Phase II-Task 10: Evaluation of Large-Volume Carbon Sequestration Test Sites in Central Appalachia

Nino Ripepi
Assistant Research Professor
Virginia Center for Coal and Energy Research
Virginia Tech
and
Edward K. Diminick
Sr. Petroleum Engineer

SECARB 6th Annual Stakeholders' Briefing, Atlanta, GA, March 9-10, 2011
Acknowledgement

This material is based upon work supported by the Department of Energy National Energy Technology Laboratory under DE-FC26-05NT42590

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
Phase II Update – Final Reports Submitted

❖ Task 2
  – Central Appalachian Basin Field Validation Test in Coal - 2009
    • (Host: CONSOL/CNX Gas)
  – Black Warrior Basin Field Validation Test in Coal - 2010
    • (Host: El Paso)

❖ Task 10
  – Evaluation of Large-Volume Carbon Sequestration Test Sites in Central Appalachia
SECARB Coal Group - Research Team

- Southern States Energy Board
- Marshall Miller and Associates
- VCCER/Virginia Tech
- Geological Survey of Alabama
- Kentucky Geological Survey
- Advanced Resources International
- CONSOL Energy
- West Virginia University
SECARB Coal Group – Phase II Partners (Cost Share, Data, Wells)

- Alawest
- Alpha Natural Resources
- AMVEST
- Appalachian Production Serv.
- Buckhorn Coal
- CCP2 Project
- CDX Gas
- Clean Energy Tech. Inst (MSU)
- CNX Gas
- CONSOL Energy
- Cumberland Resources
- Dart Oil & Gas
- Denbury Resources
- Dominion

- EPRI
- Equitable Production
- GeoMet
- International Coal Group
- McJunkin Appalachian
- Norfolk Southern
- Natural Resource Partners
- Oak Ridge National Laboratory
- Penn Virginia
- Pine Mountain Oil & Gas
- Piney Land
- Pocahontas Land
- Praxair
- RMB Earth Science Consultants
- Univ. British Columbia
## Task 10 Team Leaders

### Geologic Storage Options

<table>
<thead>
<tr>
<th>Devonian Shale</th>
<th>Depleted Oil &amp; Gas Fields</th>
<th>Unmineable Coal Seams</th>
<th>ECBM</th>
<th>Saline Aquifers</th>
<th>Stacked Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>KGS</td>
<td>MM&amp;A</td>
<td>MM&amp;A</td>
<td>VCCER</td>
<td>WVU</td>
<td>GSA</td>
</tr>
</tbody>
</table>

## Technical Tasks

<table>
<thead>
<tr>
<th>Public Outreach</th>
<th>Legal, Permitting and Regulatory</th>
<th>Monitoring, Verification and Accounting</th>
<th>Modeling</th>
<th>Closeout</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCCER</td>
<td>CONSOL</td>
<td>VCCER</td>
<td>ARI</td>
<td>MM&amp;A</td>
</tr>
</tbody>
</table>
Primary Objectives

- Characterize potential large volume test sites in Central Appalachian Basin for coal seam sequestration and ECBM recovery
- Identify depleted oil and gas fields that could support a large volume test
- Study saline formations to develop a secondary storage option
- Analyze the potential of shale reservoirs for sequestration
Primary Objectives (cont.)

- Model potential CO$_2$ injection test sites and develop injection profiles for large-scale test
- Identify options for stacked storage reservoirs
- Select several test sites for a large volume sequestration project
Stacked Storage Target Formations

EXPLANATION
- Coal
- Sandstone
- Red shale
- Black shale
- Gray shale
- Limestone
- Dolostone
- Hiatus (disconformity)

Coal reservoirs
Regional seal
Depleted oil and gas reservoirs
Shale gas reservoir
Saline formation
Regional seal
Saline formation
Saline formation?
Saline formation?
Target Formations
## Reservoir Characteristics of Targeted Sinks

<table>
<thead>
<tr>
<th>Stratigraphic Unit</th>
<th>Rock Type</th>
<th>Sink Type</th>
<th>Average Porosity (%)</th>
<th>Average Perm. (mD)</th>
<th>Average Pay Thickness (ft)</th>
<th>Average Depth (ft)</th>
<th>Reservoir Pressure (psi)</th>
<th>Reservoir Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norton, Lee and Pocahontas</td>
<td>Shale, Sandstone, Coal</td>
<td>Coal</td>
<td>7.5</td>
<td>50</td>
<td>19</td>
<td>800</td>
<td>200</td>
<td>24.0</td>
</tr>
<tr>
<td>Formations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big Lime</td>
<td>Limestone, some Dolostone</td>
<td>Depleted conventional reservoir</td>
<td>16</td>
<td>6.3</td>
<td>38</td>
<td>2,050</td>
<td>507</td>
<td>25.5</td>
</tr>
<tr>
<td>Big Injun Sandstone (Price Fm.)</td>
<td>Sandstone</td>
<td>Depleted conventional reservoir</td>
<td>16</td>
<td>6.3</td>
<td>38</td>
<td>2,050</td>
<td>507</td>
<td>25.5</td>
</tr>
<tr>
<td>Weir Sandstone (Price Fm.)</td>
<td>Sandstone</td>
<td>Depleted conventional reservoir</td>
<td>11</td>
<td>6.3</td>
<td>38</td>
<td>4,157</td>
<td>73</td>
<td>37.7</td>
</tr>
<tr>
<td>Berea Sandstone</td>
<td>Sandstone</td>
<td>Depleted conventional reservoir</td>
<td>10</td>
<td>10.0</td>
<td>40</td>
<td>4,400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Devonian Shale</td>
<td>Organic-rich Shale</td>
<td>Shale</td>
<td>40</td>
<td>3,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oriskany Sandstone</td>
<td>Sandstone</td>
<td>Saline formation</td>
<td>8</td>
<td>52</td>
<td>2,612</td>
<td>3,074</td>
<td>45.3</td>
<td></td>
</tr>
<tr>
<td>Tuscarora Formation</td>
<td>Sandstone</td>
<td>Saline formation</td>
<td>10</td>
<td>10.0</td>
<td>82</td>
<td>6,496</td>
<td>3,074</td>
<td>50.6</td>
</tr>
</tbody>
</table>
CBM Fields in Study

- Bradshaw
- Lick Creek
- Sourwood
- Frying Pan
- Loup Creek
- South Oakwood
CBM Characterization Study Area

VERTICAL CBM WELL  DEEP MINE  DETAILED STUDY AREA

KY  VA  VA  WV
Pike  VA  KY
Buchanan
Frying Pan
Dickenson
Lick Creek
Sourwood
Russell
Tazewell
Bradshaw
McDowell
SECARB Pilot Injection Test

0  5 Miles
Loup Creek Study Area
# CO₂ Storage Estimate of CBM Fields

<table>
<thead>
<tr>
<th>Field Name</th>
<th>State</th>
<th>Cumulative Production (Bcf)</th>
<th>Ultimate Recovery (Bcf)</th>
<th>Current State of Depletion (%)</th>
<th>Current Storage Capacity (tonnes)</th>
<th>Total Storage Capacity (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frying Pan</td>
<td>VA</td>
<td>17.1</td>
<td>35.6</td>
<td>48%</td>
<td>1,613,000</td>
<td>3,360,000</td>
</tr>
<tr>
<td>Sourwood</td>
<td>VA</td>
<td>18.8</td>
<td>55.3</td>
<td>34%</td>
<td>1,772,000</td>
<td>5,209,000</td>
</tr>
<tr>
<td>Lick Creek</td>
<td>VA</td>
<td>80.8</td>
<td>231.1</td>
<td>35%</td>
<td>7,616,000</td>
<td>21,783,000</td>
</tr>
<tr>
<td>South Oakwood</td>
<td>VA</td>
<td>90.6</td>
<td>321.9</td>
<td>28%</td>
<td>8,535,000</td>
<td>30,345,000</td>
</tr>
<tr>
<td>Loup Creek</td>
<td>WV</td>
<td>30.1</td>
<td>47.4</td>
<td>64%</td>
<td>2,835,000</td>
<td>4,464,000</td>
</tr>
<tr>
<td>Bradshaw</td>
<td>WV</td>
<td></td>
<td></td>
<td></td>
<td>1,839,000</td>
<td></td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td></td>
<td><strong>237.4</strong></td>
<td><strong>691.3</strong></td>
<td></td>
<td><strong>22,371,000</strong></td>
<td><strong>67,000,000</strong></td>
</tr>
</tbody>
</table>
## ECBM Estimates by Field

<table>
<thead>
<tr>
<th>Field Name</th>
<th>State</th>
<th>Recovery Factor</th>
<th>Ultimate Recovery (Bcf)</th>
<th>GIIP (Bcf)</th>
<th>Residual Gas (Bcf)</th>
<th>ECBM Potential* (Bcf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frying Pan</td>
<td>VA</td>
<td>60%</td>
<td>35.6</td>
<td>59.4</td>
<td>23.8</td>
<td>5.9</td>
</tr>
<tr>
<td>Sourwood</td>
<td>VA</td>
<td>60%</td>
<td>55.3</td>
<td>92.1</td>
<td>36.8</td>
<td>9.2</td>
</tr>
<tr>
<td>Lick Creek</td>
<td>VA</td>
<td>50%</td>
<td>231.1</td>
<td>462.2</td>
<td>231.1</td>
<td>57.8</td>
</tr>
<tr>
<td>South Oakwood</td>
<td>VA</td>
<td>50%</td>
<td>321.9</td>
<td>643.8</td>
<td>321.9</td>
<td>80.5</td>
</tr>
<tr>
<td>Loup Creek</td>
<td>WV</td>
<td>85%</td>
<td>47.4</td>
<td>55.6</td>
<td>8.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Bradshaw</td>
<td>WV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.4</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td>--</td>
<td>--</td>
<td><strong>691.3</strong></td>
<td><strong>1,313.1</strong></td>
<td><strong>621.9</strong></td>
<td><strong>160.9</strong></td>
</tr>
</tbody>
</table>
Depleted Oil & Gas Fields in Study

- Weir Formation – 2 Fields
- Big Injun Formation – 2 Fields
- Big Lime Formation – 10 Fields
Weir & Big Injun Fields in Study

- Roaring Fork
- Ashland – Clark Gap – Eckman
- Granny Creek
- Rock Creek
Weir & Big Injun Study Area

Characterization Study Areas

- Depleted Oil Field
- Depleted Gas Field

0 - 20 Miles

Rock Creek
Granny Creek
Ashland-Clark Gap-Eckman
Roaring Fork
### CO₂ Storage Estimate in Weir and Big Injun Fields

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Mid-Point Depth (ft)</th>
<th>Estimated Ultimate Recovery</th>
<th>Storage Capacity (tonnes)</th>
<th>Enhanced Oil Recovery (bbls)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roaring Fork</td>
<td>4,550</td>
<td>157.9 Bcf</td>
<td>27,773,165</td>
<td>--</td>
</tr>
<tr>
<td>Ashland-Clark Gap-Eckman</td>
<td>4,210</td>
<td>411.5 Bcf</td>
<td>29,043,433</td>
<td>--</td>
</tr>
<tr>
<td>Granny Creek</td>
<td>2,050</td>
<td>11.9 MMbo</td>
<td>149,792</td>
<td>84,597</td>
</tr>
<tr>
<td>Rock Creek</td>
<td>2,029</td>
<td>25.5 MMbo</td>
<td>311,333</td>
<td>162,369</td>
</tr>
</tbody>
</table>
Big Lime Fields in Study

- Banks
- Blackey South
- Bull Creek Consolidated
- Daley
- Highsplint
- Big Creek
- Bulan
- Cutshin
- Happy
- Lotts Creek
Big Lime Fields in Study
# CO₂ Storage Estimate in Big Lime Fields

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Recovery factor</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 10 Fields</td>
<td>100%</td>
<td>397,175</td>
<td>2,717,650</td>
<td>17,516,542</td>
<td>32,264,296</td>
</tr>
<tr>
<td></td>
<td>40%</td>
<td>158,870</td>
<td>1,087,060</td>
<td>7,006,617</td>
<td>12,905,718</td>
</tr>
<tr>
<td></td>
<td>20%</td>
<td>79,435</td>
<td>543,530</td>
<td>3,503,308</td>
<td>6,452,859</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>32,497</td>
<td>265,060</td>
<td>1,748,217</td>
<td>3,220,904</td>
</tr>
</tbody>
</table>
Saline Reservoirs in Study

- Oriskany Sandstone
- Tuscarora Sandstone
Tuscarora Study Area
CO₂ Storage Estimate in Oriskany and Tuscarora SS

<table>
<thead>
<tr>
<th>Formation</th>
<th>High Estimate E=0.04 (tonnes)</th>
<th>Low Estimate E=0.01 (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oriskany</td>
<td>4,983,000,000</td>
<td>1,246,000,000</td>
</tr>
<tr>
<td>Tuscarora</td>
<td>423,069,942</td>
<td>105,767,485</td>
</tr>
</tbody>
</table>
Devonian Shale Study Area
## CO₂ Storage Estimate in Shale in SW Virginia

<table>
<thead>
<tr>
<th>Area</th>
<th>CO₂ (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buchanan Co.</td>
<td>2,043,906</td>
</tr>
<tr>
<td>Dickenson Co.</td>
<td>7,215,155</td>
</tr>
<tr>
<td>Lee Co.</td>
<td>575,206</td>
</tr>
<tr>
<td>Norton City</td>
<td>352,267</td>
</tr>
<tr>
<td>Russell Co.</td>
<td>154,636</td>
</tr>
<tr>
<td>Scott Co.</td>
<td>158,958</td>
</tr>
<tr>
<td>Wise Co.</td>
<td>16,921,749</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>27,421,877</strong></td>
</tr>
</tbody>
</table>
## CO₂ Storage Estimate for Geologic Sinks

<table>
<thead>
<tr>
<th>CO₂ Sink</th>
<th>Estimated CO₂ Storage Capacity (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unmineable Coalbeds</td>
<td>453,408,000</td>
</tr>
<tr>
<td>Depleted Oil &amp; Gas Fields</td>
<td>89,542,019</td>
</tr>
<tr>
<td>Saline Reservoirs</td>
<td>5,406,069,942</td>
</tr>
<tr>
<td>Organic-Rich Shales</td>
<td>27,421,877</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5,976,441,838</strong></td>
</tr>
</tbody>
</table>
Other Tasks

- Reservoir Modeling
- Monitoring, Verification, and Accounting
- Permits
- Public Outreach and Education
Modeling Results of Injectivity of CBM Fields

*Compares favorably with characterization results.*
Modeling Results of Injectivity of Depleted Oil and Gas Fields

*With a developed area of 15,360 acres (62.2 square kilometers), the Rock Creek field may be capable of accepting nearly five million tonnes of CO₂ in the first year.*
## Reservoir Modeling Results

<table>
<thead>
<tr>
<th>Reservoir Type</th>
<th>Field Name</th>
<th>Reservoir Name</th>
<th>Injection Spacing</th>
<th>Injection Duration for 100,000 metric tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Bed Methane</td>
<td>Frying Pan</td>
<td>Lee and Pocahontas</td>
<td>640</td>
<td>396 (13 months)</td>
</tr>
<tr>
<td></td>
<td>Sourwood</td>
<td>Lee and Pocahontas</td>
<td>640</td>
<td>335 (11 months)</td>
</tr>
<tr>
<td></td>
<td>Sourwood</td>
<td>Lee and Pocahontas</td>
<td>640</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lick Creek</td>
<td>Lee and Pocahontas</td>
<td>640</td>
<td>441 (14 months)</td>
</tr>
<tr>
<td></td>
<td>Buck Knob</td>
<td>Lee and Pocahontas</td>
<td>640</td>
<td>517 (17 months)</td>
</tr>
<tr>
<td></td>
<td>South Oakwood</td>
<td>Lee and Pocahontas</td>
<td>640</td>
<td>381 (12.5 months)</td>
</tr>
<tr>
<td>Depleted Oil and Gas</td>
<td>Rock Creek</td>
<td>Big Injun Sandstones</td>
<td>320</td>
<td>240 (8 months)</td>
</tr>
<tr>
<td></td>
<td>Granny Creek</td>
<td>Big Injun Sandstones</td>
<td>320</td>
<td>584 (19 months)</td>
</tr>
<tr>
<td></td>
<td>Ashland-Clark</td>
<td>Weir Sandstones</td>
<td>320</td>
<td>383 (13 months)</td>
</tr>
<tr>
<td>Gas Shale</td>
<td>Big Sandy</td>
<td>Devonian Lower Huron</td>
<td>~40</td>
<td>21,900 (720 months)</td>
</tr>
<tr>
<td>Deep Saline</td>
<td>N/A</td>
<td>Tuscarora Sandstones</td>
<td>N/A</td>
<td>1,460 (48 months)</td>
</tr>
<tr>
<td></td>
<td>N/A</td>
<td>Oriskany Sandstones</td>
<td>N/A</td>
<td>3,106 (102 months)</td>
</tr>
</tbody>
</table>
Site Selection Parameters

- Footprint - storage capacity (tonnes/acre)
- Modeled injectivity (tonnes/day)
- Confinement characteristics
- Target depth range (m)
- Storage reservoir availability
- ECBM-EGR potential
- Storage risks
- MVA challenges
- Distance to large CO$_2$ emitters
Selected Sites

- Site 1 – Southwestern Virginia
  - Unmineable coal seams, depleted gas reservoirs and Devonian Shale
- Site 2 – Wyoming County, West Virginia
  - Horizontally developed coal seams, depleted gas reservoirs and Tuscarora saline reservoir
- Site 3 – Clay County, West Virginia
  - Oriskany and Tuscarora saline reservoirs
Potential Sites for Large-Volume CO$_2$ Injection and Sequestration
Sources and Sinks

* Dominion Hybrid Energy Center currently under construction
Conclusions

- 3 sites identified for large volume CO$_2$ testing in Central Appalachian Basin
- Significant potential exists for long term commercial-scale storage of CO$_2$
- Sites are close to CO$_2$ sources
- Good geological characterization and vast number of wells in region
Recommendations

- 3 year pre-injection engineering study
- Complete storage system design and cost analysis
- Conduct 3D seismic study at site
- Drill shallow and deep test wells
- Inject moderate volume of CO₂ to confirm commercial potential