“Carbon Storage and Utilization in Kansas – Are We Ready?”

based on --

a) Characterization of CO₂ storage capacity southern Kansas evaluation of CO₂ sources and sinks (DE-FE0002056)

b) Small scale field test at Wellington Field, Sumner County (DE-FE0006821)

c) Arbuckle modeling with horizontal drilling (DE-FE0004566)

W. Lynn Watney & Jason Rush, Joint PIs
Jennifer Raney, Asst. Project Manager
Kansas Geological Survey
Lawrence, KS 66047

Oil and Gas Seminar
August 7, 2014
1. Framing the opportunity for CO$_2$ utilization in the oil patch
2. Highlight current and potential CO$_2$ supplies
3. Opportunities, risks and uncertainties for CO$_2$-EOR
4. Brief summary of selected case studies that highlights approaches to next-generation CO$_2$-EOR applicable to Kansas oil reservoirs
1. Framing the opportunity for CO$_2$ utilization in the oil patch
Implementing CO$_2$ Utilization and Storage (CCUS) in Kansas

- Carbon storage and utilization offers significant potential to revitalize Kansas’ oil fields.
  - A 2010 report for the Midwest Governor’s Association indicated more than 750 million barrels of oil are potentially recoverable in Kansas with enhanced recovery methods using carbon dioxide.
  - Over 50 million metric tons of CO$_2$ are injected annually into oil reservoirs in the US, mainly in West Texas, with roughly 400,000 bbls of incremental oil recovered per day using the available supplies of naturally occurring CO$_2$.

- Why now?
  - Sustained oil prices
  - Improved reservoir characterization with the widespread use and availability of cost-effective 3D seismic
  - Improved engineering models and recovery technologies
  - All combined will likely overcome the decades of inertia that have faced the implementation of CO$_2$-EOR in Kansas

Are you ready to be part of this?
Utilization of CO$_2$ in Kansas

– Establish demand for CO$_2$ in the oil field
– Future use – develop scenarios for implementation and infrastructure
– Technical timeframe
  • Oil field and operator readiness
  • Field modeling and implementation plan to ensure success
  • Scenarios for aggregating CO$_2$ supply and distribution to the field
  • Economic incentives?
Kansas has considerable remaining technically recoverable oil reserves using CO₂.
• Kansas holds more than **750 million barrels** of technical CO₂-EOR potential.
• Kansas has by far the largest oil resources in the MGA region.
• Economic results based on Hall Gurney field suggest an after-tax project IRR of about 20%.
• Kansas ...would have access to the significant volumes of ethanol-based CO₂ in Nebraska, which produces approximately 6 million metric tons per annum.

**750 million barrels of oil would utilize --**
• ~240-370 million metric tons of CO₂ (**4.62-7.12 BCF CO₂)**.
• ~30 years of a 500 MW coal-burning plant

<table>
<thead>
<tr>
<th>Basin</th>
<th>EOR potential (Mil bbl)</th>
<th>Net CO₂ Demand (MMT)</th>
<th>Direct Jobs Created</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois/Indiana</td>
<td>500</td>
<td>160 – 250</td>
<td>1,550 – 3,100</td>
</tr>
<tr>
<td>Ohio</td>
<td>500</td>
<td>190 – 300</td>
<td>1,550 – 3,100</td>
</tr>
<tr>
<td>Michigan</td>
<td>250</td>
<td>80 – 130</td>
<td>800 – 1,800</td>
</tr>
<tr>
<td>Kansas</td>
<td>750</td>
<td>240 – 370</td>
<td>2,300 – 4,600</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>2,000</strong></td>
<td><strong>670 – 1,050</strong></td>
<td><strong>6,200 – 12,400</strong></td>
</tr>
</tbody>
</table>

19.25 MCF/tonne | $2.00 cost per MCF | $38.50 cost per tonne
2. Highlight current and potential CO₂ supplies

Midwest is rich in ethanol based CO₂...

...hence can deliver portion of CO₂ at/below “market” prices

Oklahoma’s CO₂ Pipelines

Over 400 miles of CO₂ pipelines already exist in Oklahoma.
- A new 50+ mile, 50 MMcf/d pipeline is under construction linking the Coffeyville Fertilizer Plant with the Burbank oil field.
- Western Oklahoma CO₂-EOR projects are linked to natural as well as anthropogenic CO₂ supplies.
Major oil and gas reservoirs as candidates for CO$_2$-EOR and CO$_2$ sources in Kansas and a pipeline scenario

J. Raney, KGS

Wellington Field

### Cumulative Oil Produced (as of 2013)

<table>
<thead>
<tr>
<th>Arbuscule Fields</th>
<th>Lansing-KC Fields</th>
<th>Mississippian Fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1,000,000 bbls</td>
<td>0 - 1,000,000 bbls</td>
<td>0 - 1,000,000 bbls</td>
</tr>
<tr>
<td>1,000,000 - 10,000,000</td>
<td>1,000,000 - 10,000,000</td>
<td>1,000,000 - 10,000,000</td>
</tr>
<tr>
<td>10,000,000 - 100,000,000</td>
<td>10,000,000 - 100,000,000</td>
<td>10,000,000 - 100,000,000</td>
</tr>
</tbody>
</table>

Source: USGS, Kansas Geological Survey, DASC
Linde Group – A CO₂ supplier for the Wellington Field pilot CO₂ injection

Hammerfest LNG Project Norway – CO₂-Reinjection

World’s first industrial project to deliver CO₂ separated onshore back offshore and injected into a reservoir

- Europe’s first export facility for liquified natural gas (LNG)
- Terminal and process plant on Melkøya island outside Hammerfest in northern Norway
- Annual LNG export: 5.67 billion sm³
- CO₂ Content: 5.0% to 8.0 %
- CO₂ captured in onshore plant
- Conveyed back with subsea pipeline
- Storage underground
- Emission reduction of more than 50 %
- Norwegian CO₂-Tax: 50 Euro/ton
Upstream Oil and Gas

- **Enhanced Oil Recovery**
  - Over 30 years experience with Gas Displacement Recovery (GDR)
    - Nitrogen
    - Carbon Dioxide
  - More than 25 projects

- **Well Stimulation Services**
  - Fracing
  - Wellbore damage cleanup

- **CO₂/N₂ EOR Services**
  - Pilots
  - Injection test and huff-n-puffs

- **CO₂ Capture & Purification**
Rubart Station engine-generator sets undergo extensive testing

From an outside view of Rubart Station, it appears that the majority of the work is complete at the new electric generating facility. However, inside major work and fine tuning continues on state-of-the-art technology.

All 12 of the 120 MW Caterpillar engine-generator sets have undergone early commissioning tests, such as firing the engines with natural gas but at no load, verifying proper fuel management and engine speed controls, measuring temperatures on numerous key engine components, and synchronizing the generators to the grid.

Each engine-generator set must then log at least several hours of operation at full load in order to produce enough engine heat to “run in” the engine prior to loading the catalyst into each engine’s selective catalytic reactor module. Once the catalyst is loaded, each engine-generator set is operated at various load points to start and tune the urea injection system.

Simultaneous with all of these tests are countless other tests and checks for details, such as checking the adequacy of operating procedures, ensuring effectiveness of communications systems, verifying instrumentation accuracy, and validating control and alarm systems.

Once the project team accomplishes all of these tests and more, the facility will be taken through a formal battery of tests to demonstrate the ability to meet contract requirements, such as output, fuel efficiency, emissions performance, and reliability.

Even after verifying all these complicated tests on the individual units, staff will conduct more tests to verify that the facility is capable of meeting those same requirements running all 12 units simultaneously or any combination of unit operation.

Rubart Station is an important system asset that will serve the needs of our Members and regional consumers, and by this fall all units will be available for service that will last for decades to come.
1. **NeuStream® CO₂ systems for EOR** are readily adaptable to a range of CO₂ sources including steam generators, flare-gas burners, natural gas power generators and **diesel generators**. ([http://www.neustream.com/products/co2eor.html](http://www.neustream.com/products/co2eor.html))

2. **Alternatively the system can provide its own CO₂ source.** The modular, factory-built, design approach allows deployment in a range of sizes from 50 ton/day to over 1000 ton/day of EOR ready CO₂.
   A. • 50 to 1000 tons (17 MMCF) per day EOR quality CO₂
   B. • Adaptable to any CO₂ source, or generates its own CO₂
   C. • Transportable system

### Products
*CO₂ for EOR*  
*CO₂ for Coal*  
*SOₓ for Coal*  
*SOₓ DSI*  
*Chemical*  
*Recovery*  
*NOₓ Add-On*
Existing anthropogenic CO₂ sources being used for EOR!

Ethanol and Biodiesel Plant Activity in Kansas

September 2012

Ethanol Plants
- Existing: 12 plants, 519.5 MGY
- Under Construction: 3 plants, 170 MGY
- Permitted*: 0 plants, 0 MGY
- Permit Pending*: 1 plant, 60 MGY
- Idle: 0 plants, 0 MGY

Biodiesel Plants
- Existing: 3 plants, 7.4 MGY
- Under Construction: 0 plants, 0 MGY
- Permitted*: 0 plants, 0 MGY
- Permit Pending*: 0 plants, 0 MGY
- Idle: 1 plant, 1.8 MGY

* Permitted and Permit Pending codes refer to KDHE Bureau of Air and Radiation – All Construction permits.
Rail map – South-Central Kansas to examine potential to ship CO₂ by rail to Wellington Field
Potential to deliver CO$_2$ by train and run short pipeline to Wellington Field
3. Opportunities, risks and uncertainties for CO$_2$-EOR
Carbon storage in saline aquifers currently has high technical risk; CO$_2$-EOR low risk

INVESTMENT-RISK CURVE OF INDIVIDUAL CCS TECHNOLOGIES

EPA Class VI well permit
-- Monitoring, verification, accounting, & closure
Wellington Field small scale test – 40,000 tonnes in the Arbuckle

Class II transition to Class VI

Class II well permit
Kansas has primacy

Source: SBC Energy Institute
Next generation CO$_2$-EOR methods and anthropogenic CO$_2$ are essential to sustain this type of oil recovery in U.S. beyond 2030.
Next Generation CO₂-EOR is needed to improve efficiencies of oil recovery and CO₂ storage.

Example of Channeling of CO₂ in an Oil-Bearing Formation

<table>
<thead>
<tr>
<th>% Pore Space</th>
<th>% Injected CO₂</th>
<th>PV Throughput (1 HCPV of CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>75%</td>
<td>3.0</td>
</tr>
<tr>
<td>20</td>
<td>16%</td>
<td>0.8</td>
</tr>
<tr>
<td>20</td>
<td>9%</td>
<td>0.4</td>
</tr>
<tr>
<td>35</td>
<td>Not Contacted</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: Modified by Advanced Resources, based on data from Wasson Denver Unit CO₂ flood observation pilot (Goodyear and Jensen, 2011).
Injected CO₂ gets entrapped (stored) in the reservoir in 4 different ways – estimated by reactive transport models and reaction kinetics, modeled via compositional fluid flow simulators based on field and lab measurements of rock and brine.


- some dissolves in brine
- some gets locked as residual gas (saturation)
- some trapped as minerals
- Remaining CO₂ – resides as free phase
  - Sub- or super-critical as per in situ conditions
  (depth/pressure and temperature)

**CO₂ Entrapment Audit:**

1. **Residual gas**
   - Start 45% to End 65%
2. **Solution**
   - Start 18% to End 28%
3. **Minerals**
   - Start negligible to End 5%
4. **Free Phase**
   - Start 37% to End 2%

Ozah, 2005 – In situ CO₂ distribution after 50 years of injection
Kansas oil and gas fields are currently isolated from the major regional CO₂ pipeline systems ... when will this change?

Legend
- CO₂ pipelines
- Oil fields favorable to CO₂-EOR
- Geologic sources of CO₂

~3 billion cu feet (~156 million tonnes) CO₂ injected daily into oil fields for EOR

Oil-bearing formations favorable for CO₂-EOR, onshore lower 48 states.
(Source: ARI disaggregated database, Ventex Velocity Suite Database)
Kansas H.B. 2419 creates tax incentives for carbon capture and storage, namely income tax deductions for the amortization of CCS equipment costs and property tax exemptions.

But, we need more $CO_2$ . . . and we need to bring the costs of capture and transport down. . .

### NEORI CO$_2$ Capture & Transport Cost Assumptions ($/tonne)

<table>
<thead>
<tr>
<th></th>
<th>Transportation Cost ($/tonne)</th>
<th>Core Scenario Capture Cost ($/tonne)</th>
<th>Core Scenario + Transp. Costs ($/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Plant Tranche</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pioneer - First of a Kind Projects</td>
<td>$10</td>
<td>$60</td>
<td>($70, 30-year Payback)</td>
</tr>
<tr>
<td>Projects #2-#5</td>
<td>$10</td>
<td>$50</td>
<td>$60</td>
</tr>
<tr>
<td>Nth of a Kind (Projects #6-onward)</td>
<td>$10</td>
<td>$45</td>
<td>$55</td>
</tr>
<tr>
<td><strong>Industrial - Low Cost Tranche</strong></td>
<td>($/tonne)</td>
<td>($/tonne)</td>
<td>($/tonne)</td>
</tr>
<tr>
<td>Pioneer- First of a Kind Projects</td>
<td>$10</td>
<td>$28</td>
<td>$38</td>
</tr>
<tr>
<td>Projects #2-#5</td>
<td>$10</td>
<td>$28</td>
<td>$38</td>
</tr>
<tr>
<td>Nth of a Kind (Projects #6-onward)</td>
<td>$10</td>
<td>$28</td>
<td>$38</td>
</tr>
<tr>
<td><strong>Industrial - High Cost Tranche</strong></td>
<td>($/tonne)</td>
<td>($/tonne)</td>
<td>($/tonne)</td>
</tr>
<tr>
<td>Pioneer- First of a Kind Projects</td>
<td>$10</td>
<td>$55</td>
<td>$65</td>
</tr>
<tr>
<td>Projects #2-#5</td>
<td>$10</td>
<td>$45</td>
<td>$55</td>
</tr>
<tr>
<td>Nth of a Kind (Projects #6-onward)</td>
<td>$10</td>
<td>$35</td>
<td>$45</td>
</tr>
</tbody>
</table>
Price Forecast of CO2

West Texas market: 2% of price of oil
Spot market, new contracts higher
Cumulative Oil & Gas in southern Kansas
1,180 million (M) bbls oil + 3,880 Billion (B) cu. ft of natural gas

Spivey-Grabs Basil - largest Mississippian oil field in Kansas
- 69 MM BO & 841 BCFG
- promising for future CO₂-EOR after CH4 produced

Welch-Bornholdt
NCRA McPherson Refinery

Welllington Field

Gerlach, Sept. 2011
Welch-Bornholdt-Wherry Field
McPherson & Rice Counties – near McPherson Refinery

- 60+ million bbls cumulative production
- 80 active wells
- Producing zones – Mississippian, Basal Pennsylvanian, and Lansing Kansas City
Economic viability

- $500-$1,000 million investment on ammonia plant will yield ~ $50 million in annual profits*

- +50% potential income* from waste CO2 byproduct

  $50 million + $25 million
  = $75 million potential annual profits

Market for CO2:

- CO₂ Utilization in Enhanced Oil Recovery (EOR)
- Geologic resources in Kansas for CO2 disposal
- Existing infrastructure within petroleum industry

*assuming 5-10% ROI
*assuming $25 per ton CO2 & 1 million tons annual production (dotyenergy.com)
Role of Anthropogenic CO$_2$

- Due to limits of natural CO$_2$ supply, CO$_2$ will necessarily come from man-made sources such as ammonia, ethanol, refinery, and power plants.
- Their utilization will require varying but large capital investments in addition to preparing oil fields to receive the CO$_2$.
- Success will require all of the stakeholders including CO$_2$ suppliers, oil companies, local and state policy makers, and the research community.
- Unified understanding of the potential CO$_2$ supply, oil resources, field readiness
  - infrastructure requirements, field readiness
  - financial and human resource needs, and
  - environmental and regulatory guidelines and incentives.
Total Kansas 2012 CO2 emissions from point sources = 44.5 million metric tons (846 BCF)/yr.
http://ghgdata.epa.gov/
Kansas could become a hub to receive CO₂ by regional pipeline systems to serve EOR


4. Brief summary of selected case studies that highlights approaches to next-generation CO$_2$-EOR applicable to Kansas oil reservoirs
CO$_2$-EOR Field Implementation Sites and Study Areas

- **Sedgwick Basin**
- **Hugoton Field**
- **Wellington Field** (BEREXCO, INC.)
- **Westar Jeffrey Energy Center, Saint Marys**
- **Cutter Field** (BEREXCO, INC.)
- **Pleasant Prairie Eubanks Schuck**
- **McPherson Oil Refinery**
- **Mississippian Chert/dolomite Fields**
- **Chaparral Energy Hall-Gurney Field**
- **Petrosantander Stewart Field**
- **Sunflower Electric, Holcomb (Garden City)**
- **Mississippi Oil Refinery**
- **Wichita**
- **Butler**
- **Coffeyville CO2**
- **Stewart Field**
- **C12 Energy**
- **Frontier Oil Refinery**
- **Cowley**
- **Eastern Calibration Site Wellington Field (BEREXCO, INC.)**

---

**Central Kansas Uplift**

---

DE-FE0004566 -- Jason Rush PI, “Prototyping and testing a new volumetric curvature tool for modeling reservoir compartments and leakage pathways in the Arbuckle saline aquifer: reducing uncertainty in CO$_2$ storage and permanence”

---

Regional study assessing carbon storage potential → ~25,000 sq. miles

---

50 miles
CO₂ Oil & Gas Mapper With Type Logs (green)
access to well and lease data and assist in screening of fields

http://maps.kgs.ku.edu/co2
Java Applets (freeware)
-- assist in geoengineering analysis of reservoirs
CO$_2$ and Oil & Gas Mapper
Cumulative Oil Fields with LKC Production

Northwest Kansas
Cumulative Oil Lease Production
Hall-Gurney Field, 2012

http://www.kgs.ku.edu/PRS/Ozark/GBubbleMap/GBubbleMap.html

Decline curve
1 MM bbl lease

Early 2000’s
KU-Murfin
CO2-EOR test site

http://www.kgs.ku.edu/software/production/
CO2 move off pattern
KU-Murfin Study in Hall-Gurney
early 2000’s
Structure Contour Map, Top Plattsburg Limestone

incremental oil increase attributed to CO2

Area illustrated in cross sections
- Colliver #4 (injector) – (cuttings) dominant fine gr. tight ooid grainstone – *elevated GR*

- Colliver #7 (new oil) – (cuttings) bioclastic, oolitic pkst-grnst. with some interparticle Ø, forams, crinoids, encrusters; 40% ooid – thin clean GR

- Colliver #CO2-1 (CO2 injection) and Colliver #16 (upper) – (cored) oomoldic grainstone, clean porous (shoal #2); Shoal #1 in well #16; finer grained and less porous, lower permeability -- #2 lowest GR, youngest shoal

**Seismic defined lineament**

**Structural profile at top Plattsburg Ls.**

- **Ooid shoal unit**
  - Low GR, high k?

**CO2 injected into crest of Shoal #2**
Southwest Kansas CO2 EOR Initiative

Chester and Morrow Reservoirs

Western Annex to Regional CO2 Sequestration Project (DE-FE0002056) run by the Kansas Geological Survey

The SW Kansas part of project

- CO2 EOR technical feasibility study – Chester IVF and Morrow
- Part of larger KGS-industry CCS and EOR study
- Will not inject CO2 – paper study only
- Get fields in study “CO2-ready”

Technical Team:

<table>
<thead>
<tr>
<th>Name</th>
<th>Project Role</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martin Dubois</td>
<td>Team Lead, geo-model</td>
<td>Consultant - IHR LLC</td>
</tr>
<tr>
<td>John Youle</td>
<td>Core &amp; depo-models</td>
<td>Consultant - Sunflower</td>
</tr>
<tr>
<td>Ray Sorenson</td>
<td>Data sleuth &amp; advisor</td>
<td>Consultant</td>
</tr>
<tr>
<td>Eugene Williams</td>
<td>Reservoir engineering</td>
<td>Williams Petrol. Consultants</td>
</tr>
<tr>
<td>Dennis Hedke</td>
<td>3D Seismic</td>
<td>Consultant - Hedke &amp; Sanger</td>
</tr>
<tr>
<td>Peter Senior</td>
<td>Reservoir modeling</td>
<td>MS student</td>
</tr>
<tr>
<td>Ken Stalder</td>
<td>Geotech</td>
<td>IHR, LLC</td>
</tr>
<tr>
<td>Susan Nissen</td>
<td>3D Seismic</td>
<td>Consultant</td>
</tr>
<tr>
<td>Lynn Watney</td>
<td>Project PI</td>
<td>KGS</td>
</tr>
<tr>
<td>Jason Rush</td>
<td>Project PI</td>
<td>KGS</td>
</tr>
<tr>
<td>John Doveton</td>
<td>Log Petrophysics</td>
<td>KGS</td>
</tr>
<tr>
<td>Paul Gerlach</td>
<td>Data support</td>
<td>Consultant - Charter</td>
</tr>
</tbody>
</table>

Six Industry partners:

- Anadarko Petroleum Corp.
- Berexco LLC
- Cimarex Energy Company
- Glori Oil Limited
- Elm III, LLC
- Merit Energy Company

Support by:

Sunflower Electric Power Corp.
Southwest Kansas CO$_2$-EOR Initiative
Evaluate CO$_2$ sequestration potential in Arbuckle Group saline aquifer and CO$_2$-EOR in four fields in southwestern Kansas – Anadarko, Berexco, Cimarex, Glori, Elm III, Merit

Southwest Kansas CO2 Consortium (Western Annex)
Oil production unevenly distributed in valleys shown by well and OOIP in North Eubank unit

Dubois, Youle, and Williams, in prep.
Reservoir heterogeneity—stratigraphically complex

— Four Parasequences in North Eubank unit

Sandstone = yellow; Sandy shale = brown; Gray = shale
Length of section ~ 5 miles

Dubois, Youle, and Williams, in prep.
1. By 2011 water injection exceeded production by approximately one million barrels per year.

2. The reservoir system was significantly under-pressured, having an original BHP of 1572 psig.

3. Normal BHP for the reservoir depth would be 2350 psi (5500 ft deep x 0.43 psi/ft).

4. Rock fracture pressure is likely to be approximately 3500 psi if the fracture gradient is 0.65 psi/ft.

5. Fractures and conduits were not open until reservoir pressure exceeded approximately 2500 psi.

--- sinkholes possibly responsible for loss of injected water → limit injection pressures

Seismic depth maps, Top Meramec and location of probable sinkholes in North Eubank unit

Reservoir simulations done with four suspected leak points
CO₂ EOR Projections – Pleasant Prairie South Field

Assumptions:
1. Convert WIW to CO₂ IW
2. Oil wells as is
3. Inject 5 mmcf/d CO₂, not exceeding bhp 2600 psi
4. Continuous CO₂, no WAG
5. Injection = production
6. No optimization

Projections:

**Oil (mmbo)**
- Cumulative 2011: 4.48
- NFA cum. 2026: 4.64
- CO₂ case cum.: 6.59
- Increment. CO₂: 1.95
- Cum. 2012-2026: 2.11

**CO₂**
- CO₂ injected (mmcf): 23.7
- CO₂ produced (mmcf): 13.2
- CO₂ sequestered (mmcf): 10.5
- Gross utilization (mcf/bo): 11.2
- Net utilization (mcf/bo): 5.0

RF as f (OOIP)
- Primary: 15.8%
- Secondary: 15.8%
- CO₂: 13.3%
- 45.0%

*Assume 56% CO₂ is recycled*
## SMALL SCALE FIELD TEST
**Wellington Field, Sumner County, Kansas**

**Awaiting permission from DOE to commence field work on September 1, 2014**

<table>
<thead>
<tr>
<th>Task</th>
<th>Task Name</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 10. Build Infrastructure for CO₂ Pressurization at Mississippian Injection Well for Carbon Storage</td>
<td>BP2</td>
<td>Aug '14</td>
<td>Nov '14</td>
<td></td>
</tr>
<tr>
<td>Subtask 10.1. Build a Receiving and Storage Facility at Injection Site</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtask 10.2. Install Pumping Facility at Well Site for Super Critical CO₂ Injection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 11. CO₂ Transported to Mississippian Injector and Injection Begins</td>
<td>Subtask 11.1. Transport CO₂ to Injection Borehole</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 12. Monitor Performance of Mississippian CO₂ Injection</td>
<td>Subtask 12.1. Inject CO₂ in Mississippian Borehole Under Miscible Conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtask 12.2. Monitor Production of Surrounding Wells</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 13. Compare Performance of Mississippian Injection Well with Model Results</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtask 13.1. Revise Geomodel If necessary</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 14. Evaluate Carbon Storage Potential During the Mississippian CO₂ Injection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 15. Evaluate Potential to Move Oil and Optimize for Carbon Storage in the Mississippian Reservoir – Wellington Field</td>
<td>Subtask 15.1. Revise Wellington Field Geomodel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtask 15.2. Use Simulation Studies to Estimate Carbon Storage Potential</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtask 15.3. Estimate Field-Wide Carbon Storage Potential in Mississippian</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Beginning April 2015** -- Inject 26,000 tonnes of CO₂ into Mississippian oil reservoir to demonstrate CO₂-EOR and 99% assurance of storage with MVA
- InSAR, CGPS surface deformation
- 15 seismometers and 3 active 3-component accelerometers – possibly monitor low energy fluid movement and far-field earthquakes in region
- Monitor produced fluids for tracers, CO₂, aqueous geochemistry
Wellington Field
Site of Proposed Small Scale Field Test

Top Mississippian Structure, 10 ft C.I.

20 MM Barrel Oil Field above Arbuckle Group
Porosity inversion from PSDM in (Petrel™) geocellular model

Top Miss.
Porosity (pay)
20 MM bbl field

J. Rush, 2012
Progradation of the Mississippian on West Side of Wellington Structure

Porosity Model (log/3D seismic) of the Siliceous Dolomite Reservoir
Upper Mississippian, Wellington Field

Rush, KGS
Can we relate real data seismic amplitude and frequency to reservoir thickness as it has been suggested by the modeling?
Extensive monitoring network Wellington Field CO₂ Injection Tests

KGS Study Area - Sumner County, KS
- Seismometer Locations
- KGS 1-28 CO₂ Injection Well
- Proposed Miss Inj Well
- KGS 1-32 Characterization Well
- KGS 2-28 Proposed Monitoring Well
- Existing 2D Shear P-Wave Lines
- Modeled Miss CO₂ Plume Extent (Base Case)
- Maximum CO₂ Plume Extent

Sources: E.I. DeLorme, NATEO, USGS, INCOSE, PC, NGAM, Envi-geos, MEF 52, John Lyon, Deal, USGS, Faith, Envi-geos, 2x2, ESRI, HERE, DeLorme, Esri, Google, WorldImagery © OpenStreetMap contributors
Mississippian pay zone in Berexco Wellington KGS #1-32

Top Cherokee

Karst Breccia

Mixed, weathered pebble chert conglomerate

Siliceous dolosiltite (1 ohm-m pay)
Diagenetic facies and textures

Petrography, Berexco Wellington KGS #1-32 Core from Mississippian -- anhydrite possible affect CO₂-foam
Mega Model CO$_2$ Storage Capacity of the Arbuckle in Southern Kansas (25,000 mi$^2$)

- 10 local modeling sites including Cutter and Wellington fields
- Simulation of entire 25,000 mi$^2$ based on estimation of rock properties
Lower Flow Unit For Regional Modeling in Arbuckle Group
25,000 mi$^2$ in southern Kansas

Cutter KGS #1
Wellington KGS #1-32

Low Kv1 –Gasconade & Gunter Sandstone

Structure – sea level datum, 100 ft C.I.
Thickness, 10 ft C.I.
Initial Coarse Grid 7/18/2014
Arbuckle, Southern Kansas

File: MegaModel_Jul18-2014.dat
Date: 7/19/2014

Grid Top (ft) 2015-01-01

Willams, Gerlach, Fazelalavi, Doveton, CO₂
Implementing Large-scale CCUS in Kansas (A)

• **Key Ingredients**
  • CO₂ supply – sources and transportation
  • CO₂ utilization -- Readiness and needs
  • Aggregation of CO₂ supply and CO₂ utilization in Kansas oil fields

• **Economic incentives for CO₂ capture and CO₂ suppliers**

• **Regulation**
  • Well and Field permitting
  • Primacy of Class VI Injection permitting and implications of using added storage for CO₂ beneath the oil reservoir in deep saline aquifers

• **Environmental Concerns**
  • Secure CO₂ storage
  • Induced seismicity
Implementing Large-scale CCUS in Kansas (B)

- Working with CO$_2$ suppliers to get CO$_2$ to Kansas oil fields
- Refine KGS interactive CO$_2$ oil and gas mapper for access to key information
  - Highlight and extract cumulative oil; pressure; temperature; oil gravity
    - Screen and highlight candidate fields/plays for CO$_2$ miscibility, total field and lease performance, recoverable reserves and CO$_2$ requirements (volume and rates)
    - CO$_2$-EOR resources via interactive map of Kansas oil fields utilizing web apps to analyze the data “on the fly”
- Scoping models of oil fields to forecast technical success and favorable economics
- Apply results of CO$_2$ test injection at Wellington Field (DE-FE0006824)
  - and model results of four fields (Shuck, Eubanks, Cutter, and Pleasant Prairie South) in SW Kansas (DE-FE0002056)
Implementing Large-scale CCUS in Kansas (C)

• Engage stakeholders to develop, support and underwrite strategic initiative
  – Administrate (Dept. of Commerce?) and develop components of a Kansas CO₂ initiative/Kansas Model for CO₂ Utilization and Storage
    • Secure advisory group of operators, gas suppliers, officials with Department of Commerce and KU, lawmakers and regulators
    • Define needs to address uncertainties and concerns, weigh challenges and concerns against benefits to affect public perception, sequestration defined, state of readiness, engaging community, leveraging what has been learned, priorities, and opportunities via Governor’s Conference
  • Timetable and costs for planning and development
  • Establish state of the technology in Kansas via research and workshop workshops and share resources and scoping models
CO2 EOR & Geologic Storage

CO2 driven enhanced oil recovery

CO2 injection into deep saline formations

Stored CO2

Produced oil

Physical containment under caprock

Mineral formation reaction

Trapping of separated droplets

CO2 dissolving into water

Shale (caprock)

Sand (storage unit)

Carbon dioxide

Native groundwater

Carbon-bearing mineral
**Principal Investigators**

<table>
<thead>
<tr>
<th>Kansas Geological Survey</th>
<th>KU Department of Geology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Co-Principal Investigators</strong></td>
<td><strong>Co-Principal Investigators</strong></td>
</tr>
<tr>
<td>Kerry D. Newell -- stratigraphy, geochemistry</td>
<td>Evan Franseen -- sedimentology, stratigraphy</td>
</tr>
<tr>
<td>Jason Rush -- Petrel geomodeling and data integration</td>
<td>Robert Goldstein -- diagenesis, fluid inclusion</td>
</tr>
<tr>
<td>Richard Miller -- geophysics</td>
<td>David Fowlie -- reactive pathways, microbial catalysis</td>
</tr>
<tr>
<td>John Doveton -- log petrophysics and core-log modeling</td>
<td>Jennifer Roberts -- reactive pathways, microbial catalysis</td>
</tr>
<tr>
<td>Jianghai Xia -- gravity-magnetics modeling &amp; interpretation</td>
<td>George Tsoflias -- geophysics</td>
</tr>
<tr>
<td>Marios Sophocleous -- geochemistry</td>
<td></td>
</tr>
</tbody>
</table>

**Key Personnel**

<table>
<thead>
<tr>
<th><strong>Grad Research Assistants</strong></th>
<th><strong>KU Department of Geology</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>John Victorine -- Java web app development</td>
<td>Evan Franseen -- sedimentology, stratigraphy</td>
</tr>
<tr>
<td>David Lafflen -- manage core &amp; curation</td>
<td>Robert Goldstein -- diagenesis, fluid inclusion</td>
</tr>
<tr>
<td>Mike Killion -- modify ESRI map service for project</td>
<td>David Fowlie -- reactive pathways, microbial catalysis</td>
</tr>
<tr>
<td>Jennifer Raney -- ass't. project manager</td>
<td>Jennifer Roberts -- reactive pathways, microbial catalysis</td>
</tr>
<tr>
<td>Debra Stewart, Dan Suchy -- data management</td>
<td>George Tsoflias -- geophysics</td>
</tr>
<tr>
<td>Yehwen ’Eugene’ Holubnyak, Petroleum Engineer</td>
<td>Yousuf Fadalkarem -- geophysics</td>
</tr>
<tr>
<td>Fatemeh &quot;Mina&quot; FazelAlavi, Engineering Research Assistant</td>
<td>Brad King -- diagenesis</td>
</tr>
</tbody>
</table>

**UNIVERSITY OF KANSAS**

<table>
<thead>
<tr>
<th><strong>Principal Investigators</strong></th>
<th><strong>Co-Principal Investigators</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Da vid G. KOGER</td>
<td>Evan Franseen -- sedimentology, stratigraphy</td>
</tr>
<tr>
<td>Saugata Datta -- reactive pathways and reaction constants</td>
<td>Robert Goldstein -- diagenesis, fluid inclusion</td>
</tr>
<tr>
<td>Abdelmonem Raef -- seismic analysis and modeling</td>
<td>David Fowlie -- reactive pathways, microbial catalysis</td>
</tr>
<tr>
<td></td>
<td>Jennifer Roberts -- reactive pathways, microbial catalysis</td>
</tr>
</tbody>
</table>

**KU Department of Geology**

<table>
<thead>
<tr>
<th><strong>Grad Research Assistants</strong></th>
<th><strong>Seismic and Geochemical Services</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Robin Barker (graduated)</td>
<td>LOGDGI, LLC, Katy, TX -- wireline log digitizing</td>
</tr>
<tr>
<td>Derek Ohl -- seismic analysis and modeling</td>
<td>David G. Koger, Dallas, TX -- remote sensing data and analysis</td>
</tr>
<tr>
<td>Randi Isham -- seismic</td>
<td>Weatherford Laboratories, Houston, TX -- core analyses</td>
</tr>
<tr>
<td>Brent Campbell -- aqueous geochemistry</td>
<td>CMG - Simulation Services, Calgary, Alberta -- greenhouse gas simulation and software</td>
</tr>
</tbody>
</table>

**Seismic and Geochemical Services**

<table>
<thead>
<tr>
<th><strong>Services</strong></th>
<th><strong>SUBCONTRACTS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>LOGDGI, LLC, Katy, TX -- wireline log digitizing</td>
<td>Berexco, Beredco Drilling -- Wichita, KS</td>
</tr>
<tr>
<td>David G. Koger, Dallas, TX -- remote sensing data and analysis</td>
<td>Wellington Field access; drilling, coring, completion and testing; modeling and simulation</td>
</tr>
<tr>
<td>Weatherford Laboratories, Houston, TX -- core analyses</td>
<td>Dana Wreath - manager, reservoir and production engineer</td>
</tr>
<tr>
<td>CMG - Simulation Services, Calgary, Alberta -- greenhouse gas simulation and software</td>
<td>Randy Koudele -- reservoir engineer</td>
</tr>
<tr>
<td>Halliburton, Liberal, KS -- wireline logging services</td>
<td>Bill Lamb - reservoir engineer</td>
</tr>
<tr>
<td>Hedke-Saenger Geoscience, LTD., Wichita, KS -- geophysical acquisition, interpret &amp; design</td>
<td></td>
</tr>
</tbody>
</table>
Acknowledgements

• The work supported by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) under Grant DE-FE0002056 and DE-FE0006821, W.L. Watney and Jason Rush, Joint PIs. Project is managed and administered by the Kansas Geological Survey/KUCR at the University of Kansas and funded by DOE/NETL and cost-sharing partners.

Disclaimer

• 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.