CO$_2$ Foam for Enhanced Oil Recovery and CO$_2$ Storage

Field Pilots in Texas

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Carbon Capture, Utilization, and Storage (CCUS)

Capture CO₂

Transport

Injection into subsurface reservoirs for energy production and CO₂ storage

Monitoring
CO$_2$ EOR and CO$_2$ Storage

Advantages
- Low MMP
- Oil Viscosity
- Swelling
- Emissions

Disadvantages
- Corrosion
- Low Availability
- High Mobility
CO$_2$ Mobility Control Agents

Direct Thickeners

Polymers/Polymer Gel

Foams

From European Space Agency

From Kuraray
CO₂ Foam

- **What?**
  Dispersion of gas in liquid
  Stabilized by surfactant

- **How?**
  Decreases relative permeability
  Reduces IFT
  Injection: SAG or Co-injection

- **Why?**
  Mobility control
  Increase reservoir sweep
  Improve CO₂ utilization

Sc-CO₂ EOR mobility challenges: a) poor aerial sweep, b) gas channeling, c) gravity override (Hanssen et al., 1994)
Motivation

Discrepancies arise between scale dependent CO$_2$ foam displacement mechanisms associated with laboratory and field scale processes.

- A further understanding of dominant displacement forces occurring at each scale is needed
- Field trials offer unique insight to bridge the gap between the laboratory and the field
Approach

Combining verified laboratory CO$_2$ foam technology with a field scale demonstration test. Project objectives are twofold:

1) Identify multiscale CO$_2$ foam displacement mechanisms during EOR and associated CO$_2$ storage

2) provide transferrable knowledge for the design of similar projects where foam is appropriate to mitigate CO$_2$ flood challenges
Pilot Design
# Field Development History

## East Seminole

<table>
<thead>
<tr>
<th>Depletion</th>
<th>Water Injection</th>
<th>CO₂ Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1940s</td>
<td>1960</td>
<td>1971</td>
</tr>
<tr>
<td>1981</td>
<td>1987</td>
<td>Oct-2013</td>
</tr>
<tr>
<td>2017</td>
<td></td>
<td>2017</td>
</tr>
</tbody>
</table>

## Lindoss Unit

<table>
<thead>
<tr>
<th>Reservoir Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>5200 ft</td>
</tr>
<tr>
<td>Permeability</td>
<td>1 – 300 mD</td>
</tr>
<tr>
<td></td>
<td>Ave. 13 mD</td>
</tr>
<tr>
<td>Porosity</td>
<td>3 – 28 %</td>
</tr>
<tr>
<td></td>
<td>Ave. 12-15 %</td>
</tr>
<tr>
<td>Pay Thickness</td>
<td>110 ft</td>
</tr>
<tr>
<td>Reservoir Pressure (initial)</td>
<td>2500 psig</td>
</tr>
<tr>
<td>Reservoir Pressure (current)</td>
<td>3200 psig</td>
</tr>
<tr>
<td>Temperature</td>
<td>104ºF</td>
</tr>
<tr>
<td>Oil Gravity</td>
<td>31º API</td>
</tr>
<tr>
<td>Initial Oil Saturation</td>
<td>0.65</td>
</tr>
<tr>
<td>Initial Water Saturation</td>
<td>0.35</td>
</tr>
<tr>
<td>Oil viscosity (reservoir conditions)</td>
<td>1.20 cP (at 2500 psig and 104 ºF)</td>
</tr>
<tr>
<td>Bubble Point Pressure</td>
<td>1805 psig</td>
</tr>
<tr>
<td>Formation Brine Salinity</td>
<td>70,000 ppm</td>
</tr>
<tr>
<td>S_{orw}</td>
<td>0.40 (Gray, 1989)</td>
</tr>
<tr>
<td>ROZ S_{orw}</td>
<td>0.25 (Honarpour et al. 2010)</td>
</tr>
<tr>
<td>ROZ ROS, waterflood</td>
<td>0.32 (Honarpour et al. 2010)</td>
</tr>
<tr>
<td>ROZ S_{orm}</td>
<td>0.12 (Honarpour et al. 2010)</td>
</tr>
</tbody>
</table>
Pilot Design

Identify Problems – ongoing CO$_2$ injection

- Poor sweep efficiency
- High producing gas oil ratio (GOR)
- CO$_2$ channeling

Potential Opportunities for Foam

- Conformance Control
- Mobility Control
- Combination
- Reservoir Heterogeneity
Pilot Well Selection Criteria

- Rapid gas breakthrough
- An high GOR in the selected producer
- Lower injection well head pressure
- Wells in close proximity to minimize geological uncertainty and maximize interwell connectivity.
Pilot Design - Objectives

• Increase incremental oil production through improved CO$_2$ sweep efficiency

• Reduce the producing GOR while maintaining injectivity

• Improve CO$_2$ utilization

• Verify CO$_2$ storage and mobility control
Pilot Pattern
Field Scale: Geologic and Reservoir Modeling

Identify flow zones

Petrophysical props and geologic structure

Model petrophysical props

Formation Structure
Laboratory Scale: Technology Testing and Verification

Foam System Design
CO$_2$ Foam Enhanced Oil Recovery (EOR)
CO$_2$ Storage
Foam System Design

Surfactant Screening
Surfactant Concentration
Foam Quality
Surfactant Screening

Objective

Surfactant with least amount of adsorption on reservoir material, in presence of CO₂

Results:

• Non-ionic Huntsman L24-22 surfactant (highly ethoxylated surfactant)
• Low surfactant adsorption on pure calcite and dolomite (0.05-0.1mg/m²)
• Adsorption remained unchanged in experiments with CO₂
Results:

- Gas Fraction ($f_g$) of 0.70 is recommended based upon the highest apparent viscosity at economically feasible $f_g$.

- The relatively small reduction in foam strength between $f_g = 0.30$ to 0.70 does not justify the choice of a more expensive CO$_2$ to surfactant solution ratio.

1wt% surfactant solution (green curves) and 0.5 wt% surfactant solution (blue curves)
CO₂ Foam
Enhanced Oil Recovery (EOR)

EOR and CO₂ storage potential
Surfactant concentration
Foam in the presence of oil
CO₂ Baseline

CO₂ Foam

Surfactant pre-flush

CO₂ foam

Waterflood

CO₂ foam ~ 35% OOIP

Oil saturation

PV injected

A_1wt%

B_1wt%

C_0.5wt%

D_0.5wt%

E_0.5wt%

A_dP

B_dP

C_dP

D_dP

E_dP

dP [bar]
Associated CO₂ Storage
Field Scale: Technology Demonstration

Reservoir Simulation
Surface Facilities
Data Collection and Monitoring
Reservoir Simulation

Foam injection strategy impacts on oil recovery, GOR, CO₂ mobility, and CO₂ utilization
Foam Injection Strategy

Field GOR of WAG, multi-cycle SAG, single cycle SAG, and rapid SAG.

<table>
<thead>
<tr>
<th>Case</th>
<th>CO₂ Utilization factor (Mscf/bbl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAG</td>
<td>30.14</td>
</tr>
<tr>
<td>SAG</td>
<td>19.26</td>
</tr>
<tr>
<td>Single Cycle SAG</td>
<td>20.47</td>
</tr>
<tr>
<td>Rapid SAG</td>
<td>21.30</td>
</tr>
</tbody>
</table>

Multi-cycle SAG
Field Injection Unit

Bulk Properties, 100% Active

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Kinematic Viscosity, cSt</th>
<th>Density, g/ml</th>
<th>Dynamic Viscosity, cP</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>84.11</td>
<td>1.0419</td>
<td>87.635</td>
</tr>
<tr>
<td>50</td>
<td>58.021</td>
<td>1.034</td>
<td>59.394</td>
</tr>
<tr>
<td>75</td>
<td>27.809</td>
<td>1.0147</td>
<td>28.218</td>
</tr>
</tbody>
</table>

Viscosity of 100% active L24-22 as a function of temperature

Kinematic Viscosity as a function of concentration and temperature for blends of L24-22 in Tabula Kose Brine
Data Collection and Monitoring

• Demonstrate creation of stable foam in reservoir

• Monitor the propagation of CO$_2$, water, and surfactant

• Establish baseline interwell connectivity
### Data Collection and Monitoring

- Interwell Connectivity
- Injection Profiling
- Reservoir Characterization and Fluid Monitoring
- Recovery and Production Monitoring
- Corrosion

<table>
<thead>
<tr>
<th>Stage</th>
<th>Pre SAG (baseline)</th>
<th>Pilot Phase (3 SAG cycles)</th>
<th>Post SAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slug</td>
<td>Ongoing CO₂ Injection</td>
<td>Surfactant CO₂ Surfactant CO₂ Surfactant CO₂</td>
<td>CO₂, water</td>
</tr>
<tr>
<td>Tracers</td>
<td>CO₂, water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection Profiles (L14)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Fall off test</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Crosswell Seismic</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
Conclusions

Laboratory
- reservoir cores
- nonionic Huntsman L24-22
- 0.5 wt% at \( f_g = 0.70 \)
- 35% Incr. OOIP

Field
- 40 acre 5-spot
- foam model input
- water and oil
- unswept zones
- multi-cycle SAG

Site
Surfactant
Foam System
EOR
CO\(_2\) Storage
Injection Strategy
CO\textsubscript{2} Foam for Enhanced Oil Recovery and CO\textsubscript{2} Storage

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CO$_2$ Foam: Pore Scale

Baseline (CO$_2$ + brine)

CO$_2$ foam (CO$_2$ + 1 wt% surfactant solution)
CO₂ Displacement Mechanisms