Polymer Flooding in the Minnelusa

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June 5th, 2014
Why EOR in the Minnelusa

- Clean sandstone with good permeability
- Low primary production (5-15% OOIP)
- Availability of fresh Fox Hills water
- Confined reservoirs with good communication (generally…)
- Typically low to medium reservoir temperature
- Good waterflood recovery (~40% OOIP)
  - High vertical heterogeneity
  - Poor mobility
  - Good Sor
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Historical Development of Minnelusa EOR

Polymer Type Flooding

- **Polymer Flooding**
  - Improve Mobility
  - SE Kuehne Ranch
  - Kuehne Ranch

- **Cat-An Process**
  - Cat + An Polymer more resistance to flow
  - West Semlek

- **Layered Process**
  - Alternating injection An Polymer + XL
  - Stewart Ranch

- **Colloidal Dispersion Gel**
  - “weak gels”
  - Edsel
  - N Rainbow Ranch

Increasing Residual Resistance Factors
Wyoming Tertiary Projects: 2008 Wyoming O&G Stats, The WOGCC

Chemical Flooding Dominates

Distribution of Wyoming Tertiary Projects

- ~42% of polymer floods are CDG floods

- Polymer Projects: 92
- Surfactant (micellar): 21
- CO2 (includes huff and puff): 6
- Thermal: 3
- Other: 11

Total Number of Projects = 133

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“In-Depth CDGs Improve Oil Recovery Efficiency” (SPE 27780)

- Provide permeability modification and mobility control
- 29 CDG projects evaluated (83% Minnelusa)
- 22 considered successful
- Total recoveries > 40% OOIP in reservoirs with vertical heterogeneity factors ~0.75
- CDG average incremental recovery = 7.5% OOIP (1994)
- Chemical costs: $1.00-2.00 per incremental bbl
“A Comparison of 31 Minnelusa Polymer Floods with 24 Minnelusa Waterfloods” (SPE 20234)

- PF in the Minnelusa reduces the risk associated with straight waterflooding
- At equal injection volumes, PF recovers more oil and produces less water than WF
- PF recover an incremental 7.5% OOIP over waterflooding at a cost of $1.69 per incremental bbl of oil

WF vs Chemical Flooding in the Minnelusa

Chemical flooding improves recovery on average 9% OOIP compared to waterflooding*
Chemical flooding produces more oil sooner*
The sooner you start EOR, the more oil you recover*
High WF RF StDev highlights differences in Minnelusa heterogeneity

The Sooner you Start EOR the More You Recover…

- Many Minnelusa polymer type projects began immediately after primary production
- Makes it difficult to differentiate between secondary and tertiary recovery
- Commenced an internal study to estimate incremental tertiary recovery
  - Use state reported production data combined with internal reservoir / chemical flood data to estimate RF to date
  - Use Secondary Recovery Analysis Model (SRAM) to forecast waterflood recovery (pseudo steady-state linear flow Buckley Leverett model)
Big Mac Unit (1986)
Reservoir Properties

- Minnelusa “B” Sand at an average depth of 7,726 ft MD
- Average porosity: 19%
- Permeability: average 175 md (range 130-600 md)
- Average net pay: 17 ft
- Oil gravity: 21° API
- Formation water TDS: 10,841 ppm (Chlorides 8,230 ppm)
- BHT: 138° F
- Dykstra-Parson Factor = 0.5 (Minnelusa Average ~ 0.7)
Background

- Big Mac field first production was November 1983
- Primary production was by rock and fluid expansion
- A unit feasibility study (August 1985) indicated that a polymer augmented waterflood (WF/CDG) would recover additional oil
  - PV: 3,970,000 bbl
  - OOIP: 2,640,000 STBO
  - Estimated Ultimate Primary Recovery: 280,200 STBO (10.6% of OOIP)
**Injection Pattern (1986)**

- WF/CDG injection pattern consisted of 4 producing wells and 1 WI well:

<table>
<thead>
<tr>
<th>Well</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>McBeth-Brown #1</td>
<td>Injector, converted to WI (CTWI) May-1986</td>
</tr>
<tr>
<td>Powder River #1-A</td>
<td>Producer, Active</td>
</tr>
<tr>
<td>Roy #1</td>
<td>Producer, Active</td>
</tr>
<tr>
<td>Big Mac Federal #1</td>
<td>Producer, Active</td>
</tr>
<tr>
<td>Big Mac Federal #2</td>
<td>Producer, Active</td>
</tr>
</tbody>
</table>

- Other wells in the injection pattern:
  - Powder River #1 P&A’d Jul-1985 (replacement well Powder River #1-A drl’d Jul-1985)
  - Big Mac Federal #4 drilled in Apr-1991
Big Mac EOR Recommendations

- Start with Cat-An process
- Follow with CDG process (newly developed)
- Finish with straight anionic polymer for mobility control
- Total polymer volume = 25% PV
- Waterflood began in May 1986 followed by polymer in June 1986
- SRAM predicted water breakthrough in 30 months

<table>
<thead>
<tr>
<th>Incremental Forecasts</th>
<th>OOIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary Recovery</td>
<td>23.0%</td>
</tr>
<tr>
<td>Tertiary Recovery</td>
<td>32.4%</td>
</tr>
<tr>
<td>Polymer Incremental</td>
<td>9.4%</td>
</tr>
</tbody>
</table>
## Polymer Treatment Summary

<table>
<thead>
<tr>
<th>Cationic Polymer</th>
<th>Injected Vol. (Bbls)</th>
<th>CAT-AN 160 (lbs)</th>
<th>Avg Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Totals</td>
<td>122,004</td>
<td>16,000</td>
<td>375</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anionic Polymer</th>
<th>Injected Vol. (Bbls)</th>
<th>UNI-PERM 420 (lbs)</th>
<th>Avg Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Totals</td>
<td>122,786</td>
<td>15,475</td>
<td>360</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TIORCO CDG</th>
<th>Injected Vol. (Bbls)</th>
<th>UNI-PERM 420 (lbs)</th>
<th>TIORCO 677 (lbs)</th>
<th>Avg Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Totals</td>
<td>131,995</td>
<td>15,910</td>
<td>41,096</td>
<td>345</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anionic Polymer</th>
<th>Injected Vol. (Bbls)</th>
<th>UNI-PERM 420 (lbs)</th>
<th>Avg Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Totals</td>
<td>61,242</td>
<td>4,525</td>
<td>211</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TIORCO CDG</th>
<th>Injected Vol. (Bbls)</th>
<th>Hi-Vis 350 (lbs)</th>
<th>TIORCO 677 (lbs)</th>
<th>Avg Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Totals</td>
<td>407,154</td>
<td>34,360</td>
<td>59,614</td>
<td>241</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anionic Polymer Mobility Control</th>
<th>Injected Vol. (Bbls)</th>
<th>UNI-PERM 420 (lbs)</th>
<th>Avg Concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Totals</td>
<td>60,000</td>
<td>3,900</td>
<td>225/150</td>
</tr>
</tbody>
</table>
Oil Rate Actual versus Forecasted

TIORCO Progress Report #4, September 1990
Big Mac Unit Time-Rate Plot

CDG started in Jun-1986 and stopped in Apr-1991
Big Mac Unit WOR vs Cumulative Oil

WF/CDG started in May-1986 and stopped in Apr-1991
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Big Mac Unit WOR vs TIME

- First water breakthrough occurred ~24 months into flood (~6 months ahead of forecast)
- WF started May 1986
- Polymer started Jun 1986
- Polymer stopped Apr 1991
WF/CDG Production Response

- All four producing wells in the original injection pattern responded to the WF/CDG:
  - Roy #1 showed a very good response and is currently producing (reached peak tertiary rate of ~330 bopd)
  - Federal #1 showed a very weak response and was converted to PWD in Sep-1988, SI Sep-1995
  - Powder River #1-A showed good initial response but watered-out early and was converted to WIW in Dec-1991, currently active
  - Federal #2 showed a good response and eventually converted to WIW in Dec-1995, currently active
- Big Mac Federal #4 (drilled in 1991) showed a good response, and is currently producing
- McBeth-Brown #1 WIW was SI in Sep-1995
### Polymer / CDG Performance Overview

#### Big Mack Performance Review

<table>
<thead>
<tr>
<th>Incremental Forecasts</th>
<th>STBO</th>
<th>%OOIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production through 2011 (WOGCC)</td>
<td>1,255,000</td>
<td>47.5%</td>
</tr>
<tr>
<td>Estimated Ultimate Primary Recovery</td>
<td>280,000</td>
<td>10.6%</td>
</tr>
<tr>
<td>Incremental WF/Polymer Recovery</td>
<td>975,000</td>
<td>37%</td>
</tr>
<tr>
<td>Estimated Polymer Incremental</td>
<td>368,000</td>
<td>14%</td>
</tr>
</tbody>
</table>

- SRAM forecasted incremental WF recovery: 606,500 STBO (23% OOIP)
- SRAM forecasted incremental polymer recovery: 248,500 STBO (9.4% OOIP)
Economics

- Total chemical costs: $198,000
- Total equipment costs: $152,000
- Polymer incremental recovery: 368,000 STBO
- Incremental cost per STBO: $0.95

Chemical Injection Skid
Conclusions

- The WF/Poly flood was a success recovering 37% OOIP
- The polymer type flood at the Big Mac Unit recovered an estimated incremental oil of 14% OOIP
- Earlier than expected water breakthrough dictated the continued use of CDGs
  - Likely underestimated Dykstra-Parsons factor in original SRAM results
- The polymer type flood resulted in an incremental cost per STBO: $0.95
- Good first step in:
  - Quantifying incremental recoveries in secondary recovery Minnelusa polymer floods
  - Validating the use of EOR early in the life of a flood
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