Western Kentucky CO$_2$ Storage Test

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• The project proceeded in two phases:
  – Phase 1 (2009) got the well drilled and the first round of testing completed. Total cost ~$7.3 million.
    • Acquired 24.1 miles of 2-D reflection seismic data and VSP
    • Drilled to 8,126 ft, cemented casing at 441 ft and 3,060 ft, and cut 395 ft of cores
    • Injected 18,454 barrels of brine and 323 tons of CO₂ (1,765 barrels) in the open wellbore below 3,060 ft
  – Phase 2 (2010) completed a second round of testing and abandoned the injection zone. Total cost ~$1.0 million.
    • 3D seismic survey and VSP
    • Plugged the well at 5,268 – 5,545 ft, abandoning the lower 2858 ft of the well, and constructed a 230-ft test interval at 5,038 – 5,268 ft
    • Injected 4,265 barrels of brine and 367 tons of CO₂ (2,000 barrels)
    • Plugged and abandoned the test interval at 5,037 – 5,275 ft
    • Plugged the well at 3,942 – 3,477 ft and abandoned the Knox Dolomite interval, and plugged the casing at 800 ft with a cast iron bridge plug
Western Kentucky Project Timeline

2008
- Organization

2009
- Site Characterization

2010
- EPA Permitting
- Drilling
- Testing

2011
- Evaluation and Reporting

2012
- Abandonment

Monitoring
Prior to drilling, 24.1 mi of new, high-quality 2D seismic data (Lines A-D) were 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
Phase 1: Drilling and Testing

- Drilling commenced on April 24, 2009, and was finished on June 14 after 63 days of drilling.
  - Casing cemented at 441 ft and 3,660 ft
  - The hole was left open hole casing to the bottom of the well at 8,126 ft for injection testing
- Seven cores, totaling 395 ft, were cut to test the reservoir and seal properties
  - Reservoir seals
    - New Albany Shale (30 ft)
    - Maquoketa Shale (31 ft)
    - Black River Limestone (61 ft)
  - CO₂ storage reservoirs
    - Knox Group (three cores, 243 ft total)
    - Precambrian Middle Run Sandstone (30 ft)
Marvin Blan #1
Depth vs. Days

Drilling took 62 days, 13 days longer than planned, despite a shallower than planned TD.
Strata penetrated in the Marvin Blan #1
Structural contours on top of the Knox Group.
Stratigraphic correlation of the Knox Group and deeper strata.
Maquoketa Shale Core

- Maquoketa Shale was cored 2800-2831 ft to test its reservoir seal properties
- Analyses of seal properties
  - Threshold entry pressure
  - XRD mineralogy
  - Thin section petrography
  - Mechanical properties
Knox Group Cores

- Knox Group 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
  - CO₂ core flood
  - Thin section petrography
  - Threshold entry pressure
“St. Peter Sandstone” (6 inches)

Epikarst infilled with sandstone (3 inches)

Unconformity

Knox Dolomite
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
  – Mechanical properties

• Conclusion: Tight
CMI log section and corresponding core showing vuggy porosity in the Beekmantown Dolomite. Bedding planes annotated on CMI log with green lines.
Fracturing in the Knox: fracture trends from CMI log interpretation

Fractures, both open and mineralized, in the basal Beekmantown Dolomite

Chert-filled vugs

Sandstone

NNW Fracture Trend
Phase 1 Injection Project

Porosity decreases ~2% per 1000 ft of burial depth.
In general, more porous rocks have higher permeability.
Potential Reservoir Volume in the Knox

A

<table>
<thead>
<tr>
<th>Cutoff (Percent Porosity)</th>
<th>Pore Volume (Porosity-Feet)</th>
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<tbody>
<tr>
<td>Base</td>
<td>216 ~17,000 Tons/Ac*</td>
</tr>
<tr>
<td>5</td>
<td>172 ~13,500 Tons/Ac*</td>
</tr>
<tr>
<td>6</td>
<td>138</td>
</tr>
<tr>
<td>7</td>
<td>113 ~9,000 Tons/Ac*</td>
</tr>
<tr>
<td>8</td>
<td>86</td>
</tr>
<tr>
<td>9</td>
<td>61</td>
</tr>
<tr>
<td>10</td>
<td>44</td>
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- Beekmantown
- Gunter
- Copper Ridge

*Assumes a 5% CO₂ storage efficiency

B

Cumulative Pore Volume (Porosity-Feet) **

- Beekmantown (φₜ = 73)
- Gunter (φₜ = 9)
- Copper Ridge (φₜ = 90)

** Assumes a 5% porosity cutoff

~6,300 Tons/Ac = 157 Ac/MT
Injection Testing
Injection Testing

- Testing began on July 25, 2009, 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. This test design had limited success.
    - Seven tests attempted
    - Results were mixed due to leaks and communication around the packers through the formation porosity system
  - Program revised to full-wellbore injection of brine and CO₂ below a single packer in casing
Phase 1 CO₂ Injection

- Injected a total of 323 tons of CO₂ (1,765 barrels) below a packer set in casing at 3,603 ft
- After injection of CO₂ the well bore was flushed with 4,568 barrels of brine
- Long-term downhole pressure gauge was left in place to monitor pressure fall-off pending re-entry for Phase 2 testing
Wellsite at the completion of Phase 1
Long-term Borehole Pressure
August 21, 2009-September 1, 2010

Original Formation Temperature 95.7º F
Phase 2: Injection Testing

- Phase 2 testing took place on August 30 – September 30, 2010.
  - Cut 20 rotary sidewall cores through the injection interval to determine reservoir rock properties
  - Plugged the well at 5,268 – 5,545 ft, abandoning the lower 2,858 ft of the well
  - Constructed a 230-ft test interval at 5,038 – 5,268 ft by cementing a 5½-inch liner at 4,820-5033 ft

- Injected 4,265 barrels of brine and 367 tons of CO₂ (2,000 barrels)
  - Recorded pressure during injection and falloff to calculate reservoir permeability and volume
  - Recorded temperature logs before and after injection to determine which intervals were receiving the injected CO₂

- Recorded a 4-D vertical seismic program at more than 850 points around the well. Data was recorded both before and after CO₂ injection in an attempt to image the CO₂ plume.

- Abandoned the Knox Dolomite injection zone with cement plugs at 5,037 – 5,275 ft and 3,942 – 3,477 ft, exceeding EPA abandonment requirements (a single plug at 3,760 – 3,560 ft).
4-D VSP seismic data acquisition points
Seismic Survey Vibrator Truck
Workover Rig
Gunter dolomite at 5103 ft
Gunter sandstone at 5109 ft
Photomicrograph of Gunter sandstone.
Photo by ConocoPhillips.
Photomicrograph of Gunter dolomite interbed. Photo by ConocoPhillips.
Phase 2 Injection Project
What we learned:

• The Knox Dolomite could serve as an effective CO$_2$ storage reservoir.
• There are excellent reservoir sealing strata in the Black River Limestone and overlying Maquoketa Shale, above the Knox Dolomite, that would prevent any CO$_2$ migration from the Knox Dolomite to the surface.
• Most of the West Kentucky Coal Field has Knox Dolomite, comparable to that in the KGS test well, that may be suitable for CO$_2$ storage.
• Additional evaluation of the Knox Dolomite will be necessary to fully determine its potential for CO$_2$ storage.
The potential area for CO$_2$ storage in the Knox Dolomite in western Kentucky is about 6,400 mi$^2$. More research is needed to determine the actual extent.

Knox Dolomite is too deep for economic CO$_2$ storage

Reservoir sealing rocks are too shallow to ensure CO$_2$ storage
Where did the CO\textsubscript{2} go?

- The Knox Dolomite, under just the 1 acre well drill site, holds about 1.7 million barrels (71.4 million gallons) of brine that is about 200 times saltier than what is allowed in drinking water by Federal regulations.

- We injected a total of 3,765 barrels of CO\textsubscript{2} (690 tons). This is about 0.25\% of the volume of water in the Knox Dolomite under the drill site.
  - Most of the CO\textsubscript{2} dissolved in the formation water and dissipated.
  - A small amount of CO\textsubscript{2} reacted with the formation water and rock to make new minerals.

- Pepsi uses 0.35\% CO\textsubscript{2} to carbonate their sodas, and a can of beer has about 0.5\% CO\textsubscript{2} carbonation in it.
About 1.7 million barrels of brine are in the Knox Dolomite under the 1-acre drill site:

3,785 barrels of CO$_2$ were injected in 2009 – 2010 *

*About 0.25% CO$_2$ dissolved in the brine. A can of beer has ~0.5% CO$_2$ carbonation in it.
There are about 328 million barrels of brine in the Knox Dolomite under the Blan Farm:

3,785 barrels of CO₂ injected
In the end, what did we get for $8 million?

- 2D and 3D seismic surveys, and two VSPs.
- Well data from one of the deepest wells in western Kentucky:
  - Electric logs, including a formation imaging log
  - Cores from the New Albany, Maquoketa, Black River, and Knox (Beekmantown, Gunter, and Copper Ridge), with routine analysis, special core analysis, and petrography
  - The only Middle Run core in western Kentucky, with a similar core analysis program
  - Extensive sidewall cores, with routine analysis, from the Gunter
  - Water samples and analysis from the Gunter and Beekmantown
  - Injection test pressure data for the Knox, both brine and CO₂
  - Long-term pressure and temperature data from the Knox
- Two successful demonstrations of CO₂ injection in Knox Group reservoirs.
- An estimate of the carbon storage potential of the Knox, and sealing capacity of overlying strata in western Kentucky.
- Experience in operating this kind of project.
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