Kentucky Geological Survey
Western Kentucky CO₂ Storage Test: Phase 1 Project Review

Principal Investigators:
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Electric power generating and industrial plants in western Kentucky discharge ~78 million metric tons of CO$_2$ to the atmosphere each year.
Regional Coal-Fired Power Plants
The Kentucky Geological Survey is a member of three DOE-sponsored regional sequestration partnerships. Volumes of CO$_2$ injected or planned noted.
Project Purpose

• Discharge of CO₂ to the atmosphere is under regulatory review, and subsurface storage may be required for existing facilities and the financing and construction of new facilities.

• Kentucky House Bill 1, passed in a special legislature session and signed into law in August 2007, appropriated $5 million funding for KGS to research the storage and use of CO₂ throughout the Commonwealth.

• House Bill 1 mandates the drilling a CO₂ storage demonstration well in the Western Kentucky Coal Field.

• The Hancock County drillsite was chosen for its favorable geologic setting and accessibility.
Hancock County lies in the southeastern Illinois Basin, on the northeastern margin of the Western Kentucky Coal Field.

Location of Hancock County, Kentucky

Hancock County lies in the southeastern Illinois Basin, on the northeastern margin of the Western Kentucky Coal Field.

Source: Hatch and Affolter (2002, fig. 1) with annotations
Project Goals

• Demonstrate CO₂ storage in deep saline reservoirs under the Western Kentucky Coal Field through the drilling and testing of an 8350 ft well in east-central Hancock County

• Demonstrate the integrity of reservoir sealing strata for long-term CO₂ storage in western Kentucky

• Demonstrate appropriate technologies for the evaluation of CO₂ storage in Kentucky deep saline reservoirs

• Publish the project results for use by government, industry, and the public in evaluating CO₂ storage in Kentucky

• Accomplish this project with consideration of the interests and concerns of the landowner, residents of Hancock County and western Kentucky, and the citizens of the Commonwealth
Project Stakeholders

- Landowner and Hancock County residents
- Western Kentucky coal mining industry
- Electric power generators
- Clean coal syngas projects
Project Organization

- **Project management agreements in place**
  - 501(c)3 Western Kentucky Carbon Storage Foundation
  - MOA between KGS and the foundation

- **Project operations agreements**
  - Right of way and injection test well agreement with the landowners
  - Lease subordination and data sharing agreements with the oil and gas leaseholder

- **Estimated project cost was ~$7.3 Million**
  - $1.35 million of HB-1 funds
  - $5.40 million from the foundation
  - $50,000 from TVA
  - $250,000 from the Illinois Office of Coal Development
  - 250,000 from DOE-NETL
Project Management Structure

*Sandia Technologies, LLC
Public Outreach

Print Media Stories
– Eight project news releases
– At least 43 published news articles in eight newspapers

Public Presentations
– Thirteen presentations to local geological societies, governmental agencies, and academic conferences
– Eleven presentations at professional conferences
– Four presentations to local officials

• Television and Radio Stories
  – At least four stories on regional television stations
  – Three interviews on NPR radio stations

• Worldwide Web
  – KYCCS.org website
  – More than 40 websites and blog entries
Media Day at Marvin Blan #1
May 14, 2009
Recognition Awards to State Government and University of Kentucky Administrators
Effective storage of CO₂ in deep saline reservoirs requires its injection in a supercritical state to achieve a 250 times volume reduction.

- Supercritical CO₂ is a liquid with the properties of a gas
- A supercritical state achieves a 250 times volume reduction

The temperature and pressure conditions in Kentucky deep saline reservoirs requires a minimum depth of ~2350 ft to be able to store CO₂ in its supercritical state.

- Reservoir pressure > 1085 psi
- Reservoir temperature > 88° F

Reservoirs must have sufficient porosity and permeability for the injection of CO₂ as well as overlying sealing strata to ensure its long-term storage.
Deep Rock Units in Western Kentucky

Regional saline reservoirs:

- Mt. Simon Sandstone
- Knox Group dolomites
- St. Peter Sandstone
Deep Rock Units in Western Kentucky

Just as important in an injection project are the sealing units:

- Eau Claire Formation
- Maquoketa Shale
- Black River carbonates
- Devonian Shales
Although the shallowest drill depth to reach the targeted reservoirs was in east-central Hancock County, the completed CO₂ storage test well is among the deepest wells drilled in western Kentucky.
Project Goals

- Demonstrate and characterize the potential for the geologic storage of CO₂ in western Kentucky
  - Target reservoir is the Knox Dolomite
    - Found 3617 ft of Knox Dolomite, including Gunter Sandstone
    - Average porosity 6.7% calculated from logs
    - Successfully injected 18,454 BW brine and 323 T CO₂
  - Evaluate St Peter and Mount Simon Sandstones, if present
  - Test the reservoir potential of the Precambrian Middle Run Sandstone
  - Characterize the reservoir sealing properties of the New Albany Shale, Maquoketa Shale, Black River Group, and non-reservoir intervals in the Knox
Mount Simon Sandstone Reservoir

The Mt Simon Sandstone is used for waste injection in other states, but thins to the southeast in northern Kentucky. It was absent in the Marvin Blan #1 well.

Hickman et al., www.esri.com/mapmuseum/mapbook_gallery/volume19/environment3.html
The Knox Group is a widespread, thick unit of dominantly non-porous dolomite, but known to have intervals of well-developed porosity.

KGS
Marvin Blan #1
TD 8126 ft

Hickman et al., www.esri.com/mapmuseum/mapbook_gallery/volume19/environment3.html
<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
</tr>
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<tbody>
<tr>
<td>2008</td>
<td>Organization</td>
</tr>
<tr>
<td>2009</td>
<td>Site Characterization</td>
</tr>
<tr>
<td></td>
<td>EPA Permitting</td>
</tr>
<tr>
<td>2010</td>
<td>Drilling</td>
</tr>
<tr>
<td></td>
<td>Testing</td>
</tr>
<tr>
<td>2011</td>
<td>Evaluation and Reporting</td>
</tr>
<tr>
<td>2012</td>
<td>Abandonment</td>
</tr>
<tr>
<td></td>
<td>Monitoring (ongoing)</td>
</tr>
</tbody>
</table>
Prior to drilling, 24.1 mi of new, high-quality 2D seismic data (Lines A-D) was acquired to provide subsurface structural and stratigraphic control at the wellsite, and to supplement existing older, lower-quality data (Line 7).
Interpretation of Line B shows no faulting near the Marvin Blan #1
Interpretation of Line C shows no faulting at Knox depths and the Mount Simon pinchout north of the Knight Brothers #1 well.
Marvin Blan #1 Wellsite Vicinity

- **Wellsite (2.07 Ac)**
- **Leased Lands (196 Ac)**
- **Barns**
- **Historic Cemetery**
- **Landowner’s Residence**
- **KGS
  Marvin Blan #1
  TD 8126 ft**

**Scientific Line B**
Groundwater Monitoring

• **Groundwater monitoring well**
  – Required in injection permit
  – Drilled to 423 ft and abandoned, dry

• **Groundwater is being monitored in two domestic wells and two springs**
Correlation of Shallow Subsurface Geology
Domestic drinking-water supply
Flow: 1 GPM from Caseyville Formation
Sampled 5 times between 4-15-09 and 7-20-09
MB Well
(Abandoned Domestic Well)

Sampled 7 times between 12-3-08 and 7-20-09

Total depth: 64 ft
Water level: 15 fbls
MB Well

Alkalinity and TDS

Sample Date

pH

turbidity (NTU)
alkalinity (mg/L CaCO3)
TDS (mg/L)

0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00

0.00 5.00 10.00 15.00 20.00 25.00 30.00 35.00 40.00 45.00 50.00

Drilling Marvin Blan #1

• Drilling commenced on April 24, 2009
  – Casing cemented at 3660 ft, open hole below to TD
  – Drilled through the Knox Group using CaCO$_3$-based mud to mitigate potential reservoir damage

• Seven cores cut to test reservoir and seal properties
  – Reservoir seals
    • New Albany Shale (30 ft)
    • Maquoketa Shale (31 ft)
    • Black River Limestone (61 ft)
  – CO$_2$ storage reservoirs
    • Knox Group (three cores, 243 ft total)
    • Precambrian Middle Run Sandstone (30 ft)

• Reached TD at 8126 ft on June 14
Drilling Results

• St Peter Sandstone effectively absent: only six inches of sand was present at the Knox unconformity

• The Knox Group was found 85 ft structurally higher than expected and 380 ft thinner

• Eau Claire was considerably thinner than expected, only 187 ft thick including a 61 ft dolomite bed

• Top of the Precambrian Middle Run Sandstone was found 420 ft higher than expected
Strata penetrated in the Marvin Blan #1.
Maquoketa Shale Core

• Maquoketa Shale was cored 2800-2831 ft to test reservoir seal properties

• Analyses of seal properties
  – Core analysis
    • Porosity 0.4%
    • Permeability 1.63x10^{-5} md
  – Compressive strength 17,264 psi
  – XRD mineralogy
    • 39% clays, 15% carbonates, 36% silicates, balance other minerals
  – Thin section petrography
Black River Group

• Black River carbonates were cored 3335-3395 ft to test reservoir seal properties

• Analyses of seal properties
  – Core analysis
    • Porosity 0.5%
    • Permeability $9.0 \times 10^{-4}$ md
  – Compressive strength 7216-7910 psi
  – XRD mineralogy
    • 97% carbonate, 2% quartz, 1% clays
  – Thin section petrography
St. Peter Sandstone (6 inches)

Epikarst infilled with sandstone (3 inches)

Unconformity

Knox Dolomite
Structural contours on top of the Knox Group.
Generalized structure cross section of western Kentucky showing potential reservoir (+) and sealing (*) intervals. Primary reservoir targets are porous and permeable zones in the Beekmantown and Copper Ridge Dolomites of the Knox Group. Vertical x 22.
Stratigraphic correlation of the Knox Group and deeper strata.
Knox Dolomite Cores

- Knox Dolomite was cored in three intervals (total 243 ft) to test reservoir properties
  - “St Peter”-Beekmantown (123 ft)
  - Beekmantown-Gunter (101 ft)
  - Copper Ridge (19 ft)
  - Found porosity system to be a complex of preserved fabric, primary dolomite porosity, vugs, and fractures

- Extensive analysis program
  - Routine core analysis
  - Mechanical properties
  - XRD mineralogy
  - CO$_2$ core flood
  - Thin section petrography
  - Threshold entry pressure
CMI log section and core showing vuggy porosity in the Beekmantown Dolomite
Knox Reservoir Properties

Average Porosity 6.7%

NNW Fracture Trend
Potential Reservoir Volume in the Knox

- **Base**: all data
- **Cutoff cases**:
  - 1. caliper > 10½ in.
  - 2. porosity > 20%
  - 3. porosity < 5%
  - 4. porosity < 6%
  - 5. porosity < 7%
  - 6. porosity < 8%
  - 7. porosity < 9%
  - 8. porosity < 10%
Middle Run Sandstone Core

- Precambrian Middle Run Sandstone was cored 8000-8030 ft to evaluate its potential as a carbon storage reservoir
  - DOE-NETL grant for coring and analysis
- Analysis Program
  - Routine core analysis
  - Fracture orientation
  - XRD mineralogy
  - Thin section petrography
  - Provenance
  - Zircon age dating
  - Mechanical properties
Drilling Challenges

• Drilling rig and wellhead mechanical failures
• Lower than expected penetration rates
• Borehole deviation below 3000 ft
  – Angle built to 5.75°
  – Used Schlumberger Vertical Seeking Power V System to bring borehole back to vertical
• Lost circulation thief zone at 5581 ft
  – Successfully controlled with LCM
• Drilled ~250 ft deeper than necessary to achieve objectives due to missed formation tops
  – Added two days to drilling
Marvin Blan #1
Depth vs. Days

Drilling took 62 days, 13 days longer than planned, despite a shallower than planned TD.
Well Completion

• Extensive electric log program at TD
  – Triple-combo array resistivity-porosity-gamma ray suite
  – Dipole sonic rock mechanical properties
  – Formation micro-imager
  – Zero-offset vertical seismic profile (VSP)
Injection Testing

- Wellbore was treated prior to injection
  * Well flowed water at a rate of ~2 gpm at 6 psi when reopened
  * Drilling mud circulated out with Bio-31 brine
  * Knox acidized with 19,700 gallons of 15% HCl, then 13,000 gallons 10.5% HCl, and displaced with 30 BW
Injection Testing

- Testing budget ~$2 million
- Testing began on July 25 and was completed on August 22
  - Two formation water samples were collected
  - Initial injection of brine was into 285 ft intervals isolated by inflatable straddle packers on tubing
    - Seven tests attempted
    - Three packers failed during tests
    - Results mixed due to leakage and communication around the packers through the formation porosity system
  - Program revised to full-wellbore injection of brine below a single packer
**Injection Testing**

- **Three tests with straddle packers**
  - basal Copper Ridge: 218.8 BW, broke down at 0.9 psi/ft gradient and took water on vacuum
  - upper Copper Ridge: two tests, total 5192.7 BW, lost seal due to communication through formation porosity system around packers

- **Two tests with single packer**
  - Copper Ridge below 6089 ft: 2190 BW brine, 1212.1 BW with borax tracer
  - Full wellbore below 3620 ft: 7075.7 BW with borax tracer
  - Injection rates to 14 BPM at 285-500 psi wellhead pressure

- **Found 70% of water was injected above the Copper Ridge**
Temperature Logging

KGS Marvin Blan #1 CO2 Injection Well
8-5/8” Casing Shoe at 3660 ft TVDRKB with 7-7/8” Open Hole Below

- 7/25/2009 Temperature Well Static for 18 Days After Reaching TD
- 8/5/2009 Temperature After Acid Stimulation/Before 10 BPM Injection
- 8/5/2009 Temperature While Injecting Brine at 10 BPM
- 8/5/2009 Temperature 2 hrs After End of 10 BPM Brine Injection
- 8/5/2009 Temperature 6 hrs After End of 10 BPM Brine Injection
- 8/5/2009 Temperature 12 hrs After End of 10 BPM Brine Injection
- 8/6/2009 Temperature 24 hrs After End of 10 BPM Brine Injection

- Deepest Injection: ~7100 ft
- Largest Volume of Injection Shows Largest Sustained Cooling ~3600-3900 ft
- Significant Injection Shows Sustained Cooling to Approximately 5250 ft
- Lower Volumes of Injection Show Less Sustained Cooling Below ~5250 ft

David Pena
ConocoPhillips
Water Injection Test #4

Test #4 successfully tested entire open hole interval with single packer set at 3620 ft. The estimated average Kh for the Commingled Zone is ~ 28,900 md-ft.

Temperature decay log Results

<table>
<thead>
<tr>
<th>Inflow zones 1</th>
<th>Inflow zones 2</th>
<th>Inflow zones 3</th>
<th>Inflow zones 4</th>
<th>Inflow zones 5</th>
<th>Inflow zones 6</th>
<th>Inflow zones 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>From , ft</td>
<td>3630</td>
<td>4820</td>
<td>5440</td>
<td>5620</td>
<td>5700</td>
<td>7010</td>
</tr>
<tr>
<td>To , ft</td>
<td>3878</td>
<td>5220</td>
<td>5580</td>
<td>5660</td>
<td>5720</td>
<td>7040</td>
</tr>
</tbody>
</table>

David Pena
ConocoPhillips
Regional correlation of Knox injection zones
CO₂ Injection

- Injected a total of 323 Tons of CO₂ (1765 bbl or 5646 mcfg) below a packer set in casing at 3603 ft
- Limited to 4.1 BPM rate due to pump limitations
- Wellhead pressure 936 psi, bottomhole pressure 1754 psi
- Post-injection flushed with 4568 BW brine
- Long-term downhole pressure gauge in place to monitor pressure fall-off pending re-entry for additional tests
**CO₂ Injection test**

A constant CO₂ injection rate of 4.0 bpm, total injection volume of 1765 bbl of CO₂. The final injection BHP and BHT at 3580 ft were 1753.8 psia and 103.2 °F. At the end of IFOT#6, a temperature logging survey was performed across the open hole interval and determined final injection point of CO₂ to be at 5230ft in the Gunter Sandstone.

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**Dynamic and Static Pressure Gradient.**

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Pressure Gradient (psi/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>500</td>
<td>0.05</td>
</tr>
<tr>
<td>1000</td>
<td>0.1</td>
</tr>
<tr>
<td>1500</td>
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<td>3000</td>
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</tr>
<tr>
<td>3500</td>
<td>0.35</td>
</tr>
<tr>
<td>4000</td>
<td>0</td>
</tr>
</tbody>
</table>

**Interval predominantly injected with CO2**

David Pena
ConocoPhillips
Additional Work

• Testing planned for 2010, funded by DOE research award of $1.6 million
  – Additional brine, possibly additional CO₂ injection
  – 3D VSP to image injection plume
  – Knox reservoir evaluation

• Plug and abandon the Marvin Blan #1 in compliance with State and EPA regulations

• RemEDIATE DRILLSITE

• Groundwater and soil gas monitoring through 2012
Acknowledgements

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