CO$_2$ leakage and brine displacement
- Terrestrial and marine ecosystems
- Induced seismicity

**Risk assessment** is an integral element of risk-management activities. Methodologies are diverse, usually based on **scenarios** that describe possible future states of the storage facility and events that result in leakage of CO$_2$ or other risks, which are **simulated** using numerical models.

If leakage occurs a range of **remediation** measures exist.
International laws

Relevant treaties: global and regional environmental treaties, notably those on climate change and the law of the sea and marine environment.

Key issues in applying marine treaties to CO2 storage

• Is storage ‘dumping’ or not?
• Does CO₂ classify as waste arising from normal operations, or discharge or emission from them (and hence can benefit from treaty exemption)?
• Is CO₂ ‘industrial waste’, ‘hazardous waste’ or does the process of storage constitute ‘pollution’ or it is none of these?
• Does the method of CO₂ reaching the storage site involve pipelines, vessels or offshore structures?
National regulations and standards

In North America, Europe, Japan and Australia there is a lack of regulations specifically relevant for CO₂ storage.

**EU** CO₂ storage has to conform with relevant EU Directives such as those on waste, landfill, water, environmental impact assessment and strategic environmental assessment. These directives do not specifically mention CO₂ capture and storage.

**Canada** deep-well injection of fluids in the subsurface, including disposal of liquid wastes, is legal and regulated. Jurisdiction is provincial.

**USA** the Safe Drinking Water Act regulates most underground injection activities.

**Australia** Only South Australia has legislation regulating the underground injection of gases such as CO₂ for EOR and for storage. Stringent environmental impact assessments are required for all activities that could compromise the quality of surface water or groundwater.
Major cost elements:

- **Capital** costs: drilling wells, infrastructure, project management
- **Operating** costs: manpower, maintenance, fuel

Monitoring costs are usually reported separately

Some cost estimates for **saline formations**:

- Australia onshore med **0.5** US$/tCO$_2$ (0.2 – 5.1) US$/tCO$_2$
  offshore med **3.4** US$/tCO$_2$ (0.5 – 30.1) US$/tCO$_2$
- USA onshore med **0.5** US$/tCO$_2$ (0.4 – 4.5) US$/tCO$_2$
- Europe onshore med **2.8** US$/tCO$_2$ (1.9 – 6.2) US$/tCO$_2$
  offshore (4.7 – 12.0) US$/tCO$_2$

**Overall** – significant storage at cost in the range **0.5-8 US$/tCO$_2$**
Conclusions

• While there are uncertainties, the global capacity to store CO$_2$ deep underground is large

• CO$_2$ migration and trapping in geological formations are reasonably well understood

• Technologies for CO$_2$ injection, monitoring and risk assessment exist, although more work is needed to improve technologies and reduce uncertainties

• There appear to be no insurmountable technical barriers to an increased uptake of geological storage as an effective mitigation option