Historic IOR/EOR Practices in the Minnelusa

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Outline

• Introduction:
  • Why EOR in the Minnelusa?
  • Historical Development of Minnelusa EOR
• Summary of EOR in Wyoming
• N. Rainbow Ranch EOR Project
• What is Next in Improving Minnelusa Oil Recovery
• Closing Remarks
Why EOR in the Minnelusa?

- Minnelusa is a clean sandstone with good permeability
- Fresh Fox Hills Water is available for water injection
- Primary Production is low (5-15% OOIP)
- Confined Reservoirs with Good Communication
- Waterflooding is successful; 2-5 times Primary
- Waterflooding Ultimate Oil Recovery Limited (~ 35% OOIP)
  - Viscous Oil, High Permeability Variation & Good Residual Oil Saturation
  - Waterflood Efficiency Poor
Historical Development of Minnelusa EOR

• Polymer Flooding – Improve Mobility Ratio (SE Kuehne Ranch, Kuehne Ranch)

• Cat-An Process – Combining Cationic and Anionic polymers to provide more resistance to flow than polymer (W. Semlek, OK, Kummerfeld)

• Phillips Petroleum first developed the “layered process” which was first injected in the Hamm Unit in Mid-70’s (Stewart Ranch)

  - Found sequential injection of HPAM / aluminum citrate (AlCit) created higher RRF than straight polymer
Historical Development of Minnelusa EOR

• Colloidal Dispersion Gel (CDG) Process – CDGs (weak gels) generate higher viscosities & RRF than polymer solutions at lower concentrations (Edsel, Alpha, OK)

• The first CDG flood was implemented in 1985 in the Edsel Minnelusa Unit, Crook County, WY
  - The flood switched from the layered to the CDG process
  - Results showed an incremental recovery of 11.5 % OOIP

• MARCIT Bulk Gel Process – strong gels formed with Cr crosslinker to significantly reduce flow in high permeability channels (N. Rainibow Ranch, Ash, Indian Creek)
Summary of EOR Projects in Wyoming
Wyoming Tertiary Projects:
2008 Wyoming O&G Stats, The WOGCC

Chemical Flooding Dominates

Distribution of Wyoming Tertiary Projects

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

~42% of polymer floods are CDG floods

Total Number of Projects = 133
Evaluation of Chemical Flooding in the Minnelusa Formation, PRB, WY*

- EORI publication evaluated the EUR of 32 chemical (mostly polymer) and waterfloods

- The primary conclusions were:
  
  - Chemical flooding improves recovery by an average of 9% OOIP compared to waterflooding
  
  - Chemical flooding produces more oil sooner
  
  - The sooner you start EOR the more oil you recover

Minnelusa Production Analysis

CDG or CDG + polymer floods (PF’s) reported as PF only

ASP

RF at EUR (%OOIP)

Courtesy of EORI
N. Rainbow Ranch
EOR Project
N. Rainbow Ranch Unit (SPE-27773 Updates)

- Summary of reservoir and fluid properties (R71W – T49N)

<table>
<thead>
<tr>
<th>Formation</th>
<th>Minnelusa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>9,500 ft</td>
</tr>
<tr>
<td>Porosity</td>
<td>19.7%</td>
</tr>
<tr>
<td>Water Saturation</td>
<td>20%</td>
</tr>
<tr>
<td>Temperature</td>
<td>202°F</td>
</tr>
<tr>
<td>Permeability Range</td>
<td>1 - 1,000 mD</td>
</tr>
<tr>
<td>Perm. Variation (DP)</td>
<td>0.9</td>
</tr>
<tr>
<td>Oil Gravity</td>
<td>26°API</td>
</tr>
<tr>
<td>Oil Viscosity</td>
<td>3.94 cp</td>
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</table>
## N. Rainbow Ranch Unit (SPE-27773 Updates)

- Summary of CDG treatment design:

<table>
<thead>
<tr>
<th>Stage</th>
<th>Injection bbls</th>
<th>Product*</th>
<th>Pounds</th>
<th>Concentration mg / l</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>81,000</td>
<td>Cationic Polymer</td>
<td>22,000</td>
<td>775</td>
</tr>
<tr>
<td>2</td>
<td>46,000</td>
<td>Anionic Polymer</td>
<td>22,500</td>
<td>1,400</td>
</tr>
<tr>
<td>3</td>
<td>198,000</td>
<td>Anionic Polymer Al-Citrate</td>
<td>83,100</td>
<td>1,200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>654,000</td>
<td>Anionic Polymer Al-Citrate</td>
<td>68,700</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>76,000</td>
<td></td>
</tr>
</tbody>
</table>

* Polyacrylamide polymers
N. Rainbow Ranch Unit (SPE-27773 Updates)

CDG Performance (Oil rate vs. time)

#6 Casing Collapse

Marcit Treatment – March, 93
N. Rainbow Ranch Unit (SPE-27773 Updates)

WOR vs Cumulative Oil

- 900 MBO Incremental
- 300 MBO Incremental
- SPE-27773
N. Rainbow Ranch Unit Summary Conclusions

• Approximately 12% PV was injected over the life of chemical flood

• CDGs using high molecular weight polymer were successfully injected into a non-fractured, high permeability sandstone formation

• Total recovery to date of 49.4% OOIP

• Preliminary incremental recovery estimates were estimated in 8.0% of OOIP (SPE-27773). Current analysis suggests an incremental recovery of 15.7% OOIP

• Updated results estimate a development cost of $1 per incremental barrel
ASP Flooding
ASP Flooding

- First ASP Flood ever carried out in Minnelusa lower sand at West Kiehl Unit
  - Started in September 1987
  - Used Petrostep B100, Soda Ash and Pusher 700
- First ASP Flood started at the beginning of Secondary Recovery: Cambridge Minnelusa Unit
  - Started in 1993
  - Used Petrostep B100, Soda Ash, Alcoflood 1275A
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation</td>
<td>Minnelusa Upper B</td>
</tr>
<tr>
<td>Depth</td>
<td>7,108 ft</td>
</tr>
<tr>
<td>Temperature</td>
<td>132 F</td>
</tr>
<tr>
<td>Pore volume</td>
<td>7,117 Mbbl</td>
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<tr>
<td>OOIP</td>
<td>4,900 Mbbl</td>
</tr>
<tr>
<td>Thickness</td>
<td>29 ft</td>
</tr>
<tr>
<td>Average porosity</td>
<td>18%</td>
</tr>
<tr>
<td>Average Permeability</td>
<td>845 md</td>
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<tr>
<td>Initial water saturation</td>
<td>31.6%</td>
</tr>
<tr>
<td>Oil API gravity</td>
<td>20</td>
</tr>
<tr>
<td>Oil viscosity</td>
<td>31 cps</td>
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<tr>
<td>Flood date</td>
<td>1993-1998</td>
</tr>
</tbody>
</table>
Cambridge Field Pilot Test Results

Oil Production


1,000 10,000 100,000

Actual
Simulated

Primary
Forecast Secondary ASP Flood
Alkaline-Surfactant-Polymer Flood

History Match Primary
Delayed decline in Oil Production

Field Comparisons
- Cambridge
- Mellott Ranch North
- Average Waterflood
Cambridge Recovery Summary

• Ultimate Oil Recovery 69.6 %OOIP
• Primary and Water flood 36.2 %OOIP
• ASP Incremental Recovery 33.4 %OOIP

• Cost per Incremental Barrel 4.07 $/bbl (2.94$/bbl)

• Chemical cost and facilities
  - 750m lb Petrostep B-100 @ $2.00/lb
  - 1,350m lb Alcoflood 1275A @ $1.20/lb
  - 10,200m lb Na2CO3 @ $0.12/lb
  - Facilities @ $1.0MM ($170M)

• Incremental oil = 1.3MM bbl, Value @ 50$/bbl = $65MM
What is Next in Improving Minnelusa Oil Recovery

- Mature Floods with High WOR
- Need a Combination of Sweep Improvement with Reduction in Sor
- Start with Sweep Improvement – CDG or Marcit
- Follow with ASP or SP
- Follow with Polymer
- Ultimate Oil Recovery > 60% OOIP
Closing Remarks
Closing Remarks

• Minnelusa is a great formation to try EOR
  • Clean sandstone, fresh water, successful waterflood, small confined reservoirs
• Sweep improvement Processes have proven successful in improving oil recovery economically
• ASP Projects have shown good incremental oil recovery, although economics are more challenging than sweep
• Since most Minnelusa reservoirs are mature water/EOR floods, future EOR is challenging