A Nonconventional CO$_2$-EOR Target in the Illinois Basin: Oil Reservoirs of the Thick Cypress Sandstone

Project Number DE-FE0024431
Final Report

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Motivation: ROZs

- 140+ BBO in Permian Basin ROZs (Kuuskraa et al., 2013)
  - 27 BBO economically recoverable via CO$_2$-EOR
  - Successful application of CO$_2$-EOR at Wasson, Seminole, Salt Creek, Goldsmith, Tall Cotton Fields (and others)
- Evidence of widespread ROZs elsewhere in the USA
  - Big Horn, Powder River, Williston Basins, Illinois Basin
- ROZs historically overlooked/dismissed due to technical limitations
  - Methods being developed to detect and characterize ROZs
    - Direct/indirect indicators; Basin evolution models
- ROZs become a target with higher oil prices and desire for associated storage
  - Recoverable ROZ oil (+depleted/bypassed reservoirs) has potential to drive CO$_2$ demand and incentivize the development of CO$_2$ source and distribution infrastructure
Background: ILB ROZ potential

- Cypress Sandstone nCO$_2$-EOR/storage opportunity
  - NE-SW fairway of thick sandstone conducive to ROZ development though the central Illinois Basin

- Thin Oil Zones
  - Residual and mobile oil above brine
  - Fining upward (grain size) sequence / increasing permeability with depth
  - Difficult to produce economically due to water coning so historically overlooked

- Nonconventional CO$_2$-EOR
  - High net CO$_2$ utilization
  - 0.2 to 2.3 Gt saline CO$_2$ storage potential (DOE/MGSC, 2012)
## Project technical objectives

<table>
<thead>
<tr>
<th>Objective</th>
<th>Intended Outcome</th>
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<tbody>
<tr>
<td>Correlate oil production to geologic/reservoir properties</td>
<td>Detailed reservoir characterization and geologic rationale for historical production and ROZ emplacement</td>
</tr>
<tr>
<td>Obtain and analyze new core, logs, and fluid samples</td>
<td>Cypress-specific methods calibrated to detect oil in low saturations (ROZs)</td>
</tr>
<tr>
<td>Develop screening and selection criteria; full field development strategies; economics and NCNO</td>
<td>Methods for improving CO$_2$ enhanced oil recovery and increasing associated storage</td>
</tr>
<tr>
<td>Map CO$_2$-EOR and associated storage resource fairway</td>
<td>ROZ distribution; estimate of CO$_2$-EOR and associated storage resource</td>
</tr>
</tbody>
</table>
Project methodology

Study Area Selection

Data Synthesis & Analysis

Petrophysics

Geologic Modeling

Geocellular Modeling

Fluid Analysis & Geochemical Modeling

Reservoir Simulations

Economics

Development Guidelines & Resource Estimate

Task 1

Task 2

Task 3

Task 4
Technical approach

Correlate oil production to geologic/reservoir properties

- Site-specific characterization to understand reservoir performance
  - Geologic heterogeneity
  - Known oil production
- Regional characterization to understand the Cypress Ss petroleum system
  - Geologic heterogeneity
  - ROZ potential and distribution
  - Storage resource

Location of Noble and Kenner West Fields with respect to other oil fields (green shading) and Cypress oil production (green dots)
Technical approach

Obtain and analyze new core, logs, and fluid samples

- **Core**
  - Observe reservoir facies
  - Measure important parameters
    - Porosity, clay microporosity, permeability, saturation, resistivity, Archie parameters, etc.
  - Identify small-scale features missed by logs
  - Conduct core flood experiments
    - Define expected $S_{OR}$; $S_{WIRR}$
- **Geophysical logs**
  - Validate well log analysis
- **Fluid samples**
  - Determine input parameters for simulation
    - Oil and brine composition
    - Minimum miscibility pressure
Technical approach

Develop screening and selection criteria; full field development strategies; economics and NCNO

- **Screening and Selection Criteria**
  - Geology: Understand potential limitations of reservoir
  - Well log analysis: Establish expectations for saturation profiles

- **Development strategies for Noble Field**
  - Detailed geologic characterization and well log analysis
    - Reservoir models with representative heterogeneity and fluid saturation
  - Reservoir simulations
    - Historical: Calibrated to field production
    - Forward: Flood design to co-optimize CO$_2$-EOR and storage (NCNO)
  - Economic analysis
Technical approach

Map CO₂-EOR and associated storage resource fairway

- Quantify EOR and storage potential
  - How much residual oil is in the thick Cypress Ss fairway?
  - How much is economically recoverable?

- Apply lessons from Noble Field to regional assessment
  - How can ROZs be identified?
  - What are typical oil saturations?
  - What development strategies are economically viable?
Results: Geologic Characterization
Scales of investigation

• Oil field studies
  • Documented thick Cypress Ss production
  • Abundant core and log data for detailed characterization

• Regional studies
  • Core
  • Outcrop
  • Logs
Oil field studies

<table>
<thead>
<tr>
<th></th>
<th>Noble</th>
<th>Kenner West</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cypress Oil Production</td>
<td>24 MMBO</td>
<td>1.3 MMBO</td>
</tr>
<tr>
<td>OOIP</td>
<td>95-110 MMBO</td>
<td>7.8-10 MMBO</td>
</tr>
<tr>
<td>Recovery Efficiency</td>
<td>~25%</td>
<td>~15%</td>
</tr>
</tbody>
</table>
Noble correlations

Example Noble Field Cross Section

- Correlated ~1,000 logs to map geometry of stacked Cypress Sandstone
  - Lower “sheet” sandstone extends out of field
  - Upper sandstone bodies change facies laterally
• Up to 170 ft thick sandstone intersects Clay City Anticline
• SW tilted OWC; Paleo-OWC related calcite cements
• MPZ up to 55 ft thick; 110 ft closure
Kenner West correlations

• Similar to Noble Field, but better developed “upper” Cypress Ss lenses
Kenner West maps

- N-S sandstone trend intersects dome; structural-stratigraphic trap
- Sandstone up to 100 ft thick; MPZ up to 35 ft thick; 40 ft closure
- OWC tilts slightly to the southeast
Core study

Characterization relies on limited core (especially from thick sandstone) from oil fields to interpret the geology and understand the geologic controls on the reservoir

• Noble Field
  • Whole core of upper 30-40 ft in two wells
  • Chips/partial core from a handful of old wells

• Kenner West Field
  • No remaining cores, but abundant core analysis data
Core and samples

Cores allow detailed sedimentological study but are usually limited to the MPZ

Samples can reveal general lithology and texture and provide material to test for oil saturation
Sedimentology

Decreasing depositional energy
Integrating core/outcrop studies

- Leverage outcrops to supplement core and better understand internal reservoir architecture of the Cypress Sandstone
Integrating core/outcrop studies

- 259-ft core collected near roadcuts and outcrops at southern end of valley fill Cypress fairway
  - 160 ft Cypress Fm
  - 100 ft thick Ss
Tripp #1 properties

Permeability (md)

Porosity (%)

10% 12% 14% 16% 18% 20%
Relating core to outcrop

- Multistory fluvial channels
  - Channel elements likely form flow units within a reservoir
- Stacked channel elements are not continuous genetic units, despite appearance
  - Grain size increase, basal lags, juxtaposed lithofacies
Parallels to basin interior

- Consistent stratigraphy/sedimentology from outcrop to oilfield cores
  - Multistory architecture observed at multiple sites
    - Channel bases difficult to identify on traditional well logs, but can be observed in core, permeability, FMI logs
  - Dominantly vf-f cross- and ripple-bedded sandstone with coarser sand in channel bases
Controls on porosity/permeability

- Depositional environment and diagenetic history control reservoir properties
  - Porosity/permeability relationship varies
    - Minor variations in depositional environment?
    - Different diagenetic histories in different areas of the basin?

<table>
<thead>
<tr>
<th>Field</th>
<th>Location</th>
<th>Depth to Cypress, ft (m)</th>
<th>Typical porosity, %</th>
<th>Typical permeability, mD (μm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loudon</td>
<td>Eastern Fayette County</td>
<td>1,600 (487.7)</td>
<td>19.2</td>
<td>80.9 (0.080)</td>
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<tr>
<td>Noble</td>
<td>Western Richland County</td>
<td>2,600 (792.5)</td>
<td>18.0</td>
<td>482.0 (0.476)</td>
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<tr>
<td>Kenner West</td>
<td>Southwestern Clay County</td>
<td>2,600 (792.5)</td>
<td>18.0</td>
<td>106.0 (0.105)</td>
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<tr>
<td>Dale</td>
<td>Southern Hamilton County</td>
<td>2,900 (883.9)</td>
<td>13.5</td>
<td>62.5 (0.062)</td>
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</tbody>
</table>
Controls on porosity/permeability

- Hybrid pore system of primary intergranular and secondary porosity from dissolution of grains and cements
- Long, well-connected pores contribute to the exceedingly high permeability (~1,000 mD) observed in Noble Field
**Controls on porosity/permeability**

<table>
<thead>
<tr>
<th>Samples (n)</th>
<th>Planar-bedded</th>
<th>Cross-bedded</th>
<th>Massive bedded</th>
<th>Ripple-bedded</th>
<th>Ripple-bedded (w/ clay drapes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
<td>11</td>
<td>2</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>COPL</td>
<td>20.63</td>
<td>25.84</td>
<td>18.33</td>
<td>23.83</td>
<td>31.53</td>
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<tr>
<td>CEPL</td>
<td>5.65</td>
<td>5.15</td>
<td>7.68</td>
<td>4.38</td>
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<td>$I_{COMP}$</td>
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<td>0.86</td>
<td>0.70</td>
<td>0.79</td>
<td>0.99</td>
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<tr>
<td>$P_i$</td>
<td>40.37</td>
<td>38.42</td>
<td>39.80</td>
<td>40.56</td>
<td>41.80</td>
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<tr>
<td>IGV</td>
<td>24.82</td>
<td>21.90</td>
<td>26.15</td>
<td>20.85</td>
<td>15.00</td>
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<td>Thin Section Porosity</td>
<td>5.14</td>
<td>8.32</td>
<td>6.14</td>
<td>8.44</td>
<td>0.00</td>
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<td>Lab He porosity (%)</td>
<td>13.92</td>
<td>16.18</td>
<td>15.04</td>
<td>15.10</td>
<td>7.70</td>
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<tr>
<td>Total quartz (%)</td>
<td>78.26</td>
<td>77.17</td>
<td>79.02</td>
<td>78.04</td>
<td>67.43</td>
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<td>Authigenic quartz (%)</td>
<td>5.46</td>
<td>3.15</td>
<td>4.12</td>
<td>7.30</td>
<td>1.25</td>
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<td>Total Feldspar (%)</td>
<td>1.47</td>
<td>0.77</td>
<td>0.00</td>
<td>1.10</td>
<td>4.12</td>
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<tr>
<td>Lithic (%)</td>
<td>0.91</td>
<td>0.55</td>
<td>1.89</td>
<td>0.72</td>
<td>0.00</td>
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<tr>
<td>Clay (%)</td>
<td>12.54</td>
<td>9.43</td>
<td>10.46</td>
<td>10.93</td>
<td>29.20</td>
</tr>
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</table>

- Analyzed petrography of examples of various facies to relate textural and diagenetic factors to porosity / permeability.
Controls on porosity/permeability

- Fluvial Cypress Sandstone among the highest permeability sandstone reservoirs in the ILB
- Most (84.2%) samples as quartz arenite, with a small percentage of subarkose (12.4%) and sublitharenite (4.4%)
- Point-counting data showed that compaction, rather than cementation, caused most porosity loss
- Clay type is an important control on permeability (and needs to be understood)
- Permeability is controlled by both sorting/grain size and diagenesis
  - The high porosity and low permeability observed at Loudon Field could be a result of its finer grains and high authigenic clay mineral content relative to the lower porosity but higher permeability Cypress at Noble Field
Reservoir architecture

- Compartmentalization despite homogeneous appearance
  - Grain size variation relating to facies changes and channel stacking
  - Minor thin shale interbeds and heterolithic intervals within the sandstone body
    - Some can be laterally extensive
- Calcite cements
  - Some concurrent with and others unrelated to OWC
Interpreted the Cypress Sandstone at Noble Field as part of a continental-scale fluvial drainage system
- Possibly part of incised valley fill system (LST-TST)
- Erosional base, multistory sandstone, overall fining upward (f-vf)
- Becomes estuarine at the top (lower energy, more clays, lower reservoir quality)
- Distinct environment from Cypress Ss tidal shoals

Depositional environments

Wright and Marriott 1993

Dalrymple and Choi 2007
Characterizing ROZ saturations

- Developed methods to identify and characterize (extent, thickness, saturation) ROZs at oil field and regional scales
  - Well log analysis techniques to identify $S_{OR}$ across the basin
  - Core flood experiments to constrain reasonable values for $S_{OR}$
Well log analysis

- Used to identify and characterize ROZs
  - Uses existing well logs
  - Inexpensive and simple application for small operators
- Validated with new pulsed-neutron logs
- Conducted core flood experiments to provide further validation of the method
Core flood experiments

- Developed to constrain the $S_{OR}$ values that should be expected within the Cypress ROZ
- 15 core plugs represent the range of porosity/permeability
  - Porosity 11.7%-24.9%
  - Permeability 15.2 mD-856.8 mD
- Expected $S_{OR}$ ~28%

<table>
<thead>
<tr>
<th>API</th>
<th>Plug Depth (m [ft])</th>
<th>$S_{WIR}$</th>
<th>Volume</th>
<th>$S_{OR}$</th>
<th>Volume</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Mass</td>
<td>Archie</td>
<td>Mass</td>
<td>Archie</td>
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<tr>
<td>121012872700</td>
<td>275.1 (902.5)</td>
<td>17%</td>
<td>18%</td>
<td>17%</td>
<td>39%</td>
</tr>
<tr>
<td></td>
<td>276.0 (905.5)</td>
<td>25%</td>
<td>26%</td>
<td>27%</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>278.7 (914.5)</td>
<td>26%</td>
<td>26%</td>
<td>27%</td>
<td>21%</td>
</tr>
<tr>
<td></td>
<td>282.8 (927.8)</td>
<td>21%</td>
<td>26%</td>
<td>27%</td>
<td>42%</td>
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<tr>
<td></td>
<td>286.7 (940.5)</td>
<td>16%</td>
<td>22%</td>
<td>14%</td>
<td>36%</td>
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<tr>
<td>121592648800</td>
<td>831.0 (2726.4)</td>
<td>22%</td>
<td>19%</td>
<td>21%</td>
<td>30%</td>
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<tr>
<td></td>
<td>831.8 (2728.9)</td>
<td>21%</td>
<td>24%</td>
<td>23%</td>
<td>33%</td>
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<tr>
<td></td>
<td>832.1 (2729.9)</td>
<td>22%</td>
<td>24%</td>
<td>23%</td>
<td>25%</td>
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<tr>
<td></td>
<td>834.1 (2736.4)</td>
<td>18%</td>
<td>17%</td>
<td>19%</td>
<td>19%</td>
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<tr>
<td></td>
<td>834.5 (2737.8)</td>
<td>23%</td>
<td>22%</td>
<td>24%</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>840.5 (2757.7)</td>
<td>23%</td>
<td>21%</td>
<td>20%</td>
<td>31%</td>
</tr>
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<td></td>
<td>840.9 (2758.9)</td>
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<td>21%</td>
<td>22%</td>
<td>26%</td>
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<tr>
<td>120650139400</td>
<td>911.2 (2989.4)</td>
<td>24%</td>
<td>25%</td>
<td>20%</td>
<td>35%</td>
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<tr>
<td></td>
<td>923.5 (3029.8)</td>
<td>23%</td>
<td>26%</td>
<td>23%</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td>930.5 (3052.9)</td>
<td>22%</td>
<td>23%</td>
<td>20%</td>
<td>31%</td>
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<td>Average</td>
<td></td>
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<td>23%</td>
<td>22%</td>
<td>28%</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td>22%</td>
<td>23%</td>
<td>22%</td>
<td>29%</td>
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</table>
Saturation characterization

• Observations from well logs indicate
  • MPZs were not at irreducible water saturation (reflects decades of production)
  • ROZ $S_{OR}$ between 20%-30%
    • Slight differences between the $S_{OR}$ derived from log analysis vs. pulsed neutron logs (which predicted higher oil saturation in the MPZ) and core flood experiments (which suggests a higher $S_{OR}$).
Static geocellular models

- Developed models for Noble Field that reflects:
  - Geologic heterogeneity as observed in core, outcrops, logs
  - Fluid saturation distribution determined from well log analysis
Results:
Reservoir Simulation
Pattern simulation

- Developed strategies to maximize oil recovery and CO₂ storage based on:
  - Simultaneous flooding of the MPZ and ROZ (Case 1-10)
  - Sequential flooding: 1. flood ROZ after CO₂ breakthrough in MPZ (Case 11, 12), and 2. flood ROZ and produce from both MPZ and ROZ after CO₂ breakthrough in MPZ (Case 13)

- Applied strategies to field scale simulations for Noble Field

<table>
<thead>
<tr>
<th>Case</th>
<th>Injector</th>
<th>Producer</th>
<th>EOR (Mstb)</th>
<th>Net Utilization (Mscf/stb)</th>
<th>Storage ratio</th>
<th>EOR %</th>
<th>CO₂ storage efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Entire MPZ and ROZ</td>
<td>Entire MPZ and ROZ</td>
<td>86</td>
<td>319</td>
<td>18</td>
<td>9</td>
<td>36.5%</td>
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<tr>
<td>2</td>
<td>Entire MPZ only</td>
<td>Entire MPZ only</td>
<td>46</td>
<td>260</td>
<td>27</td>
<td>10</td>
<td>32.1%</td>
</tr>
<tr>
<td>3</td>
<td>Entire ROZ only</td>
<td>Entire ROZ only</td>
<td>39</td>
<td>227</td>
<td>30</td>
<td>11</td>
<td>31.5%</td>
</tr>
<tr>
<td>4</td>
<td>Lower 20% ROZ</td>
<td>Upper 20% ROZ</td>
<td>28</td>
<td>180</td>
<td>35</td>
<td>14</td>
<td>27.0%</td>
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<tr>
<td>5</td>
<td>Lower 20% ROZ</td>
<td>Upper 20% ROZ</td>
<td>28</td>
<td>191</td>
<td>32</td>
<td>14</td>
<td>25.3%</td>
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<tr>
<td>6</td>
<td>Lower 20% ROZ</td>
<td>Upper 10% MPZ</td>
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<td>203</td>
<td>27</td>
<td>14</td>
<td>19.3%</td>
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<tr>
<td>7</td>
<td>Lower 20% ROZ</td>
<td>Lower 10% MPZ</td>
<td>14</td>
<td>188</td>
<td>38</td>
<td>14</td>
<td>22.5%</td>
</tr>
<tr>
<td>8</td>
<td>Lower 20% ROZ</td>
<td>Lower 10% MPZ</td>
<td>47</td>
<td>180</td>
<td>0.19</td>
<td>0.37</td>
<td>12.1%</td>
</tr>
<tr>
<td>9</td>
<td>Lower 10% MPZ</td>
<td>Lower 10% MPZ</td>
<td>23</td>
<td>191</td>
<td>25</td>
<td>15</td>
<td>16.8%</td>
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<tr>
<td>10</td>
<td>Upper 20% MPZ</td>
<td>Entire MPZ then ROZ after CO₂ breakthrough</td>
<td>146</td>
<td>260</td>
<td>27</td>
<td>10</td>
<td>32.1%</td>
</tr>
<tr>
<td>11</td>
<td>Entire MPZ then ROZ after CO₂ breakthrough</td>
<td>Entire MPZ then ROZ after CO₂ breakthrough</td>
<td>46</td>
<td>260</td>
<td>27</td>
<td>10</td>
<td>32.1%</td>
</tr>
<tr>
<td>12</td>
<td>Entire MPZ then ROZ after CO₂ breakthrough</td>
<td>Entire MPZ then ROZ + MPZ after CO₂ breakthrough</td>
<td>46</td>
<td>260</td>
<td>27</td>
<td>10</td>
<td>32.1%</td>
</tr>
<tr>
<td>13</td>
<td>Entire MPZ and ROZ, Then Entire ROZ after 1-2 years</td>
<td>Entire MPZ and ROZ, Then Entire ROZ after 1-2 years</td>
<td>58</td>
<td>280</td>
<td>23</td>
<td>9</td>
<td>34%</td>
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<tr>
<td>13a</td>
<td>Entire MPZ and ROZ, Then Entire ROZ after 1 year</td>
<td>Entire MPZ and ROZ, Then Entire ROZ after 1 year</td>
<td>83</td>
<td>315</td>
<td>19</td>
<td>9</td>
<td>36%</td>
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<td>13b</td>
<td>Entire MPZ and ROZ</td>
<td>Entire MPZ and ROZ</td>
<td>28</td>
<td>184</td>
<td>20</td>
<td>14</td>
<td>18%</td>
</tr>
</tbody>
</table>

Comparison of results for each case at 1.0 PV CO₂ injected
Full-field simulation

- Fluid displacement mechanisms like those in homogeneous pattern floods were observed in full field simulation.
- The presence of underlying aquifer in heterogeneous field-scale model introduced new issues:
  - Oil sinking from MPZ into ROZ; Downwards movement of CO$_2$ plume.

Oil saturation at CO$_2$ breakthrough. Green wells are producers, red are injectors.
Full-field simulation

- Fluid displacement mechanisms like those in homogeneous pattern floods were observed in full field simulation.
- The presence of underlying aquifer in heterogeneous field-scale model introduced new issues:
  - Oil sinking from MPZ into ROZ; Downwards movement of CO$_2$ plume.
Full-field simulation

- Overcame challenges by developing scenarios that mitigate issues first identified in pattern models (e.g. Oil sinking from MPZ into ROZ; Downwards movement of CO\(_2\) plume)
- Scenarios include:
  - Injection pattern and well spacing
  - Perforation interval
  - Pattern sensitivities
  - Injection design
  - MPZ/ROZ WAG floods
  - High injection rates
## Simulated EOR and storage

### CO₂-EOR performance metrics after 20 years of injection

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Cases</th>
<th>EOR (Mstb)</th>
<th>CO₂ Storage (million tonnes)</th>
<th>Oil Recovery</th>
<th>Net Utilization (Mscf/stb)</th>
<th>CO₂ Storage Factor (Mscf/stb)</th>
<th>CO₂ Storage Efficiency*</th>
<th>HCPV injected*</th>
<th>Carbon Balance (tonne/stb)</th>
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</table>

*Calculated using OOIP of the pattern, MPZ case used OOIP of MPZ only without OOIP from ROZ.
+Calculated using Pore volumes (PV) of pattern, MPZ case used PV of MPZ only without PV from ROZ.
++Excessive net utilization, storage factor, and storage efficiency due to significant out of pattern injection.
Development scenario results

- Simulations of Noble Field show:
  - WAG is the injection design with the highest oil recovery
  - Flooding the MPZ and ROZ separately has higher oil recovery with low injection rates
  - For WAG cases, the 80-acre 5-spot pattern has higher oil recovery than the 40-acre 5-spot pattern in the MPZ; the inverse is true for the ROZ
  - ROZ floods have higher oil recovery when producers are perforated in the bottom 3 m (10 ft) of the ROZ
  - Continuous, high CO$_2$ injection rate increases ROZ oil recovery
  - 21 (of 22) cases are NCNO or carbon neutral
Economic analysis assumptions

- CO\(_2\) pipeline exists; trunk line required to connect to the pipeline
- CO\(_2\) recycling facility size/cost based on projected annual CO\(_2\) production
- Pattern wells require CO\(_2\) service workover, annual well work; out of pattern wells are plugged
- Wells are have a “lift” cost
- The CO\(_2\)-EOR project is deployed as a single phase

---

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<tr>
<th>Description</th>
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<td>new well</td>
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<tr>
<td>surface equipment</td>
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<td>workover/conversion</td>
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<tr>
<td>plugging</td>
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<td>CO(_2) recycling (10.5 Bscf/d)</td>
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<td>CO(_2) recycling (21 Bscf/d)</td>
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<td>trunk line construction</td>
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<td>CO(_2) gathering system</td>
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<td>annual well cost</td>
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<td>ad valorem tax</td>
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<td>lift $/bbl-fluid</td>
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<td>recycled CO(_2), $/ton</td>
<td>$10</td>
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---

- Oil price = $50 per barrel
- CO\(_2\) cost = $0
  - $20 of revenue per ton of CO\(_2\) stored in low oil production (<1 MMstb) cases with poor economics
  - ROZ-only cases required $40 per ton revenue for better economics
- G&A costs = 20% of CapEx & OpEx
- No severance tax on oil production in IL
- All CapEx expensed at t = 0; depreciation was not used
Economic analysis assumptions

- CO₂ pipeline exists; trunk line required to connect to the pipeline
- CO₂ recycling facility size/cost based on projected annual CO₂ production
- Pattern wells require CO₂ service workover, annual well work; out of pattern wells are plugged
- Wells are have a “lift” cost
- The CO₂-EOR project is deployed as a single phase

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<tr>
<th>Case</th>
<th>Producers</th>
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## Economic metrics

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<th>Payout (yr)</th>
<th>Economic Life (yr)</th>
<th>Net Revenue-Oil ($M)</th>
<th>Capital Investment ($M)</th>
<th>CO₂ Costs ($M)+</th>
<th>Operating Costs ($M)</th>
<th>Cum Cash Flow ($M)</th>
<th>IRR %</th>
<th>NPV @ 20%</th>
<th>P/I</th>
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Economic analysis results

- Payout varied from one to four years
- Economic life varied from six to twenty years
  - Maximum value based on the period of CO$_2$-EOR simulations
- Net revenue from oil production only (CO$_2$-storage-related revenue excluded) varied from $50$ to $>$ $150$ million
- The ROZ-only cases could only yield positive IRR if $40$/ton revenue was generated
Economic analysis results

- Traditional flooding approaches that minimize CO$_2$ movement out of the outer patterns did not have high economic metrics; cases with relatively higher injection rates that had more significant CO$_2$ movement out-of-pattern had higher metrics.
- ROZ-only CO$_2$-EOR without substantial CO$_2$ storage revenue (e.g., tax credits) had the lowest metrics and were uneconomic.
- WAG process had higher metrics for MPZ and ROZ CO$_2$-EOR.
- For Noble Field (a large anticline), any case could be augmented with a single CO$_2$ storage well into the aquifer that could generate revenue and improve economic metrics.
Development strategies

• Depend on:
  • goals of the project (prioritizing EOR performance versus storage performance and NCNO)
  • geologic setting (brownfield versus greenfield)
  • company’s business strategies (economic metrics)
Development strategies application

- Noble Field assumptions:
  - Mature field with (brownfield) ROZ; expect positive economic metrics

<table>
<thead>
<tr>
<th>Project Goals</th>
<th>Development Strategy</th>
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<tr>
<td>EOR, CO$_2$ storage w/NCNO</td>
<td>80-acre, MPZ and ROZ injection, continuous high injection rate</td>
</tr>
<tr>
<td>EOR from the MPZ only w/ no NCNO</td>
<td>80-acre, MPZ-only, WAG</td>
</tr>
<tr>
<td>CO$_2$ storage w/ NCNO</td>
<td>40-acre, ROZ-only, continuous high injection rate</td>
</tr>
</tbody>
</table>
Results: Resource Assessment
Regional dataset

- Refined regional isopach and facies maps using data from ~4,500 wells
- Determined regional Phi-h using core and porosity log data from ~1,700 wells
- Mapped ~17,500 wells with Cypress oil indicators (perfs, shows, core analysis, DSTs)
- Analyzed well logs from 260 wells to delineate ROZ fairways
Regional geology

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Application of well log analysis

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Cypress ROZ fairway

- Mapped extent of ROZ fairway based on
  - Oil production
  - Oil indicators
  - Well log analysis
  - Sandstone isopach
  - Basin structure

- Defined potential ROZ prospects within the fairway
  - Areas with overlapping data indicating residual oil – especially with no associated production
Cypress ROZ prospects

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Resource assessment

- Cypress ROZ fairway
  - 27 brown and greenfield prospects with 1.8 billion barrels of oil in place ($S_{OR} = 23\%$)
    - $S_{OR}$ values range from 14% to 35%
  - Thickness of ROZs in the prospects varies from 9 to 71 ft
Resource assessment

- **Cypress CO₂-EOR/storage resource**
  - 196 MMBO\(^1\) is estimated recoverable with 80-acre blanket WAG development strategy\(^2\)
    - favors EOR and economic metrics, but is carbon positive
  - 144 MMBO\(^1\) is estimated to be recoverable with 40-acre high CO₂ injection rate development strategy\(^3\)
    - favors storage and economic metrics and results in NCNO production
  - Up to 10.4 billion tonnes\(^4\) of associated CO₂ storage with EOR in ROZ prospects
    - not accounting for underlying saline storage

\(^1\)23% median S\(_{OR}\)
\(^2\)80-acre WAG flood EOR factor of 11.4% assuming miscible conditions
\(^3\)40-acre high injection rate EOR factor of 8.2% assuming miscible conditions
\(^4\)Net utilization of 1,479 Mscf/stb
Conclusions
Conclusions

- Correlate oil production to geologic/reservoir properties
  - Characterized geology and built geocellular models that reflect observed reservoir heterogeneity
    - Cypress Sandstone consists of multistory fluvial sandstone; porosity is 15% to 21% and horizontal and vertical permeability is up to 1,000 mD.
    - Where multiple sandstone stories amalgamate (e.g., in Noble Field), they create thick, relatively widespread sandstone bodies that have characteristics (e.g., high lateral and vertical permeability, limited compartmentalization, and large pore volumes) favorable for CO₂ storage

- Obtain and analyze new core, logs, fluid samples
  - Acquired two new cores with logs and pulsed neutron logs in four existing wells
    - ROZ SOR between 20%-30% from well log analysis and core flood experiments
  - Collected and analyzed oil and brine samples from Noble Field
    - MMP of 1,100-1,200 psig for the thick Cypress Sandstone crude oil at reservoir temperature of 91.4°F
    - Cypress brine \( R_w = 0.071 \)
Conclusions

- Develop screening and selection criteria; full field development strategies; economics and NCNO
  - Completed calibrated reservoir simulations of Noble Field and performed economic analysis on results
  - Proposed development strategies for Noble Field
    - Development strategy depends on the goals of the project (prioritizing EOR performance versus storage performance and NCNO), geologic setting (brownfield versus greenfield), and a company’s business strategies (economic metrics)

- Map CO$_2$-EOR and associated storage resource fairway
  - Developed new regional Cypress Ss isopach, porosity, and ROZ fairway maps
  - Analyzed logs from 260 wells across the fairway to determine ROZ distribution
  - Identified Cypress ROZ prospects and estimated resource based on volumetrics and reservoir simulation results
    - Up to 196 MMBO is estimated recoverable
    - Up to 10.4 billion tonnes of associated storage in Cypress ROZs
Acknowledgments

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• Through a university grant program, IHS Petra and Landmark Software were used for geologic and reservoir modeling, respectively

• For project information, including reports and presentations, please visit: http://www.isgs.illinois.edu/research/ERD/NCO2EOR