QUARTERLY PROGRESS REPORT

To
DOE-NETL
David P. Cercone, Program Manager
Award Number: DE-FE0006821

SMALL SCALE FIELD TEST DEMONSTRATING CO_2 SEQUESTRATION IN ARBUCKLE SALINE AQUIFER AND BY CO_2-EOR AT WELLINGTON FIELD, SUMNER COUNTY, KANSAS

Project Director/Principal Investigator:
W. Lynn Watney
Senior Scientific Fellow
Kansas Geological Survey
Ph: 785-864-2184, Fax: 785-864-5317
lwatney@kgs.ku.edu

Joint Principal Investigator:
Yevhen 'Eugene' Holubnyak
eugene@kgs.ku.edu
Ph: 785-864-2070

Prepared by Yevhen Holubnyak, Lynn Watney, Jennifer Hollenbach, Tiraz Birdie, Mina Fazelalavi, Tandis Bidgoli, Drew Schwab, Alex Nolte, George Tsoflias, John Victorine, Brandon Graham, John Doveton, Jason Bruns, Brett Blazer, Dana Wreath

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Recipient: University of Kansas Center for Research &
Kansas Geological Survey
1930 Constant Avenue
Lawrence, KS 66047

Project/Grant Period: 10/1/2011 through 9/30/2017
Twenty Third Quarterly Report
Period Covered by the Report: April 1, 2017 through June 30, 2017

Signature of Submitting Official:
eugene holubnyak
Yevhen 'Eugene' Holubnyak

EXECUTIVE SUMMARY

PROJECT OBJECTIVES

The objectives of this project are to understand the processes that occur when a maximum of 70,000 metric tonnes of CO_2 are injected into two different formations to evaluate the response in different lithofacies and depositional environments. The evaluation will be accomplished through the use of both in situ and indirect MVA (monitoring, verification, and accounting) technologies. The project will optimize for carbon storage accounting for 99% of the CO_2 using lab and field testing and comprehensive characterization and modeling techniques.

CO_2 will be injected under supercritical conditions to demonstrate state-of-the-art MVA tools and techniques to monitor and visualize the injected CO_2 plume and to refine geomodels developed using nearly continuous core, exhaustive wireline logs, and well tests and a multi-component 3D seismic survey. Reservoir simulation studies will map the injected CO_2 plume and estimate tonnage of CO_2 stored in solution, as residual gas, and by mineralization and integrate MVA results and reservoir models shall be used to evaluate CO_2 leakage. A rapid-response mitigation plan will be developed to minimize CO_2 leakage and provide comprehensive risk management strategy. A documentation of best practice methodologies for MVA and application for closure of the carbon storage test will complete the project. The CO_2 shall be supplied from a reliable facility and have an adequate delivery and quality of CO_2.

SCOPE OF WORK

Budget Period 1 includes updating reservoirs models at Wellington Field and filing Class II and Class VI injection permit application. Static 3D geocellular models of the Mississippian and Arbuckle shall integrate petrophysical information from core, wireline logs, and well tests with spatial and attribute information from their respective 3D seismic volumes. Dynamic models (composition simulations) of these reservoirs shall incorporate this information with laboratory data obtained from rock and fluid analyses to predict the properties of the CO_2 plume through time. The results will be used as the basis to establish the MVA and as a basis to compare with actual CO_2 injection. The small scale field test shall evaluate the accuracy of the models as a means to refine them in order to improve the predictions of the behavior and fate of CO_2 and optimizing carbon storage.

Budget Period 2 includes completing a Class II underground injection control permit; drilling and equipping a new borehole into the Mississippian reservoir for use in the first phase of CO_2 injection; establishing MVA infrastructure and acquiring baseline data; establishing source of CO_2 and transportation to the injection site; building injection facilities in the oil field; and injecting CO_2 into the Mississippian-age spiculitic cherty dolomitic open marine carbonate reservoir as part of the small scale carbon storage project.

In Budget Period 3, contingent on securing a Class VI injection permit, the drilling and completion of an observation well will be done to monitor injection of CO_2 under supercritical conditions into the Lower Ordovician Arbuckle shallow (peritidal) marine dolomitic reservoir.

Monitoring during pre-injection, during injection, and post injection will be accomplished with MVA tools and techniques to visualize CO_2 plume movement and will be used to reconcile

simulation results. Necessary documentation will be submitted for closure of the small scale carbon storage project.

PROJECT GOALS

The proposed small scale injection will advance the science and practice of carbon sequestration in the Midcontinent by refining characterization and modeling, evaluating best practices for MVA tailored to the geologic setting, optimize methods for remediation and risk management, and provide technical information and training to enable additional projects and facilitate discussions on issues of liability and risk management for operators, regulators, and policy makers.

The data gathered as part of this research effort and pilot study will be shared with the Southwest Sequestration Partnership (SWP) and integrated into the National Carbon Sequestration Database and Geographic Information System (NATCARB) and the 6th Edition of the Carbon Sequestration Atlas of the United States and Canada.

Project Deliverables by Task

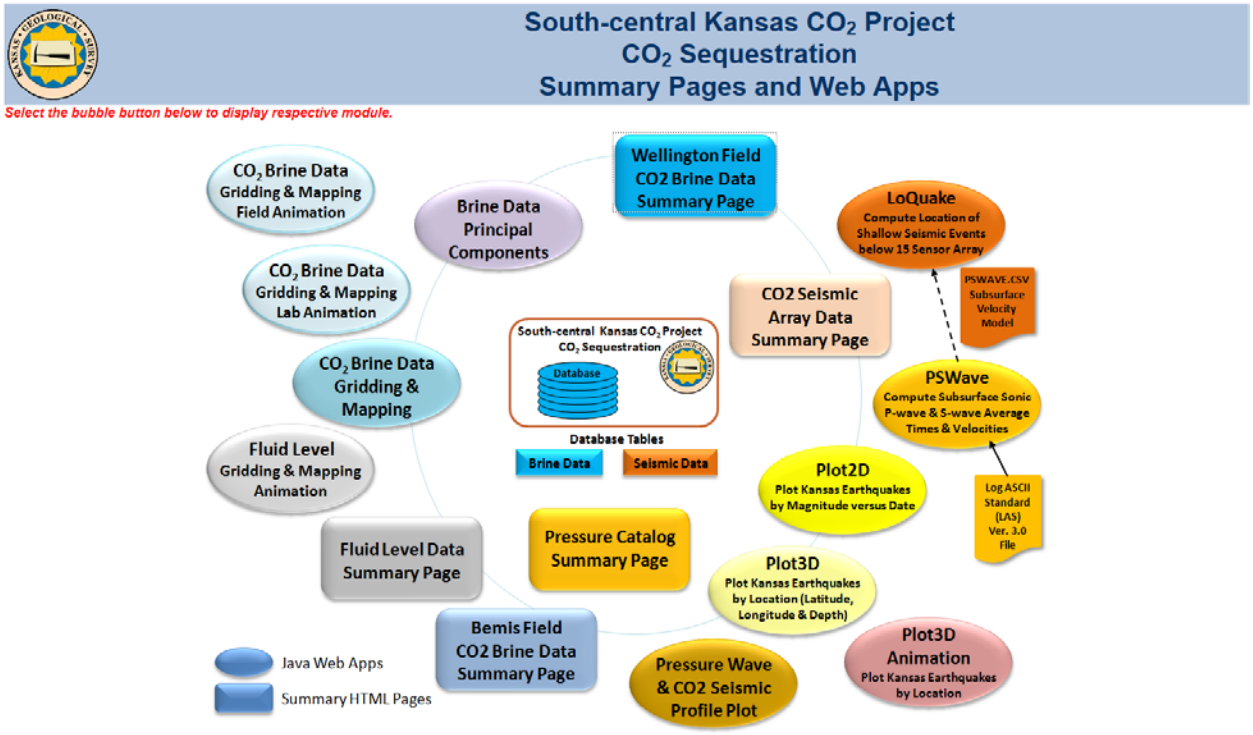
1.5 Well Drilling and Installation Plan (Can be Appendix to PMP or Quarterly Report)
1.6 MVA Plan (Can be Appendix to PMP or Quarterly Report)
1.7 Public Outreach Plan (Can be Appendix to PMP)
1.8 Arbuckle Injection Permit Application Review go/no go Memo
1.9 Mississippian Injection Permit Application Review go/no go Memo
1.10 Site Development, Operations, and Closure Plan (Can be Appendix to PMP)
2.0 Suitable geology for Injection Arbuckle go/no go Memo
3.0 Suitable geology for Injection Mississippian go/no go Memo
11.2 Capture and Compression Design and Cost Evaluation go/no go Memo
19 Updated Site Characterization/Conceptual Models (Can be Appendix to Quarterly)
21 Commercialization Plan (Can be Appendix to Quarterly Report).
30 Best Practices Plan (Can be Appendix to Quarterly or Final Report)

CO_2-EOR Accomplishments

1. Day-to-day field operations similar to that reported in previous two quarters (Q21 and Q22) and are a continuation of Tasks 12–15
2. Continued monitoring of CO_2 plume movement
   a. Recorded volumes of CO_2 produced, oil, and brine recovered
   b. Only seven wells are being monitored based on past geochemical analyses that indicate the CO_2 plume has largely stabilized. Wells are currently being sampled for on-site (performed by KGS) and lab-based geochemical analyses (performed by Baker Chemicals). CO_2 gas quality measurements are being performed by Berexco staff.
3. The primary CO_2 plume has been managed by pressure maintenance including use of two nearby injection wells and targeted fluid withdrawal in eight surrounding wells. The CO_2 injection conforms largely to the stratigraphic architecture recorded in the geocellular model. Key work for the remainder of the CO_2-EOR phase is to continue measuring all inputs and

outputs to obtain accurate measurement of CO_2 sequestered in the reservoir and the incremental oil produced from a single injection cycle.

4. On June 30, 2017 the daily CO_2 amount recorded was 1-5 MCFD. As of June 30, 2017, the cumulative produced CO_2 accounts for 18% of the injected volume (no change from December, 2016).
5. Decline curve analysis for the Mississippian CO2 EOR flood was updated, it was estimated that 32 Mstb of additional oil will be recovered from the Wellington field.
6. Analysis of the active source seismic (2D and 3D data) has continued since the last reporting period.
7. Induced seismicity monitoring at Wellington Field and surrounding area has continued with over 2100 earthquakes have been documented from April 2015 to present, ranging in magnitude from 0.4 to 2.5
8. Data collected for the project is constantly being updated and pre-processed for uploading into web-based interactive database catalogue (Figure 1).



http://www.kgs.ku.edu/PRS/Ozark/Summary/CO2_II.html

Figure 1. Wellington Field project data processing and archiving activities.

Geological storage and Class VI Permit Accomplishments

1. Wellington project team continues earthquake activity with 15 seismometer stations on loan from IRIS, 3 KGS seismometers and regional USGS stations: over 2,100 earthquakes have been documented (magnitude 0.4-2.5) since April 2015, northward progression from

Oklahoma is recorded, 2.1 TB of Wellington earthquake data provided to DOE NETL in July 2017, several publications are in preparations or have been accepted.

2. Since mid-April 2016, continuous (1-sec) baseline pressure measurements have been acquired in the perforated lower Arbuckle zone in the shut-in Class VI injector. Because of this monitoring, the well has not been retrofitted for installation of MVA tools (BP2 Milestone).
3. Berexco's financial and insurance teams are researching viable approaches for providing insurance or alternative methods to satisfy financial responsibility requirements for UIC Class VI permit.

Q23 TASKS

Site Characterization of Mississippian Reservoir for CO_2-EOR –Wellington Field

The CO_2 injection was completed in 165 days or approximately 5 months with an average of 120 tonnes per day of CO_2 injected (Figure 2). Oil production rates remain at about 22–25 BOPD with some decline due to field scheduled maintenance. On June 30, 2017 the daily CO_2 amount recorded was 0 MCFD; however, some wells occasionally still produce CO_2 with the total average production rate of 1-2 MCFD. As of June 30, 2017, the cumulative produced CO_2 remains at approximately 18% of the injected volume. Only the seven innermost wells are currently being sampled for on-site (performed by KGS) and lab-based geochemical analyses (performed by Baker Chemicals). The low amounts of recovered CO_2 (Figure 2) and evidence of diffusion in brine data indicate the flood is conformable and is not bypassing through conductive fractures. Key observations this quarter:

1) Incremental oil production is 2X greater than before injection (Figure 2);
2) Temperature fluctuations in Well 47 mainly stabilized;
3) The amount of CO_2 vented remains very low (Figure 2).

These observations are consistent with the cessation of CO_2 injection and the flood-front sweeping laterally away from the injector. In addition, efforts were made in the field to control CO_2-related corrosion within the pilot area.

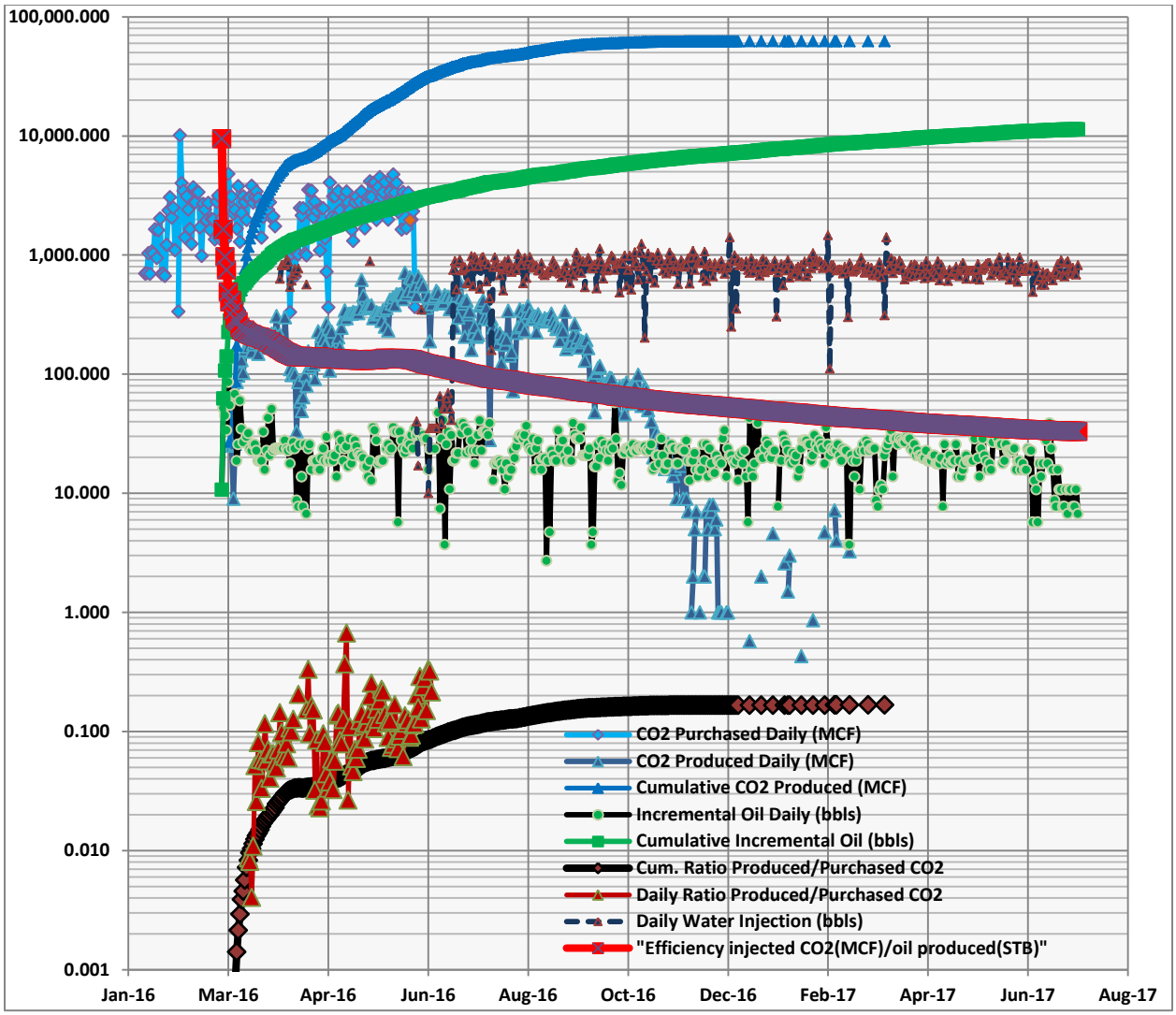


Figure 2. CO_2 injected and CO_2 and oil recovered in pilot scale injection in the Mississippian oil reservoir in Wellington Field.

DECLINE CURVE ANALYSIS UPDATE

Harmony software calculated the cumulative oil production for each curve in the table below from the start of the forecast to April 2027. The difference between the two cumulative oil productions is the cumulative additional oil by CO_2 flood (the area between the two curves in Figure 3). The area between the curves equals to ~32 Mstb, which is the cumulative additional oil production by only CO_2 flood. Cumulative oil production by CO_2+waterflood from initial CO_2 response to April 2027 is ~69 Mstb (Table 1). However, additional observations next month may change the slope.

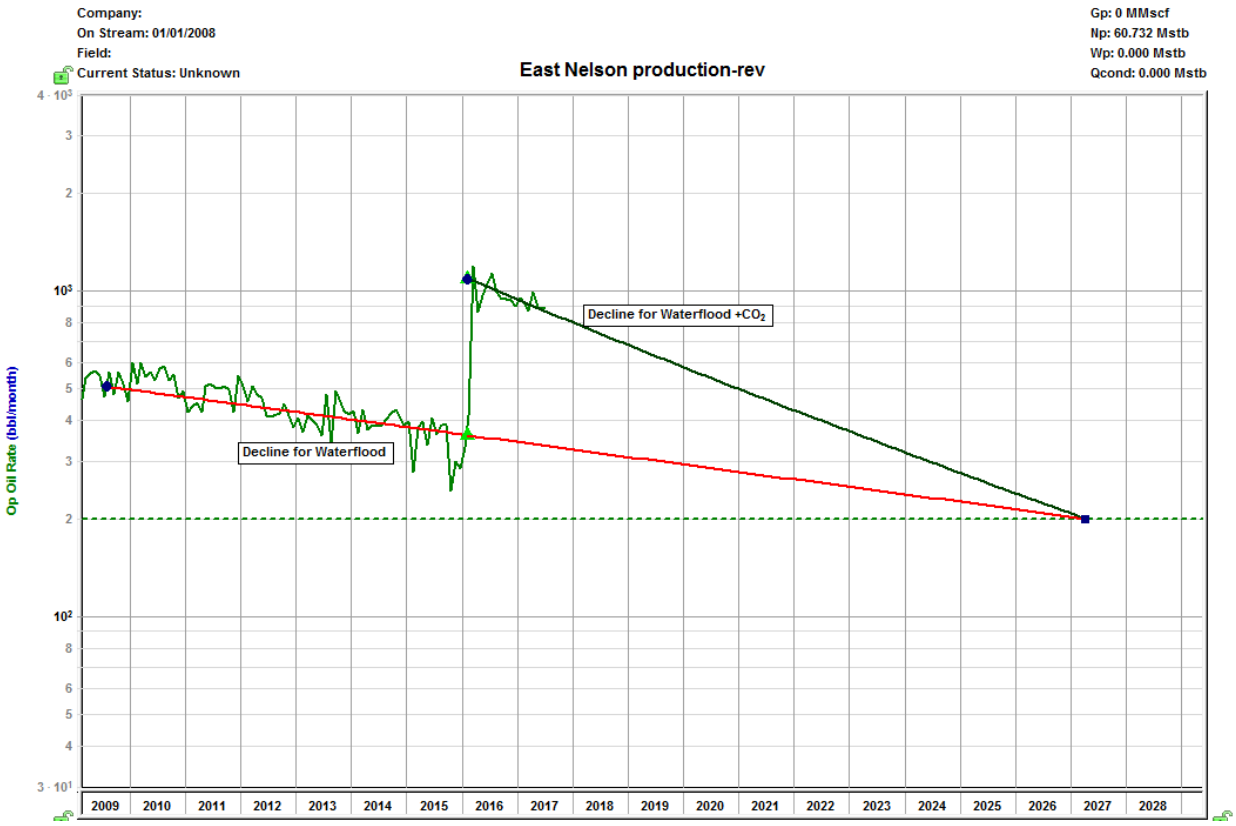


Figure 3. Decline curve analysis for Wellington Field.

Table 1. Cumulative oil production predictions

			Oil Decline						
			From Start of Decline	From Start of Forecast					
	Display Name	Analysis Name	Start Date	Initial Oil Rate	Forecast Start Date	Initial Cumulative Oil Production	End Date	Delta Time	Delta Cumulative Oil Production
			MM/DD/YYYY	stb/d	MM/DD/YYYY	Mstb	MM/DD/YYYY	month	Mstb
1	East Nelson production-rev	CO2 +Waterflood	02/01/2016	35.9	02/01/2016	44.894	04/06/2027	134.134	68.982
2	East Nelson production-rev	Waterflood only	08/01/2009	11.8	02/01/2016	44.894	04/06/2027	134.134	36.542

ACTIVE SOURCE SEISMIC (2D AND 3D DATA) ANALYSIS

Analysis of the active source seismic (2D and 3D data) has continued since the last reporting period.

Monitoring of the CO_2 injection in KGS 2-32 using time-lapse 2D seismic

One 2D seismic line was acquired along KGS 2-32 by Paragon in early summer of 2016 (June-July) immediately following completion of the CO2 injection in the Mississippian reservoir. Data was processed and delivered in December 2016. Analysis of the 2D seismic is ongoing, comparing to the pre-injection data acquired in 2010.

Fluid substitution seismic modeling in the Mississippian has been revised using actual CO_2 injection properties and well-logs from KGS 2-32. Post stack (normal incidence reflection) modeling shown in figure below. It predicts impedance decline of approximately 3% (Figure 4).

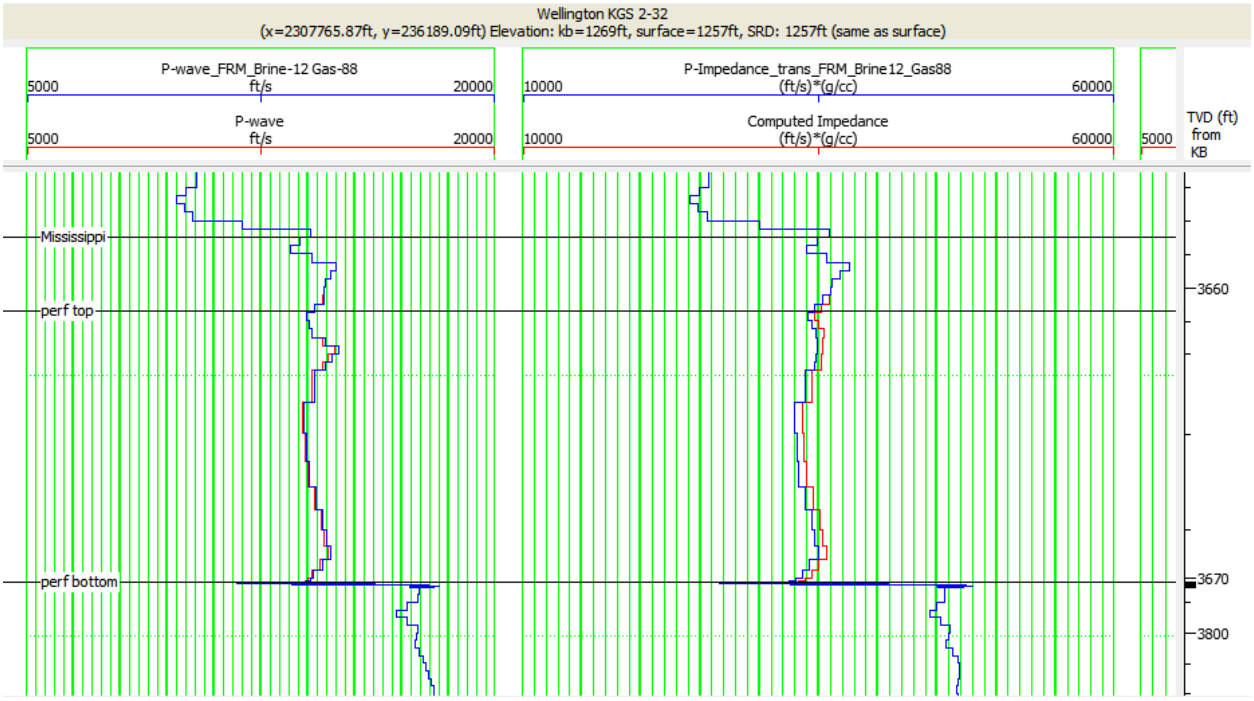


Figure 4. Fluid substitution model of P-wave velocity (left) and acoustic impedance (velocity * density) (right) for the Mississippian CO_2 injection interval in KGS 2-32. Measured well curves are shown in red. Modeled curves in blue. Impedance and P-wave velocity decrease due to the presence of CO_2

Analysis of the new 2D stacked seismic line exhibits a small decrease in amplitude which is in agreement with the predicted small impedance decline. However, ambiguity in delineating the CO_2 plume remains due to the small magnitude of changes that can be easily masked by data noise. Furthermore, the plume column is "thin" relative to seismic wavelengths, further challenging imaging. Ongoing analysis is examining seismic data in the pre-stack domain employing AVO (Amplitude Variation with Offset) and impedance inversion for assessing seismic reflection imaging of the CO_2 plume in the Mississippian.

Seismic reflection imaging of stress and fracture zones in the Mississippian and Arbuckle

Group has continued to assess the use of AVAZ (Amplitude Variation with AZimuth) pre-stack method for mapping of subsurface seismic anisotropy which is linked to subsurface stress field, fracture density and orientation in the Mississippian reservoir and the Arbuckle saline acquirer (Figure 5). Seismic anisotropy observations are in agreement with natural fracture sets observed in borehole Formation Micro Imaging (FMI) logs, dipole-dipole sonic logs, regional fault maps, and regional earthquake focal mechanism analysis. Furthermore, seismically mapped fractures in

the Mississippian reveal reservoir permeable paths that are in agreement with borehole monitoring of CO_2 migration through the reservoir.

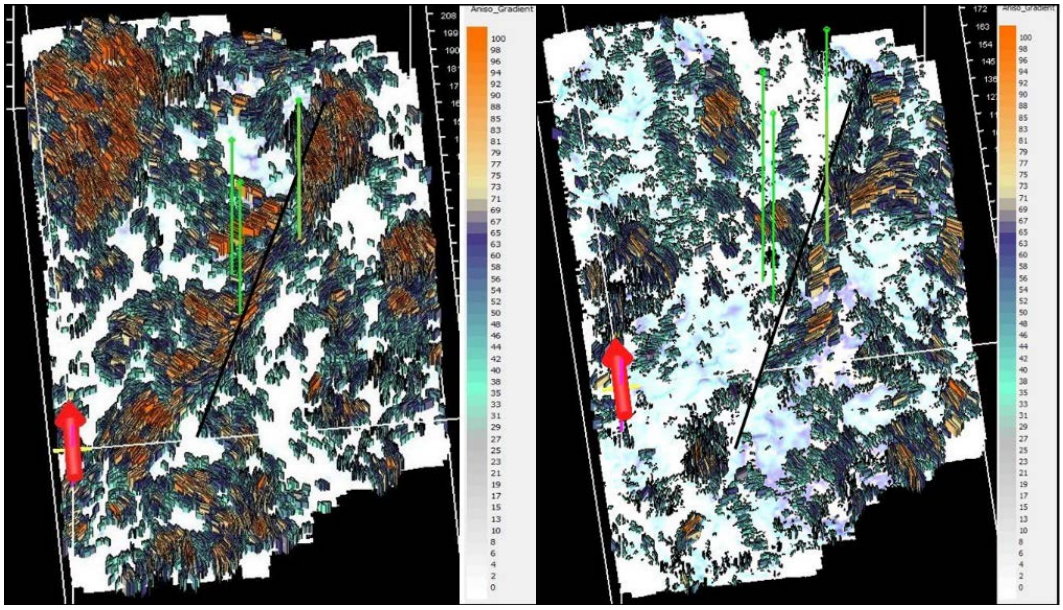


Figure 5. Tilted perspective of the azimuthal planes of isotropy at the Mississippian reservoir (anisotropy gradient 33%-100% in color) (left) and the Arbuckle (anisotropy gradient 25%-100% in color) (right). The orientation can be interpreted as fractures and stress direction, and the size and color is the degree of anisotropy. The black line delineates a fault mapped in the 3D seismic. Wells KGS# 1-32, 2-32 and 1-28 are sown in green (from left to right).

Induced seismicity monitoring at Wellington Field and surrounding area

Group has continued to diligently monitoring local earthquake activity using 15 seismometer stations on loan from IRIS, 3 KGS seismometers and regional USGS stations (Figures 6 & 7).

- Over 2,100 earthquakes have been documented from April 2015 to present, ranging in magnitude from 0.4 to 2.5, constituting a uniquely dense, high-resolution[1] seismicity data set.
- No seismicity has been detected at or near the Mississippian CO_2 injection well KGS 2-32.
- The regional earthquake data has revealed a northward progression of seismicity during the monitoring period, from the Oklahoma border to now reaching the Wichita metropolitan area.
- Time-lapse analysis of seismic anisotropy by observation of S-wave splitting shows that fluid pore pressures in the area have increased. This is the first direct observation of pore fluid pressure induced earthquakes in the region (Nolte et al., in review Science Advances).

[1] It should be noted that the USGS reports earthquakes greater than magnitude 2.5, thus information on smaller magnitude induced events is only available through the Wellington network.

- This unprecedented pore pressure increase inferred by earthquake observations has also been monitored by pressure/temperature sensing in KGS 1-32 at the lower Arbuckle (30 m above basement).
- Group continues to communicate with DOE NETL, Pittsburgh, PA regarding 2.1 TB of Wellington earthquake data shared with the group.

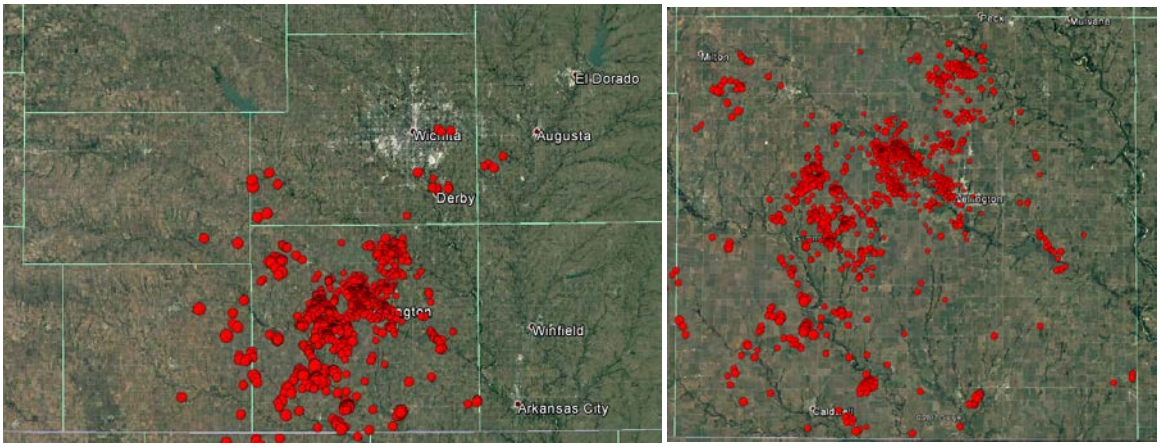


Figure 6. (left) Regional map of earthquake epicenters from the Wellington catalogue. (right) Earthquakes observed in Sumner County, KS.

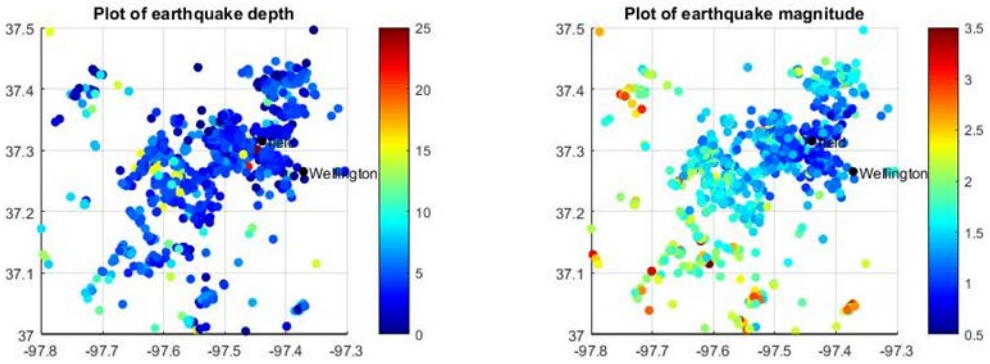


Figure 7. (left) Local map of earthquake hypocenter depth from the Wellington catalogue. (right) Earthquake magnitudes.

SUMMARY

1. Produced (i.e., vented) CO_2 accounts for 18% of the CO_2 injected, no significant changes from previous quarter.
2. The Wellington seismometer array provides a dependable earthquake catalog and is updated on a weekly basis.
3. CO_2 fluid substitution seismic modeling in the Mississippian was completed and it predicts 15% change in zero-offset (stacked seismic) reflectivity.
4. Additional confirmations of Arbuckle saline aquifer reginal pore pressure increase are continue to arrive from various sources

5. Mapping of fracture density and orientation in the Mississippian reservoir and the Arbuckle saline acquirer was performed and it is currently in agreement with field performance and geochemistry data.
6. Shallow vs. deep pressure monitoring techniques were compared and initial results are being prepared for a peer-revived publication.
7. AoR related RfIs were successfully closed with EPA UIC Class VI well permit review team.

PROJECT SCHEDULE

Wellington project currently is scheduled to end is September 30, 2017.

MILESTONE STATUS REPORT

Task	Budget Period	Number	Milestone Description	Status
Task 2.	1	1	Site characterization of Arbuckle Saline Aquifer System – Wellington Field	Completed
Task 3.	1	2	Site Characterization of Mississippian reservoir for CO_2 EOR – Wellington Field	Completed
Task 10.	2	3	Pre-injection MVA – establish background baseline readings	Completed
Task 13.	2	4	Retrofit Arbuckle injection well (#1-28) for MVA tool installation	Completed
Task 18.	3-yr1	5	Compare simulation results with MVA Data and analysis and submit update of site characterization, modeling, and monitoring plan	Completed
Task 22.	3-yr1	6	Recondition Mississippian boreholes around Mississippian CO_2-EOR injector	Completed
Task 27.	3-yr2	7	Evaluate CO_2 geologic storage potential of CO_2 EOR pilot	Completed
Task 28.	3-yr2	8	Evaluate potential of incremental oil recovery and CO_2 geologic storage by CO_2 EOR – Wellington Field	In Progress

FUTURE PLANS

1. Discuss and outline filed closure and reporting activities with DOE.
2. Continue post-injection monitoring on a monthly basis for wells that are responding to flood.
3. Continue operation of the Wellington seismometer array.
4. Continue baseline pressure measurements in the perforated lower Arbuckle zone of the shut-in Class VI injection well.
5. Continue to acquire SAR satellite images and recording cGPS for analysis of ground motion
6. Continue contrast 2-D seismic (pre-and post-CO_2 injection in the Mississippian) to determine plume's extent.
7. Passive seismic monitoring will continue as a very important component for DOE and EPA.

PRODUCTS

Publications, conference papers, and presentations (* indicates student presenter)

Holubnyak Y., Watney W., Bidgoli T.S., Tsoflias G., Birdie T., and Hollenbach J., Wellington Field Faults and CO_2-EOR, Webinar with British Geological Survey, July 25, 2017

Holubnyak Y., Williams E., Watney W., Bidgoli T.S., Rush J., Fazelalavi M., and Birdie T., Calculation of Fluid Storage Capacity for Arbuckle Group in Southern Kansas: Implications for a Seismically Active Region, Webinar with Oklahoma Corporate Commission, Kansas Department of Health and Environment, and others, July 7, 2017

Holubnyak Y., Watney W., Bidgoli T.S., Tsoflias G., Birdie T., and Hollenbach J., Small Scale Field Test Demonstrating CO_2 Sequestration in Arbuckle Saline Aquifer and by CO_2-EOR at Wellington Field Sumner County, Kansas, 12^{th} CO_2 GeoNet Open Forum, May 9, 2017

Holubnyak Y., Watney W., Birdie T. Hollenbach J., and Bidgoli T.S., Experience of Wellington Field Small Scale Demonstration Project with US EPA UIC Class VI Application Process, 12^{th} CO_2 GeoNet Open Forum, May 9, 2017

Holubnyak Y., Watney W., Jackson C., Campbell B., and Victorine J., Geochemical Monitoring Survey Results from CO_2 EOR at Wellington Field in South Kansas

Nolte K.A., Tsoflias G.P., Bidgoli T.S. and L.W. Watney, Shear-Wave Anisotropy Reveals Pore Fluid Pressure Induced Seismicity in the US Midcontinent, Science Advances (in review).

Molina Z.*, Nolte K.* and G. Tsoflias (2017), An Overview of Injection Induced Seismicity in Kansas and Oklahoma, SACNAS National Conference, Salt Lake City, UT., USA, Oct. 19 - 21, 2017 (submitted).

Nolte K. A.*, Tsoflias G. P., Bidgoli T. S., and W. L. Watney (2017), Monitoring Seismicity Near an Active CO2 EOR Injection, in DOE NETL Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting, Pittsburgh, PA, August 1-3, 2017. (accepted)

Graham, B. L. *, Haga, L. N. *, Nolte, K. A. *, Tsoflias, G. P., and W. L. Watney (2017), Fracture Mapping and Feasibility of Monitoring CO2 in situ From Seismic Data at the Mississippian Carbonate Reservoir, Wellington Oil Field, South-Central Kansas, in DOE NETL Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting, Pittsburgh, PA, August 1-3, 2017. (accepted)

Molina Z.*, Nolte K.* and G. Tsoflias (2017), Injection Induced Seismicity in Sumner County, Kansas, KU Undergraduate Research Symposium, Lawrence, Kansas, July 28, 2017.

Molina Z.*, Nolte K.* and G. Tsoflias (2017), Monitoring Induced Seismicity in Sumner County, Kansas, KU Undergraduate Research Symposium, Lawrence, Kansas, April 22, 2017. Awarded "Outstanding Student Presentation".

Nolte A.*, Tsoflias G. P., Bidgoli T. S. and W. L. Watney (2017), Understanding the Temporal-Spatial Relationship of Induced Seismicity in Southern Kansas, KU Graduate Research Symposium, Lawrence, Kansas, April 6, 2017.

Personnel and additional cost-share funding sources

George Tsoflias, Professor, KU Department of Geology, Geophysics

3D AVAZ analysis: Brandon Graham, MS graduate student, Graduate Research Assistantship (GRA) funded by DOE and Kansas Interdisciplinary Carbonates Consortium (KICC).

2D CO_2 monitoring: Lauren Haga, MS graduate student, hourly wage from KICC and Tsoflias overhead account, Summer GRA from KICC.

Earthquake monitoring

Alex Nolte, MS graduate student, academic year Graduate Teaching Assistantship (GTA), KU Department of Geology, and summer GRA support from DOE.

Zalma Molina, Undergraduate research assistant, funded by KU Emerging Scholars, Center for Undergraduate Research during academic year. Summer support as hourly undergraduate research assistant from DOE.

Other activities

Yevhen Holubnyak,CO_2GeoNet Open Forum participation was funded by KU Department of Geology and Kansas Geological Survey

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

A project organization chart follows (Table 2). The work authorized in this budget period includes office tasks related to preparation of reports and application for a Class VI permit to inject CO_2 into the Arbuckle saline aquifer, and operational field activities relevant to the project.

Table 2. Updated Organizational Chart.

Organizational Structure
Small Scale Field Test – Wellington Field (FE0006821)

Name	Project Job Title	Primary Responsibility
UNIVERSITY OF KANSAS Center for Research		
Kansas Geological Survey		
W. Lynn Watney	Joint PI	Geology, Information Synthesis
Yevhen 'Eugene' Holubnyak	Joint PI, Project Manager	Reservoir Engineering, Dynamic Modeling, Data Integration, Synthesis, Point of Contact
Tiraz Birdie	Consulting Engineer	Hydrological Engineering, Dynamic Modeling, Injection Permit Application Preparation, Synthesis
John Doveton	Co-PI	Log-petrophysics, geostatistics
Kerry D. Newell	Co-PI	Fluid geochemistry
Tandis Bidgoli	Strucrural Geologist	Strucrural geology, induced seismicity
Fatemeh 'Mina' FazelAlavi	Engineering Assistant	Log analysis, well test analysis, reservoir engineering
John Victorine	Software Programmer	Database management, well tool design, data processing
KU Department of Geology		
George Tsoflias	Co-PI	Wellington Seismometer Array, Seismic imaging
Jenifer Roberts	Co-PI	Microbial geochemistry
Leigh Sterns	Affiliated Scientist	cGPS processing for InSAR interpretation
Berexco, LLC		
Dana Wreath	Vice President	Management, engineering
Staff at Wellington Field		Daily operations
Berexco Drilling Team		Drilling, completions
Lawrence Berkley National Laboratory		
Tom Daley	Co-PI	Geophysics, crosshole and CASSM data
Barry Freifeld	Co-PI	Mechanical engineering, U-Tube
T.Birdie Consulting		
Trilobite Testing, Inc.		

Wellington project is currently participating in site-twining activities associated with ENOS European initiative that includes European geological surveys, universities, and research centers (project website: http://www.enos-project.eu/)

IMPACT

The response of the CO_2-EOR has been successful. Downhole pressure monitoring is important in validating hypotheses to explain the effects of large scale injection and induced seismicity in Mid. Continent region. All of information requested by EPA by has been submitted for the application of a Class VI injection permit with exception of financial responsibility documents.