SMALL SCALE FIELD TEST
DEMONSTRATING CO$_2$ SEQUESTRATION
IN ARBUCKLE SALINE AQUIFER AND BY
CO$_2$-EOR AT WELLINGTON FIELD
SUMNER COUNTY, KANSAS
DE-FE0006821

W. Lynn Watney, & Jason Rush (Joint PIs)
Jennifer Hollenbach (Asst. Project Manager)
Kansas Geological Survey
Lawrence, KS 66047
1. Project Overview
   - Oil field in rural area operating since 1929
   - 55 wells, 21 million barrels produced, 46,000 barrels annually
   - Effective waterflood, ready for CO2-EOR
   - **Phase I** – Completed June 21, 2016 → 20,000 tonnes CO2 injected into Mississippian dolomite for EOR
   - **Phase II** – 26,000 tonnes CO2 into Arbuckle saline aquifer, pending Class VI permit (2017)
Project Team

DOE-NETL Contract #FE0006821

Project established November 2011

(static & dynamic modeling, petrophysics, well test analysis, install/maintain seismometer array, Structural, geochemical, geomechanical analysis, project management)

Tom Daley, Barry Freifeld
(CASSM, U-Tube for Arbuckle Class VI geosequestration)

Saugata Datta, Ian Andree
(KANSAS STATE UNIVERSITY USDW monitoring)

T. Birdie (aquifer modeling, EPA Class VI permit)

Jennifer Roberts, Leigh Sterns, George Tsoflias, B. and K. Graham, A. Nolte, D. Schwab, B. Norwood
(InSAR-cGPS, active and passive seismic, geochemistry)
Benefits to the Program

- Demonstrate that 99 percent permanence of injected CO₂
  → 20,000 metric tons tonnes injected into KGS #2-32 into Late Mississippian siliceous dolomite reservoir between January 9 and June 21, 2016 → CO₂ plume and EOR response as forecast by model (Class II UIC permit)
  → 26,000 metric ton injection into underlying Lower Ordovician Arbuckle Group dolomitic saline aquifer (Pending Class VI UIC permit)
- Demonstrate reliable and cost effective MVA (monitoring, verification, and accounting) tools and techniques
- Develop best practices for effective and safe CO₂-EOR and CO₂ saline storage
Technical Status

Task 15. Evaluate Potential to Move Oil and Optimize for Carbon Storage

• Begin CO₂ injection into KGS #2-32 on January 9, 2016
• Completed injection on June 21, 2016
• 1,101 truckloads, 21,784 US tons, 19,803 metric tons, average of 120 tonnes per day, approximately 374,000 MCF of CO₂
• Total expenditures for purchasing CO₂ were $1,964,000. Our overall price for CO₂ was $90.16 per US ton from Linde Group
• Behaving as forecasted by gemodel/simulation

Monitoring technologies during Class II injection
1) Surface water analysis
2) 18- seismometer array for passive seismic
3) cGPS and InSAR
4) Weekly analysis of 17 wells surrounding injector
5) Repeat 2D seismic survey (July 2016)
6) Post-CO₂ injection well performance around Class II well
7) Arbuckle pressure monitoring since April 2016

Original field O/W contact: ~2494 ft @ 3763 ft in Wellington KGS #2-32
150 ft oil column

Well-based structure map
Top Mississippian

#2-32 drilled in March 2015
→ CO₂-EOR injector
Petrel map of permeability distribution in the Mississippian dolomite

CO₂ injection well is red vertical line

Lower permeability noted east and south of the injection well, Berexco Wellington KGS #2-32

Residual oil saturation in cored injection well averages 23%

Targeted area \(\rightarrow\) High CO₂-EOR potential
Wellington Field small scale CO$_2$-EOR

Jason Bruns above (Caanon Well Services) and Dana Wreath upper right (VP Berexco, LLC) with KGS staff

- 30% oil cut
- Compared to ~1-2% field average

SCADA System installed on wells
CO₂ Injection Begins 1-09-16

Oil Recovery Starts 2-26-16

Minor CO₂ Production Starts 2-29-16

Pause in CO₂ Injection

CO₂ Injection Ends

CO₂ Injection Ends

Sustained High Volume Water Injection Begins 7-14-16
~850 BWPD

~850 BWPD

CO₂ Injected and Recovered & Oil Produced Through 7/31/16

Legend

- CO₂ Injected and Recovered & Oil Produced Through 7/31/16

- ~11% of CO₂ injected has been produced

- 4,000+ BO
Time Lapse Alkalinity
- During and Post CO₂ Injection

High Alkalinity → CO₂
Supercritical CO₂
Small fault

Dashboard
Run/Pause/Step Control

6/23/2016
End of CO₂ injection

7/19/2016
4/27/2016
3/23/2016
Higher BOPD
Lower BHP
Higher BOPD
Lower BHP

**Time-Lapse of Production**

- % oil cut
- BOPD
- BHP (estimated from echometer)

- Supercritical core of CO2 and oil bank on perimeter
- Lack of CO2 fingering
- Evidence for oil bank
Web Applications Built to Display and Analyze Data “in Real-Time” by the Team During Monitoring →

time lapse maps, cross plots, analytical tools, csv download

Example shown: Alkalinity animation
Modeled Oil Production Rate (bbls/day)

Compare 2-32 water injection post CO$_2$: 500 vs 850 bbls/day

Pre-injection BOPD = 9.3
CO₂ Plume (mole fraction) Forecast for September 2016 in Mississippian Reservoir

KGS #2-32

Porosity

Water Injection Well

Structurally Higher

Water Injection Well

Small fault

Area with lower porosity and permeability

Holubnyak (KGS)
Forecasted Oil Production Rates and Cumulative Production for Wells 53, 61, & 62

Total incremental oil production for CO₂ EOR: 68,600 bbls
Total oil production for waterflood only: 12,456 bbls
- **Milestone 3. Pre-injection MVA baseline recording**

  - 18 seismometer array since Fall 2014
  - cGPS and inSAR for processing since August 2014
  - Five shallow monitoring wells around KGS #1-28 and domestic wells in vicinity
  - Weekly baseline geochemistry and production data from 17 wells during CO₂-EOR
  - Static bottom hole pressure in lower Arbuckle from KGS #1-28 since April 2016
Induced Seismicity Southwest of Wellington Field

Total salt water injected by well ( ), BOE produced by oil lease ( ) and earthquakes ( ) in 2014, Harper and Sumner Counties, Kansas

- Wellington Field Arbuckle Injection 26,000 tonnes = 142,000 bbls of fluid over 7 mo. or ~650 bbls per day
- Salt Water Disposal (Class II) in Harper and Sumner counties in 2014
  - 128,254,699 bbls
  - Equivalent to ~23 MM tonnes CO₂
- Oklahoma salt water disposal in 2014
  - >4,000,000,000 bbls
  - >20 billion tonnes CO₂

Jennifer Hollenbach, KGS

Composite BW/BOE = 16:1
(6 % oil cut)

- Min 1.9
- Max 4.8
- Mean 2.8
- 127 earthquakes in 2014
Bottom Hole Pressure Monitoring in Arbuckle KGS #1-28 (idle Class VI)
12-18 May 2016 UTC

Residual Pressure Showing Anomalies

Filtered Pressure Wave minus Earth Tidal Pressure Wave

Δp = 0.3 psi (2 kPa)

Slope of the Filtered Pressure Wave
Start = 2121.77 psi; End = 2121.8 psi

Slope of the Filtered Pressure Wave plus Tidal Pressure Wave.
{ φ = 0.09 [PU]; C_w = 0.4437 1/[Gpa]; φ_corr = -180 °}

Noise Filtered Pressure Wave

- On 4-25-16, BHP in lower Arbuckle was +31.4 psig higher than what was recorded on 8/23/11.
- Since April the pressure has risen to +32.9 psi (August 6) → 1.5 psi in 103 days (0.0147 psi/day or 0.44 psi/mo).
- Increase in pressure forecast by simulation of 2-county brine disposal

J. Victorine (KGS)
Earthquake catalog for Central Sumner County, near Wellington oil Field

- 827 events from April 2015 through July 2016 in area of interest
- Mw ranges from 0.4 – 2.7
- ~1.0 Mw Magnitude of Completeness for area of interest
- b-value of 1 for complete catalog
- Average accuracy within ~0.5 miles in X, Y, and Z

Gutenberg-Richter Law

Magnitude of Completeness of Area of Interest

Wellington Seismometer Array

Nolte & Tsoflias (KU)
Earthquakes Recorded by the Wellington Seismometer Array

Magnitude vs Depth

Low magnitude Earthquakes → Challenge is to distinguish natural vs induced?

>2.5 M → felt earthquake usually detected by regional seismometers

~ Top Proterozoic basement

PreC basement
Top Arbuckle
Top Mississippian

6581 ft
32,908 ft
26,246 ft
19,658 ft
13,123 ft

Nolte & Tsoflias (KU)
Example of shear wave splitting in local earthquake

- Anisotropy can be identified through shear-wave splitting
  - Larger $\delta t$ indicates higher anisotropy
  - Method can be used to identify fracture orientation
  - Next step to integrate with geomechanical modeling!!

Schematic diagram of shear wave splitting due to upper mantle...

- Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/fi
gure/222413701_fig2_Fig-2-Schematic-diagram-of-shear-wave-splitting-due-to-upper-
table-anisotropy-after [accessed Aug 11, 2016]

Focal mechanism inversion from 173 Mw ≥ 2 local earthquakes
- Maximum horizontal stress at ~80 degrees
- Compared to 75 degrees derived from well logs

Earthquakes with focal mechanisms calculated

- Wellington Field
Technical Status

- **Milestone 2 - Submitted Class VI application, June 2014**
  - Awaiting determination of Area of Review (AoR) → Constructed STOMP model to run alongside CMG-GEM
  - Successfully identified mechanism and cost to service financial assurance requirements for the Class VI permit → inject 26,0000 tonnes of CO₂ (7 mo.) and a one-year Post Injection Site Care (PISC) to closure.
  - Enhanced borehole seismic capability to measure sub M -2 to 3 magnitude events and combine with surface seismometer array.

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![Permeability K (md) 2014-01-01 J layer: 66](image1)

- Top of Arbuckle
- #1-28
- Perforation Zone, 150 ft

![Simulation of Arbuckle CO₂ Injection Bottom Hole Pressure and Free-Phase CO₂ Maximum Plume](image2)

- Without Capillary pressure
- With Capillary pressure ($\Delta p \sim 235$ psi)
- 40,000 tonnes
- 2000 ft (610 m)
## Status of Attachments in the Wellington Class VI Permit

- Permit details are in the following 9 attachments
- 7 Attachments near completion

<table>
<thead>
<tr>
<th>Attachment Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. SUMMARY OF OPERATING REQUIREMENTS</td>
<td>Draft Prepared</td>
</tr>
<tr>
<td>B. AREA OF REVIEW AND CORRECTIVE ACTION PLAN</td>
<td>Awaiting confirmation of Area of Review by EPA modelers</td>
</tr>
<tr>
<td>C. TESTING AND MONITORING PLAN</td>
<td>Draft Prepared</td>
</tr>
<tr>
<td>D. WELL PLUGGING PLAN</td>
<td>Draft Prepared</td>
</tr>
<tr>
<td>E. POST-INJECTION SITE CARE AND SITE CLOSURE PLAN</td>
<td>Awaiting confirmation of Area of Review by EPA modelers</td>
</tr>
<tr>
<td>F. EMERGENCY AND REMEDIAL RESPONSE PLAN</td>
<td>Draft Prepared</td>
</tr>
<tr>
<td>G. CONSTRUCTION DETAILS</td>
<td>Draft Prepared</td>
</tr>
<tr>
<td>H. FINANCIAL ASSURANCE DEMONSTRATION</td>
<td>Preferred financial instruments established and costs estimated to guarantee financial obligations</td>
</tr>
<tr>
<td>I. STIMULATION PROGRAM</td>
<td>Draft Prepared</td>
</tr>
</tbody>
</table>

Berexco/KGS Class VI Permit

**The Kansas Team is Ready**

*KGS, Berexco, T. Birdie Consulting*
Accomplishments of the Wellington Project during BP2

ACTIVITIES CARRIED OUT TO DATE BY THE KANSAS TEAM

- Successful CO\textsubscript{2} injection in the Mississippian carried out by Berexco, LLC, Wichita, KS
- Injection done in a highly controlled and monitored environment
- Linde Group, a leader in CO\textsubscript{2} capture and supply, an excellent partner for the project, provided steady supply of CO\textsubscript{2}
- Assisting in defining safe disposal and economic potential for Kansas reservoirs
- Rapid-response detection & mitigation procedures being tested are as part of a comprehensive operation & risk management plan
- Advanced monitoring technologies
- Wellington Field is proving to be a viable field laboratory
Future Plans and Expectations

• Continue post-injection monitoring of Mississippian wells and operation of seismometers and deep well pressure.
• Continue to acquire SAR satellite images and recording cGPS, operation of seismometer array, pressure monitoring, and surface and well sampling.
• Complete processing of the long offset repeat 2D seismic line acquired over the Mississippian injection site to validate CO₂ plume.
• Updated BP3 monitoring technologies and budget for the Arbuckle injection, ready to inject in the Arbuckle saline aquifer, pending receipt of Class VI permit in early 2017.
• Basis for Determination and Findings (D&F) filed to extend the project beyond September 30, 2016 in order to carry out Arbuckle injection.
Acknowledgements & Disclaimer

Acknowledgements
• The work supported by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) under Grant 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.

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Synergistic Activities

• Collaboration with Susan Carroll, PI, LLNL

– Task addition → *Experimental calibration of NMR well logs to determine pore connectivity in the injection zone at the Wellington CO₂ storage demonstration site, Kansas*

• Data rich site with considerable data sharing with all data publically available
  • Carbonate and caprock cores, modern wireline logs, tests → KU, KSU et students and faculty; industry consortium
  • Water and oil samples
  • Multicomponent 3D → new processing techniques → KU, KSU, BEG
  • Earthquake catalog being built from operating IRIS/KGS 18-seismometer array
  • Monitoring and risk analysis from operational plan for safe and effective injection and adaptation by EPA for this project
  • Test NRAP tools

• Extensive Web (Java) application tools and development, petrophysical application focus, data archiving
  – Need more users and explore incorporation into NATCARB
Appendix
Bibliography


- Yevhen Holubnyak1, Lynn Watney, Mina FazeAlavi, Jason Rush, Tandis Bidgoli, Eugene Williams, Paul Gerlach, and Saugatta Datta, 2015, SHALLOW GROUNDWATER MONITORING BEFORE AND AFTER CO2 SEQUESTRATION IN SOUTH CENTRAL KANSAS: Aapg, Geoscience Technology Workshop, Golden, CO.


Bibliography

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• Pilot Scale CO\textsubscript{2} EOR at Wellington Field in South-Central Kansas, by Yevhen Holubnyak, Lynn Watney, Jason Rush, Mina Fazelalavi, and Dana Wreath. Carbon Capture, Utilization & Storage Conference, June 14-16, 2016, Tysons, VA. (Acrobat PDF, 4 MB)

• Lessons Learned from Waste Water Disposal in Kansas: Applications for CO\textsubscript{2} Geological Storage, by Yevhen Holubnyak, Lynn Watney, and Tandis S. Bidgoli. Carbon Capture, Utilization & Storage Conference, June 14-16, 2016, Tysons, VA. (Acrobat PDF, 5 MB)


• Technical Economic and Regulatory Challenges Facing Large Scale Adaption of Carbon Geologic Sequestration, by Tiraz Birdie, Lynn Watney, and Jennifer Hollenbach. Carbon Management Technology Conference, November 18th 2015. (Acrobat PDF, 3.3 MB)

• Advanced Subsurface Characterization for CO\textsubscript{2} Geologic Sequestration and Induced Seismicity Evaluations, by Tiraz Birdie, Lynn Watney, Aimee Scheffer, Jason Rush, Eugene Holubnyak, Mina Fazelalavi, John Doveton, Jennifer Raney, Saugata Datta, Dennis Hedke, and Jennifer Roberts. Carbon Management Technology Conference, November 19th 2015. (Acrobat PDF, 2.5 MB)

• Advanced Subsurface Characterization for CO\textsubscript{2} Geologic Sequestration and Induced Seismicity Evaluations, by Tiraz Birdie, Lynn Watney, Aimee Scheffer, Jason Rush, Eugene Holubnyak, Mina Fazelalavi, John Doveton, Jennifer Raney, Saugata Datta, Dennis Hedke, and Jennifer Roberts. Carbon Management Technology Conference, November 19th 2015. (Acrobat PDF, 2.5 MB)
KGS #2-32 Mississippian reservoir interval, composition plot, core analysis, and moveable oil

3763 (-2494 ss) -- Original O/W contact
– Mina Fazelalvi, KGS

~70 ft of residual oil
~23% $S_o$

~70 ft of residual oil
~23% $S_o$

40 ft (12 m)

Average log calculated absolute permeability using NMR compared to whole core C/A
Refined March 2-16 Events
2016 events
Occurrence by Month for events <1 km deep

Occurrence by Month for events 1-2 km deep

Occurrence by Month for events 2-3.5 km deep

Occurrence by Month for events >3.5 km deep
Monitoring and Rapid Response Plan is designed to alert the team of anomalies while injecting CO₂, based on prioritizing the monitoring technologies –

1) Reliability of the data and approaches used to analyze
2) Frequency that data is acquired during injection
3) Sensitivity and precision of the monitoring method → detect small changes in CO₂ plume behavior
4) Location and therefore resolution of the data
5) Detection of spatial extent of the CO₂ plume
6) Ability to detect movement above and below the injection zone.
\[ \Delta p = 16 \text{ psi (100.3 kPa)} \]
Class VI Permitting Timeline

- Prepared Opinion on Induced Seismicity in Kansas
- Wellington Seismic Action Plan prepared in response to EPA’s concern about induced seismicity
- Conduct analytical studies to demonstrate absence of USDW at site
- Conduct modeling for 26,000 tons and prepare new report
- Prepared Site Structure and Induced Seismicity Report

Work with EPA to prepare permit


- August 20, 2014: Face-to-face kickoff meeting with EPA in KC
- Permit application submitted April 2014
- February 2014: CMG model updated.
  October 2013: Draft to Dana Wrench
  May 2013: Arbuckle Petrel model updated.
  January 2013: The internal and external review of the draft permit began.
- February 2012: Conversations were held with Joseph Tipec and Bruce kobelty of US EPA regarding financial requirements. The wellfield operator, Berexco, was informed of the findings and the consensus is that Berexco will be able to meet the financial requirements.

Respond to Request For Information on all sections of permit

- Permits reformatted and resubmitted using new GS Tool
- Conduct Water Quality Testing and Analysis at shallow wells
- Prepare Quality Assurance and Surveillance Plan (QASP)
- Operation Plan for Safe and Efficient Injection (OPSEI) prepared as a monitoring response plan.
- Conducted STOMP simulations to assist EPA in AoR evaluations
- At EPA’s request, prepare plan for monitoring pressures in Mississippian reservoir

Planned permitting efforts as budgeted and tasked in PMP

Unplanned efforts requested by EPA to address induced seismicity, USDW determination, and detailed operation/monitoring to address EPA “lessoned learned” from legal and technical challenges”
Pressure Measurement – 29 July to 5 August 2016 UTC

No Anomalies

Filtered Pressure Wave minus Tidal Pressure Wave

Slope of the Filtered Pressure Wave
Start = 2122.77 psi; End = 2122.88 psi

Slope of the Filtered Pressure Wave plus Tidal Pressure Wave.
\[ \phi = 0.09 \text{ [PU]}; \ C_w = 0.4437 \text{ 1/[Gpa]}; \ \phi_{corr} = -13 \degree \]

Filtered Pressure Wave

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1.496 \times 10^{11} \text{ [m]} = 1 \text{ Astronomical Unit [AU]}
Pressure Events: 16 May 2016 16:00 to 17:00 (UTC)

A: "piston like" pull up then down
- dip 05:40 to 06:10 Min: 05:41:18 2122.042 psi
- pulse 06:10 to 08:00 Max: 06:42:42 2122.235 psi
Base: 21:40 2122.161 psi

B: 4 pulses
1. 16:40 to 17:15 Max: 16:59:42 2122.254 psi
2. 17:15 to 18:05 Max: 17:35:00 2122.341 psi
3. 18:05 to 18:20 Max: ~18:15:08 2122.261 psi
4. 18:20 to 19:00 Max: 18:35:36 2122.292 psi
Base: 19:00 2122.225 psi

C: dip 22:00 to 22:30 Min: 22:10:14 2122.111 psi

\[ \Delta p = 0.34 \text{ psi (2.3 kP)} \]
Spatial and Temporal Relationships of Earthquake Catalog

Earthquake Depth

Earthquake Magnitude

Occurrence by Month

Magnitude

Depth

2 events of Mw 2.5 or greater in area of interest

Nolte & Tsoflias (KU)

Diamonds indicate locations of Wellington Seismometer Array
Pressure (psi) -- Mississippian reservoir
September 2016

Injection well KGS #2-32 (CO2 injection)

Area with lower porosity and permeability

Holubnyak (KGS)