“Modeling CO₂ Sequestration in Saline Aquifer and Depleted Oil Reservoir to Evaluate Regional CO₂ Sequestration Potential of Ozark Plateau Aquifer System, South-Central Kansas”

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²Currently China Geosciences University, Wuhan

DOE Contract #FE0002056 and partner cost share
Industry Partners (Enhancement to FE0002056)

SW Kansas CO₂ Consortium/Western Annex

HEDKE-SAENGER GEOSCIENCE, LTD

Industrial and Electrical Power Sources of CO₂

Dawson-Markwell Exploration Co.
Outline

• Background
• Status of Project
• Regional Analysis
• Wellington Activities
  – Drilling, coring, core and log analysis
  – Step rate test between #1-32 and #1-28
  – 3D multicomponent (converted wave) and 2D-9C seismic processing and interpretation → toward refined 3D geomodel and simulation
  – Hydrogeochemistry and Microbial Research
• Southwest Kansas CO₂ Consortium (Chester/Morrow EOR)
• Summary

NETL Program Manager: Brian Dressel
Project Overview

- Start Date - Dec 2009
- Build static geomodels
  - Wellington field (Sumner County, KS)
    - Depleted Mississippian oil field
    - Underlying Arbuckle saline aquifer
  - Four Chester/Morrow field in SW KS
    - Regional Arbuckle saline aquifer
- Conduct simulation studies to estimate CO₂ storage capacity
- Arbuckle saline aquifer – 23 county area
  - Identify potential ~8 CO₂ storage sites
  - Estimate storage capacity of Arbuckle saline aquifer in southern KS
- Risk analysis related to CO₂ sequestration
  - Caprock integrity
  - Rock heterogeneity including fault mapping
  - Assess abandoned wells
- Technology transfer
Regional Arbuckle Saline Aquifer & EOR-CO2 Mississippian chert reservoir Wellington Field (DE-FE0002056)
2009-2013

Small Scale Field Test @Wellington DOE-FOA -441 (FE0006821) (BEREXCO) Funded Oct 1, 2011-2015

Horizontal Test in Arbuckle -- Bemis-Shutts Field, Ellis Co. DE-FE0004566 (Vess-Murfin Drilling) 2010-2013

Regional Assessment of deep saline Arbuckle aquifer

Abengoa Bioenergy (Colwich ethanol) Western Annex CO2 Industry Consortium (Chester-Morrow oil fields & Arbuckle)

Sunflower Electric Holcomb Station Power plant

Westar Jeffrey Energy Center

50 miles

http://www.kgs.ku.edu/PRS/petro/ogSheetMap.html
Gantt Chart Review
FE00002056
2011 (BP2) Tasks - Completed, In Progress

**Start Date Dec. 8, 2009**
End date: August 7, 2013

Regional geomodel development of Arbuckle saline aquifer
- Collect, process, interpret 3D seismic data - Wellington field
- Collect, process, interpret gravity and magnetic data - Wellington field
- Drill, core, log, and test - Well #1
- Collect, process, and interpret 2D shear wave survey - Well #1
- Analyze Mississippian and Arbuckle core
- PVT - oil and water
- Geochemical analysis of Arbuckle water
- Cap rock diagenesis and microbiology
- Drill, log, and test - Well #2
- Complete Wellington geomodels - Arbuckle and Mississippian reservoirs
  - Evaluate CO2 sequestration potential in Arbuckle underlying Wellington
  - Evaluate CO2 sequestration potential in CO2-EOR in Wellington field
- Risk assessment - in and around Wellington field
- Regional CO2 sequestration potential in Arbuckle aquifer - 17+ counties
- Technology transfer
  (Site visits; stakeholders and legislative, Governor presentations; Wellington Chamber of C.)

* Updated geomodels to be completed in January-March 2012 --
  1) Depth migrated, converted shear wave, volumetric curvature, and simultaneous inversion of multicomponent 3D
  2) Core analysis from #1-32 to calibrate porosity and permeability estimates from wireline logs (NMR)
  3) Petrel geomodel to utilize shear wave anisotropy and fracture analysis, dynamic bulk moduli from seismic calibrated with core measurements and dipole (spectral) sonic, NMR, microresistivity imaging, and density logs
Well Data Inventory
Wells with LAS or Raster = 3792

Regional Team
- Developed regional database
- Correlated logs and identified Type Wells for digitizing to LAS files
- Established that Arbuckle is an open aquifer system, hydraulically connected to outcrops in Missouri (~150 miles to east)
- Evaluating faults, fractures, flexures
- Establishing additional 8+ sites in region for additional simulation beyond field studies

Non-Faulted Structural Closures
Candidate: Township 22S-2W
Arbuckle Subsea C.I. 25 ft

Precambrian Test

Calculated Pressure vs. Observed Pressure (psi)

6874 ARBK Dst's (observed gradient filtered)

0.465 psi/ft

6874 DSTs
Published faults are being compiled and new ones are under investigation. Focus on quantitative assessment of CO₂ storage capacity of Arbuckle saline aquifer is within dashed blue area.

Supertype Wells (263):
- Digitized to LAS
- Penetrate at least 2/3rd Arbuckle
- Modern log suite

Wellington Field

- Top Arbuckle Group

...
Quantitative characterization of Arbuckle in southern Kansas

Lower Arbuckle Porosity Zone (Gasconade to Gunter Ss.) at Wellington Field

Quantitative Reservoir Characteristics  Correlated to  Internal Arbuckle Stratigraphy

Example stratigraphic cross section of lower Arbuckle from top Rubidoux (datum) to basement including new and old well data (insoluble residue logs, georeports, and modern suite of logs managed as LAS files)
2-10 mile filtered Total Magnetic Field Intensity and Magnetic Tilt Angle overlain by isopach Gasconade to Gunter Sandstone

--> Lower Arbuckle Porosity Zone at Wellington Field

Menu used to select maps on interactive mapper (link below)

http://maps.kgs.ku.edu/co2/?pass=project
Wellington Field

1) Mississippian tripolitic chert/dolomite reservoir (20+ million barrels produced)

1) Arbuckle saline aquifer

2) Intervening caprocks

- New core and logs from KGS #1-32 and logs from #1-28 obtained in Jan-Feb. 2011
- Using to assess --
  - Integrity of caprocks
  - Porosity types, injectivity, and storage
  - Model potential for CO2-EOR in Mississippian saline aquifer
  - Sequestration in Arbuckle

(Start Oct. 1, 2011) Small scale field test with 70k tonnes CO2 into Arbuckle – MVA deployment and testing – LiDAR/InSAR, shallow groundwater monitoring, microseismic monitoring Mississippian reservoir – underpressured, well sampling, 2D high resolution seismic Arbuckle - in situ cross hole tomography, U-tube plume sampling, CASM (continuous seismic imaging), repeat 3D

Also, 30 Tonnes CO2) into Mississippian reservoir
Surface location of stratigraphic tests drilled in Wellington Field during Jan-Feb 2011

- KGS 32-1
- KGS 28-1 (Proposed injector, Small scale field test)

Map showing the surface location of the tests with distances marked and wells labeled.
Drill, Core, Log, Test Berexco Wellington #1-32
Spudded 12/30/10
Reached TD 2/9/11

Ran new, API 5½", 15.5# casing. Set @5238'. **Cemented from 5238’ to surface in three stages.** Ran casing to TD. Tagged bottom & pulled up 2’. DV’s @3938’ and 2460’. Baskets @4860’, 4480’, 3980’, 3510’, 2500’, and 980’. Centralizers every 3rd collar from TD to 3100’. Centralizer above and below each basket and above and below each DV. Had good circulation. Cemented bottom stage w/200 sacks AA2 @15 ppg w/10% salt, 6# Gilsonite, and **C-44 Gas Blok CO2 resistant additive.** Had good circulation during job.
Stratigraphic Column
Berexco Wellington KGS #1-32
Completed at Wellington Field
February 2011
Conventional 4.5 inch core from base Pennsylvanian shales to basement (3550-5178 interval, 1628 gross ft, 1528 net feet)

Top core = 3550 ft

Pennsylvanian shales – OPAS caprock
Mississippian – chert (EOR)
Tight lower Mississippian argillaceous carbonates
Chattanooga-Simpson Group caprock
Arbuckle Group
Potential baffles

Strong oil show

Proposed injection zone

Multiple intervals of thick shale and interbedded Pennsylvanian and Permian carbonate strata

Top core = 3550 ft

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Multiple intervals of thick shale and interbedded Pennsylvanian and Permian carbonate strata

http://www.kgs.ku.edu/stratigraphic/PROFILE/
Pennsylvanian Cherokee Shale (primary caprock on top of OPAS /Mississippian)

Lower Mississippian-Devonian shale & argillaceous carbonate on shale and sandstone of Upper Ordovician Simpson Group (caprock on top of Arbuckle)
Preliminary analysis of nuclear magnetic resonance (Halliburton’s MRIL) log in Arbuckle Group compared with core in Wellington #1-32

Lithofacies from core (vertical columns) (x)
0 = no core recovered
1 = shale
1.5 = argillaceous dolomudstone
2 = mudstone-wackestone
3 = packstone-grainstone
4 = grainstone
5 = incipient autoclastic breccia
6 = autoclastic breccia
7 = quartz sandstone

Derived from relaxation time of NMR log:
$$\text{PHI} (+) = \text{sum of porosity in T2 channels}$$
$$\text{CG} (\Delta) = \text{center of gravity of T2 spectrum}$$
units are powered relaxation times
e.g. $T2 = CG^2$

=>larger number, larger the size of pores

• Discontinuous fracturing
• Karst overprinting
• Lithofacies control porosity & permeability in persistent stratal packages
ZONAL FRACTURES AND AUTOCLASTIC BRECCIAS IN THE POROUS INTERVALS OF THE ARBUCKLE
Proposed Arbuckle CO₂ Injection
Well At Wellington Field
Berexco Wellington KGS #1-28

Cement Integrity

1. CO₂ resistant cement
2. 3-stage centralizers
3. Ran Halliburton’s Radial Cement Bond Log to evaluate cementing of casing string
4. Eight sectors concentric cement map (image)

- Cement map showing good bonding (brown) and no channeling
- Less well cemented, horizontally oriented zones (white and blue)
MAXIMUM HORIZONTAL COMPRESSIVE STRESS from microresistivity imaging and dipole sonic logs (KGS #1-32)

Fracture Statistics: 5239’-3528’

Natural mineralized “closed” fractures

Induced fractures

There are natural mineralized “closed” fractures with two orientations, one E x W and the other NE x SW.

There are 132 drilling induced fractures in this pass, oriented 75°/255°, indicating the maximum stress direction.
Cross section showing location of step rate test and proposed swab intervals in the Arbuckle Group.

Prospective disposal zone (4900 ft to 5030 ft)

Preliminary upscaled hydrostratigraphic units in Arbuckle Group

Coates & Bin Permeability (NMR)

Total & Effective Porosity (NMR)

Cross flow test #1

Step Rate Test 4995-5015 ft

Swab #12 = 4080-4100 ft (Simpson Ss.)

Swab #11 = 4090-4095 ft

Swab #10 = 4096-4097 ft

Swab #9 = 4030-4066 ft

Swab #8 = 4070-4075 ft

Swab #7 = 4050-4056 ft

Swab #6 = 4045-4050 ft

Swab #5 = 4040-4045 ft

Swab #4 = 4025-4035 ft

Swab #3 = 4010-4025 ft

Swab #2 = 4000-4010 ft

Swab #1 = 3985-3995 ft

Cross flow test #2

DST #2 4026-4028 ft

Cross flow test #3

Swab #8 = 3970-3980 ft

Swab #7 = 3950-3960 ft

Swab #6 = 3925-3930 ft

Swab #5 = 3910-3915 ft

Swab #4 = 3900-3905 ft

Swab #3 = 3885-3890 ft

Swab #2 = 3865-3870 ft

Swab #1 = 3850-3855 ft

Swab #8 = 3830-3835 ft

Step Rate Test 5000-20 ft

DST #4 4865-4870 ft

DST #3 4870-4890 ft

DST #2 4890-4900 ft

DST #1 4900-4910 ft

Prospective disposal zone (4900 ft to 5030 ft)
NMR composite log showing locations of test & swabbing intervals in lowermost Arbuckle of well #1-32

- Pulse Test 4995-15 ft
  - 4997.5 to 5049.7; No Core Recovery

- Swab #3 = 5040-45 ft
  - Corresponding to DST #2 in #1-28

- Swab #2 = 5130-45 ft
  - Corresponding to DST #1 in #1-28
STEP-RATE TEST RESULTS: Pressure and temperature vs. delta T in the test injection well, Berexco Wellington KGS #1-32. Note eight separate periods of injection (blue) that are labeled consecutively as at beginning and end of each period. Temperature in red.
STEP-RATE TEST RESULTS: Pressure response in Berexco Wellington KGS #1-28 matches pressure pulses introduced into #1-32

- Tested interval has the best wireline log properties of the Arbuckle and test-based permeability is high, perhaps multiple darcies.
- Pulse test was designed for limited layer and results appear to confirm this.
- Barrier does not limit flow between #1-32 and #1-28 boreholes as suggested by continuity of 3D seismic reflectors.
- 20 ft thick zone may not be optimal for injection since it could act as a “thief zone.”
- Other flow units in the 120 ft thick lower porous Arbuckle (Gasconade to Gunter Sandstone) appear to be better suited for CO2 injection pending final calibration of logs with core analyses and simulation.
Incomplete Set of Whole Core Analyses for Berexco Wellington KGS #1-32

• 475 whole core analyses to be done
• Other intervals → Helical CT Scans
Current Studies in Hydrogeochemistry
Dr. Saugata Datta and Robin Barker, Kansas State U.

• Using collected water (8 DSTs and 1 swab test thus far) and 2-inch core plugs from #1-32 and #1-28 to characterize the hydrogeochemistry and mineralogy of the Arbuckle formation
• Water chemistry defined by ICP-OES and IC from 8 DSTs and one swab test (so far)
• Mineralogy data from thin section, XRD, SEM and CT-scan
• Supercritical flow experiment conducted at the National Energy Technology Lab in Pittsburgh, PA
• Provide kinetics for key reactions of CO₂ with actual rock and brine obtained from Kansas Arbuckle
Depth profiles of DST (connected line) and first swab test (black dot)

Top Arbuckle @ 4160 feet
@ 4520 ft -- Changes in brine composition and microbes at (also low DOC & PO4) indicate low microbiological activity, corresponding with low Ø & k

@ 5000 ft – microbial anomaly suggesting availability of nutrients corresponding with high Ø & k (in interval with step rate test)
Completing Converted (Shear) Wave Processing and Depth Migration of 3D Seismic

Weekend July 31st @ Wellington

#1-28 – completing well for step rate interference test with 1-32 Followed by selective perf & swab in #1-32

Aimee Scheffer - Microbial studies of Arbuckle brines

Wireless recording

6.5 miles 2D-9C Seismic Survey obtained in July-August 2011 for calibration

2D-9C survey by Paragon
2D Shear Wave Line #1 Index Map

Prestack Time Migrated (PSTM) – Top Pennsylvanian Kansas City Group

Test Borehole Location #28-1

Test Borehole Location #32-1
Prestack Time Migration
Coincident w/ Shear Wave Line #1 (3 mi)

Mississippian
Arbuckle
Prestack Depth Migration
Coincident w/ Shear Wave Line #1
(preview of converted wave, depth migrated 3D seismic)
<table>
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<th>Activity-Entity / Timeline</th>
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<th>Dec-11</th>
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<td>Wellington Area</td>
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Southwest Kansas CO2 Consortium (Western Annex)

Seismic blocks are color coded by operator (~120 mi² of 3D seismic)

Chester/Morrow Sandstone (IVF) & Deep saline Arbuckle aquifer
**Southwest Kansas CO₂ Consortium – Technical Team**

### 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.

### 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 Energy</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>
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<tr>
<td>Susan Nissen</td>
<td>3D Seismic</td>
<td>Consultant</td>
</tr>
<tr>
<td>Lynn Watney</td>
<td>Project PI</td>
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<td>Jason Rush</td>
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<td>John Doveton</td>
<td>Log Petrophysics</td>
<td>KGS</td>
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<tr>
<td>Paul Gerlach</td>
<td>Data support</td>
<td>Consultant - Charter</td>
</tr>
</tbody>
</table>
Fields in study in relation to Chester IVF

(Above) Regional isopach of lowermost Chesterian incised valley fill *(Montgomery & Morrison, 2008)*

(Upper Right) Four fields in study. Green – Oil; Brown – Oil and Gas. Grid is Township-scale (6 mi.).
Summary

• Project Start Date Dec. 8, 2009; End date: August 7, 2013
• Delayed start of BP2 until test bore holes #1 & #2 drilled and revised schedule
• Key personnel changes with joint PI Saibal Bhattacharya replaced by Jason Rush and simulation engineering by Eugene Williams
• $5 million budget enhancement used to fund Southwest Kansas CO₂ Sequestration Consortium to anchor western side of regional study area --
  – Led by additional science team with five industry partners
  – 120+ mi² 3D seismic donation
  – Reprocess portion of and interpret donated 3D seismic
  – Field data on four major Chester/Morrow sandstone oil fields
  – Simulate reservoirs to maximize CO₂ storage
  – Select field for 10 mi² multicomponent 3D seismic and basement test with ~2200 ft core
• 2D shear wave survey acquired in Wellington Field in August
  – Use to refine processing and interpretation of existing 12 mi² multi-component 3D seismic survey
• Core Analysis – delivery end November 2011
• Geochemistry & Geobiology – ongoing into 2012
• Revise Geomodel & Simulation – early 2012
Acknowledgements & Disclaimer

Acknowledgements

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