Stacked Greenfield and Brownfield ROZ Fairways in the Illinois Basin Geo-Laboratory: Co-optimization of EOR and Associated CO$_2$ Storage

DOE Project Number DE-FE0031700

Nathan Webb - PI
Nathan Grigsby, Fang Yang, Scott Frailey

ILLINOIS
Illinois State Geological Survey
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U.S. Department of Energy
National Energy Technology Laboratory
Carbon Management Project Review Meeting
August 15 - 19, 2022
Program Overview

- Funding: $4,373,828
  - DOE Share: $3,455,947
  - Cost Share: $917,881
- Project Performance Dates: 2/1/19 to 1/31/23
- Project Participants:
  - University of Illinois – Illinois State Geological Survey (Prime)
  - Podolsky Oil Co.
  - Projeo Corp.
  - Indiana Geological and Water Survey
Field Laboratory Tests

**Greenfield Test ✓**
Existing well with validated greenfield ROZ
- Conducted Huff n’ Puff to characterize efficacy of CO₂-EOR in siliciclastic ROZ
  - Completed pressure transient tests (9/20)
  - Completed 1,000-ton CO₂ injection test (huff n’ puff) to acquire oil rate change (12/20)
  - Completed post-CO₂ production (9/21)
- Concluded field work and reclaimed site (2/22)

**Brownfield Test ✓**
New well in previously characterized brownfield ROZ
- Drilled new well for reservoir characterization
  - Collected core and logs to validate Cypress ROZ
    - Correlated with previous field laboratory RST logging
    - Investigated geologic controls on residual oil saturation
    - Refined geologic interpretation
  - Sampled reservoir fluids
  - Performed drill stem test
- Concluded field work (11/19)
Greenfield Test: Pre-test Predictions

Carper Sandstone has low permeability matrix (0.2 mD), is naturally fractured, and pre-HnP water injection tests found hydraulic fracture dominated pressure response. Thus, pre-HnP simulations predicted:

- Low EOR and CO₂ storage due to low permeability matrix relative to natural fracture network
- CO₂ would stay in fractures, has no interaction with matrix; CO₂ readily produced when pumping starts
- Produced oil derived from 2% S_{OI} added to fractures to get models to run; oil in matrix not produced
Greenfield Test: Observations

- Injected: 1,000 tons of CO\(_2\)
- Produced: 350 tons of CO\(_2\); 65 bbls of oil; 25,000 bbl of water
- Stored: 650 tons of CO\(_2\)
- EOR and CO\(_2\) storage outperformed simulations

Graph of oil and CO\(_2\) production
Pre-test simulation projections are shown with simulated oil production shifted to match lag in actual oil production following a few months of CO\(_2\) venting.
Greenfield Test: Observations

- Operational factors affected production:
  - Vented 150 tons CO$_2$ to pull fluids into wellbore before pumping began
  - Pressure constrained by surface equipment
  - Oil/brine produced in emulsion; required chemical demulsifier; resulted in some oil bypassing oil/water separator
  - Reduced pumping rate resulted in lower oil production

- Produced oil was denser and more viscous than expected
  - GC analysis showed that light hydrocarbons were naturally attenuated before CO$_2$ injection (typical of ROZs); more severely stripped after

- Core flood using 30 cP oil:
  - $S_{ORW}=60\%$; $S_{ORCO2}=16\%$
  - CO$_2$ could mobilize oil from tight matrix but needs 25% $S_{OI}$ to swell to 60% for Darcy flow

Box and whisker plots of density (left) and viscosity (right) of oil collected from the test well compared to published values of Carper oils. Oil from the test well was significantly denser and more viscous than published values.
Greenfield Test: Evolved Characterization

Observations from field test permitted an evolved characterization of the Carper ROZ and we revisited the reservoir model to:

- Add hydraulic fractures and adjust natural fracture parameters to match observed pressure responses
- Tune EOS data to measured oil properties (29° API and 30 cP at 60 °F); adjust $S_{oi}$ and $S_{or}$ in both matrix (60%) and fracture (15%)
- Constrain CO$_2$ venting and fluid production rates according to observed gas and water production rates
Greenfield Test: Revised Model Simulations

- Simulated total oil production at 7 month 86 stb (vs. measured 63 stb)
- Better character match than before, but difficult to account for all operational constraints that impacted real production in simulation

Graph of observed oil production rate (green), cumulative production (pink), and simulated oil production (blue) after adjusting model per the evolved characterization.
Greenfield Test: Revised Model Simulations

- Produced residual oil **from fractures** via Darcy flow
- Stored CO$_2$ via flow through fractures
  - CO$_2$ moved far enough away that it was not produced during pumping

Map view of change in oil saturation in the matrix (left) and fractures (right)
Note: scales are different for each map. Almost no saturation change in matrix.
Greenfield Test: Conclusions

- Rock and fluid properties impacted injection and production behavior
  - Natural fractures were more pervasive and influential than expected
  - Natural fractures diminished EOR but improved CO₂ storage
- Oil was denser and more viscous than expected but still able to be produced
  - $S_o$ must be 15% in the fractures to match historical production
  - Simulations suggest no contribution from matrix, but core flood indicates it is possible
- The Carper Greenfield ROZ extends over a large area and has potential as CCS reservoir with limited EOR potential
  - Additional data is needed to characterize the natural fracture network
Greenfield Co-optimization of EOR and Storage

Field development area (640 acre = 1 mi x 1 mi)

<table>
<thead>
<tr>
<th>Carper Ss ROZ</th>
<th>Geneva Dol ROZ + Aq.</th>
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</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>15 ft</td>
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<td>Poro/Perm</td>
<td>11.5%, 0.2 mD</td>
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<td>SOR</td>
<td>25% (matrix)</td>
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</table>

18 ft ROZ, 40 ft Aq.
10%, 20mD ROZ; >20%, >350 mD Aq.
20% ROZ

15% (fractures)
Greenfield Co-optimization well arrangement

For improved economics, Carper pattern size increased and well count reduced due to low EOR potential

Carper: Line drive leverages natural fracture anisotropy
Geneva: 5-spot for isotropic reservoir properties

<table>
<thead>
<tr>
<th>Formation</th>
<th>Producer</th>
<th>CO2 injector</th>
<th>Pattern count</th>
<th>Pattern size</th>
<th>Perforation interval, ft in MD</th>
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<td>9</td>
<td>18</td>
<td>8</td>
<td>80-acre</td>
<td>3688-3703</td>
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<td>Geneva ROZ</td>
<td>12 (4 shared)</td>
<td>20 (10 shared)</td>
<td>12</td>
<td>53-acre</td>
<td>4010-4028</td>
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<td>Geneva Aquifer</td>
<td>12 (all shared)</td>
<td>20 (all shared)</td>
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<td>Total</td>
<td>17</td>
<td>28</td>
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<td>Geneva ROZ</td>
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<td>Geneva Aquifer</td>
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<td>Total</td>
<td>12</td>
<td>20</td>
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<td>640-acre</td>
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Brownfield Reservoir Simulations

Calibration

• Primary production (25 years for Ste. Gen; 45-65 years for others depending on field history)
  – 10-acre well spacing: Cypress and Aux Vases Sandstones
  – 20-acre well spacing: Ste. Genevieve, St. Louis, Salem, and Ullin Limestones

• Waterflooding (40 years)
  – Ste. Genevieve Limestone (5-spot, 40-acre pattern size)

Forward simulation

• CO$_2$ flood (5-spot pattern, 20 years)
  – 80-acre pattern size: Cypress and Aux Vases Sandstones
  – 40-acre pattern size: Ste. Genevieve, St. Louis, Salem, and Ullin Limestones
Brownfield Model Calibration

- Cypress Sandstone and Ste. Genevieve Limestone are the most prolific oil producers in the field
  - EOR strategies for the stacked reservoirs designed to prioritize these formations
Brownfield Development Strategy

- Perform miscible CO$_2$ EOR and associated storage
- Estimate CO$_2$ EOR and associated storage by formation
- Estimate CO$_2$ EOR and associated storage of the stacked reservoir complex
- Identify and simulate strategies for co-optimizing CO$_2$ EOR and storage in the stacked reservoirs
- Provide input for performance of economic and CCUS system analyses
Brownfield Development Strategy

- **Conventional EOR w/ associated storage:** Simultaneous EOR floods
- **Advanced EOR w/ associated storage:** Sequential EOR floods w/ miscibility enhancement via hydrocarbon enriched CO₂
- **Advanced EOR w/ maximum storage:** Simultaneous or sequential EOR floods and “once through” recycled and/or purchased CO₂ injected into Ullin Ls brine aquifer

- Purchased CO₂
- Recycled CO₂
- Produced oil
- HC enriched recycled CO₂
- Produced oil
- Recycled and purchased CO₂
Resource Assessment

- Conducting resource assessment of four formations based on ROZ screening

**Illinois Basin Stratigraphy**

<table>
<thead>
<tr>
<th>System</th>
<th>Series</th>
<th>Lithology</th>
<th>Oil Reservoirs</th>
<th>ROZ Potential</th>
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<td>MIDDLE</td>
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<td>Grand River Limestone</td>
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**Legend**

- Field Laboratory Sites:
  - Brownfield
  - Greenfield

**Oil Indicators**

- Geneva Dolomite
- Dutch Creek Sandstone
- Carper Sandstone
- Tar Springs Sandstone
- Cypress Sandstone

**Map**

- 0 5 10 20 Miles
- 0 7.5 15 30 Kilometers
Resource Assessment

A 121933245000
Gamma Ray
Hall 3
Tar Springs Sandstone
Resistivity
Porosity
Water Saturation

B 121592533701
Gamma Ray
Cen 4
Cypress Sandstone
Resistivity
Porosity
Water Saturation

C 120512794100
Gamma Ray
Kisler Unit 19
Carper Sandstone
Resistivity
Porosity
Water Saturation

D 120512841700
Gamma Ray
King Christy 1
Geneva Dolomite
Porosity
Water Saturation

\[\text{30 m} \quad \text{20 m} \quad \text{10 m} \quad \text{0 m}\]
Resource Assessment

- Example Fairway map of Carper ROZ
  - ROZ bounded by thickness and depth (miscibility) cutoffs
- Fairway maps for other formations indicate opportunities for stacker ROZ potential in many areas of Illinois
Potential pipeline corridors (grey lines) and preferred/most efficient pipeline corridors (green lines) that link Ethanol plant CO$_2$ sources with sinks in the Cumberland Greenfield.
Project summary

Key Findings

• **Greenfield Lab Site is a potential associated storage resource**
  – Carper HnP test allowed for evolved characterization and improved reservoir simulations
    • EOR likely to perform better with line drive flood with excellent associated storage potential
  – Geneva likely provides additional EOR and storage target

• **Brownfield Lab Site is prototypical ROZ/depleted reservoir stacked storage target in the Illinois Basin**
  – Reservoir simulations currently determining the magnitude of EOR and Storage potential
  – Various development strategies create flexibility for operators in prioritizing or co-optimizing EOR and storage depending on market conditions
Project summary

Lessons Learned

• Field laboratory research is unpredictable and requires extra attention to detail
• Stacked reservoir models require prioritization of important parameters to balance detail with computational efficiency

Next Steps

• Integrating co-optimized simulation results into LCA, CCUS systems analysis
• Final classification of stacked CO$_2$-EOR and storage resources
Acknowledgments

- Research herein supported by US Department of Energy contract number DE-FE0031700, FPM Andrea McNemar
- Through a university grant program, IHS Petra, Geovariences Isatis, and Landmark Software were used for the geologic, geocellular, and reservoir modeling, respectively
- For project information, including reports and presentations, please visit: http://www.isgs.illinois.edu/research/ERD/NCO2EOR
Appendix: Organization chart

U.S. Department of Energy

Prime Organization - ISGS
Nathan Webb
Contact P.I.

Fang Yang
P.I.

Michelle Johnson
Project Coordinator

Task 1
Project Management and Planning –
Nathan Webb, Nate Grigsby, Fang Yang, Scott Frailey

Task 2
Screening and Selection of ILB ROZs for Resource Assessment
Zohreh Askari

Task 3
Illinois Basin ROZ Resource Assessment
Charles Monson

Task 4
Greenfield Field Laboratory: Stacked ROZ Storage Complex
Nathan Grigsby

Task 5
Brownfield Field Laboratory: Stacked ROZs and Conventional Reservoir Storage Complex
Nathan Webb

Task 6
Co-optimization, LCA, and Classification of CO2-EOR and Storage Resources in Stacked Reservoirs
Fang Yang

Scott Frailey
P.I. – Technical Advisor

Steve Whittaker
Project Advisor
Appendix: Gantt chart

<table>
<thead>
<tr>
<th>Task Names</th>
<th>Budget Period 1</th>
<th>Budget Period 2</th>
<th>Budget Period 3</th>
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<td>2.0 - Screening and Selection of LB ROZs for Resource Assessment</td>
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<td>2.1 - Generate &amp; test for testable LB ROZ characterization</td>
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<td>2.2 - Collect LB and operator data of generated and tested lab ROZ sites</td>
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<td>2.3 - Identify analogous behavior</td>
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<td>2.4 - Selection of LB analogues: formation by test for resource assessment</td>
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<td>3.0 - Illinois Basin ROZ Resource Assessment</td>
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<td>3.1 - Characterize Illinois ROZ behavior</td>
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<td>3.2 - Characterize the ROZ that alters the ROZ behavior</td>
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<td>3.3 - Material of interest and formation to ROZ behavior</td>
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<td>3.4 - Create a model of the Illinois ROZ behavior</td>
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<td>4.0 - Greenfield Field Laboratory: Stacked ROZ Storage Complex</td>
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<td>4.1 - Develop conceptual models of ROZ storage capacity</td>
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<td>4.2 - Develop generic models based on the conceptual model</td>
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<td>4.3 - Design and implementation of pressure transient testing and visualization test</td>
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<td>4.4 - Conduct core-cut-off log, production, and reservoir analysis</td>
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<td>4.5 - Calibration of all models to field data</td>
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<td>4.6 - Develop improved strategy to maximize storage, EOR, and net present value</td>
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<td>Pilot plan for data collection and testing at pre-development site</td>
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<td>5.0 - Illinois Field Laboratory: Stacked ROZ and Conventional Reservoir Storage Complex</td>
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<td>5.1 - Develop conceptual models based on standard ROZs and conventional reservoirs</td>
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<td>5.2 - Develop parameters for each model based on the conceptual model</td>
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<td>5.3 - Design, such that sampling pressure transient testing and logging program</td>
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<td>6.0 - Co-optimization, ICA, and Classification of CO2, EOR and Storage Reservoirs in Stacked Reservoirs</td>
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<td>6.3 - Evaluate and develop CO2 storage capacity and CO2 EOR for the IL storage capacity</td>
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<td>6.4 - Complete database of modeled ROZs, commercial capacity, and value</td>
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<tr>
<td>Complete database for co-optimization of CO2 EOR to selected reservoirs</td>
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<td>Complete narrative</td>
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