Geologic Carbon Sequestration Research in Kansas: Subsurface Storage Capacities and Pilot Tests for Safe and Effective Disposal

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Overview

• Completed evaluation of CO$_2$ storage and utilization in 25,000 mi$^2$, 33-county area in southern Kansas, DOE-NETL contract DE-FE0002056 and partner cost share
  – Southwest Kansas CO$_2$-EOR Initiative
  – CO$_2$ utilization in oil fields and storage in Arbuckle saline aquifer in southern Kansas
  – Cutter Field site characterization, Stevens Co.
  – Wellington Field site characterization, Sumner Co.
• Pilot CO$_2$-EOR injection began January 9, 2016 in Mississippian dolomite reservoir in Wellington Field, Sumner County, Kansas (DE-FE0006821)
• Pilot CO$_2$ injection into Arbuckle at Wellington, pending EPA Class VI permit
• Steps toward implementing CO$_2$ Utilization and Storage (CCUS) in Kansas

Summary

Close Class VI Arbuckle injection
August 30, 2018 with repeat 3D seismic
Total annual CO$_2$ emissions in Kansas in 2015
45.92 million tonnes

*Potential Saline storage capacity for 210 to 1,853 years of Ks emissions*

*Oil and gas reservoir storage capacity for 271 years*
Global annual CO₂ emissions ≈ 8 × 10⁹ tons

Earth Policy Institute
CO₂-EOR Technology & Carbon Management Research in Kansas

- Utilize oil and gas field infrastructure
- Utilize comparable approaches to characterization and simulation of oil and reservoirs
- Evaluated 10 sites for commercial scale carbon storage sites in aquifers beneath existing oil fields
- Conduct small scale CO₂-EOR injection at Wellington Field, Sumner County Kansas
- KU & partners have performed extensive research on:
  - monitoring
  - verification
  - accounting of the CO₂ over the long term

**SW Kansas CO₂-EOR Initiative**

**Partners**

- IHR
- Sunflower Energy LLC
- CIMAREX
- GloriOil
- Anadarko
- BEREXCO
- Dawson-Markwell Exploration Co.
- Ne noble energy
- fairfield nodal
- Sunflower Electric Power Corporation
- Devibiss Coring Service
- Basic Energy Services
- Paragon Geophysical
- Halliburton
- MUDCO
- Weatherford Laboratories
- HAEDKE-BAENGER GEOSCIENCE, LTD
- COPLAX
- Bittersweet Energy Inc.
- Charter Consulting
- KOCHEL Remote Sensing
- Lawrence Livermore National Laboratory
- UC Berkeley
- Lawrence Berkeley National Laboratory
- PARAGON GEOPHYSICAL
- BEREXCO
- Engineers consultant services
- DOE-NETL Contract #FE0006821

70,000 metric ton (small scale) CO₂ injection test at Wellington

433,000 bbls equivalent (620 bbls/day)
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 based on injectivity and storage)
- Site characterization → Cutter Field site, Steven Co., Wellington Field, Sumner Co.

Project workflow

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

Interactive mapper: http://maps.kgs.ku.edu/co2/
Regional Scale CO₂ Storage Capacity Simulation in the Lower Ordovician Arbuckle Group

- South Western and South Central Kansas
- 10 areas – benchmark sites
- One “mega” model
- Utilized database for simulating large scale brine disposal to understand induced seismicity in south-central Kansas

G. Williams (2015)
West-East structural cross section showing permeability distribution in 16 Arbuckle flow units, southern Kansas

- Based on realizations of horizontal permeability, md
- Calibrated with core, logs, test data at Wellington and Cutter Fields

Williams, Gerlach, Fazelalvi, Doveton, KGS team, KS CO₂
Rock types mapped in Arbuckle at Wellington Field Based on RQI

\[ RQI \text{(reservoir quality index)} = 0.0314 \sqrt{\frac{\text{Perm}}{\text{Porosity}}} \]

Subregional highly porous and permeable hydrostratigraphic unit with local compartmentalization.
Vertical permeability (mD) distribution in the Arbuckle saline aquifer beneath Wellington oil field -- east-west cross section through the injection well (KGS 1-28)

Class VI CO2 Arbuckle

Subregional highly porous and permeable hydrostratigraphic unit with local compartmentalization
Proposed area of reduction of disposal for management of induced seismicity

Large Volume Arbuckle Injection Wells

Kansas Corporation Commission & Kansas Induced Seismicity Task Force
Dynamic simulation suggests that the four small fields could be a viable target for CO$_2$ storage with concurrent EOR. Combined the four fields are projected to be capable of storing 5.41 million tons of CO$_2$ (93.3 bcf) while producing an additional 13.2 million barrels of oil (18% of original oil in place).
WELLINGTON FIELD PILOT DEMONSTRATION

DOE-NETL Contract #FE0006821

L. Watney (Joint PI), J. Rush (Joint PI), T. Bidgoli, J. Doveton, E. Holubnyak, M. Fazelalavi, R. Miller, D. Newell, J. Hollenbach
(static & dynamic modeling, well test analysis, high-resolution seismic, passive seismic, accelerometers, geomechanical analysis, project management)

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

KANSAS STATE UNIVERSITY

Jennifer Roberts, Leigh Stearns (cGPS), Mike Taylor (InSAR), George Tsoflias (passive and active seismic)

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

CO₂ supply

donated 15 seismometers

Brian Dressel, DOE Project Manager

Dana Wreath & Adam Beren
(field operator and operations, repeat 3D multicomponent seismic)
Wellington Field
Site of Small Scale Field Test

Top Mississippian Structure, 10 ft C.I.

20 Million Barrel Oil Field above Arbuckle Group
Wellington Field – eastern calibration site
Mississippian siliceous dolomite reservoir &
Arbuckle aquifer saline aquifer

CO$_2$-EOR
Saline aquifer
CO$_2$ Sequestration
Inject in deep Arbuckle
Class VI Permit applied for

J. Rush (KGS)
Pilot CO₂-EOR well drilled in 2015 and injection began in January 2016
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
Linde Group – 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

- CO$_2$/N$_2$ EOR Services
  - Pilots
  - Injection test and huff-n-puffs

- CO$_2$ Capture & Purification

Exxon Hawkins Field,
85 MMscf/d 2,000 psi
Wellington Field site characterization
Sumner County, Kansas under DE-FE0002056

Cherty Sucrosic Dolomite
Sedimentary Features Have Been Masked During Dolomitization

Montalvo, KU & Barker, KSU
No Osage or Kinderhook Mississippian $\rightarrow$ mid ramp

Lenticular Spiculite Wacke/Packestone
Extensive Micro-Porosity Through Dissolution and Etching of the Silica Matrix

Mississippian pay zone in Berexco Wellington KGS #1-32

Rhombic Dolomite Euheral (idiotopic)
Different Phases, Feroan and Non-Feroan

Acid etched; stained with alizarin red S and K ferrocyanide

Sketch of dolomite phases

Montalvo (2015)
Berexco Wellington KGS #2-32 showing well logs, lithologic interpretation from logs, core analysis, lithology from core description, and moveable oil (green, residual oil saturation).

J. Victorine (KGS)
Halliburton Nuclear Magnetic Resonance (MRIL) Log → *uniform pore distribution*

**Formation microresistivity imaging log**

– Small to large pores indicated by increasing T2 times

– Mississippian oil reservoir

– Pore size distribution

– 3657 ft

– 3706 ft
Top Mississippian structural elevation (25 ft contour interval), (upper right) forecasted CO2 movement after 26,000 tonnes, (lower right) pore pressure distribution used to control the sweep of the CO2, and (lower left) relative permeability curves determined for each reservoir rock type (reservoir quality index).
CO$_2$-EOR injection in area of reservoir with uniform porosity profile of reservoir

- Porosity thickening indicative of low-angle, westward progradational wedges
- Confirmed by 3D seismic

Small fault acting as barrier to flow on east side of pilot site (250 ft from the fault)
• Petrel-based porosity map of the Mississippian reservoir
• CO2 injection well is red colored vertical line
• Low porosity noted east and south of the injection well, KGS #2-32.
• Thin north-northwest trending yellow line is the trace of the medial fault.

J. Rush (KGS)
• Petrel-based map of permeability for the Mississippian oil reservoir.
• CO2 injection well is red colored vertical line.
• Lower permeability noted east and south of the injection well, KGS #2-32.
• Thin north-northwest trending yellow line is the trace of the medial fault.

J. Rush (KGS)
• AVO (amplitude vs. offset) derived porosity along zone of maximum porosity in upper Mississippian oil reservoir.
• White area to east and south of the CO2 injection well corresponds with lower porosity.

B. Graham and G. Tsofilas (KU)
Wellington Mississippian CO2-EOR Small Scale Injection began January 9, 2016 → operated by Berexco, LLC
Wellington Field small scale CO2-EOR
Jason Bruns (Canon Well Services) and Dana Wreath (VP Berexco, LLC) with KGS staff
CO₂ Utilization in Enhanced Oil Recovery (EOR)

CO₂ mixes with oil and CO₂ is recycled.
Combined pH, Temp brine, and alkalinity

Some CO₂ being vented, but less than 2-day’s supply in total, 4,500 MCF
Cumulative CO2 injection through 3-31-16 = 96,949 BBL. ~10,000 tons
Cumulative CO2 injection through 4-14-16 = 101,600 BBL., ~13,500 tons

- **Cumulative CO2 injected (MCF)**
- **Cumulative CO2 vented (MCF)**
- **CO2 injected (MCFD)**
- **CO2 vented (MCFD)**
- **Cumulative oil (barrels)**
- **Incremental oil (barrels)**
- **Ratio MCF CO2 vented to barrels of oil recovered**

- **CO2 injection starts 1-09-16**
- **Oil recovery starts 2-26-16**
- **CO2 venting starts 2-29-16**
Modeled pressure (psi) map and profile

$CO_2$ injection at KGS 2-32, vertical cross-section view
Modeled supercritical $\text{CO}_2$ at KGS 2-32
vertical cross-section
Ideal oil recovery with 26,000 tonnes of CO₂ injected

Value of incremental oil to be offset by added cost share
Pilot CO$_2$ injection anticipated for Arbuckle at Wellington, pending EPA Class VI permit

Simulation of CO$_2$ injection at Wellington into high permeability hydrostratigraphic unit in lower Arbuckle

Comparison to CMG Simulation for Commercial-scale injection -- Area 1 (Wellington Field) – CO$_2$ 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
A) 18- Seismic Array (Sept 2014) – Miller, ERS, KU
CGPS & InSAR (Sept 2014) & 3D seismic interp.
– KU/KGS

B) Drill Miss Injection Well (April 2015) & Inject CO₂ (January 2016)
– Berexco, Praxair, Linde

C) Drill Arbuckle Monitoring Well (Fall 2016) – Berexco

D) Equip KGS 2-28 for MVA (CASSM, Utube) & 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 (26,000 tons), 2017?

F) Fluid sampling & analysis of Mississippian for Pre- and post-Injection Monitoring
– Berexco, KGS, KU

G) Geomodeling, simulation, and testing (ongoing since 2011)
– KGS Energy Research Section (ERS)

H) Class VI permitting & project reporting – KGS, Birdie Consulting, Berexco

200k bbls or 0.4 BCF CO₂
18 seismic seismometer array operating at Wellington Field to monitor CO\textsubscript{2} pilot tests

G. Tsoflias
Alex Nolte
KU Geology
J. Hollenbach & J. Victorine, KGS

IRIS Seismometer Installation

Housing setup for Sercel (Mark Products) L-22D-3D sensors, 5 ft below surface to minimize surface noise, installed below frost line in bedrock.

Shelby Petelle, KGS Exploration Services, checking installation in July 2014

Resolution of Hypocenters from IRIS Seismometer Array at Wellington

Adapting Java toolset to manage, interpret, and display solutions on project maps (Victorine, KGS)

G. Tsoflias
Alex Nolte
KU Geology
J. Hollenbach & J. Victorine, KGS

Network Sensitivity

Local Activity

- Earthworm software for automated detection of earthquakes
- Reporting 2.5+ magnitude per USGS convention
- Minimum magnitude versus distance from the network
- Operational sensitivity from active waterflood being recorded at Wellington Field
- Research underway to improve location of hypocenters of events

KGS Study Area - Sumner County, KS
Seismometer Locations:
- KGS-1-2 CO\textsubscript{2} Injection Well
- KGS-1-2 CO\textsubscript{2} Injection Wall
- Proposed Miss 1-2 Wall
- KGS-1-3 3-D Injection Wall
- KGS-2-8 Proposed Monitoring Wall
- Existing 2D Shoot P-13 Line
- Existing Miss CO\textsubscript{2} Plane Datum (Miss CO\textsubscript{2})
- Maximum CO\textsubscript{2} Plane Datum

Mossupian and Arbuckle injection zones have good impedance

Mississippian and Arbuckle injection zones have good impedance
Map showing magnitudes of earthquakes recorded by USGS in NEIC catalog during the period 7-17-15 and 3-27-16 in Harper and western Sumner Co.

Wellington Field

Harper

Sumner
Earthquakes recorded within 5 km of the array are highlighted as a solid triangle. The events within 5 km are more reliable due to proximity to the array.
- Histogram of earthquake dates compared to longitude, latitude, and depth for earthquakes recorded from Wellington seismometer array

- 10 x 10 mi area surrounding Wellington Field

- April 2015 through the end of March 2016
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

Real time detection using continuous source cross-well seismic

CASSM & Croswell Seismic Tomography

InSAR in conjunction with cGPS

M. Taylor, KU

T. Daley, LBNL

B. Freifeld, LBNL
Operational plan for safe and effective injection in the Arbuckle at Wellington Field

The success of the Monitoring and Rapid Response Plan developed for the Wellington Project is based on prioritizing the monitoring technologies:

1) Reliability of the data and approaches used to analyze the data,
2) Frequency that the data is acquired during injection
3) Sensitivity and precision of the monitoring method and its ability to detect small changes in CO₂ plume behavior;
4) Location and therefore resolution from which the data is collected,
5) Spatial resolution and coverage of the CO₂ plume; and
6) Ability to detect movement out of the injection zone both above and below the injection zone.
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)

Wellington Field (small scale field test & calibration)
Implementing CO₂ 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 with input from Tertiary Oil Recovery Program 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 geologic sourced 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?
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 wells, multicomponent 3D seismic)
    • Cutter Field, Stevens County (1 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, monitoring, verification, and accounting
    – 52,000 metric tons CO₂ pilot injections from Praxair and Linde sources
  • Spin-off research on the Mississippian Lime Play, lower Paleozoic hydrocarbon system, induced seismicity
  • Are you ready for CCUS in Kansas?
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