Enhanced Gas Recovery and CO$_2$ Storage in Coal Bed Methane Reservoirs: Optimized Injected Gas Composition for Mature Basins of Various Coal Rank*

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Abstract

Nitrogen (N$_2$) and carbon dioxide (CO$_2$) injection has been a subject of enhanced coal bed methane (ECBM) and carbon capture and storage (CCS) research during the past decade. N$_2$ and CO$_2$ injection produce substantially different recovery processes. Coal has a higher affinity for CO$_2$ as compared to methane (CH$_4$), making it an ideal candidate for CCS and address environmental issues related to green house gas emissions. However, preferential adsorption of CO$_2$, a larger molecule than CH$_4$, onto the coal surface results in a dramatic decrease in cleat permeability due to coal swelling. This ultimately induces a loss of injectivity creating a significant technical hurdle for CCS operations in coal. In contrast, N$_2$ increases cleat permeability because of its lower coal storage capacity relative to CH$_4$. As a result, injectivity increases during N$_2$-ECBM. Theoretically, the injection of a mixture of CO$_2$ and N$_2$ will result in ECBM and CCS without a loss of injectivity. This study presents an investigation of that concept.

Based on the lessons learned from several actual large-scale and small-scale field demonstrations to date, this paper will focus on the improvement of CO$_2$ sequestration and associated ECBM by optimization of gas composition and injection designs for different coal ranks. To characterize resources and identify key geological and reservoir parameters driving ECBM and sequestration processes in deep unminable coal seams, a Monte Carlo probabilistic approach was implemented for coal seams of different rank. To perform the study, a matrix of simulation scenarios consisting of multiple coal types (taken from mature coal basins such as San Juan, Black Warrior, Central Appalachian and Powder River), permeability values, pattern sizes and injected gas mixtures (from 100% CO$_2$ to 100% N$_2$) was established. First results show that, for a specific coal rank, ECBM and CCS can drastically improve by increasing N$_2$ content in the injected gas stream.
ENHANCED GAS RECOVERY AND CO₂ STORAGE IN COAL BED METHANE RESERVOIRS: OPTIMIZED INJECTED GAS COMPOSITION FOR MATURE BASINS OF VARIOUS COAL RANK – PART 2

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OBJECTIVES

- Identify key parameters driving ECBM and sequestration processes in deep unminable coal seams.
- Better understand cleat permeability changes in response to injected gas composition during ECBM process, by coal rank.
- Optimize injected gas composition to maintain injectivity while sequestering carbon dioxide.
OUTLINES

- Objectives
- Key reservoir parameters driving CBM and CO$_2$ sequestration
- Cleat permeability changes during ECBM
- Optimizing enhanced gas recovery while sequestering carbon dioxide
- Summary and Conclusions
GAS STORAGE VS. COAL RANK

Coal rank

Gas Content (scf/t)

Gas Content (cm/g)

Depth (meters)

Depth (meters)
Fracture permeability directly related to cleat frequency:

- The higher cleat intensity, the higher permeability
- Low permeability for low rank coal (early coalification) and high rank coal (metamorphism)
- Highest permeability for Medium to Low-Volatile bituminous
PORE COMPRESSIBILITY VS. COAL RANK

- **Compressive strength**: 
  - Capacity of a material to withstand axially-directed pushing forces.
  - Minimum where cleats are most developed: medium rank.
  - Opposite to pore compressibility (1/psi).
  - Maximum where cleats are most developed: medium rank.
  - High rank \( C_P = 250 \times 10^{-6} \text{ psi}^{-1} \)
  - Low rank \( C_P = 125 \times 10^{-6} \text{ psi}^{-1} \)

![Compressive Strength of Coal](Adapted from Jones, 1989)
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

CLEAT PERMEABILITY VS. COAL RANK

- a) Low Rank Coals
- b) Medium Rank Coals
- c) High Rank Coals
MOST COMMERCIAL CBM PROJECTS ARE MEDIUM RANK COALS

- High Rank Coal: high gas content but low injectivity
- Low Rank Coal: low gas content but high injectivity
- Good compromise are medium rank coals with average gas content and initial permeability
Preferential adsorption of CO$_2$ induces coal swelling resulting in an injectivity loss.

Preferential adsorption of CO$_2$: high storage capacity.
Lower adsorptivity of N₂:
- N₂ stays in fractures while CH₄ is stripped out of matrix sites
- Rapid N₂ breakthrough

Preferential adsorption of CH₄ induces coal matrix shrinkage resulting in injectivity improvement
ECBM OPTIMIZATION PROCESS

- How can injected gas composition be optimized to maintain injectivity while sequestering CO₂ for different coal ranks?
MODEL CONSTRUCTION

- Simulation performed using COMET3.
- 5-spot injection pattern, vertical wells.
- 10 years of primary production followed by 15 years of injection.
- Well spacing determined based on CO₂ breakthrough occurring after 8 to 10 years of 100% CO₂ injection.
**PARAMETRIC STUDY: POROSITY AND PERMEABILITY PER COAL RANK**

<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>
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<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>
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<tr>
<td>CO2/CH4 Differential Swelling Factor</td>
<td>1.25</td>
<td>2</td>
<td>3</td>
<td></td>
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<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>

Note: CO₂ swelling factor will be referred as Ck

*Presenter’s notes:* Example of high rank coal: Illinois basin coal where tectonics (semi-anthracite) and low-vol. bituminous in Arkoma Basin or Arkansas; medium coal: San Juan Basin outside fairway (medium volatile). Low rank coal: Powder River basin (low C-bituminous)
INJECTION SCENARIOS

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

- Injection rate constraint: 5 MMcfd max.
- Injection pressure constraint: 0.6 psia/ft maximum bottom-hole pressure.
LOW RANK COALS

- 35 acres spacing to reach CO₂ breakthrough after 8.5 years of injection
- At end of primary production, permeability was down from 1 mD to 0.7 mD: moderate loss due to low pore compressibility.
- *Can we maintain or improve this permeability?*
Presenters notes: Delayed breakthrough
Injectivity loss due to coal swelling under CO₂ injection

Presenter’s notes: Depletion from 1800 to 307 psia. Then injection and repressurization until 1600 psia.
Presenter’s notes: At 4,015 days, reservoir pressure higher than initial pressure. Also 0.5 diff. swelling for N2+CH4 stripping: matrix shrinks and fractures open.
1. Moderate permeability loss (~30%) during depletion (low $C_p$).

2. Drastic permeability loss (~90% from initial value) once injection starts due to coal swelling (high $C_p$), even with N$_2$ mixture.

3. Permeability increase of 35% when 100% N$_2$ injection starts, as matrix shrinks.

Presenter's notes: Higher the N$_2$ content, faster the reservoir pressurization too.
LOW RANK COALS - SUMMARY

- CO₂ sequestration optimum with 100% CO₂ but lowest incremental CH₄ recovery.
- Best mixture at 20% N₂/80% CO₂:
  - ECBM increase of 69% (from 100% CO₂ injection).
  - Minimal sequestration capacity loss of 27%.

- 57 MMcf incremental methane
- 600 MMcf CO₂ sequestered CO₂ above 40% N₂, no additional incremental recovery.
MEDIUM RANK COALS

- 640 acres spacing necessary to achieve breakthrough after 9.4 years of injection
- At end of primary production, permeability reduction of 82% due to highest $C_p$
- *Can we maintain or improve this permeability?*
MEDIUM RANK COALS

1. Drastic permeability loss (-80%) during depletion (high $C_p$)

2. Moderate permeability loss of 10% once injection starts due to coal swelling (average $C_p$), followed by permeability increase (10%) due to re-pressurization and $C_p$

3. Permeability increase of 50% when $N_2$ injection starts, as matrix shrinks

Presenter’s notes: For 100% N2, pressure above initial pressure, hence permeability higher than initial
MEDIUM RANK COALS

Medium Rank Coals

Initial Conditions

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

Permeability vs Pressure

Pressure (psia)

Depletion

Swelling

Re-pressurization

Methane
Carbon Dioxide

Injection

Depletion
MEDIUM RANKS COALS OPTIMIZATION

- Best mixture at 30% N₂/ 70% CO₂
- ECBM increase of 95% (from 100% CO₂ injection)
- Minimal sequestration capacity loss of 20%

![Graph showing the relationship between injection mixture CO₂ content and volume of CO₂ sequestered and incremental recovery.](image-url)
1. Permeability gain of 20% during depletion (high $C_m$).
2. Drastic permeability loss of 90% once injection starts due to coal swelling (average $C_k$).
3. Permeability increase of 300% when pure N$_2$ injection starts, as matrix shrinks (highest $C_m$).

**Presenter’s notes:** For 100% N$_2$, pressure above initial pressure, hence permeability higher than initial.
- Best mixture at 45% N₂/ 65% CO₂
- ECBM increase of 93% (from 100% CO₂ injection)
- Minimal sequestration capacity loss of 20%
CONCLUSIONS: INCREMENTAL RECOVERY DUE TO N₂ INJECTION

![Cumulative CH₄ Production Graph]

- **Medium Rank**
- **High Rank**
- **Low Rank**

Increasing nitrogen content
### Low Rank Coal

<table>
<thead>
<tr>
<th>Incremental CH4, MMcf</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>
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<tbody>
<tr>
<td>Breakthrough time, years</td>
<td>8.4</td>
<td>8.8</td>
<td>8.7</td>
<td>9.1</td>
<td>Not reached (25%@15years)</td>
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<tr>
<td>Sequestered CO2 volume @ breakthrough time, MMcf</td>
<td>672</td>
<td>599</td>
<td>586</td>
<td>478</td>
<td>330</td>
<td>N/A</td>
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### Medium Rank Coal

<table>
<thead>
<tr>
<th>Incremental CH4, MMcf</th>
<th>100% CO2</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>
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<tbody>
<tr>
<td>Breakthrough time, years</td>
<td>9.5</td>
<td>11.3</td>
<td>11.6</td>
<td>14</td>
<td>Not reached (25%@15years)</td>
<td>N/A</td>
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<tr>
<td>Sequestered CO2 volume @ breakthrough time, MMcf</td>
<td>7,009</td>
<td>4,510</td>
<td>4,064</td>
<td>4,413</td>
<td>4,413</td>
<td>N/A</td>
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### High Rank Coal

<table>
<thead>
<tr>
<th>Incremental CH4, MMcf</th>
<th>100% CO2</th>
<th>75%CO2/25%N2</th>
<th>55%CO2/45%N2</th>
<th>50%CO2/50%N2</th>
<th>25%CO2/75%N2</th>
<th>100%N2</th>
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<tr>
<td>Breakthrough time, years</td>
<td>10</td>
<td>7.3</td>
<td>5.8</td>
<td>5.5</td>
<td>Not reached (25%@15years)</td>
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<tr>
<td>Sequestered CO2 volume @ breakthrough time, MMcf</td>
<td>4,424</td>
<td>4,386</td>
<td>4,127</td>
<td>4,014</td>
<td>2,921</td>
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</table>

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

- By injecting a 100% nitrogen mixture in high rank coals, cleat permeability is improved beyond initial conditions due to reservoir pressurization. Laboratory research would be helpful to better illustrate this phenomenon.

- Results presented here are specific to samples and their reservoir properties - optimized mixture content might vary for different coal samples of similar rank.