CO₂ ENHANCED OIL RECOVERY IMPROVEMENT IN CONVENTIONAL FIELDS USING RICH GAS

DE-FE0031789

U.S. Department of Energy National Energy Technology Laboratory
Oil and Gas Virtual Project Review Meeting
August 23, 2021

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**Research Hypothesis:** The injection of a blend of rich hydrocarbon gas and CO$_2$ into an oil reservoir will reduce molecular weight (MW) selectivity, lower minimum miscibility pressure (MMP) and viscosity of the oil, and improve gas solubility, resulting in an overall improvement in enhanced oil recovery (EOR) performance.
Project Goal: Determine the effect of injecting blended CO₂ and rich gas into an active CO₂ EOR field to improve production performance.

Project Objectives: The goal will be accomplished by completing several specific research objectives:

- Determine the quantity, transportation, compression, and injection needs for a field-based injection test.

- Inject blended CO₂ and rich gas in the Bell Creek Field for incremental recovery and associated CO₂ storage.

- Develop field-based data to determine the effects of rich gas additives in CO₂ on oil production.

- Use laboratory experiments and reservoir simulation to determine the potential for varying compositions of rich gas blended with CO₂ to improve oil recovery in other conventional reservoirs currently undergoing CO₂ EOR.

- Develop business case scenarios to assess the potential for using rich gas added to CO₂ at other EOR locations in the United States.
## FUNDING AND PROJECT PERFORMANCE DATES

<table>
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<tr>
<th></th>
<th>BP1 ($) 10/1/2019–9/30/2021</th>
<th>BP2 ($) 10/1/2021–9/30/2024</th>
<th>Total</th>
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<tr>
<td></td>
<td>Federal</td>
<td>Nonfederal</td>
<td>Federal</td>
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<td>DOE</td>
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<td>–</td>
<td>$5,789,517</td>
</tr>
<tr>
<td>Schlumberger</td>
<td>–</td>
<td>$334,400</td>
<td>–</td>
</tr>
<tr>
<td>CMG</td>
<td>–</td>
<td>$212,993</td>
<td>–</td>
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<tr>
<td>Total</td>
<td>$2,184,364</td>
<td>$547,393</td>
<td>$5,789,517</td>
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<tr>
<td>Total Cost Share %</td>
<td>80%</td>
<td>20%</td>
<td>80%</td>
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</table>

*Note: Denbury – Additional collaboration in the form of field support, infrastructure development, design and implementation, gas supply, and injection/production operations.*
TECHNOLOGY BACKGROUND: CO₂ BLENDED WITH RICH GAS

• Previous laboratory and modeling work showed ethane can solvate a wider MW range of hydrocarbons than CO₂ alone, which could lead to more oil from the reservoir with better efficiency.

• Blending rich gas components with CO₂ may provide means of improving oil recovery in fields either undergoing or planned for tertiary recovery.

• Use of rich gas or rich gas–CO₂ blends for flooding operations can greatly reduce the quantity of CO₂ needed for EOR injection.
TECHNICAL APPROACH/PROJECT SCOPE

• Task 1.0 – Project Management and Planning

• Task 2.0 – Engineering Design
  – 2.1 – Rich Gas Source, Compression, and Transportation Evaluation
    DP: Go/no-go decision based on whether rich gas source is secured 6/30/2021
  – 2.2 – Core and Fluid Laboratory Evaluations
  – 2.3 – Blended CO₂-Rich Gas Injection Modeling and Simulation
  – 2.4 – Injection/Monitoring Program Design
TECHNICAL APPROACH/PROJECT SCOPE (CONT.)

• Task 3.0 – Field Operations and Monitoring (BP2)
  – 3.1 – Field Preparation
  – 3.2 – Field Validation and Monitoring
  – 3.3 – Rich Gas Supply Monitoring
  – 3.4 – Sample Analysis
  – 3.5 – Field Validation Decommissioning Activities

• Task 4.0 – Business Case for Blended CO₂-Rich Gas Utilization (BP1 and BP2)
  – 4.1 – Laboratory Studies
  – 4.2 – Data Management and Machine Learning Studies
  – 4.3 – Modeling and Simulation
  – 4.4 – Business Case Analysis
PROGRESS AND CURRENT STATUS OF PROJECT

Subtask 2.1 Rich Gas Source, Compression, and Transportation Evaluation

• The EERC and Denbury are working toward a gas delivery plan and contract with a gas supplier.

• Preliminary considerations:
  – Trucking with 1-week storage at the location
  – Natural gas liquid (NGL) with injection rate of 150 bbl/day
  – Total blended gas injection rate is 2.5 MMscf/day
  – Water alternating gas (WAG) cycle or NGL + CO\(_2\) followed by chasing CO\(_2\)
  – Monitor gas rate of each stream, gas composition, well production, and production oil composition
Subtask 2.2 – Core and Fluid Laboratory Evaluations

- Core and oil samples were collected for the Bell Creek Field.
- Testing was performed to determine:
  - Porosity/permeability.
  - Relative permeability of CO$_2$–ethane blends.
  - Pressure, volume, temperature (PVT) data regarding swelling and solubility of CO$_2$–rich gas blends in the presence of Bell Creek oil.
  - CO$_2$–rich gas MMP.
CORE FLOODING SETUP

- Purpose: to test the oil recovery performance in the Bell Creek Field using CO$_2$, C2 and C3, and verify the oil recovery improvement by C2 and C3.

Vinci Core Flood System Used for CO$_2$/C2/C3 Injection

Schematic of the Core Flooding System
OIL COLLECTION PROCESS

Co$_2$-Flooded Oil – Easy To Flow

C3-Flooded Oil – Sticky, Viscous, And Foamy
OIL RECOVERED FROM CO₂, C2, AND C3 FLOODS

Co₂-Flooded Oil, 2 mL

C2-Flooded Oil, additional 1 mL after CO₂ flood

C3-Flooded Oil, additional 0.95 mL after C2 flood

More oil could be recovered after CO₂ flooding by sequential C2 and C3 floods.

Figure 1. Oil recovered in the flooding process with different gases.
OIL COLLECTED FROM CO$_2$, C2, AND C3 FLOODS

CO$_2$-flooded oil; oil can flow under room temperature.

C2-flooded oil after CO$_2$ flood; oil is difficult to flow under room temperature.

C3-flooded oil after C2 flood; oil cannot flow under room temperature.

Oil viscosity increases in the flooding process with different gases.
SWELLING AND SOLUBILITY DATA

**CO₂ solubility and swelling factor**

**Ethane solubility and swelling factor**

**Propane solubility and swelling factor**

**Ethane and propane saturation pressure**

**Ethane and propane swelling factors**
Subtask 2.3 – Blended CO$_2$–Rich Gas Injection Modeling and Simulation

• The injection pattern and site were selected.
• The simulation model for the pilot pattern has been updated, and equation of state (EOS) modeling based on the injection gas composition is complete.
• The EERC and Denbury are working together on detailed EOR predictive simulation to optimize the sweep efficiency in the pilot pattern.
FIVE-SPOT SECTION FOR THE 04-01 PATTERN

• Based on the history-matched model, a sectional model was cut out to include wells in the 04-01 pattern only:
  o One water/gas injector: 04-01
  o Four producers: 03-04, 04-02, 04-08, and 33-16
• No injected rich gas flows out of the 04-01 pattern in the predictive cases to maximize the sweep efficiency in the pattern.
WAG AND CGI EOR SCENARIOS FOR AN ECONOMIC ANALYSIS

- **CGI**: Aimed at an even sweep in the 04-01 pattern for an upscaling purpose, the injection and production constraints were set up under bottomhole conditions for continuous gas injection (CGI) scenarios.

- **WAG**: Because of the uneven distribution of reservoir thickness around the wells in the 04-01 pattern, the production rate allocation may be adjusted to maximize the overall oil production from the pattern.
RECOVERIES OF OIL AND INJECTED PROPANE IN WAG AND CGI OPERATIONS

• Simulation shows that adding propane to the injection gas can effectively improve the oil recovery.

• A considerable quantity of injected propane can be produced back in both WAG and CGI operations.

WAG – Oil
- Oil Recovery with Different Gas Injection Scenarios

WAG – C3
- Injected Propane Recovery with Different Injection Scenarios

CGI – Oil
- Oil Recovery with Different Gas Injection Scenarios

CGI – C3
- Injected Propane Recovery with Different Injection Scenarios
DISCUSSION

• The density of liquid propane is unknown at this moment; specific data are needed from the vendor as gallon is volume unit and its numerical value changes with temperature and pressure.

• The preliminary economic analysis is optimistic, as the gas-processing cost was not included in the analysis.

• Blended gas injection has better economic performance, as less propane is needed for injection, although it yields lower oil recovery than the pure propane injection scenario.
PROGRESS AND CURRENT STATUS OF PROJECT

Task 4 – Business Case for Blended CO$_2$–Rich Gas Utilization

• Business case development has been initiated.
  – The EERC is working closely with Denbury on economic analyses to determine the potential for field-scale implementation of blended CO$_2$–rich gas EOR.
  – Rock samples were collected for the Rocky Mountain region.
  – Porosity, permeability, thin sections, and mercury injection capillary pressure (MICP) are all complete for this set.
  – Additional samples for the Gulf Coast region are being acquired.
  – Data collection for both regions continues.
### PROGRESS AND CURRENT STATUS OF PROJECT

#### Characteristics of CO₂ EOR Fields in Proposed Project

<table>
<thead>
<tr>
<th>Field</th>
<th>Basin</th>
<th>Zone</th>
<th>Dominant Lithology</th>
<th>Porosity Range, %</th>
<th>Permeability Range, mD</th>
<th>Thickness, ft</th>
<th>API Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bell Creek</td>
<td>Powder River</td>
<td>Muddy</td>
<td>Marine sandstone</td>
<td>25–35</td>
<td>150–1175</td>
<td>30–45</td>
<td>32–41</td>
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<tr>
<td>Cedar Hills</td>
<td>Williston</td>
<td>Red River</td>
<td>Dolostone</td>
<td>13–23</td>
<td>15</td>
<td>10</td>
<td>30</td>
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<tr>
<td>Tinsley</td>
<td>Mississippi</td>
<td>Woodruff</td>
<td>Shallow marine sandstone</td>
<td>26–28</td>
<td>1040–1300</td>
<td>80–90</td>
<td>32</td>
</tr>
<tr>
<td>Heidelberg</td>
<td>Mississippi</td>
<td>Eutaw</td>
<td>Marine sandstone</td>
<td>28</td>
<td>10–3115</td>
<td>550</td>
<td>23</td>
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</table>
A simplified equation was applied to evaluate economic feasibility of EOR with propane in the 04-01 pattern:

\[
\text{net income} = \text{oil sale income} + \text{produced gas sale income} - \text{gas injection cost}
\]

- Propane price varies between 0.5 and 1.0 $/gallon(US).
- Liquid propane density is 4.24 lb/gallon(US).
- Oil price is assumed at $74/bbl.
### Preliminary Economic Analysis

#### C3 Price = 0.5 $/gallon

<table>
<thead>
<tr>
<th>Inj. Method</th>
<th>C3 Mole Frac.</th>
<th>Oil income, $</th>
<th>C3 income, $</th>
<th>C3 cost, $</th>
<th>Net income, $</th>
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</thead>
<tbody>
<tr>
<td>WAG</td>
<td>0.3</td>
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<td>11,312,728</td>
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<tr>
<td>CGI</td>
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<td>20,127,076</td>
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<td>20,191,270</td>
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<td>1.0</td>
<td>22,725,252</td>
<td>26,110,694</td>
<td>53,132,029</td>
<td>-4,296,083</td>
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</tbody>
</table>

#### C3 Price = 1.0 $/gallon

<table>
<thead>
<tr>
<th>Inj. Method</th>
<th>C3 Mole Frac.</th>
<th>Oil income, $</th>
<th>C3 income, $</th>
<th>C3 cost, $</th>
<th>Net income, $</th>
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<tbody>
<tr>
<td>WAG</td>
<td>0.3</td>
<td>12,290,457</td>
<td>15,032,829</td>
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<td>22,725,252</td>
<td>52,221,388</td>
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<td>-31,317,417</td>
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</tbody>
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#### Diagrams

- **WAG Operations with Optimized Rate Allocation**
- **CGI Operations with Even Sweep in the Pattern**
PROGRESS AND CURRENT STATUS OF PROJECT

• Subtask 4.1 – Laboratory Studies
  – Rock samples were collected for the Rocky Mountain region.
  – Porosity, permeability, thin sections, and MICP are all complete for this set.
  – Oil samples for Tinsley, Heidelberg, and Cedar Hills Fields have been collected.
  – MMP studies are complete.
  – MW distributions for each oil sample have been determined.
  – Swelling and solubility testing will be initiated and completed during the next quarter.
  – Additional laboratory testing of rock samples will be performed to determine relative permeability using CO$_2$–rich gas blends.

• Subtask 4.2 – Data Management and Machine Learning (ML) Studies
  – Data for each field have been collected.
  – Development of ML algorithms will be initiated during the next quarter and applied to field cases during BP2.

• Subtask 4.3 Modeling and Simulation
  – The EERC is working with Denbury to refine a workflow process that can be applied to each business case scenario.
  – Bell Creek modeling is being used as the template that will be applied to each of the business case fields.
  – Wireline logs have been collected, and modeling for the Cedar Hills Field has been conducted.

![Graph of MMP between Diff. Oils and Mixture of CO2/Ethane](image-url)
BP2 ACTIVITIES

Field Validation and Monitoring
- Blended gas injection
- Well production
- Fluid sampling (gas and oil)
- Monitoring (rate, pressure, temperature)

Pilot Test Evaluation
- Improvement in oil recovery factor
- MW shifting

Business Case for Other Potential Target Fields
- Data management
- ML
- Modeling and simulation
PLANS FOR FIELD INJECTION AND MONITORING

• Field preparation
  – Build the rich gas field pilot test infrastructure (e.g., rich gas storage, compression, monitoring, sampling, etc.)

• Field validation and monitoring
  – Continuous blended gas (rich gas and CO$_2$) injection with WAG cycle or blended gas followed by chasing CO$_2$ gas
  – Production monitoring to evaluate the improvement on oil recovery
  – Periodic sample collection to monitor MW shifting

• Field validation decommissioning
PLANS FOR FUTURE TESTING/DEVELOPMENT/COMMERCIALIZATION

• The pilot test during BP2 will provide a unique U.S. data set on rich gas EOR, paving the way for larger-scale tests and deployment.

• Positive pilot test results would support the development of infrastructure and a market for stranded rich gas.

• Results would be applicable to develop business cases for other potential target fields.

• Because of the ability to leverage existing oilfield infrastructure, commercial implementation of rich gas EOR could occur quickly.