Improving Conformance in CO₂ Floods with Polymer Gel Treatments

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Agenda

• Conformance Improvement
• Polymer Gels
• Designing a Gel Treatment for CO₂ Floods
• SACROC Case Study
“Next Generation” CO$_2$ EOR

- DOE reports “Next Generation” CO$_2$ EOR technologies could technically recover 137 billion barrels

- Next Generation CO$_2$ EOR
  - Increase CO$_2$ injection by 50% or more
  - Horizontal injection/production wells
  - Advanced flood monitoring
  - Improved mobility ratio
  - Conformance improvement
Conformance Improvement

“Applying a method or technology from the injection side intended to significantly reduce flow into a high permeability anomaly leading to improved distribution of injected materials”
Problems

- Poor aerial and vertical sweep
- Adverse injection profiles
- Gravity override
- Early gas breakthrough
- Producing at high GORs
CO$_2$ Conformance Improvement Techniques

- Water-Alternating-Gas
- Mechanical Methods (packers, cement, sand back, etc.)
- Well Control (well placement, choking)
- Foams
- Polymer Gels
What is a Polymer Gel?

- Polyacrylamide polymer and crosslinker mixed in water
- Polymer MWs range 0.5 to 18 million Daltons
- Referred to as a bulk gel
- Reservoir temperature dictates crosslinker
- Two most common polymer gels
  - MARCIT: Chromium Acetate (Cr$^{+3}$)
  - UNOGEL: HMT/HQ
Bulk Polymer Gel Systems

- Blocks flow into channels, fractures and thief zones
- Penetrates in-depth as far as feature extends
- Delayed crosslinking mechanism
- Robust non-degrading chemistry
- Resistant to H₂S, CO₂ & high TDS water
Gel Strengths

3000 PPM
6,000 PPM
10,000 PPM
Gel Treatment Sizing Strategies

- Injection well volumes are based off a percentage of the channel or thief zone volume
  - Estimate the amount of oil produced before water or gas breakthrough
  - Tracers
- Other considerations
  - Well spacing
  - Reservoir characteristics (i.e. fractured vs. matrix)
- Ultimate volume / concentration of treatment will be dictated by pressure response
Tailoring Gel Treatments to CO$_2$ Floods

- Larger gel volumes
  - Overcome high mobility of CO$_2$
  - Can be dependent on thief zone location
- Higher ending gel concentrations
  - Must withstand high near wellbore differential pressure
Channel Volume Calculation

CO₂ Flood

Channel Volume = 5,000 bbl

Cum Oil (bbls) vs. GOR
Channel Volume Calculation
WAG Flood

Graph showing WOR (bbls/MMscf) and Injection Volume (swpdp/mtcfd) with key dates and values.
Polymer Gel Injection Well Heuristics

<table>
<thead>
<tr>
<th>Volume</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 - 4,000 bbl</td>
<td>1,500 – 6,000 ppm</td>
</tr>
<tr>
<td>4,000 - 20,000+ bbl</td>
<td>4,500 – 25,000 ppm</td>
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</table>

- Thin Well Defined Thief Zone
  - Thin high permeability matrix anomaly
  - Micro-fractures
  - Close well spacing
  - Crossflow

- Thick / Multiple Thief Zone(s)
  - Thick high permeability matrix anomaly
  - Large well spacing
  - Significant crossflow

- Direct Fracture / Wormhole
  - Highly conductive natural or hydraulic fracture
  - Wormhole

- Complex Fracture Network / Karsted
  - Extensive and highly conductive fracture network
  - Vuggy Porosity
Past Case Studies

• Wertz WAG Conformance Improvement (SPE 27825)
  - Avg. incremental pattern reserves of 87,000 bbl with avg. payout of 2.3 months

• Rangely WAG Conformance Improvement (SPE 36912, 56008)
  - Total incremental oil rate of 625 bopd with 80% success rate and ROR = 365%

• Brookhaven CO₂ Conformance Improvement (16th Annual Flooding Conference Midland, TX)
  - HT gel application
SACROC Conformance Improvement
SACROC Unit

- Located in West Texas encompasses over 50,000 acres
- OOIP = 2.8 billion barrels
- Initiated in 1972, it was the first commercial CO₂ EOR project
- Gas handling capacity of 0.6 BCF
- Produces 29,300 bpd of incremental oil
- CO₂ EOR resulted to date in 10% HCPV incremental
- Currently operated by Kinder Morgan
SACROC Reservoir Description

- Produces from a thick carbonate build-up on the Horseshoe Atoll
- Middle Pennsylvanian through Early Permian age
- Stratigraphically complex reservoir
- Average matrix permeability = 3 mD
- Average porosity = 9.4%
- Fractured, vuggy porosity in some areas
Conformance Issues

• Variability in geology led to difficulty in predicting pattern performance

• Poor pattern performance characterized by:
  - Early gas breakthrough
  - Unfavorable injection profiles
  - Poor oil responses
141-3 Injection Pattern
141-3 Injection Pattern: Poor Conformance

12/08 Pattern Test Oil Rate = 0 bpd
141-3 Channel Volume Estimation

Two producers added to pattern

39,500 BWI

87,000 BWI
Gel Treatment Design

- Evolution of SACROC designs:
  - Set a base design (25% of channel volume)
  - Change design based on pressure response

<table>
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<tr>
<th>Stage</th>
<th>Volume (bbl)</th>
<th>Polymer (ppm)</th>
<th>Polymer (lbs)</th>
<th>Poly:CL Ratio</th>
<th>MW (Daltons)</th>
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<td>Preflush</td>
<td>50</td>
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<tr>
<td>2</td>
<td>1,000</td>
<td>4,000</td>
<td>1,458</td>
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<td>10-12</td>
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<tr>
<td>3</td>
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<td>5,500</td>
<td>10,025</td>
<td>40</td>
<td>16-18</td>
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<tr>
<td>4</td>
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<td>7,000</td>
<td>15,306</td>
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<td>16-18</td>
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<td>5,000</td>
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<td>14,580</td>
<td>40</td>
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<tr>
<td>6</td>
<td>3,000</td>
<td>10,000</td>
<td>10,935</td>
<td>40</td>
<td>16-18</td>
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<tr>
<td>7 (CAPIT)</td>
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<td>30,000</td>
<td>525</td>
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<td>10-12 + 0.5</td>
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<td>Postflush</td>
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<tr>
<td>Total</td>
<td>20,100</td>
<td></td>
<td>52,829</td>
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141-3 Gel Treatment Log

Switch to HMW gel
141-3 Treatment Response

141-3 Injection Pattern

- Oil Rate
- Water Rate
- Gas Rate
- Gel Treatment
- Water Injection
- Gas Injection

28,025 bbl Gel Treatment

The Science of Enhanced Oil Recovery
141-3 GOR/WOR vs Np

Incremental Oil = 90,000 bbl

GOR (mscf/bbl) / WOR (bbl/bbl)

Cumulative Oil (bbl)
141-3 Treatment Summary

- Pressure response dictated increasing treatment volume to 28,025 bbl
- Treatment lowered pattern GOR from ~1,000 to under ~100
- Extended pattern life by 1.5 years
- Incremental oil = 90,000 bbl
- Treatment Cost = $400,000
- Incremental cost per bbl = $4.45 per IBO
28-5a Injection Pattern

- Prior to CO$_2$ injection, pattern exhibited production at high WOR
- Due to recent success of gel treatments, operator decided to treat pattern prior to CO$_2$ injection
- Typically, the earlier in the life of a flood conformance improvement is undertaken leads to more sustained results
- Same base design as 141-3
28-5a Injection Pattern
28-5a Gel Treatment Log

Cumulative BBLs. Injected

- Inj. Rate (BPD)
- BHP (psi)
- WHIP (psi)
- Polymer Conc. (ppm)
28-5a Treatment Response

28-5a Injection Pattern

28,100 Gel Treatment

Graph showing various rates and injection patterns over time with specific dates and key labels for oil rate, water rate, gas rate, water injection, gas injection, and gel treatment.
28-5a GOR/WOR vs Np
28-5a Treatment Summary

• Injection of large volume of gel suggest highly conductive fractures and voids

• Pattern has maintained a low GOR two years post-treatment

• Pattern has performed well relative to other non-treated patterns
166-6 Injection Pattern Treatment

Cumulative BBLS. Injected

- Inj. Rate (BPD)
- BHP (psi)
- WHIP (psi)
- Polymer Conc. (ppm)
166-6 Injection Pattern Response

166-6 Injection Pattern

2,000 bbl Gel Treatment

Production Rate (bpd/mstd)

Injection Rate (bwpjpd / mstdjpd)

4/28/07 11/14/07 6/1/08 12/18/08 7/6/09 1/22/10 8/10/10 2/26/11 4/1/12 10/18/12

- Oil Rate
- Water Rate
- Gas Rate
- Gel Treatment
- Water injection
- Gas injection
SACROC Conformance Improvement

• Overall, large volume treatments were correlated with successful and sustained results

• Estimated 500,000 bbl incremental to date

• Due to the success of polymer gel treatments, Kinder Morgan has adopted these treatments as one of their conformance improvement strategies

• Treated nearly every injector in their new CO₂ expansion area
  - Results will be known in late 2012
CO₂ Gel Treatment Observations

- Field results demonstrate polymer gel is stable in CO₂ floods
- Large volume treatments necessary to combat highly mobile CO₂
- Higher end concentrations necessary
- Upfront thorough design work is necessary but ultimate volume/concentration pumped is dictated by pressure response
Thanks and Questions

- Kinder Morgan
- TIORCO, LLC
- Enhanced Oil Recovery Institute