Seal Integrity for Geologic Sequestration of CO₂

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Seal Integrity for Geologic Sequestration of CO$_2$

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Stanford University
Geomechanics and Seal Capacity

In all potential reservoirs

• How will the CO₂ injection process influence the reservoir/seal?

In depleted oil and gas reservoirs

• Did production and depletion affected the reservoir/seal?

• What are the initial trap and seal mechanisms governing reservoir capacity?
In all potential reservoirs

• How will the CO₂ injection process influence the reservoir/seal?

In depleted oil and gas reservoirs

• Did production and depletion affected the reservoir/seal?

• What are the initial trap and seal mechanisms governing reservoir capacity?
Geomechanical Characterization

The Stress Tensor

\[
S = \begin{bmatrix}
S_{H\text{max}} & 0 & 0 \\
0 & S_v & 0 \\
0 & 0 & S_{h\text{min}}
\end{bmatrix}
\]

- Vertical Stress
- Least principal stress
- Max. horizontal stress

Stress Orientation → Orientation of Wellbore Failures

\[
S_v(z_0) = \int_{0}^{z_0} \rho g \, dz
\]

\(S_{h\text{min}} \Leftarrow \text{LOT, XLOT, minifrac}\)

\(S_{H\text{max}} \text{ magnitude} \Leftarrow \text{modeling wellbore failures}\)
Geomechanical Characterization

- Pore pressure \( P_p \) \( \leftarrow \) Measure, sonic, seismic
- Rock Strength \( \rightarrow \) Lab, Logs, Modeling well failure
- Faults/Bedding Planes \( \rightarrow \) Wellbore Imaging
CO2 Sequestration
Seal Integrity
Research Projects

**Powder River Basin**
- CBM Production
- ECBM/Environment/Sequestration
- Collaboration with Western Res. Foundation

**Mountaineer, West Virginia**
- Deep aquifer injection
- Point source - Coal Burning power plant
- Collaboration with DOE, NETL, Battelle, AEP, BP, Schlumberger, Ohio Coal Development Office

**Teapot Dome**
- Depleted Oil and Gas Reservoir
- Sequestration seal capacity
- Collaboration with LLNL, DOE, RMOTSI
Teapot Dome Project

Principal Objectives:

• Assess possible leakage mechanisms and the assessment of volume, rates, location & probability of CO₂ leaks

Unique for carbon-storage research:

• High well density, abundant data, excellent geological characterization of all units

• Federal ownership ➔ data sets and experimental results be public domain, long-term stable research
Teapot Dome Field

- 1300 wells total ~ 600 currently producing
- Over 100 years production data
- Target reservoirs for CO$_2$ injection 500’ – 8000’
- 9 oil and gas bearing formations,
- > 6 aquifers of varying salinity
- Recoverable reserves ~600 million barrels oil, 0.5 billion ft$^3$ gas
- Excellent Seismic Data
Teapot Dome Project

• 55 - 75 million years old

• Target reservoirs:
  – Diverse rocks
  – Oil & water bearing
  – 500’ – 8000’ depth range

• CO₂ injection planned for summer of 2005
Production and/or Injection can Induce Fault Slip

Production Induced Faulting
*Normal Fault Regimes*

Valhall Chalk Reservoir, North Sea

Injection Induced Faulting
*All Faulting Regimes*

Rangely Oil Field, CO
Fluid Injection and induced seismicity

*Gas Cloud*
*Seismic Push-down*

Modified from Zoback and Zinke, 2002

*Modified from Raleigh et al., 1976*
Assessment of Potential Fault Slip

Calculating Fault Slip Potential Using the Coulomb Criterion

\[ \tau = \mu(S_n - P_p) \]

\[ P_{p\text{_crit}} = S_n - \tau / \mu \]

\[ P_{p\text{_crit}} - P_{\text{ref}} = \text{Critical Pressure Perturbation} \]

\[ S = \begin{bmatrix} S_{H\text{max}} & 0 & 0 \\ 0 & S_v & 0 \\ 0 & 0 & S_{h\text{min}} \end{bmatrix} \]

\[ \hat{t} = S \hat{n} \]

\[ S_n = \hat{n} \cdot t \]

(Wiprut & Zoback, 2002)
Analogy with Assessment of Leakage Potential in North Sea Fields

Can predict the rate & volume of injection needed to trigger slip on faults of different orientations and potential loss of seal integrity

(Wiprut & Zoback, 2002)
AEP Mountaineer Project: New Haven, WV

- Field investigation of CO2 injection in a deep saline aquifer
- 183 Coal burning plants in Ohio River Valley
- 7 Megaton of CO2 emitted in 2000 at Mountaineer
- Collaboration with Battelle, DOE, NETL, AEP, Schlumberger, BP, Ohio Coal Development Office

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Period</th>
<th>Predominant Lithology</th>
<th>Formation</th>
<th>Thickness (ft)</th>
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<td>Cambrian</td>
<td>Unconsolidated</td>
<td>Arkose</td>
<td>100</td>
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<td></td>
<td>Ordovician</td>
<td>Limestone/</td>
<td>Black River</td>
<td>640</td>
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<td>Dolomite</td>
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<td>Beechmontown</td>
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<td></td>
<td>Cambrian</td>
<td>Sandstone</td>
<td>Niceville</td>
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<td></td>
<td>Pro cambrian</td>
<td>Gravels</td>
<td>(Pro cambrian)</td>
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</table>
Low $S_{hmin}$ magnitude in the Rose Run injection zone is beneficial to hydraulic fracturing and sequestration potential.
Reservoir Simulations with Hydraulic Fractures to Stimulate Injection

Hydraulic Fracture:
1000 mD Permeability

Geostatistics based on data from a Single well

6 km x 6 km
Simulation Results After 30 Years

Realization 4: With Hydraulic Fracture

CO₂ Saturation

Formation Pressure

Permeability x 10

Base Permeability

CO₂ Saturation [%]

Formation Pressure [MPa]

<table>
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<tr>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
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<td>26</td>
<td>28</td>
<td>30</td>
<td>32</td>
<td>34</td>
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</table>

1 km

N
Preliminary Reservoir Simulations

Cumulative CO₂ Injection

- HF_R4_k10
- RO_k10
- HF_R4_base
- RO_base

Injection Rate

- HF_R4_k10
- RO_k10
- HF_R4_base
- RO_base
Potential for Induced Seismicity?

Optimally oriented strike-slip faults

Need Seismic Monitoring of Sequestration Sites
Pore Pressure Increase Precedes CO₂ Saturation Front

Simulation Results After 30 Years
Realization 4: With Hydraulic Fracture

CO₂ Saturation
Formation Pressure

Permeability x 10

CO₂ Saturation [%]
Formation Pressure [MPa]

| 1 km |

N
• Adsorption of CO$_2$ is critical as geological seals are likely to be ineffective at shallow depth

• Much less is known about detailed geology than oil and gas reservoirs. Coals tend to be very heterogeneous.

• Complex flow and surface chemistry in matrix/fracture systems

• Recovery of CH$_4$ may offset cost of sequestration
Coal Bed Methane Production and CO₂ Sequestration

**DESORPTION**

Desorption from Internal Coal Surfaces

**DIFFUSION**

Diffusion Through the Matrix and Micropores

**DARCY FLOW**

Fluid Flow in the Natural Fracture Network

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**Coal rank**

<table>
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<th>% carbon</th>
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<tr>
<td>Peat</td>
<td>&lt;50</td>
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<tr>
<td>Lignite</td>
<td>60</td>
</tr>
<tr>
<td>Sub-bituminous coal</td>
<td>75</td>
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<tr>
<td>Bituminous coal</td>
<td>85</td>
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<tr>
<td>Anthracite</td>
<td>90</td>
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<tr>
<td>Graphite</td>
<td>&gt;95</td>
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Advanced Resources International, 2004
Powder River Basin, Wyoming and Montana

- Extensive CBM development
- ~12,000 wells already drilled
- ~50,000 wells to be drilled
- Environmental problems due to water production could be alleviated (in part) by CO$_2$ sequestration
- Potential for CO$_2$ sequestration and CH$_4$ production
Preferential adsorption of CO$_2$ over CH$_4$, will displace the CH$_4$ from the coal matrix.

T=22°C

CO$_2$ adsorption
CO$_2$ desorption
CH$_4$ adsorption
CH$_4$ desorption
N$_2$ adsorption
N$_2$ desorption

Courtesy Tony Kovscek and G.-Q. Tang
Hydraulic Fracturing Needed to Stimulate Injection for CO\textsubscript{2} Sequestration and CH\textsubscript{4} Recovery

Schematic of horizontal hydraulic fracture placed at base of injector
Preliminary 3D Model
(Powder River Basin Model)

CBM well

Grid dimensions:

\[ \text{nx} = 45, \text{dx} = \sim 50 \text{ m} \]
\[ \text{ny} = 44, \text{dy} = \sim 50 \text{ m} \]
\[ \text{nz} = 6, \text{dz} = \] top three grid layers are 5 m and bottom three grid layers are 1.6 m

\[ L = 2200 \text{ m} \]
\[ H = 310 - 360 \text{ m} \]
\[ \text{Big George coal} \]
\[ h = \sim 20 \text{ m} \]
\[ \text{N} \]
\[ L = 2250 \text{ m} \]
Cleat Permeability Realizations

Cleat Properties are a Major Factor
Cleat Permeability Realizations

Cleat Properties are a Major Unknown
CO$_2$ Adsorption After 1800 Days

Base case with matrix shrinkage and swelling

Hydraulic fracture case with matrix shrinkage and swelling (orientated NW-SE)
Gas Saturation in the Coal Cleats After 1800 Days

- **Base case with matrix shrinkage and swelling**
- **Hydraulic fracture case with matrix shrinkage and swelling (orientated NW-SE)**

**Realization 1**

- Production well
- Injection well
Cumulative CO₂ Injection

**Cumulative CO₂ Injection at Surface Conditions**

- **Y-axis:** Ton (ranging from 0 to 2.0e+6)
- **X-axis:** Time (days) (ranging from 0 to 1800)

Legend:
- Red line: Base case with no matrix shrinkage and swelling
- Blue dashed line: Hydraulic fracture case with no matrix shrinkage and swelling
- Green line: Base case with matrix shrinkage and swelling
- Pink dashed line: Hydraulic fracture case with matrix shrinkage and swelling
CO₂ Injection Rate and Hydraulic Fracturing

**CO₂ Injection Rate at Surface Conditions**

- Injection rate ~2-3x higher with introduction of hydraulic fracture
- Start see decline in injection rate, probably due to onset of matrix swelling

Realizations 1 and 2

- **Green dotted line**: Base case with matrix shrinkage and swelling, Realization 1
- **Green line**: Base case with matrix shrinkage and swelling, Real 2
- **Pink dotted line**: Hydraulic fracture case with matrix shrinkage and swelling, Real 1
- **Pink line**: Hydraulic fracture case with matrix shrinkage and swelling, Real 2
CH$_4$ Production Offsets
Cost of Sequestration

Cumulative CH$_4$ Production
at Surface Conditions

Realization 1

Mcf

Time (days)

Prod 4
Prod 2
Prod 4
Prod 2
Prod 1
Prod 1
Prod 3
Prod 3

Base case with matrix shrinkage and swelling
Hydraulic fracture case with matrix shrinkage and swelling
For each case there are four producers; Prod = Producer
Geological Storage Potential

Outstanding Questions

• Improved models of shrinkage and swelling as well as transport and adsorption processes. This requires new data on adsorption isotherms for wet coal

• Characterizing and modeling heterogeneities (challenges for transport, geostat and reservoir simulation)

• Assessing the need for hydraulic fracturing/appropriate stress/depth conditions

• Assess the potential for ECBM and CO₂ Sequestration in regions where poor water quality prevents CBM production
Outstanding Questions

- Flow characterization and modeling in the absence of comprehensive data (challenges for geostatistics and reservoir simulation)
- Limited porosity and permeability of many deep aquifers provide challenges for sequestering significant volumes of CO₂. Hydraulic fracturing needed to stimulate injectivity
- Geomechanical characterization in the absence of comprehensive data (stress tensor, elastic moduli, fractures and faults, porosity, permeability, etc.)
- Assessing the potential for injection-induced fault slip and/or seismicity
Geological Storage Potential

Outstanding Questions

• Assessing initial trap/seal mechanisms
• Assessing the effects of production and depletion
• Predicting whether sequestration will affect seal (hydraulic fracturing of cap rock)
• Assessing the potential for injection-induced fault slip and/or seismicity
• Development of comprehensive geomechanical model requires modern well data
Seal Integrity for Geologic Sequestration of CO$_2$

FOR MORE INFORMATION
PLEASE VISIT POSTERS

Amie Lucier, Hannah Ross, Laura Chiarmonte