Historic IOR/EOR practices in the Minnelusa

Jim Mack & Mike Lantz

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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
The Science of Enhanced Oil Recovery

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
Chemical Flooding Dominates

Distribution of Wyoming Tertiary Projects

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

~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

![Graph showing 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>
</tr>
</tbody>
</table>
### 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>71,000</td>
<td>1,000</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>330</td>
</tr>
</tbody>
</table>

* Polyacrylamide polymers
CDG Performance (Oil rate vs. time)

- #6 Casing Collapse

Marcit Treatment – March, 93

CDG Process

Monthly Oil Rate (BOPD)
N. Rainbow Ranch Unit (SPE-27773 Updates)

WOR vs Cumulative Oil

- 900 MBO Incremental
- 300 MBO Incremental
- SPE-27773

The Science of Enhanced Oil Recovery
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>
</tr>
<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>
</tr>
<tr>
<td>Flood date</td>
<td>1993-1998</td>
</tr>
</tbody>
</table>
Cambridge Field Pilot Test Results

Oil Production

100,000

10,000

1,000


Oil (bbl/month)

Primary

History Match Primary

Forecast Secondary ASP Flood

Alkaline-Surfactant-Polymer Flood

Actual

Simulated

The Science of Enhanced Oil Recovery
Delayed decline in Oil Production

Field Comparisons
- Cambridge
- Mellott Ranch North
- Average Waterflood

Cumulative Waterflood Oil - ASP Oil (Vp)
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