CO$_2$-EOR in the Wellington Field
Sumner County
South Central Kansas

W. Lynn Watney
Kansas Geological Survey
1930 Constant Avenue
The University of Kansas
Lawrence, KS 66047

2015 KU TORP
Improved Oil Recovery
Conference
May 4, 2015
Overview

• Completed evaluation of CO₂ storage and utilization in 25,000 mi², 33-county area in southern Kansas, DOE-NETL contract DE-FE0002056 and partner cost share
  – Southwest Kansas CO₂-EOR Initiative
  – CO₂ utilization in oil fields and storage in Arbuckle saline aquifer in southern Kansas
  – Cutter Field site characterization, Steven Co.
  – Wellington Field site characterization, Sumner Co.
• Pilot CO₂-EOR in summer & fall 2015 in Mississippian dolomite reservoir in Wellington Field, Sumner County, Kansas (DE-FE0006821)
• Pilot CO₂ injection in 2016 into Arbuckle at Wellington, pending EPA Class VI permit
• Implementing CO₂ Utilization and Storage (CCUS) in Kansas
• Summary
CO$_2$-EOR field implementation sites and study areas on map of Kansas oil and gas fields

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” – Bemis-Shutts (Vess, Murfin)
Completed evaluation of CO₂ storage capacity of a 25,000 mi², 33-county area in southern Kansas

- Southwest Kansas CO₂-EOR Initiative
- CO₂ utilization in oil fields and storage in Arbuckle saline aquifer in southern Kansas (8-70 billion metric tonnes CO₂, P10/P90; volumetrically; 4 billion by simulation with injectivity)
- Site characterization → Cutter Field site, Steven Co., Wellington Field, Sumner Co.

**Project workflow**

- Select and digitize key wells
- Core, log & well test analysis
- Seismic analysis
- Regional study area outline (65,000 km²)
- Mapper & Java tools
- Geomodels
- Regional “Mega Model” simulation

**Maximize new information gained to quantify key variables in CO₂ injection and storage in Kansas**

- CO₂ well inventory
  - 3D view of stratigraphic tops
    - Regional Petrol database
    - Most surface >10,000 wells
  - + scanned images of 90,000 shallower wells
- Digital Type logs and correlation
  - 3D view of 18 structure surfaces
    - 2500 x2500 ft grids
    - Convergent gridding algorithm

**Interactive mapper**: http://maps.kgs.ku.edu/co2/
Dynamic simulation suggests that the four small fields could be viable target for CO₂ storage with concurrent EOR. Combined the four fields are projected to be capable of storing 5.41 million tons of CO₂ (93.3 bcf) while producing an additional 13.2 million barrels of oil (18% of original oil in place).

Potential for CO₂ Storage and Enhanced Oil Recovery in Four Southwest Kansas Oil Fields - an extended abstract

Martin K. Dubois, Eugene T. Williams, John C. Youle, and Dennis E. Hedke

Final Report, DE-FE0002056 in preparation
DOE-NETL Contract #FE0006821

(static & dynamic modeling, well test analysis, high-resolution seismic, passive seismic, accelerometers, geomechanical analysis, project management)

KANSAS STATE UNIVERSITY

Saugata Datta (brine and USDW monitoring)

TBirdie Consulting, Inc

4705 McCormick Street • Lawrence • KS 66047 • 785 843 1085 • 785 865 0678 (fax) • tbirdie@sunflower.com

T. Birdie (Class VI, engineering, monitoring, synthesis, reporting, closure)

KANSAS GEOLOGICAL SURVEY

The University of Kansas

Berkeley Lab

Lawrence Berkeley National Laboratory

Tom Daley, Barry Freifeld (CASSM, U-Tube, cross well seismic)

BEREXCO

Hanford Site, DOE

Mike Taylor (cGPS, InSAR), George Tsoflias (passive seismic)

Linde

The Praxair Group

CO₂ supply
donate 15 seismometers

Dana Wraith & Adam Beren
(field operator and operations, repeat 3D multicomponent seismic)

Brian Dressel, DOE Project Manager
Wellington Field site characterization
Sumner County, Kansas under DE-FE0002056

Mississippian Oil Reservoir & Arbuckle Saline Aquifer
Showing Newly Drilled Wells and Wells with Modern Logs

Cherty Sucrosic Dolomite
Sedimentary Features Have Been Masked During Dolomitization

Montalvo, KU & Barker, KSU
Wellington Field has experienced an excellent waterflood
Site characterization of the Mississippian oil reservoir

Wellington Field → 1600 ft core (base Penn to granite), 2 wells, 3D multi-component seismic, 420 whole core analyses, multiple Mississippian and saline Arbuckle tests

Oil Pay

50 ft

Drainage Capillary Pressure Curves for Each RQI Range in the Mississippian

Relative Permeability Curves for Each RQI Range in the Mississippian

RQI = 0.0314 \((K/\Phi_e)^{0.5}\)
Pilot CO$_2$-EOR in summer & fall 2015 in Mississippian dolomite reservoir in Wellington Field
Sumner County, Kansas

Berexco LLC
Wellington KGS #2-32
2680'FSL & 709'FEL, Sec 32, T 31S, R 1W
Sumner County, Kansas

Drilled in March 2015
Praxair -- CO₂ supplier for Wellington Pilot

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

Exxon Hawkins Field, 85 MMscf/d 2,000 psi
Linde Group – CO₂ supplier for the Wellington Field pilot CO₂ injection

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
March 2015 -- Drilled, cored, logged, and cased **Berexco Wellington KGS #2-32**
Perforated and acidized, completed April 30th, preparing for 5-well interference test mid May

[http://www.kgs.ku.edu/stratigraphic/PAYLOAD/](http://www.kgs.ku.edu/stratigraphic/PAYLOAD/)

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**Microlog**

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2 preserved 1 1/2 inch diameter plug samples (for relative permeability)

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<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Top Depth</th>
<th>Bottom Depth</th>
<th>K(max)</th>
<th>K(90)</th>
<th>K(vert)</th>
<th>POR</th>
<th>GD</th>
<th>Su</th>
<th>Sw</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>feet</td>
<td>feet</td>
<td>md</td>
<td>md</td>
<td>md</td>
<td>%</td>
<td>%</td>
<td>%</td>
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</tr>
</tbody>
</table>

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Full Diameter Analysis Dean Stark

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File: Wellington Field: Wellington Formation: Mississippian Location: 2680' FSL & 709' FEL, Sec 32, T 31S, R 1W Co. & St.: Sumner County, Kansas Elevation: 1269' KB File Number: 57181-20573 Date: 04/16/2015 API Number: 15-191-22770 Full Diameter Sample List

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Pf: 3663-3706 ft

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3685 ft, top dolomite reference depth for next slide

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http://www.kgs.ku.edu/stratigraphic/PAYLOAD/
Reservoir at residual oil saturation ~40% ref 3685 ft

Mississippian Reservoir

Reservoir at residual oil saturation, ~40% ref 3685 ft

Colors = Depth

Porosity

Resistivity

http://www.kgs.ku.edu/software/PfEFFER-
Well logs, DST, and acidizing results used to characterize perforation interval and design interference test

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**Log interpretation of Berexco Wellington KGS #2-32**

Waterflooding has been effective in well with only residual oil is left. Residual oil is in **green color**, about 23%-30%.

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**Acidizing results 4/27/15**

**Berexco workover report**

Wellington KGS 2-32:

Acidized with **2500 gallons of 10% nefe**, 250 balls. Started treating at 3 BPM 1300#, finished treating at 5.7 bpm, 700#, ISIP 50#, went on a vacuum in 30 seconds. Waited 1 hour then began swabbing. TIH with swab, hit fluid @ 1100'fs. Swab down 44.66 br(2hrs) swabbed 1hr and recovered 20.82br. Total 65.48br. Show of oil and all acid was spent. Shut down.

**Final treatment at 5.7 bpm (~8200 BPD)**, 700#, ISIP 50#, went on a vacuum in 30 seconds

**Equivalent barrels of CO₂ to inject**

~500 BPD
Pore size distribution

Small to large pores indicated by increasing T2 times

Formation microresistivity imaging log depicting pores in the Wellington Mississippian reservoir
Dipole Sonic log used in fracture and geomechanical analysis

Conventional sonic log presentation from Halliburton’s Wave Sonic log
P- and shear wave → geomechanical properties of reservoir

Utilize logs, core, seismic, and well tests to characterize fracture systems that impart additional heterogeneity to the Mississippian reservoir

- Seismic amplitude slice through Mississippian reservoir showing discontinuity immediately east of the CO₂ pilot site
- Black line – line of section for well log based porosity cross section showing lateral variability in the Mississippian dolomite
Interference test to be conducted help verify simulation model before reservoir is repressurized and CO$_2$ is injected.

Wellington KGS 2-32 Pump Test Procedure

A) Pump at 2 bpm for 20 minutes, then shut down for 20 minutes.
B) Pump at 4 bpm for 20 minutes, then shut down for 20 minutes.
C) Pump at 6 bpm for 20 minutes, then shut down for 20 minutes.
D) Pump at 7 bpm for 20 minutes, then shut down for 20 minutes.
E) Pump at 6 bpm for 20 minutes, then shut down for 20 minutes.
F) Pump at 4 bpm for 20 minutes, then shut down for 20 minutes.
G) Pump at 2 bpm for 20 minutes, or until out of water, then shut down.

M. Fazelalavi & D. Wreath

Initial pressurization model for Wellington Field prior to CO$_2$ injection to achieve miscibility

According to this model at least 20 days are required to increase pore pressure from ~ 1000 psi to ~ 1500 psi near proposed KGS 2-32 well.

Model assumes homogeneous reservoir with open boundary conditions, k = 70, phi = 0.25, thickness = 60 feet, rel. perm. and cap. press. calculated by Mina FazelAlavi

E. Holubnyak, KGS
A) 15-‐Seismic Array (Sept 2014) – Miller, ERS CGPS & InSAR (Sept 2014) & 3D seismic interp. – KU/KGS – Taylor, Schwab, & Tsoflias, Bidgoli

B) Drill Miss Injection Well (April 2015) & Inject CO₂ (late summer 2015) – Berexco, Praxair, Linde

C) Drill Arbuckle Monitoring Well (Fall 2015) – Berexco

D) Equip KGS 2-28 for MVA & KGS 1-28 for CO₂ Injection (~October 2015 to March 2016) – LBNL (Daley, Freifeld), Berexco – Distributed Fiber Optic Arrays, pending, EPRI (Trautz)

E) Begin Arbuckle CO₂ Injection, ~ March 2016

F) Fluid sampling & analysis of Mississippian for Pre- and post-Injection Monitoring – Berexco, & KSU (Datta and Reese)

G) Geomodeling, simulation, and testing (ongoing) – KGS Energy Research (ERS)

H) Class VI permitting & project reporting – Birdie Consulting

MVA Activity at Wellington CO₂ injection site
Sumner County, Kansas
Twn 31S - R 1W
14 seismic seismometer array operating at Wellington Field to monitor CO₂ pilot tests

R. Miller and S. Peterie, KGS

IRIS Seismometer Installation

Resolution of Hypocenters from IRIS Seismometer Array at Wellington

R. Miller and S. Peterie, KGS
Monitoring, Verification, and Accounting in the Arbuckle pilot injection

- Innovative monitoring technologies:
  - cGPS recording since August 2014
  - Satellite based radar data being collected to monitor ground motion at mm-scale
  - Observe small (-0.5 to 1 M) operational (Mississippian waterflood) seismicity since Sept. 2014
  - Prospect remains to secure Distributed Fiber Optic Arrays with VSP for Arbuckle monitoring

B. Freifeld, LBNL

T. Daley, LBNL

M. Taylor, KU
Multiple seismic shots currently budgeted to create a pseudo-3D volume to image the CO₂ plume → low cost alternative to repeat 3D

High Resolution Vibroseis source for VSP, R. Miller, KGS
Pilot CO₂ injection in 2016 into Arbuckle at Wellington, pending EPA Class VI permit

Simulation of CO₂ injection at Wellington into high permeability hydrostratigraphic unit in lower Arbuckle

CMG Simulation → Commercial scale injection model
Area 1 (Wellington Field) – CO₂ gas saturation
In the Arbuckle → Up to 207 MM tonnes at Wellington Field

Vertical pressure distribution at maximum stress just before small scale pilot injection (40 k tonnes) stops
Implementing CO₂ utilization and storage (CCUS) in Kansas

• Carbon storage and utilisation offers significant potential to revitalise Kansas’ oil fields.
  – A 2010 report for the Midwest Governor’s Association with input from TORP and KGS 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 CO₂ 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 CO₂.

• Why now?
  – Improved reservoir characterization with the widespread use and availability of cost-effective 3D seismic
  – Improved geoengineering models and monitoring technologies
  – All combined will likely overcome the decades of inertia that have faced the implementation of CO₂-EOR in Kansas

Are you ready?
Kansas concept of large-scale commercial carbon storage via CCUS

- Major oil and gas reservoirs as candidates for CO₂-EOR & existing CO₂ sources in Kansas
- Regional study area of the Arbuckle saline aquifer (yellow box)
Summary

• **Accomplishments**
  – Regional geology & estimate of CO₂ storage capacity in the Arbuckle saline formation in southern Kansas
  – Source-sink network for CO₂ utilization and storage
  – Calibration sites for CO₂-EOR and Arbuckle saline formation
    • Wellington Field, Sumner County (3 new wells, multicomponent 3D seismic)
    • Cutter Field, Stevens County (1 new well, multicomponent 3D seismic)
    • Pleasant Prairie South, Eubank North, and Shuck fields (120 mi² of donated seismic data and
  – **Small scale field test at Wellington Field**
    – Assessment of CO₂ injection zone, caprocks, and isolation from USDW
    – CO₂ plume management through simulation and Monitoring, Verification, and Technology
      – 70,000 metric tons CO₂ from Praxair and Linde
  • Spin-off research on the Mississippian Lime Play, lower Paleozoic hydrocarbon system, induced seismicity
  • **Are you ready for CCUS in Kansas?**
Acknowledgements & Disclaimer

Acknowledgements

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Interdisciplinary Collaboration

CO$_2$-EOR Technology & Carbon Management Research
Under DOE-DE-FE0006821 & DE-FE0002056

SW Kansas CO$_2$-EOR Initiative

Industrial and Electrical Power Sources of CO$_2$

Well Green Tech

Well Green Tech

Well Green Tech

Well Green Tech

Well Green Tech

Well Green Tech

Well Green Tech

Well Green Tech
Utilization of Arbuckle beneath oil fields to optimally and safely manage CO₂ obtained from anthropogenic source

West-east structural cross section showing permeability distribution in 16 Arbuckle flow units, southern Kansas, 2500 x 2500 grid

Model 2 – Gridded injection sites for CO₂ expressed as supercritical gas in place after 150 yrs injection

Regional CO₂ sequestration – numerical models at 9 sites analogous to Wellington

Continuing analysis of safe injection and disposal in a complex Midcontinent structural setting

Use of DOE-CO₂ interactive mapper

http://mops.kes.ku.edu/co2/
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>
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<tr>
<td>25</td>
<td>75%</td>
<td>3.0</td>
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<tr>
<td>20</td>
<td>16%</td>
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<tr>
<td>20</td>
<td>9%</td>
<td>0.4</td>
</tr>
<tr>
<td>35</td>
<td>Not Contacted</td>
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Source: Modified by Advanced Resources, based on data from Wasson Denver Unit CO2 flood observation pilot (Goodyear and Jensen, 2011).
Next generation CO$_2$-EOR methods and anthropogenic CO$_2$ are essential to sustain this type of oil recovery in U.S. beyond 2030.

Current Best Practices CO$_2$ EOR Technology Scenario

- CO$_2$ Demand
- Crude Oil Production

9 Billion metric tons of CO2 demanded and stored, 24 billion barrels of crude oil production.

Phil DiPietro, 2013, Carbon Dioxide Enhanced Oil Recovery in the United States, DOE-NETL
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