Enhanced Coalbed Methane Recovery

presented by:

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Advanced Resources International
Houston, TX

SPE Distinguished Lecture Series
2002/2003 Season
Outline

• Introduction

• ECBM Process

• Pilot Projects

• Economics

• Closing Remarks
Introduction

• Enhanced coalbed methane recovery (ECBM) involves gas injection into coal to improve methane recovery, analogous to EOR.

• Typical injection gases include nitrogen and carbon dioxide.

• Relatively new technology - limited field data to gauge effectiveness.

• Growing interest in carbon sequestration spurring considerable R&D into integrated ECBM recovery/carbon sequestration projects.
Integrated Power Generation, CO$_2$ Sequestration & ECBM Vision
## U.S. CO₂-ECBM/Sequestration Potential

<table>
<thead>
<tr>
<th>Basin</th>
<th>CO₂ Sequestration Potential (Gt)</th>
<th>ECBM Potential (Tcf)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Replacement of Primary Recovery Volume</td>
<td>Injection for ECBM in “Commercial” Area</td>
</tr>
<tr>
<td>N. Appalachia</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>C. Appalachia</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Black Warrior</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Illinois</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Cherokee/Forest City</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Arkoma</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Gulf Coast</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>San Juan</td>
<td>7.0</td>
<td>2.3</td>
</tr>
<tr>
<td>Raton</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Piceance</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Uinta</td>
<td>1.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Greater Green River</td>
<td>3.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Hanna-Carbon</td>
<td>1.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Wind River</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Powder River</td>
<td>3.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Western Washington</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Alaska</td>
<td>18.0</td>
<td>8.1</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>39.3</strong></td>
<td><strong>16.3</strong></td>
</tr>
</tbody>
</table>
Outline

- Introduction
- ECBM Process
- Pilot Projects
- Economics
- Closing Remarks
Gas Storage in Coal (CBM 101)

- Dual-porosity system (matrix and cleats)
- Gas stored by adsorption on coal surfaces within matrix (mono-layer of gas molecules, density approaches that of liquid)
- 1 lb coal (15 in³) contains 100,000 – 1,000,000 ft² of surface area
- Pore throats of 20 – 500 angstrom
- Production by desorption, diffusion and Darcy flow (3 D’s of CBM production)
Example Coal Sorption Isotherms

San Juan Basin coal

CO₂/CH₄ ratio = 2:1
N₂/CH₄ ratio = 0.5/1
CO₂/N₂ ratio = 4:1

Carbon Dioxide

Methane

Nitrogen

Absolute Adsorption (SCF/ton)

Pressure (psia)
Variability of CO$_2$/CH$_4$ Ratio

**CO$_2$/CH$_4$ Sorption Ratio vs Coal Rank**

$$y = 2.5738x^{-1.5649}$$

$$R^2 = 0.9766$$

- Sub
- HV
- HVA
- MV
- LV

- 100 psi
- 1000 psi
- 3000 psi
**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.
- Methane/nitrogen produced at production well.
- Rapid N₂ breakthrough expected.
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.
- Methane produced at production well.
- Efficient displacement process – slow CO$_2$ breakthrough.
Modeling Sensitivity Study

• San Juan Basin setting (3000 ft, 40 ft coal, 10 md).
• Inject CO₂ and N₂ at rates of 10 Mcfd/ft, 25 Mcfd/ft and 50 Mcfd/ft.
• 15 year period.

Quarter 5-Spot Well Pattern
Gas Production Response – N$_2$ Injection

Incremental Recoveries:
- 10 Mcfd/ft – 0.6 Bcf (21%)
- 25 Mcfd/ft – 1.1 Bcf (39%)
- 50 Mcfd/ft – 1.6 Bcf (57%)
Gas Production Response – CO₂ Injection

Incremental Recoveries:
- 10 Mcfd/ft – 0.1 Bcf (4%)
- 25 Mcfd/ft – 0.4 Bcf (14%)
- 50 Mcfd/ft – 0.8 Bcf (29%)

- No CO₂ breakthrough
- CO₂/CH₄ ratio is 2:1 whereas N₂/CH₄ ratio is 0.5:1
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  - Pilot Projects
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Only Two “Large-Scale” Field Tests Exists Worldwide

• San Juan Basin, Upper Cretaceous Fruitland Coal
• Allison Unit
  • Burlington Resources
  • Carbon dioxide injection
  • 16 producers
  • 4 injectors
  • 1 pressure observation well
• Tiffany Unit
  • BP
  • Nitrogen injection
  • 34 producers
  • 12 injectors
Field Sites, San Juan Basin
Well Configurations

Injector

Producer
Allison Production History

16 producers, 4 injectors, 1 POW

Line pressures reduced, wells recavitated, wells reconfigured, onsite compression installed

Injectivity reduction

Peak @ +/- 57 MMcfd

+/- 3 1/2 Mcfd
# Site Description

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Depth to Top Coal</td>
<td>3100 feet</td>
</tr>
<tr>
<td>No. Coal Intervals</td>
<td>3 (Yellow, Blue, Purple)</td>
</tr>
<tr>
<td>Average Total Net Thickness</td>
<td>43 feet</td>
</tr>
<tr>
<td></td>
<td>Yellow – 22 ft</td>
</tr>
<tr>
<td></td>
<td>Blue – 10 ft</td>
</tr>
<tr>
<td></td>
<td>Purple – 11 ft</td>
</tr>
<tr>
<td>Permeability</td>
<td>100 md</td>
</tr>
<tr>
<td>Initial Pressure</td>
<td>1650 psi</td>
</tr>
<tr>
<td>Temperature</td>
<td>120°F</td>
</tr>
</tbody>
</table>
Progression of CO$_2$ Displacement (@ mid-2002)
# Incremental Recovery

<table>
<thead>
<tr>
<th>Case</th>
<th>Total Methane Recovery (Bcf)</th>
<th>Incremental Recovery (Bcf)</th>
<th>Total CO₂ Injection (Bcf)</th>
<th>CO₂ Production (Bcf)</th>
<th>CO₂/CH₄ Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/o CO₂ injection</td>
<td>100.5*</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>W/CO₂ injection</td>
<td>102.1</td>
<td>1.6</td>
<td>6.4**</td>
<td>1.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>

*6.3 Bcf/well  
** 20 Mcfd/ft

Small incremental recovery due to limited injection volumes.  
INJECTIVITY IS CRITICAL!

Note: OGIP for model = 152 Bcf.
Tiffany Unit Base Map

Previous Study Area

Producer-to-Injector Conversions
Well Configurations

Multiple Injector Wells

Producer Well
Tiffany Production History

34 producers, 12 injectors

Gas Rate, Mcf/mo
N2 Injection Rate, Mcf/mo

Peak @ 26 MMcfd
Max Inj Rate = 26 MMcfd
Injection initiated
Suspension periods

+/- 5MMcfd
## Site Description

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Depth to Top Coal (A)</td>
<td>2970 feet</td>
</tr>
</tbody>
</table>
| No. Coal Intervals                | 7 total (A, A2, B, C, D, E, F)  
                              | 4 main (B, C, D, E)               |
| Average Net Thickness             | 47 feet        |
| Permeability                      | <5 md          |
| Initial Pressure                  | 1600 psi       |
| Temperature                       | 120°F          |
Progression of N\textsubscript{2} Displacement
(@ mid-2002)
## Current Field Results
*(through mid-2002)*

<table>
<thead>
<tr>
<th>Case</th>
<th>Total Methane Recovery (Bcf)</th>
<th>Incremental Recovery (Bcf)</th>
<th>Total $N_2$ Injection (Bcf)</th>
<th>$N_2$ Production (Bcf)</th>
<th>$N_2$/CH$_4$ Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/o $N_2$ injection</td>
<td>*35.3</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>W/$N_2$ injection</td>
<td>45.8</td>
<td>10.5</td>
<td>14.0**</td>
<td>1.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>

*1.0 Bcf/well
** 46 Mcfd/ft

At $N_2$/CH$_4$ ratio of 0.75:1 and reproduced volume of 25%, ultimate incremental recovery estimated to be +/- 14 Bcf or 40% improvement over primary.

Note: OGIP for model = 438 Bcf.
Summary of Field Results

• Field results are in general agreement with theoretical understanding; reservoir models can reasonably replicate/predict field behavior.
• Low-incremental recovery with CO$_2$ injection at Allison due to low injection volumes.
• CO$_2$ injectivity key success driver; strong evidence that coal permeability (and injectivity) reduced with CO$_2$ injection.
• Incremental recoveries with N$_2$ injection at Tiffany currently; estimated to provide 40% improvement over primary.
Outline

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- Pilot Projects
- Economics
- Closing Remarks
Hypothetical Field Setting
(US onshore)

Example CBM Basin

Well Injection Pattern
(4 Sections)

Sec. 6
Sec. 7
Sec. 5
Sec. 8

Conventional Recovery – 48 Bcf
(2.5 Bcf/well)
Incremental Recovery – 16 Bcf
(1 Bcf/well)
### Economics of CO₂ ECBM

<table>
<thead>
<tr>
<th>Description</th>
<th>US $/Mcf</th>
</tr>
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<tbody>
<tr>
<td>Hub Gas Price</td>
<td>$3.00</td>
</tr>
<tr>
<td>Less: Basin Differential</td>
<td>($0.30)</td>
</tr>
<tr>
<td>BTU Adjustment (@ 5%)</td>
<td>($0.15)</td>
</tr>
<tr>
<td><strong>Wellhead Netback</strong></td>
<td>$2.55</td>
</tr>
<tr>
<td>Less: Royalty/Prod. Taxes (20%)</td>
<td>($0.51)</td>
</tr>
<tr>
<td>O&amp;M/Gas Processing</td>
<td>($0.50)</td>
</tr>
<tr>
<td><strong>Gross Margin</strong></td>
<td>$1.54</td>
</tr>
<tr>
<td>Capital Costs(1)</td>
<td>($0.25)</td>
</tr>
<tr>
<td>CO₂ Costs (@ ratio of 3.0 to 1)(2)</td>
<td>($0.90)</td>
</tr>
<tr>
<td><strong>Net Margin</strong></td>
<td>$0.39</td>
</tr>
</tbody>
</table>

(1) Capital Costs = $500,000 * 4 (inj wells) = $2,000,000/16 Bcfg = $0.13/Mcfg * 2 = $0.25/Mcfg

(2) CO₂ Costs = $0.30/Mcf * 3.0 = $0.90/Mcf (CO₂)
# Economics of N$_2$ ECBM

<table>
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</tr>
<tr>
<td>Gross Margin</td>
<td>$1.04</td>
</tr>
<tr>
<td>Capital Costs$^{(1)}</td>
<td>($0.25)</td>
</tr>
<tr>
<td>N$_2$ Costs (@ ratio of 0.5 to 1)$^{(2)}$</td>
<td>($0.30)</td>
</tr>
<tr>
<td>Net Margin</td>
<td>$0.49</td>
</tr>
</tbody>
</table>

(1) Capital Costs = $500,000 * 4 (inj. wells) = $2,000,000 / 16 Bcfg = $0.13/Mcf * 2 = $0.25/Mcf

(2) N$_2$ Costs = $0.60/Mcf * 0.5 = $0.30/Mcf (N$_2$)
ECBM Economic Considerations

- $N_2$ – ECBM appears favorable, but early breakthrough requires costly post-production gas processing.
- $CO_2$ - ECBM also appears favorable, but maintaining injectivity a key success driver.
- More experience required to validate & optimize economic performance.
- $CO_2/N_2$ mixture may be optimum.
  - High $N_2$ concentrations early for rapid methane recovery
  - Increasing $CO_2$ concentrations later for efficient methane displacement.
Outline

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Closing Remarks

- ECBM recovery appears to hold considerable promise; on the verge of commerciality with a bright future.
- CO₂ sequestration economic drivers (carbon credits) will substantially improve financial performance and accelerate commercial adoption.
- In U.S., CO₂-ECBM/sequestration potential is substantial; recently assessed at 90 Gt CO₂ and 150 Tcf of incremental gas recovery.
Closing Remarks

• More work is needed to economically optimize the process.
  - $N_2/CO_2$ mixtures
  - CO$_2$ injectivity
  - Spacing, patterns, rates, etc.
  - Reservoir settings (coal rank)

• Reservoir response is generally consistent with theoretical understanding of CO$_2/N_2$ processes.
  - Reasonable predictions of reservoir response possible.
  - Informed investment decisions.

• Acknowledgements:
  - U.S. Department of Energy
  - Burlington Resources
  - BP America

• For more information:
  [www.coal-seq.com](http://www.coal-seq.com)
Well #132 Performance

CH₄ Recovery w/o CO₂ injection = 6.1 Bcf
CH₄ Recovery w/ CO₂ injection = 6.9 Bcf
CH₄ Incremental Recovery = 0.8 Bcf
Nitrogen Content of Produced Gas

Average = 12.3 %
Matrix Shrinkage/Swelling

![Graph showing permeability and adsorption isotherm](image)

*Relevant Formulas*

Pressure-Dependence

\[ \phi = \phi_i + \phi_i C_p (P - P_i) + (1 - \phi_i) C_m \left( \frac{dP_i}{dC_i} (C - C_i) \right) \]

Shrinkage/Swelling

\[ k = \left( \frac{\phi}{\phi_i} \right)^n \]

\[ n = +/- 3 \]

*Used in COMET2. Alternative formulation presented by Palmer & Mansoori; SPE 36737, 1996.*
Permeability Changes with Net Stress, Gas Concentration, and Sorptive Capacity
Typical Injection Profile, Allison Unit

![Graph showing typical injection profile over time, with dates from January 1989 to January 2000. The graph includes data on rates and pressures, with CO2 and BHP measurements.](image-url)
Permeability History for Injector

- Start
- Depletion
- Displace w/ CO2
- Continued Injection
CO$_2$ Sorption Behavior
(Pc=1073psi, Tc=88ºF)

Pure Gas Gibbs Adsorption on Tiffany Coals at 130° F

\[
N_{\text{abs}} = \frac{N_{\text{Gibbs}}}{1 - \frac{\rho_{\text{gas}}}{\rho_{\text{ads}}}}
\]

- N2 on Mixed Coal
- CH4 on Well #1
- CH4 on Well #10
- CH4 on Mixed Coal
- CO2 on Mixed Coal

Gibbs Adsorption (SCF/ton) vs. Pressure (psia)
CO₂ Absolute Adsorption on Tiffany Mixed Coal Sample Using Different Adsorbed-Phase Densities

Absolute Adsorption (SCF/ton) vs Pressure (psia) for different adsorbed phase densities:
- 1.18: Saturated liquid density at triple point
- 1.25: ZGR estimate
- 1.40: Graphical estimate
Multi-Component Sorption Behavior

Extended Langmuir Theory

\[ C_i(p_i) = \frac{V_{Li} p_i}{p_{Li} \left(1 + \sum_{j=1}^{n} \left(\frac{p_j}{p_L}\right)\right)} \]

Other Langmuir Models:
- Loading Ratio Correlation (LRC), Real Adsorbed Solution (RAS),
- Ideal Adsorbed Solution (IAS)

Equations of State:
- Van der Walls (VDW), Eyring, Zhou-Gasem-Robinson (EOS-S, PGR)

Simplified Local Density Models:
- Flat Surface (PR-SLD), Slit (PR-SLD)
Accuracy of Model Predictions for Pure Gas Adsorption

<table>
<thead>
<tr>
<th>Component</th>
<th>Quality of Fit, % AAD, for Specified Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Langmuir</td>
</tr>
<tr>
<td>Methane</td>
<td>2.6</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>3.5</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Accuracy of Model Predictions for Binary/Ternary Gas Adsorption
(based on pure-gas adsorption data)

<table>
<thead>
<tr>
<th>Mixture, (Feed Mole %)</th>
<th>Langmuir % AAD</th>
<th>LRC (n=0.9) % AAD</th>
<th>ZGR-EOS % AAD</th>
<th>Experimental Error % AAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄ – N₂:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₄ (50%)</td>
<td>15.8</td>
<td>12.0</td>
<td>11.9</td>
<td>7.0</td>
</tr>
<tr>
<td>N₂ (50%)</td>
<td>6.2</td>
<td>9.3</td>
<td>10.0</td>
<td>17.0</td>
</tr>
<tr>
<td>Total</td>
<td>12.2</td>
<td>8.2</td>
<td>11.5</td>
<td>7.0</td>
</tr>
<tr>
<td>CH₄ – CO₂:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₄ (40%)</td>
<td>25.9</td>
<td>21.0</td>
<td>27.0</td>
<td>7.0</td>
</tr>
<tr>
<td>CO₂ (60%)</td>
<td>9.0</td>
<td>10.5</td>
<td>10.4</td>
<td>6.0</td>
</tr>
<tr>
<td>Total</td>
<td>12.2</td>
<td>2.2</td>
<td>1.4</td>
<td>4.0</td>
</tr>
<tr>
<td>N₂ – CO₂:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂ (20%)</td>
<td>44.9</td>
<td>37.3</td>
<td>48.7</td>
<td>29.0</td>
</tr>
<tr>
<td>CO₂ (80%)</td>
<td>5.2</td>
<td>5.7</td>
<td>4.9</td>
<td>6.0</td>
</tr>
<tr>
<td>Total</td>
<td>3.5</td>
<td>3.8</td>
<td>3.5</td>
<td>5.0</td>
</tr>
<tr>
<td>N₂ – CH₄ - CO₂:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂ (10%)</td>
<td>47.8</td>
<td>44.5</td>
<td>55.9</td>
<td>14.0</td>
</tr>
<tr>
<td>CH₄ (40%)</td>
<td>20.7</td>
<td>5.2</td>
<td>21.6</td>
<td>27.0</td>
</tr>
<tr>
<td>CO₂ (50%)</td>
<td>13.2</td>
<td>15.8</td>
<td>17.6</td>
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<td>2.9</td>
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</table>