Lessons Learned from the Illinois Basin – Decatur Project:
Integration of Deep Saline CO₂ Storage into the Value Change

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*Mark of Schlumberger
The Industrial Carbon Capture and Storage (ICCS) project is administered by the U.S. Department of Energy's Office of Fossil Energy and managed by the National Energy Technology Laboratory (award number DE-FE-0001547) and by a cost share agreement with the Archer Daniels Midland Company, University of Illinois, Schlumberger Carbon Services, and Richland Community College.

This ICCS project received DOE funding from the American Recovery and Reinvestment Act of 2009 ($141.4 million).
ADM - Decatur CCS Projects

Illinois Basin - Decatur Project
- Large scale geologic test to inject 1.0 million mt of CO$_2$ over a three year period (1,000 MT/day).

Illinois Industrial CCS Project
- Target & demonstrate advanced CCS technologies at industrial scale facilities.
- Inject and store 1.0 million mt CO$_2$ per year (3,000 tons/day).
- Study the interaction of two separate plumes.
Illinois Industrial Carbon Capture & Storage (ICCS) Project

IBDP Wells (Series 1) and ICCS wells (Series 2) at ADM in Decatur, Illinois

Class VI permit issued Sept 24, 2014
A collaboration of the Midwest Geological Sequestration Consortium, the Archer Daniels Midland Company (ADM), Schlumberger Carbon Services, and other subcontractors to inject 1 million metric tons of anthropogenic carbon dioxide at a depth of 7,000 +/- ft (2,000 +/- m) to test geological carbon sequestration in a saline reservoir at a site in Decatur, IL.

- Prove injectivity and capacity
- Demonstrate security of injection zone
- Contribution to best practices
Illinois Basin –
Decatur Project Site
(on ADM industrial site)

A Dehydration/ compression facility location
B Pipeline route (1.9 km)
C Injection well site
D Verification/ monitoring well site
E Geophone well
Operational Injection: 17 November 2011

• IBDP fully operational 24/7
• IBDP is the first 1 million tonne carbon capture and storage project from a biofuel facility in the US
• Injection completed November 2014
• Intensive post-injection monitoring under MGSC through 2017

Total Injection (26 November 2014): 999,215 tonnes
Injection Well Completion 2009

Packer @ 6,365 ft (1,929 m)

10% Porosity Cutoff

Perforations: 6,985 - 7,015; 7,025 - 7,050
55 ft (16.7 m) open interval

Base of Mount Simon

Pre-Mt. Simon

Granite

7,000 ft

6,500 ft

2,000 m

TD=7236
IBDP Environmental Monitoring Framework

Near Surface
- Atmos.
  - Eddy covariance
  - Meteorological conditions
  - Ambient CO₂
  - Tunable diode laser for CO₂
- Soil and vadose zone
  - CIR aerial imagery
  - InSAR and GPS
  - Soil gases
  - Soil CO₂ flux
- Shallow groundwater
  - Geophysical surveys
  - Geochemical sampling
  - P/T monitoring

Deep Subsurface
- Above seal
  - Geophysical surveys
  - Geochemical sampling
  - P/T monitoring
- Injection zone
  - Geophysical surveys
  - Geochemical sampling
  - P/T monitoring
At 500 m in total thickness at Decatur, the Mount Simon Sandstone has been shown to be a substantial storage resource meeting criteria of injectability and storage capacity.

Storage capacity of 11 ($P_{90}$) to 150 ($P_{10}$) billion metric tons have been assessed for the entire Illinois Basin.

Intervals of tens of meters of exceptional reservoir quality in the Lower Mount Simon show a combination of primary and secondary porosity in a sand-rich fluvial system.

Original depositional units are well-connected as flow units based on pressure response in the injection and verification wells.

**Outcome:** We Better Understand Depositional and Diagenetic History of a Major Storage Resource
Mount Simon Depositional Analogue: Brahmaputra River System
3D Seismic Defines Reservoir

Eroded Precambrian surface

from Leetaru, ISGS
Outcome: We Better Understand Reservoir Fluid Distribution and Impacts of Heterogeneity on Pressure

- Pulsed neutron logs (Schlumberger RST* Log) help estimate the depth, thickness and saturation of CO₂ around injection and verification wells and arrival time at verification well
- CO₂ reached verification well in March 2012 in Zone 3 and July 2012 in Zone 2, much sooner than expected
- Revised reservoir simulation, including permeability distribution, was calibrated to CO₂ arrival at VW1
- Pressure distribution in lower Mt. Simon shows rapid in-zone response to injection variations
Repeat Pulsed Neutron* Logging has Defined CO₂ Distribution at the Injection and Observation Wells

Pre-injection

Five post-injection logging runs: March, July, and November 2012; July 2013; July 2014

*Schlumberger Reservoir Saturation Tool (RST)
Westbay* Pressure Monitoring Output – 28 February 2015

Injection zone Increase: 144 psi (9.9 bar)

Zone 5 increase: 21 psi (1.5 bar)

263 ft (80.2 m) above
Mudstone Baffle Between Injection Zones

6,863-6,863.25
Porosity: 1.5%
$K_v$: <0.01 mD
$K_h$: 4.13 mD in siltstone laminae
Three 3D Vertical Seismic Profiles Acquired

<table>
<thead>
<tr>
<th>3D VSP Survey Name</th>
<th>Survey Date</th>
<th>Ground Conditions</th>
<th>Vibrator Sweep</th>
<th>Repeated Shots</th>
<th>Volume of CO₂ Injected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline 1 (B1)</td>
<td>January 2010</td>
<td>Wet</td>
<td>2 – 100 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline 2 (B2)</td>
<td>April 2011</td>
<td>Dry</td>
<td>8 – 120 Hz</td>
<td>467</td>
<td>0</td>
</tr>
<tr>
<td>Monitor 1 (M1)</td>
<td>February 2012</td>
<td>Frozen dry</td>
<td>8 – 120 Hz</td>
<td>385</td>
<td>~74,000 tonnes</td>
</tr>
<tr>
<td>Monitor 2 (M2)</td>
<td>April 2013</td>
<td>Damp</td>
<td>8 – 120 Hz</td>
<td></td>
<td>~433,000 tonnes</td>
</tr>
<tr>
<td>Monitor 3 (M3)</td>
<td>February 2014</td>
<td>Frozen</td>
<td>8 – 120 Hz</td>
<td>384</td>
<td>~730,000 tonnes</td>
</tr>
</tbody>
</table>
Outcome: Microseismic Activity Has Supported Insight Into Reservoir Pressure Distribution

- Microseismic activity started only after injection began at site
- Clusters north of injection well first to occur and lie over Precambrian topography that may have localized planes of weakness due to compaction
- Cluster orientation consistent with northeast principal stress direction
- No pre-existing fault planes seen in 3D seismic
- Timing of events ties to pressure propagation
- Most events are in the pre-Mt. Simon and Precambrian basement; none are above the lower Mt. Simon
Microseismic Events Began in January 2012

- June-August 2013: average 89 located events/month
- Mean moment magnitude = -0.98
- Max. event for three months: +0.25
- Recent max event = +1.02 in September 2013

December 2014:
- Peak frequency at -1.2
- Peak MM at -0.05

from Schlumberger Carbon Services
Microseismic Cluster Activity: Cluster Locations in Relation to Surface Features

from Schlumberger Carbon Services
Microseismic Cluster Activity: Relationship to Basement Structure

Microseismic locations are in the Precambrian.
Key Operational Results – IBDP at Completion of Injection

- Mount Simon Sandstone reservoir accepted CO$_2$ more easily than expected resulting in quicker detection at verification well.
- Upward plume growth limited by reservoir permeability stratification, as modeled, and confirmed by pressure observations.
- Resulting plume believed thinner than expected and was not detected with a 3D vertical seismic profile until April 2013.
- Mt. Simon 200,000 ppm brine is more corrosive than expected.
- With 999,215 tonnes injected, CO$_2$ remains in lowermost Mt. Simon; internal reservoir heterogeneity affecting CO$_2$ distribution.
- No CO$_2$ leakage or adverse impacts detected to date.
- Second project (ICCS) will add opportunity to monitor two plumes.
CCS1 Transition from IEPA Class I to USEPA Class VI

- Injection period covered under IEPA Class I
- Post injection site care covered under USEPA Class VI
  - CCS1 becomes monitoring well for CCS2
  - Direct ground water quality monitoring
  - Indirect ground water quality monitoring
  - Mechanical integrity testing (MIT)
  - Plume monitoring
  - Seismic monitoring
  - Pressure-front monitoring
- Interim phase between end of IBDP/CCS1 injection and start of CCS2 injection
Direct Ground Water Monitoring Above Eau Claire

- Formations:
  - Quaternary and/or Pennsylvanian
  - St. Peter
  - Ironton-Galesville

- Activity:
  - Fluid sampling
  - Distributed temperature sensing (DTS)
  - Pressure/temperature monitoring (SP and IG)

- Wells: Shallow groundwater, CCS1, CCS2, GM2, VW1, and VW2

- Frequency (changes over time):
  - Interim period
  - CCS2 injection phase
  - CCS2 post-injection phase
At end of PISC period:

• Operator submits a demonstration of non-endangerment of USDW to UIC Program Director (40 CFR 146.93(b)(2) or (3))
• Based on evaluation of site monitoring data in conjunction with computational model
• Uses site-specific conditions to confirm and demonstrate non-endangerment
• Includes:
  – Summary of existing monitoring data
  – Comparison of monitoring data and model predictions and model documentation
  – Evaluation of CO₂ plume
  – Evaluation of mobilized fluids
  – Evaluation of reservoir pressure
  – Evaluation of potential conduits for fluid movement
  – Evaluation of passive seismic data
### Plume Monitoring

#### Direct Plume Monitoring

<table>
<thead>
<tr>
<th>Target Formation</th>
<th>Monitoring Activity</th>
<th>Monitoring Location</th>
<th>Frequency: Interim Period</th>
<th>Frequency: CCS2 Injection Phase</th>
<th>Frequency: CCS2 Post-Injection Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mt. Simon</td>
<td>Fluid Sampling</td>
<td>VW1</td>
<td>Once</td>
<td>Year 1-3: Annual</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Year 4-5: None</td>
<td></td>
</tr>
<tr>
<td>Mt. Simon</td>
<td>Fluid Sampling</td>
<td>VW2</td>
<td>None</td>
<td>Annual</td>
<td>Annual</td>
</tr>
</tbody>
</table>

#### Indirect Plume Monitoring

<table>
<thead>
<tr>
<th>Target Formation</th>
<th>Monitoring Activity</th>
<th>Monitoring Location</th>
<th>Frequency: Interim Period</th>
<th>Frequency: CCS2 Injection Phase</th>
<th>Frequency: CCS2 Post-Injection Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mt. Simon</td>
<td>Pulse Neutron logging/ RST</td>
<td>VW1 VW2</td>
<td>Once</td>
<td>Year 2, Year 4</td>
<td>Year 1, 3, 5, 7, 10</td>
</tr>
<tr>
<td>Mt. Simon</td>
<td>Pulse Neutron logging/ RST</td>
<td>CCS1 CCS2</td>
<td>Once</td>
<td>Year 2, Year 4</td>
<td>Year 1, 3, 5, 7, 10</td>
</tr>
</tbody>
</table>
# Seismic Monitoring

<table>
<thead>
<tr>
<th>Timing</th>
<th>Survey</th>
<th>Extent/Coverage/Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CCS1</strong></td>
<td><strong>Injection Phase</strong></td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Baseline 3D Surface Seismic Survey</td>
<td>Extent = 2,600 Acres</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fold Coverage = 2,000 Acres</td>
</tr>
<tr>
<td>2011</td>
<td>Baseline 3D Surface Seismic Survey</td>
<td>Extent = 2,600 Acres</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fold Coverage = 2,000 Acres</td>
</tr>
<tr>
<td>2011</td>
<td>Baseline GM1 3D VSP</td>
<td>Resolution = 30 Acres</td>
</tr>
<tr>
<td>2012</td>
<td>GM1 3D VSP</td>
<td>Resolution = 30 Acres</td>
</tr>
<tr>
<td>2013</td>
<td>GM1 3D VSP</td>
<td>Resolution = 30 Acres</td>
</tr>
<tr>
<td>2014</td>
<td>GM1 3D VSP</td>
<td>Resolution = 30 Acres</td>
</tr>
<tr>
<td><strong>CCS1</strong></td>
<td><strong>Post-Injection Phase</strong></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>Expanded 3D Surface Seismic Survey</td>
<td>Extent = 3,000 Acres</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fold Coverage = 2,200 Acres</td>
</tr>
<tr>
<td>2020</td>
<td>Time Lapse Surface Seismic Survey</td>
<td>Extent = 2,000 Acres</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fold Coverage = 600 Acres</td>
</tr>
<tr>
<td>2030</td>
<td>Time Lapse Surface Seismic Survey</td>
<td>Extent = 2,000 Acres</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fold Coverage = 600 Acres</td>
</tr>
</tbody>
</table>
# Pressure-Front Monitoring

<table>
<thead>
<tr>
<th>Target Formation</th>
<th>Monitoring Activity</th>
<th>Monitoring Location</th>
<th>Frequency: Interim Period</th>
<th>Frequency: CCS2 Injection Phase</th>
<th>Frequency: CCS2 Post-Injection Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mt. Simon</td>
<td>Pressure/temperature monitoring</td>
<td>VW1</td>
<td>Continuous</td>
<td>Y1-3: Continuous Y 4-5: None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VW2</td>
<td>None</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CCS1</td>
<td>Continuous</td>
<td>Continuous</td>
<td>Y1-3: Continuous Y 4-10: Annual</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CCS2</td>
<td>None</td>
<td>Continuous</td>
<td>Y1-3: Continuous Y 4-10: Annual</td>
</tr>
<tr>
<td>Mt. Simon</td>
<td>DTS</td>
<td>CCS1</td>
<td>Continuous</td>
<td>Continuous</td>
<td>Y1: Continuous Y 2-10: None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CCS2</td>
<td>None</td>
<td>Continuous</td>
<td>Y1: Continuous Y 2-10: Annual</td>
</tr>
<tr>
<td>Multiple</td>
<td>Passive seismic (detect M 1.0 events)</td>
<td>Borehole &amp; surface seismic stations within AoR</td>
<td>None</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
</tbody>
</table>