Enhanced Coalbed Methane (ECBM) Recovery
提高煤层气（ECBM）采收

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Introduction
Isotherms for Different Gases

\[ CO_2 \]
\[ V_m = 1128 \text{ SCF/ton} \]
\[ b = 0.00489 \text{ psi}^{-1} \]

\[ CH_4 \]
\[ V_m = 759 \text{ SCF/ton} \]
\[ b = 0.00276 \text{ psi}^{-1} \]

\[ N_2 \]
\[ V_m = 616 \text{ SCF/ton} \]
\[ b = 0.000686 \text{ psi}^{-1} \]
CO$_2$-ECBM Recovery Mechanism

- Inject CO$_2$ into cleats.
- Due to high adsorptivity, CO$_2$ preferentially adsorbed into coal matrix.
  - Methane displaced from sorption sites.
- Efficient displacement process – slow CO$_2$ breakthrough.
- Swelling of matrix due to higher sorptive capacity for CO$_2$, reducing porosity and permeability.
CO$_2$/CH$_4$ Sorptive Capacity vs. Coal Rank

The graph shows the relationship between the CO$_2$/CH$_4$ ratio and coal rank. The data points are categorized by coal rank, with different symbols and colors representing various pressure levels: 100 psi (red), 1000 psi (purple), 2500 psi (yellow), and 5000 psi (blue). The equation $y = 1.6282x^{-0.9812}$ with $R^2 = 0.6116$ is fitted to the data, indicating a power function relationship between the CO$_2$/CH$_4$ ratio and coal rank.
N₂-ECBM Recovery Mechanism

• Inject N₂ into cleats.

• Due to lower adsorptivity, high percentage of N₂ remains free in cleats:
  – Lowers CH₄ partial pressure
  – Creates compositional disequilibrium between sorbed/free gas phases

• Methane “stripped” from coal matrix into cleat system.

• “Shrinkage” of coal, increasing porosity and permeability

• Rapid N₂ breakthrough expected.
N$_2$/CH$_4$ Sorptive Capacity vs. Coal Rank

$y = 0.4794x^{0.3785}$

$R^2 = 0.7426$

N$_2$/CH$_4$ Ratio

Coal Rank (%Vro)

- < 0.23, peat
- 0.23 - 0.36, lignite
- 0.36 - 0.47, sub-bit.
- 0.47 - 0.51, hi vol bit C
- 0.51 - 0.69, hi vol bit B
- 0.69 - 1.11, hi vol bit A
- 1.11 - 1.60, med vol bit
- > 1.60, low vol bit

- Power (2500 psi)
- 100 psi
- 2500 psi
- 5000 psi
- 1000 psi
- VL ratio
Field Pilots - San Juan Basin

Previous Study Area
Producer to Injector Conversions

Pump Canyon
Tiffany
Allison
Injector
## Pilot Descriptions

### 现场试验描述

<table>
<thead>
<tr>
<th></th>
<th>CO₂ Injection</th>
<th>N₂ Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>Allison Unit</td>
<td>Tiffany Unit</td>
</tr>
<tr>
<td></td>
<td>San Juan Basin, USA</td>
<td>San Juan Basin, USA</td>
</tr>
<tr>
<td><strong>Operator</strong></td>
<td>Burlington Resources</td>
<td>Amoco (now BP)</td>
</tr>
<tr>
<td></td>
<td>(now ConocoPhillips)</td>
<td></td>
</tr>
<tr>
<td><strong>Start</strong></td>
<td>1995</td>
<td>1998</td>
</tr>
<tr>
<td><strong>Duration</strong></td>
<td>6 ½ years continuous</td>
<td>4 years intermittent</td>
</tr>
<tr>
<td></td>
<td>injection</td>
<td>injection</td>
</tr>
<tr>
<td><strong>No. Injection Wells</strong></td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td><strong>Volume Injected</strong></td>
<td>6.4 Bcf</td>
<td>15.0 Bcf</td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td>3,100 ft</td>
<td>3,000 ft</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>43 ft</td>
<td>47 ft</td>
</tr>
<tr>
<td><strong>Rank (％VR)</strong></td>
<td>Med vol bit (1.33%)</td>
<td>Med vol bit (1.33%)</td>
</tr>
<tr>
<td><strong>Permeability</strong></td>
<td>~100 md</td>
<td>~1 md</td>
</tr>
</tbody>
</table>
Optimizing Injection Gas Composition

优化注入气体的成分
Optimizing Injected Gas Composition
优化注入的气体成分

- How can injected gas composition be optimized to maintain injectivity while sequestering CO₂ for different coal ranks?
- 怎样才能使注入气体成分进行优化，以保持在对不同等级的煤的CO₂封存时的注入性能？
- Simulation performed using COMET3.
- 使用COMET3的模拟表现
- 10yr of primary production followed by 15yr of injection.
- 由15年的注射的井的最初10年的生产
- 5-spot injection pattern, vertical wells.
- 5-spot注入模式，垂直井
- Well spacing determined based on CO₂ breakthrough occurring after 8 to 10 years of 100% CO₂ injection.
  井距测定根据8–10年100%CO₂注入后的CO₂的突破点发生

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Producer

Injector
Cleat Permeability versus Coal Rank
夹板渗透性与煤级的比对

- Fracture permeability directly related to cleat frequency:
  - The higher cleat intensity, the higher permeability
  - 夹板的强度越高, 渗透性越强
  - Low permeability for low rank coal (early coalification) and high rank coal (metamorphism)
  - 低渗透, 低煤级煤 (早煤化) 和高煤级煤 (变质)
  - Highest permeability for Medium to Low-Volatile bituminous
  - 最高渗透-中煤到低的易挥发性烟煤
Pore Compressibility versus Coal Rank

孔压缩性与煤级的比对

- Compressive strength: 抗压强度
  - Capacity of a material to withstand axially-directed pushing forces
  - 材料的性能来承受直接轴向推力
  - Minimum where cleats are most developed: medium rank
  - 最小的夹板是最发达: 中阶
  - Opposite to pore compressibility (1/psi)
  - 对面孔的可压缩性
  - Maximum where cleats are most developed: medium rank
  - 最小的夹板是最发达: 中阶
  - Cp=500*10^{-6} psi^{-1} (1/2,000)
  - Minimum for low and high rank:
    - High rank Cp=250*10^{-6} psi^{-1}
    - Low rank Cp=125*10^{-6} psi^{-1}
Matrix Shrinkage versus Coal Rank

- Matrix shrinkage:
  - Low rank with early stage coalification, lower gas content, matrix less likely to swell or shrink: lower matrix compressibility -> minimum fracture permeability improvement
  - 低等级与早期煤化作用，气体含量低，不太可能膨胀或收缩的基质：基质的压缩性较低 - >最低裂缝渗透率改善

![Graphs showing matrix shrinkage versus coal rank](image)
### Model Inputs

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Low Rank</th>
<th>Medium Rank</th>
<th>High Rank</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Fracture Permeability</td>
<td>1</td>
<td>100</td>
<td>10</td>
<td>mD</td>
</tr>
<tr>
<td>Fracture Permeability Anisotropy</td>
<td>1:2</td>
<td>1:2</td>
<td>1:2</td>
<td>%</td>
</tr>
<tr>
<td>Fracture Porosity</td>
<td>0.25</td>
<td>1.50</td>
<td>0.50</td>
<td>%</td>
</tr>
<tr>
<td>Pore Compressibility</td>
<td>1.25E-04</td>
<td>5.00E-04</td>
<td>2.50E-04</td>
<td>1/psia</td>
</tr>
<tr>
<td>Permeability Exponent (S&amp;P)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Matrix Shrinkage</td>
<td>5.00E-07</td>
<td>1.00E-06</td>
<td>2.00E-06</td>
<td>1/psia</td>
</tr>
<tr>
<td>CO2/CH4 Differential Swelling Factor</td>
<td>1.25</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>N2/CH4 Differential Swelling Factor</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>
Injection Scenarios

Gas mixtures
- 100% CO₂
- 75% CO₂/25% N₂
- 50% CO₂/50% N₂
- 25% CO₂/75% N₂
- 100% N₂

Injection rate constraint: 5 MMscfd max.

Injection pressure constraint: 0.6 psia/ft maximum bottom-hole pressure.
Low Rank Coals 100% N2 Injection

 Injectivity increase due to coal shrinking under N₂ injection

 Immediate breakthrough
Low Rank Coals – Mixtures
低煤级煤—混合

1. Moderate permeability loss (-30%) during depletion (low $C_p$) during depletion (low $C_p$) 适度的渗透损失（-30%）在消耗期内

2. Drastic permeability loss (-90% from initial value) once injection starts due to coal swelling (high $C_k$), even with N₂ mixture 较强的渗透损失（-90%从开始的价值 一旦注射开始，因为碳的膨胀会与氮气混合）

3. Permeability increase of 35% when 100% N₂ injection starts, as matrix shrinks 当氮气注射开始，基质收缩渗透率增加到35%
Low Rank Coals – Summary

- CO₂ sequestration optimum with 100% CO₂ but lowest incremental CH₄
- CO₂封存最有利的是100%CO₂封存，但是最少的甲烷
- Best mixture at 20% N₂/ 80% CO₂
- 最好混合是20%的N₂和80%的CO₂
  - ECBM increase of 69% (from 100% CO₂ injection)
  - ECBM增加到69%（100%的CO₂的注入）
  - Minimal sequestration capacity loss of 27%
  - 最小的封存容量损失27%

- 57 MMcf incremental methane
- 600 MMcf sequestered CO₂
- above 40% N₂, no additional incremental recovery
Medium Rank Coals

1. Drastic permeability loss (-80%) during depletion (high $C_p$)
   极强的渗透率损失（-80%）
   在消耗期间

2. Moderate permeability loss of 10% once injection starts due to coal swelling (average $C_k$), followed by permeability increase (10%) due to re-pressurization and $C_k$
   温和的渗透率损失10%一旦注入开始，因为碳的膨胀（平均$C_k$），同时伴随着渗透率的增加，因为重复的压力

3. Permeability increase of 50% when $N_2$ injection starts, as matrix shrinks
   当氮气注入开始时，同时混合物收缩，渗透率增加到50%
Medium Rank Coals

- 50% N2/50% CO2
- 75% N2/25% CO2
- 25% N2/75% CO2
- 100% CO2
- 100% N2

Initial Conditions

Depletion

Swelling

Re-pressurization

Pressure, psia

Methane
Carbon Dioxide

Pressure
**Medium Rank Coals Optimization**

- Best mixture at 30% N₂/70% CO₂
  - 最好的混合是30%的氮气和70%的CO₂
- ECBM increase of 95% (from 100% CO₂ injection)
  - ECBM增加到95%（源于100%的CO₂的注入）
- Minimal sequestration capacity loss of 20%
  - 最小的封存容量损失到20%
High Rank Coals

1. Permeability gain of 20% during depletion (high $C_m$)
   渗透率增加到20%

2. Drastic permeability loss of 90% once injection starts due to coal swelling (average $C_k$)
   极强的渗透率损失90%
   一旦开始注入，因为碳的膨胀（平均$C_k$）

3. Permeability increase of 300% when pure N$_2$ injection starts, as matrix shrinks (highest $C_m$)
   当纯的N$_2$注入开始时，混合物收缩（最高$C_m$）渗透率增加到300%
High Rank Coals Optimization

- Best mixture at 45% N₂/55% CO₂
- 最好的混合是45%的N₂和55%的CO₂
- ECBM increase of 93% (from 100% CO₂ injection)
- ECBM增加到93%（源于100%的CO₂的注入）
- Minimal sequestration capacity loss of 20%
- 最少的封存容量损失到20%
**Injection Optimization Conclusions**

## Low Rank Coal

<table>
<thead>
<tr>
<th></th>
<th>100% CO2</th>
<th>80% CO2/20%N2</th>
<th>75% CO2/25%N2</th>
<th>50% CO2/50%N2</th>
<th>25% CO2/75%N2</th>
<th>100% N2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Incremental CH4, MMcf</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>57</td>
<td>57</td>
<td>58</td>
<td>48</td>
<td>Not reached</td>
<td>48</td>
</tr>
<tr>
<td><strong>Breakthrough time, years</strong></td>
<td>8.4</td>
<td>8.8</td>
<td>8.7</td>
<td>9.1</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td><strong>Sequestered CO2 volume @ breakthrough time, MMcf</strong></td>
<td>670</td>
<td>599</td>
<td>586</td>
<td>478</td>
<td>330</td>
<td>N/A</td>
</tr>
</tbody>
</table>

## Medium Rank Coal

Increasing N₂ content with coal rank to achieve optimum ECBM and CO₂ sequestration.

<table>
<thead>
<tr>
<th></th>
<th>75% CO2/25%N2</th>
<th>70% CO2/30%N2</th>
<th>50% CO2/50%N2</th>
<th>25% CO2/75%N2</th>
<th>100% N2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Incremental CH4, MMcf</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>807</td>
<td>1,152</td>
<td>1,177</td>
<td>956</td>
<td>956</td>
</tr>
<tr>
<td><strong>Breakthrough time, years</strong></td>
<td>10</td>
<td>7.3</td>
<td>5.8</td>
<td>5.5</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Sequestered CO2 volume @ breakthrough time, MMcf</strong></td>
<td>4,424</td>
<td>4,127</td>
<td>4,014</td>
<td>2,921</td>
<td>N/A</td>
</tr>
</tbody>
</table>

## High Rank Coal
Office Locations

Washington, DC
4501 Fairfax Drive, Suite 910
Arlington, VA 22203
Phone: (703) 528-8420
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