A Strategy for Enhanced Recovery and CO$_2$ Sequestration in Gas Shales

*or Getting From Here to There*

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Getting from Here to There?

Significant Utilization of Unconventional Natural Gas – With Carbon Capture and Storage – Can and Should Play a Major Role in the Transition Away From Fossil Fuels Over the Next ~20-30 Years

Enhanced Utilization of Gas for Electrical Power Generation*

- Extremely Large Domestic (and Global) Resource
- Dramatically Reduces CO₂ Emissions and Other Pollutants Associated With Coal
- Depends on Existing Technologies
- Makes Economic Sense and Provides Incentives (and New Geologic Opportunities) for CCS

* Gas is also a viable transition fuel for transportation
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## Air Pollution and Energy Source*

<table>
<thead>
<tr>
<th></th>
<th>CH$_4$</th>
<th>Oil</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>117,000</td>
<td>164,000</td>
<td>208,000</td>
</tr>
<tr>
<td>CO</td>
<td>40</td>
<td>33</td>
<td>208</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>92</td>
<td>448</td>
<td>457</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>0.6</td>
<td>1,122</td>
<td>2,591</td>
</tr>
<tr>
<td>Particulates</td>
<td>7.0</td>
<td>84</td>
<td>2,744</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>0.75</td>
<td>0.22</td>
<td>0.221</td>
</tr>
<tr>
<td>Mercury</td>
<td>0</td>
<td>0.007</td>
<td>0.016</td>
</tr>
</tbody>
</table>

*Pounds/Billion BTU

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EIA, 1998
I. Shale Gas Reservoirs

2009 Estimates of Gas Resources Over 2000 TCF
II. Enhanced Gas Recovery and CO$_2$ Sequestration

Overview of Geological Storage Options
1. Depleted oil and gas reservoirs
2. Use of CO$_2$ in enhanced oil and gas recovery
3. Deep saline formations — (a) offshore (b) onshore
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Enhanced Gas Shale Recovery and CCS

Enhanced Coalbed Methane and CCS

IPCC (2005)
AEP Mountaineer Project: New Haven, WV

NY Times Sept. 21, 2009

Current Plans to Inject 100 ktons/y for 2-5 years
AEP Mountaineer Project: New Haven, WV

AEP Mountaineer CO₂ Emissions ~7 Mton/year limited to ~35 kton/year per injection zone - 200 injection zones required!

Lucier and Zoback (2008)

183 Coal burning plants in Ohio River Valley (emitting 700 Megatons of CO₂/year)
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Intraplate Seismicity Limits Injection Pressures

Brittle Failure in Critically-Stressed Crust Results From Creep in Lower Crust and Upper Mantle

\[ \dot{\epsilon} = A e^{Q/RT} \left( S_1 - S_3 \right)^n_{\text{brittle}} \]

\[ \tau = \mu \sigma_n \]

- Seismogenic Zone
- Brittle
- Ductile
- Moho

Plate-driving forces ~ $3 \times 10^{12}$ N

Zoback, Townend and Grollimund (2002)

Zoback and Harjes (1997)
Intraplate Seismicity Limits Injection Pressures

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Zoback, Townend and Grollimund (2002)
A Quick Primer on Shale Gas Reservoirs

2009 Estimates of Gas Resources Over 2000 TCF
Putting 2000 TCF in Perspective

- 1 TCF \((10^{12} \text{ ft}^3)\) of \(\text{CH}_4\) \(\approx 10^{15}\) BTU \(\equiv 1\) Quad

- Current Annual Coal Consumption in U.S.
  - 23 Quads \(\equiv 23\) TCF

- Current Annual Gas Production in U.S.
  - \(\sim 20\) TCF \(\equiv 20\) Quads
  - 2000 TCF Represents “100 Years of Gas”
Global Potential for Shale Gas

Preliminary studies have identified over 688 shales in 142 basins around the world.
Global Potential for Shale Gas

World Total: 32,560 tcf
roughly 300 years of supply
Organic Shales - Deep Water - Anaerobic / Clay Matrix

Organic Rich Source Rock
Extremely Low Permeability
Gas Shales Were Booming

<table>
<thead>
<tr>
<th>Shale</th>
<th>TCF</th>
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</thead>
<tbody>
<tr>
<td>Barnett</td>
<td>44</td>
</tr>
<tr>
<td>Fayetteville</td>
<td>42</td>
</tr>
<tr>
<td>Haynesville</td>
<td>251</td>
</tr>
<tr>
<td>Marcellus</td>
<td>262</td>
</tr>
<tr>
<td>Woodford</td>
<td>11</td>
</tr>
<tr>
<td>Antrim</td>
<td>20</td>
</tr>
<tr>
<td>New Albany</td>
<td>19</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>649 TCF</strong></td>
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DOE (2009)

Barnett Production Through 2006

2008 Production 1.4 TCF

2.3 Trillion Cubic Feet Produced Since 2000
Drilling/Completion Technology Key To Barnett Development

Horizontal Drilling and Multi-Stage Slick-Water Hydraulic Fracturing Induces Microearthquakes (M ~ -1 to M ~ -3) To Create a Permeable Fracture Network
A “Slick-Water” Fracturing Operation

Micro-earthquake magnitudes typically range between -3.0 to 0

A “relatively large” induced microearthquake (M = -1.6) has a fault patch area of ~ 1 m² and a slip distance of ~ 0.1 mm (cannot be detected by seismometers at the earth’s surface)

Releases $10^{-9}$ Energy of a M 3 (felt) Earthquake

*(after Pinnacle Technologies)*
Many Fundamental Questions About Gas Shale Reservoirs

- How do these rocks respond mechanically during slick-water fracturing?

- How do the mechanical properties evolve during production and gas adsorption/desorption?

- What are the controls on permeability and surface area development during fracturing?

- How to assess and model stimulated volume?
Shale Basins are Diverse

Geologically, the shales in question are quite diverse in composition, temp., depth, pressure, organic content and maturity, etc.

The Barnett shale is not really a shale.
Significant Environmental Impacts of Gas Production

10 natural gas wells: 165 MW per year

10 wind turbines: 12.5 MW per year
Meeting CO$_2$ Reduction Targets

- Current climate/energy bills calls for a 17% - 20% reduction of CO$_2$ emissions by 2020
- Replacing 30% of coal-fired generation with gas (without CCS) almost meets this goal, but..
  - Requires doubling gas power generation
  - Increasing gas production by $\sim$7 TCF/year
  - Assure inexpensive (and stable) gas prices
- Combining enhanced gas production with CCS results in greater emission reductions
Meeting CO₂ Reduction Targets

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Double gas generating capacity?

Current Gas Power Electrical Generation Capacity 400 GW

Current Average Utilization ~20%

To Meet CO₂ Reduction Targets for 2020, Need to Increase Utilization of Existing Plants to ~40%

(Could Also Replace Oldest and Least Efficient Coal Plants with Combined-Cycle Gas Plants)
Increase gas production by ~7 TCF/year?

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DOE (2009)

![Map of US with production data](image)

2008 Production 1.4 TCF

2.3 Trillion Cubic Feet Produced Since 2000!

Barnett Production Through 2006
Assure inexpensive (and stable) gas prices?

Short-Term Energy Outlook, September 2009
Assure inexpensive (and stable) gas prices?
(from America’s Energy Future)
Assure inexpensive (and stable) gas prices?
(from America’s Energy Future)

$6/Million BTU
Inexpensive (and stable) gas prices?

With essentially no limit on the domestic supply of gas for several decades, at $6/M BTU operators can make money, utilities can save money and CO$_2$ emissions can be significantly reduced.
Enhanced Gas Recovery and CO₂ Sequestration

Overview of Geological Storage Options
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Illustration: Enhanced Gas Shale Recovery and CCS

IPCC (2005)
Now Evaluating Multi-Well Stimulation Schemes

Microseisms from various hydro-frac stages

Multi-lateral completions
Desorption of Biogenic Gas and Flow In Coal

adsorption on internal coal surfaces

diffusion through matrix and micropores

bulk flow in the fracture network

Biogenic Gas

Desorption

Flow
Adsorption Isotherms – Powder River Basin

CO₂ Preferentially Adsorbed to CH₄

Kovscek and Tang, 2004
ECBM/CO₂ Sequestration Potential of Coalbeds

Modeling requires accurate input parameters

Ross et al. (2009)
Methane Adsorption in Shales

Ross and Bustin (2008)
Changes in Physical Properties of Coal With CO\textsubscript{2}

- Static Bulk Modulus decreases by \(~2\times\) with adsorption of CO\textsubscript{2} at a given effective stress
- Permeability decreases due to effective stress and adsorption of CO\textsubscript{2} are approximately the same magnitude
- Coal samples swell in presence of CO\textsubscript{2}
- CO\textsubscript{2} saturated samples exhibit viscoplastic behavior (creep)

Will these effects be seen in shale?

See Poster by Yi Yang et al.
CO₂/CH₄ Adsorption in Appalachian Devonian Shales

- To date, only one study on shale adsorption for both CO₂ and CH₄
- ~5x greater adsorption of CO₂
- Linear relation between TOC and adsorption capacity

Nuttall et al. (2005)
Many Fundamental Questions About the Potential for CO₂ Sequestration in Gas Shale Reservoirs

How do these rocks respond mechanically during slick-water fracturing?
How do the mechanical properties evolve during production and gas adsorption/desorption?
What are the controls on permeability and surface area development during fracturing?

Enhanced Recovery and Carbon Sequestration
Is there the potential for significant adsorption of CO₂ and desorption of CH₄ at the pore scale?
Gas Shale Reservoirs

~2000 TCF potential means large-scale development and production is inevitable so

Let’s Do It Right!
Now Evaluating Multi-Well Stimulation Schemes

Microseisms from various hydro-frac stages

Multi-lateral completions
Innovative Completion Strategies Have the Potential for Enhanced Recovery and Environmental Benefit
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Enhanced Utilization of Gas for Electrical Power Generation
• Economically Viable/Technologically Feasible
• Dramatically Reduces CO$_2$ Emissions
• Reduces Other Pollutants Associated With Coal
• Provides New Opportunities for CCS