Keys to Achieving a Successful Waterflood and Estimating Waterflood Reserves

Presented at
The Dallas SPEE Chapter Meeting
March 28, 2013

Dr. William M. Cobb
Petroleum Engineering & Geological Consultants
Dallas, Texas
PRIMARY RECOVERY VS WF

- **Primary Recovery**
  Requires the Reservoir Pressure be Constantly Declining

- **Waterflooding is**
  1. A Displacement Process
  2. Most Efficient When Reservoir Pressure is Maintained or Increased
PRIMARY RECOVERY VS WF

- When converting from primary to waterflooding

1. The reservoir recovery mechanism changes.

2. Consequently reservoir evaluation and reservoir management procedures generally need to be changed.
WHAT ARE THE KEY FACTORS THAT DRIVE THE OUTCOME OF A WATER INJECTION PROJECT?

\[ N_P \propto N \times E_A \times E_V \times E_D \]

\( N_P \) = Cumulative Waterflood Recovery, BBL.
\( N \) = Oil in Place at Start of Injection, BBL.
\( E_A \) = Areal Sweep Efficiency, Fraction
\( E_V \) = Vertical Sweep Efficiency, Fraction
\( E_D \) = Displacement Efficiency, Fraction
$\frac{N_p}{N} = RF$

$E_A = f \text{(MR, Pattern, Directional Permeability, Pressure Distribution, Cumulative Injection & Operations)}$

$E_V = f \text{(Rock Property variation between different flow units, Cross-flow, MR)}$

$E_{VOL} = \text{Volumetric Sweep of the Reservoir by Injected Water}$

$E_D = f \text{(Primary Depletion, So, } \bar{So}, K_{rw} & K_{ro}, \mu_o & \mu_w)$

$RF \propto \frac{E_A * E_V * E_D}{E_{VOL}}$
Willhite's Correlation for Five Spot Volumetric Sweep Efficiency with WOR = 50.
THE QUARTERBACK OF ALL INJECTION PROJECTS IS THE INJECTION WELL

Properly Locate Injection Wells:

✓ They provide appropriate areal distribution of the injected water
✓ They deliver the water at the correct time
✓ They deliver the water in the proper volume
✓ Effective utilization of injection wells is the important key to optimizing the WF by allowing EA and EV values and RF to be maximized
Injectors and producers are located to form confined patterns
Patterns take advantage of $K_x/K_y$
Injection profiles are monitored and effectively managed
The most efficient waterfloods are when the injection to production well count ratio is near 1:1 ($I/P > 1.0$ not always bad)
Good producers make good injectors - bad producers make bad injectors
Waterflood Reserve Forecasting

1. Numerical simulation
   ✓ Detailed geological description
   ✓ Reliable PVT and relative permeability
   ✓ Accurate history matching of production and pressure on a well by well basis
2. Decline curve analysis by well

- Rate versus time should be used with caution
- Rate versus cumulative oil should be used with caution
- Log WOR versus cumulative oil when WOR > 2.0 is probably best
- Reliable forecast require accurate well tests
Oil and water production rates are directly related to injection rates. Therefore, DCA of $q_o$ vs $t$ or $q_o$ vs $N_P$ must be evaluated only after giving consideration to historical and projected water injection rates.
OIL RATE VS CUMULATIVE OIL PRODUCED

Start Water Injection

EUR 49 MMBO

EUR 53 MMBO
OIL RATE VS CUMULATIVE OIL PRODUCED

Start Water Injection

EUR 49 MMBO

EUR 53 MMBO
WOR IS INDEPENDENT OF INJECTION RATE BUT DEPENDENT ON STRATIFICATION

\[
WOR = \frac{q_w}{q_o}
\]

\[
WOR = \frac{i_w \cdot f_w}{i_w \cdot (1 - f_w)}
\]

\[
WOR = \frac{f_w}{(1 - f_w)}
\]

\[
(WOR)_{STD.\ COND.} = \frac{f_w}{(1 - f_w)} \cdot \frac{B_o}{B_w}
\]

Conclusion

✓ WOR is independent of injection rate
✓ WOR should be applied to individual wells and not field
✓ WOR should be applied using values greater than 2.0
WATER OIL RATIO VS CUMULATIVE OIL

Cumulative Oil Production (MMBbls.)

WOR

EUR 55 MMBO
3) Analogy Requires:

✓ Saturations similar at start of injection, So, Swc, & Sg

✓ Rock Properties are similar
  ▪ Relative permeability
  ▪ Dykstra-Parson V factor

✓ Fluid Properties, viscosity ($\mu_o$)
NORTH AMERICA
LIQUID EXPANSION - SOLUTION GAS DRIVE

Pi = 4400 Psi
RF = 1%
Swc = 24%
So = 76%
Boi = 1.75
OOIP = 100 MMSTBO

Pbp = 4000 Psi
Swc = 24%
So = 76%
Bobp = 1.78

P = 400 Psi
RF = 19%
Swc = 24%
Sg = 36%
So = 40%
Bo = 1.15
OIP = 80 MMSTBO
Dykstra-Parson Coefficient of Permeability Variation 'V'

V = (k50 - k84.1) / k50

V = 0.86

V = 0.62
4) Secondary to Primary Ratio (S/P):

✓ Projects must be analogous

✓ Use with extreme caution because most projects are not analogous
Voidage Replacement Ratio Analysis (VRR)

Desired Ratio 1.1 to 1.2

- Calculated at reservoir conditions
- Includes:
  - Oil
  - Water
  - Gas (solution and free)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_i$ = $P_{bp}$</td>
<td>2250 Psi</td>
</tr>
<tr>
<td>$R_{si}$</td>
<td>550 SCF/STBO</td>
</tr>
<tr>
<td>$B_{oi}$</td>
<td>1.39 RB/STB</td>
</tr>
<tr>
<td>$\mu_{oi}$</td>
<td>0.44 CP</td>
</tr>
<tr>
<td>$P$</td>
<td>2100 Psi - At Start Of Injection</td>
</tr>
<tr>
<td>$S_{wc}$</td>
<td>29%</td>
</tr>
<tr>
<td>$S_g$</td>
<td>3%</td>
</tr>
<tr>
<td>$M_R$</td>
<td>0.30</td>
</tr>
</tbody>
</table>
### ASIAN WATERFLOOD RESPONSE

<table>
<thead>
<tr>
<th>AREA</th>
<th>PRF W/O H2O %</th>
<th>Current RF %</th>
<th>EUR %</th>
<th>VRR Since Start of Inj.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15-18</td>
<td>18</td>
<td>27</td>
<td>0.51</td>
</tr>
<tr>
<td>2</td>
<td>15-18</td>
<td>21</td>
<td>31</td>
<td>0.63</td>
</tr>
<tr>
<td>3</td>
<td>15-18</td>
<td>25</td>
<td>33</td>
<td>0.71</td>
</tr>
<tr>
<td>4</td>
<td>15-18</td>
<td>31</td>
<td>44</td>
<td>1.09</td>
</tr>
</tbody>
</table>
Asian Waterflood

Voidage Replacement Ratio - VRR

- 0.51 VRR: 27% EUR
- 0.63 VRR: 31% EUR
- 0.71 VRR: 33% EUR
- 1.09 VRR: 44% EUR
Ain’t Acceptable Spaghetti Graph for a Production Well
Single String of Spaghetti – Oil Rate vs Time

Years
Two Strings of Spaghetti – Oil & Water Rate vs Time

Start of Injection in a Deeper Horizon

Injection reduction
Spaghetti String – Exponential Decline
**Spaghetti String – Exponential Decline**

Cumulative Oil - MBO
Spaghetti String – Exponential Decline

Start of Injection in a Deeper Horizon

Injection reduction

EUR @ 10 BOPD = 625 MBO

Cumulative Oil - MBO
Take-a-way Points for Today:

1) Waterflooding is very different from Primary Depletion

2) Test wells on a monthly basis (oil, H2O, gas)

3) Keep liquid levels in wells pumped off for
   ✓ Consistency in monthly production tests
   ✓ Maximize injection rate
   ✓ Maximize primary production from intervals not receiving injection
Take-a-way Points for Today:

4) **Maintain simple graphs:** Oil, GOR, WOR by well (no spaghetti today)

5) **Oil and Water Production Rates** are directly related to injection rates and stratification.

6) **Variable injection rates and stratification make traditional decline curve forecasts unreliable.**
Take-a-way Points for Today:

7) Voidage replacement ratio > 1.2

8) Analogy requires similarity of:
   - rock properties,
   - fluid properties,
   - fluid saturations at the start of the injection
Take-a-way Points for Today:

9. Reserve Forecasting in Waterfloods is not for Sissies