A Nonconventional CO₂-EOR Target in the Illinois Basin: Oil Reservoirs of the Thick Cypress Sandstone

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Champaign, Illinois 61820

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Reporting Period End Date: 9/30/2018
Report Term: Quarterly
Signature of Submitting Official:

Nathan D. Webb: [Signature]
2. ACCOMPLISHMENTS

What was done? What was learned?

Major accomplishments include:

- A preliminary CO\textsubscript{2} storage and EOR resource assessment of the Cypress Sandstone ROZ play was completed. Using the median S\textsubscript{or} from well log analysis of 23\%, an estimated 1.7 billion barrels of ROZ oil in place is contained within defined prospects, of which up to 168 million barrels is estimated recoverable using a continuous CO\textsubscript{2} flood EOR factor of 9.9\%, assuming miscible conditions. Associated CO\textsubscript{2} storage in the ROZs, not accounting for main pay zones or underlying brine aquifers, is estimated to be 7.6 billion tonnes, assuming 45 tonnes/1000 barrels.

What are the major goals of the project and what was accomplished under these goals?

The major goals of the project include identifying and quantifying nonconventional carbon dioxide (CO\textsubscript{2}) storage and enhanced oil recovery (EOR) opportunities in the thick Cypress Sandstone in the Illinois Basin through geologic reservoir characterization, three-dimensional geocellular modeling, fluid properties and interaction modeling, and reservoir simulation. A study of the economics of potential storage and EOR programs in the thick Cypress will be made with considerations for production of net carbon negative oil. Field development strategies will be recommended with emphasis on near-term deployment. Accomplishments towards these goals are listed below by task as outlined in the SOPO.

Task 1.0–Project Management and Planning (on schedule)

- Progress on completion of tasks, subtasks, deliverables, and milestones is tracked using Microsoft Project to ensure timely completion. Overall, this project is on schedule.
- Principal investigator (PI) Nathan Webb and co-PI Scott Frailey, along with Nathan Grigsby, met weekly to discuss project management.
- There were regular meetings with the PI and subtask leaders for active subtasks.
- Daniel Byers, Damon Garner, and Nathan Webb have packaged data and imagery from the two cores collected for the project for online core visualization using the accessible PDF portfolio format. The core visualizations portfolios will be available on the Illinois
Oil and Gas Online Resources (ILOIL) map and data viewer system
(http://maps.isgs.illinois.edu/ILOIL/). An example from the Tripp #1 core is available at
https://uofi.box.com/v/Tripp-Core

Task 2.0–Geology and Reservoir Characterization (on schedule)
Subtask 2.1–Literature Review and Oilfield Selection

- Subtask concluded on 6/30/2015.

Subtask 2.2–Petrophysical Analysis

- Subtask concluded 10/31/2017.
- Nathan Grigsby and Scott Frailey continued work on a publication tentatively titled
  “Methodology for using well logs to identify residual oil zones: An example from Noble
  Field, Illinois.” This method provides a screening tool to assess ROZ potential using
  existing well logs.

Subtask 2.3–Geologic Model Development

- Kalin Howell, Nathan Webb, and collaborators from the University of Illinois Geology
  department continued work on a manuscript that details the Cypress Sandstone geologic
  model with implications for reservoir properties titled “The Sedimentology of a Large
  Fine-Grained Carboniferous River: Facies, Palaeohydraulics, and Implications for
  Reservoir Heterogeneity”

Task 3.0–Geocellular and Reservoir Modeling (on schedule)
Subtask 3.1–Historical Production and Injection Data Analysis


Subtask 3.2–Illinois Basin Crude Oil/Brine-CO₂ Fluid Property Characterization

- Dmytro Lukhtai conducted ambient-condition core flood experiments, using surrogate
  fluids to determine the irreducible water saturation (S_{wirr}) and residual saturation (S_{res})
  of Cypress Sandstone and analogous Pennsylvanian core plugs continued. These
experiments are necessary to determine typical $S_{or}$ that may be encountered in a Cypress ROZ to validate well log techniques (Archie equation) of saturation determination.

- 15 plugs representing the range of porosity (10 to 25%) and permeability (50 mD to 1 D) typically encountered in the Cypress were selected for flooding. $S_{wirr}$ and $S_{or}$ are determined by three methods to increase confidence in results: 1) mass of the saturated plug, 2) Archie equation using the resistivity of the saturated plug, and 3) volume of the effluent produced during the core flood.

- Results from the first five plugs show typical $S_{or}$ values that may be expected in a Cypress ROZ are in the mid-30% range (Table 1). In general, the Archie equation, which is used in well log analysis, underestimates the $S_{or}$.

**Subtask 3.3–Geocellular Modeling of Interwell Reservoir Characteristics**

- The report titled “Assessing the Cypress Sandstone for CO$_2$-Enhanced Oil Recovery and Carbon Storage: Part II - Leveraging geologic characterization to develop a representative geocellular model for Noble Oil Field, Western Richland County, Illinois” has been approved for publication.

**Subtask 3.4–Reservoir Modeling**


**Task 4.0–CO$_2$ EOR and Storage Development Strategies (on schedule)**

**Subtask 4.1–Field Development Strategies**

- To improve the Noble Field history match of from the main pay zone and prepare for full-field development simulations, Fang Yang, Roland Okwen, and Scott Frailey have:
  - a. Performed sensitivity analyses to calibrate the static model of the Noble Field.
  - b. Generated input files of selected field development strategy scenarios as selected based on pattern modeling results.
- Nathan Grigsby determined pore volumes and OOIPs for 40 and 80 acre patterns used for the Noble model (Table 2). These numbers will help determine how effective the
reservoir simulations are (how much of the pore space is filled with CO₂ and how much of the oil was produced).

**Subtask 4.2–CO₂ EOR and Storage Resource Assessment**

- In collaboration with Drs. Steve Henderson and George Asquith (Texas Tech University), Nathan Grigsby continued to refine the regional well log analysis by identifying erroneous resistivity of mud filtrate (Rmf), and calibrating resistivity of formation water (Rw) and cementation exponents.

- Nathan Grigsby re-evaluated wells from Kenner West Field to determine if old e-logs can be used to identify ROZs as part of the regional resource assessment. Nine wells from the 1990s with neutron/density porosity and resistivity/spontaneous potential logs are being used to estimate input parameters for 27 wells from the 1940s have only old e-logs.
  - Oil production from the Cypress between the 1940s and 1990s is expected to move the producing oil water contact (top of ROZ) up, but the oil water contact (base of ROZ) is expected to stay constant. If this outcome can be observed from the log analysis, then the old e-log analysis may prove useful for the regional resource assessment.

  - 27 Cypress ROZ prospects, defined as areas within the ROZ fairway that meet the criteria of having both well log analysis and historical records indicative of the presence of a ROZ, were identified in the Illinois Basin (Figure 1).
  - Using the median S_{or} from well log analysis of 23%, an estimated 1.7 billion barrels of ROZ oil in place is contained within defined prospects, of which up to 168 million barrels is estimated recoverable using a continuous CO₂ flood EOR factor of 9.9% assuming miscible conditions. Associated CO₂ storage in the ROZs, not accounting for main pay zones or underlying brine aquifers, is estimated to be 7.6 billion tonnes, assuming 45 tonnes/1000 barrels.
Subtask 4.3–Economic Analysis

- Scott Frailey selected development scenarios from the results of the new pattern model simulations to use in the revised Noble static model simulations. These scenarios will be used to for the economic analyses of to identify economically feasible CO₂-EOR and storage strategies for the Cypress ROZ in the ILB.
Figure 1. Map of potential ROZ prospects within the Cypress ROZ Fairway. The fairway boundaries are outlined in black and the prospects are shaded in brown. The prospect polygons are overlaid on the regional net isopach map.
### Table 1. Results of first five core flood experiments.

<table>
<thead>
<tr>
<th>Well</th>
<th>Plug Depth</th>
<th>Porosity</th>
<th>Permeability</th>
<th>Mass Swirr</th>
<th>Archie Swirr</th>
<th>Vol Swirr</th>
<th>Mass Sor</th>
<th>Archie Sor</th>
<th>Vol Sor</th>
</tr>
</thead>
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<tr>
<td>121592648800</td>
<td>2757.7</td>
<td>16.8%</td>
<td>374.8</td>
<td>23.0%</td>
<td>20.9%</td>
<td>19.8%</td>
<td>31.0%</td>
<td>35.0%</td>
<td>31.9%</td>
</tr>
<tr>
<td>121012872700</td>
<td>940.5</td>
<td>22.6%</td>
<td>428.2</td>
<td>16.0%</td>
<td>21.5%</td>
<td>13.5%</td>
<td>36.0%</td>
<td>36.0%</td>
<td>45.0%</td>
</tr>
<tr>
<td>121012872700</td>
<td>927.8</td>
<td>24.92%</td>
<td>406.9</td>
<td>21.0%</td>
<td>25.9%</td>
<td>26.9%</td>
<td>42.0%</td>
<td>37.0%</td>
<td>44.9%</td>
</tr>
<tr>
<td>120650139400</td>
<td>2989.4</td>
<td>13.69%</td>
<td>49.5</td>
<td>24.0%</td>
<td>24.8%</td>
<td>21.0%</td>
<td>35.0%</td>
<td>33.0%</td>
<td>34.8%</td>
</tr>
<tr>
<td>121592648800</td>
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<td>19.23%</td>
<td>821.7</td>
<td>21.0%</td>
<td>23.8%</td>
<td>23.4%</td>
<td>33.0%</td>
<td>29.0%</td>
<td>31.8%</td>
</tr>
</tbody>
</table>

### Table 2. Pore volume and OOIPs for the Noble geocellular model. Volumes shown for the entire model and contained within the 40 and 80 Acre patterns.

<table>
<thead>
<tr>
<th>Whole Model</th>
<th>12% porosity cutoff</th>
<th>whole model</th>
<th>Pore Volume</th>
<th>Cubic Feet</th>
<th>US Barrels</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>oil bearing rock</td>
<td></td>
<td>1.35E+10</td>
<td>2.40E+09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All oil (1.033 formation factor)</td>
<td>Pore Volume</td>
<td>1.33E+09</td>
<td>2.37E+08</td>
</tr>
<tr>
<td>Whole Model</td>
<td></td>
<td>MPZ: layers 59-72 So=65%</td>
<td>OOIP</td>
<td>4.99E+08</td>
<td>8.89E+07</td>
</tr>
<tr>
<td>Whole Model</td>
<td></td>
<td>ROZ: layers: 54-58 So=25%</td>
<td>Pore Volume</td>
<td>2.89E+08</td>
<td>5.15E+07</td>
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<tr>
<td></td>
<td></td>
<td>all oil Regime</td>
<td>Pore Volume</td>
<td>4.02E+08</td>
<td>7.16E+07</td>
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<tr>
<td></td>
<td></td>
<td>all oil</td>
<td>OOIP</td>
<td>3.44E+08</td>
<td>6.13E+07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MPZ: layers 59-72 So=65%</td>
<td>Pore Volume</td>
<td>2.47E+08</td>
<td>4.40E+07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ROZ: layers: 54-58 So=25%</td>
<td>Pore Volume</td>
<td>9.73E+07</td>
<td>1.73E+07</td>
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<tr>
<td></td>
<td></td>
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<td>1.41E+08</td>
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<td>6.99E+07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ROZ: layers: 54-58</td>
<td>OOIP</td>
<td>4.02E+08</td>
<td>7.16E+07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>all oil</td>
<td>Pore Volume</td>
<td>3.44E+08</td>
<td>6.13E+07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MPZ: layers 59-72 So=65%</td>
<td>Pore Volume</td>
<td>2.47E+08</td>
<td>4.40E+07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ROZ: layers: 54-58 So=25%</td>
<td>Pore Volume</td>
<td>9.73E+07</td>
<td>1.73E+07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>all oil</td>
<td>Pore Volume</td>
<td>7.77E+08</td>
<td>1.38E+08</td>
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<td></td>
<td></td>
<td>MPZ: layers 59-72</td>
<td>Pore Volume</td>
<td>3.97E+08</td>
<td>7.06E+07</td>
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<tr>
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<td></td>
<td>ROZ: layers: 54-58</td>
<td>Pore Volume</td>
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<td></td>
<td>all oil</td>
<td>Pore Volume</td>
<td>3.42E+08</td>
<td>6.09E+07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MPZ: layers 59-72 So=65%</td>
<td>Pore Volume</td>
<td>2.50E+08</td>
<td>4.45E+07</td>
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<tr>
<td></td>
<td></td>
<td>ROZ: layers: 54-58 So=25%</td>
<td>Pore Volume</td>
<td>9.21E+07</td>
<td>1.64E+07</td>
</tr>
</tbody>
</table>
What opportunities for training and professional development has the project provided?

Three undergraduate students and one recent MS graduate have been involved in research on the project during the quarter. Under advisement of project staff and University of Illinois professors, each student is developing skills in a particular discipline, such as routine and advanced core analysis, thin section petrography, and stratigraphy and sedimentology. The students are learning various techniques for their respective disciplines, and they are meeting and sharing findings with each other to better understand their roles in the larger framework of the project and to gain experience in presenting their research.

How have the results been disseminated to communities of interest?

- The project website (http://isgs.illinois.edu/research/ERD/NCO2EOR) hosts a project summary, staff bios, and downloadable reports and presentations to disseminate project information and findings to the public and other interested parties.
- Draft manuscripts include:
  - Grigsby, N.P., and S.M Frailey, Methodology for using well logs to identify residual oil zones: An example from Noble Field, Illinois.


What do you plan to do during the next reporting period to accomplish the goals?

Task 1.0–Project Management and Planning (on schedule)

- Progress on completion of tasks, subtasks, deliverables, and milestones will continue to be tracked using Microsoft Project to ensure timely completion.
- The PI and co-PIs will continue to meet weekly to discuss project management.
- Regular meetings with the PI and subtask leaders will continue for active subtasks.
- Work will conclude with the availability of core visualization portfolios on the ILOIL website.

Task 2.0–Geology and Reservoir Characterization (on schedule)

Subtask 2.1–Literature Review and Oilfield Selection

- Subtask concluded on 6/30/2015.

Subtask 2.2–Petrophysical Analysis

- Subtask concluded 10/31/2017.
- Nathan Grigsby and Scott Frailey will continue to work on a paper tentatively titled “Methodology for using well logs to identify residual oil zones: An example from Noble Field, Illinois.”

Subtask 2.3–Geologic Model Development

- Kalin Howell, Nathan Webb, and collaborators from the University of Illinois Geology department will continue work on a manuscript that discusses the geologic model of the Cypress Sandstone and implications for reservoir properties titled “The Sedimentology of
a Large Fine-Grained Carboniferous River: Facies, Palaeohydraulics, and Implications for Reservoir Heterogeneity”

Task 3.0–Geocellular and Reservoir Modeling (on schedule)

**Subtask 3.1–Historical Production and Injection Data Analysis**


**Subtask 3.2–Illinois Basin Crude Oil/Brine-CO₂ Fluid Property Characterization**

- SOR core-flood experiments using analog fluids will continue to provide important calibration data for well log analyses.

**Subtask 3.3–Geocellular Modeling of Interwell Reservoir Characteristics**


**Subtask 3.4–Reservoir Modeling**


Task 4.0–CO₂ EOR and Storage Development Strategies (on schedule)

**Subtask 4.1–Field Development Strategies**

- Roland Okwen, Scott Frailey and Fang Yang will complete:
  - History-matching the updated Noble Field reservoir model;
  - Full-field development simulations of selected development strategies based on pattern model results after calibration of static reservoir model;
  - Analysis, interpretation, and reporting of results.

**Subtask 4.2–CO₂ EOR and Storage Resource Assessment**

- Nathan Grigsby and Scott Frailey will continue to work with Drs. Steve Henderson and George Asquith (Texas Tech University) to determine how widespread erroneous Rmfs are and to develop a method to compensate for them.
- Nathan Grigsby will continue to refine the method of using old e-logs to identify ROZs, and attempt to use it in other fields that have many e-logs and few or no neutron/density porosity logs.
- Nathan Webb, Nathan Grigsby, Scott Frailey, and Chris Korose will continue to refine the regional play analyses of the Cypress ROZ.

Subtask 4.3–Economic Analysis

- Scott Frailey will conclude the final economic analysis once the final results of the simulated CO2-EOR scenarios are available.
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<th>Calendar Year</th>
<th>Milestone Title/Description</th>
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<tr>
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<td>Final selection of oilfields for study</td>
<td>3/31/2015</td>
<td>3/20/2015</td>
<td>Agreement between ISGS and DOE project manager to proceed with specific areas of study</td>
<td>100% Complete</td>
</tr>
<tr>
<td>2.0</td>
<td>2</td>
<td>Oilfield data synthesis and analysis</td>
<td>10/31/2015</td>
<td>10/21/2015</td>
<td>Wells/leases grouped into classes representing relative degree of productivity</td>
<td>100% Complete</td>
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<td>2.0</td>
<td>3</td>
<td>Analogous Lower Pennsylvanian study areas selected</td>
<td>4/30/2016</td>
<td>4/29/2016</td>
<td>Agreement between ISGS and DOE project manager to proceed with specific areas of study</td>
<td>100% Complete</td>
</tr>
<tr>
<td>2.0, 3.0</td>
<td>3</td>
<td>Complete petrophysical analysis, geologic and geocellular modeling of the thick Cypress</td>
<td>10/31/2016</td>
<td>10/31/2016</td>
<td>Completion of draft topical report on geology of the thick Cypress in the ILB</td>
<td>100% Complete</td>
</tr>
<tr>
<td>2.0</td>
<td>4</td>
<td>Complete new coring near outcrop belt</td>
<td>9/30/2017</td>
<td>9/21/2017</td>
<td>Send DOE confirmation that core has been obtained and is in ISGS warehouse</td>
<td>100% Complete</td>
</tr>
<tr>
<td>4.0</td>
<td>3</td>
<td>Complete guidelines to develop thin oil zones and store CO₂ in the thick Cypress</td>
<td>12/31/2017</td>
<td>1/31/2018</td>
<td>Completion of draft topical report on guidelines to develop thin oil zones in the thick Cypress</td>
<td>100% Complete</td>
</tr>
<tr>
<td>4.0</td>
<td>4</td>
<td>Complete estimates of CO₂-EOR and storage potential and economic analysis of implementing program</td>
<td>8/31/2018</td>
<td>8/31/2018</td>
<td>Completion of draft topical report on CO₂-EOR, storage, and economics of the thick Cypress in the ILB</td>
<td>100% Complete</td>
</tr>
<tr>
<td>All</td>
<td>4</td>
<td>Document project results</td>
<td>10/31/2018</td>
<td></td>
<td>Complete final report</td>
<td>In progress</td>
</tr>
</tbody>
</table>
3. PRODUCTS

What has the project produced?

a. Publications, conference papers, and presentations

Presentations and manuscripts listed on pages 9-10.

b. Website(s) or other Internet site(s)

The project website is located at http://www.isgs.illinois.edu/research/erd/nco2eor.

4. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

Nothing to report.

5. IMPACT

Nothing to report.

6. CHANGES/PROBLEMS

Changes in approach and reasons for change
There have been no changes in approach on this project.

Actual or anticipated problems or delays and actions or plans to resolve them
There are currently no anticipated problems or delays in the project.

Changes that have a significant impact on expenditures
As no changes have been made or are anticipated, none are expected to impact expenditures.

Significant changes in use or care of human subjects, vertebrate animals, and/or Biohazards
Not applicable.

Change of primary performance site location from that originally proposed
Not applicable.

7. Special Reporting Requirements

Nothing to report.
8. Budgetary Information

Financial Reporting Table

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<th>Budget Period 1</th>
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<tr>
<td>Baseline non-Federal Share</td>
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</tr>
<tr>
<td>Total Baseline Cumulative Cost</td>
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<td>Actual Federal Share</td>
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<td>Actual non-Federal Share</td>
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<tr>
<td>Variance non-Federal Share</td>
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<td>(2,584)</td>
<td>(821)</td>
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<tr>
<td>Total Variance Cumulative Cost</td>
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<td>107,050</td>
<td>78,617</td>
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