The Mechanism of Improved Oil Recovery by Sequential Waterflooding

Nina Loahardjo, Xina Xie, Winoto Winoto, Jill Buckley, Norman Morrow
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Oil Recovery : Waterflooding

Single 5-Spot Well Pattern
Laboratory Measurement of Oil Recovery by Waterflooding

**Graph: Oil Recovery by Waterflood**
- **X-axis**: Brine Injected, PV
- **Y-axis**: Oil Recovery, % OOIP
- **Target for Tertiary Recovery**: 100%

**Diagram: Brine Injection Flow Through Core**
- **Brine** flows into a core sample, resulting in oil recovery.
- **Core** section shows oil displaced by brine.

**Legend**
- **Core**: Core sample
- **Brine**: Flowing brine

**Note**: The graph illustrates the oil recovery process under waterflooding conditions, aiming to achieve the target recovery efficiency.
Further observations at UW that developed from investigation of low salinity flooding with re-use of individual reservoir cores.
Cyclic flooding with cleaning, re-aging and change in salinity
Baselines for assessment of improved oil recovery

No previous study of reproducibility of consecutive floods of recovery of crude oil had been reported
Sequential waterfloods of outcrop sandstones and carbonates

- No initial cleaning needed
  (the notorious problems of cleaning reservoir cores are avoided)
- No change in salinity
- No cleaning or re-aging between floods

*Can a water flood be reproduced?*
Outcrop Berea Sandstone

- $T_a = 75^\circ C$
- $t_a = 14$ days
- $T_d = 60^\circ C$
- WP Crude Oil
Sequential flooding of sandstone with crude oil at 60°C
Outcrop Bentheim Sandstone
(very low clay content)

- $T_a = 75^\circ C$
- $t_a = 14$ days
- $T_d = 60^\circ C$
- WP Crude Oil
Sequential flooding of Bentheim sandstone (Bth 01) with seawater
Sequential flooding of Bentheim sandstone (Bth 02) with seawater.
Outcrop Limestone (EdGc)

- $T_a = 75^\circ C$
- $t_a = 14$ days
- $T_d = 60^\circ C$
- WP Crude Oil
Sequential flooding of Limestone with crude oil at 60°C
Summary of change in $S_{or}$ for sequential waterflooding

$(T_d = 60^\circ C)$
Residual oil for sequential waterflooding for LK reservoir, limestone and sandstone cores at $T_d = 60^\circ C$ at 6 PV of seawater injection.
Confirmation of Reduction in Residual Oil Saturation by Sequential Waterflooding

Magnetic Resonance Imaging (ConocoPhillips Facility)
Waterflood – 2D images

WF1
$S_{wi} = 26\%$

WF2
$S_{wi} = 30\%$

WF3
$S_{wi} = 30\%$

$S_{or} = 37\%$

$S_{or} = 25\%$

$S_{or} = 20\%$
Residual oil for sequential waterflooding for displacement of WP crude oil at 60°C
Conclusion

Sequential waterfloods for recovery of crude oil without core cleaning and restoration between floods and without change of salinity, \textit{usually exhibit large reductions in residual oil.}
Sequential waterflooding has potential application as a new improved recovery technique

Two patents filed by UW:
1. Field wide application (disclosure and provisional patent)
2. Single well testing and diagnostics (disclosure)

*Explanation of the recovery mechanism?*
The Mechanism

The mechanism should be much less complex than for low salinity flooding because there is *no change* in brine composition and *no cleaning* or *no re-aging* between floods.

*Clues!*
When does sequential waterflooding not give increased oil recovery?
Recovery of Refined Oil
Berea Sandstone

- No Aging
- $T_d = 22^\circ C$
Sequential flooding with refined oil at 22°C

BS 2 (Refined Oil)
No Aging

$k_g = 297 \text{ md}$

$T_d = 22^\circ \text{C}, \mu_{LVO} = 3.9 \text{ cP}$

$R_{wf} (%OOIP)$ vs. $PV \text{ Brine Injected}$

- R1/C1 (LVO) : $S_{wi} = 23% : S_{or} = 37%$
- R1/C2 (LVO) : $S_{wi} = 24% : S_{or} = 36%$
Observation

Recovery of refined oil from outcrop rock (very strongly water wet conditions) by sequential flooding gives closely reproducible results.
Recovery of Crude Oil
– No Aging –
(no elevation of temperature and minimal time of contact with the crude oil)

• $T_d = 22^\circ C$
Sequential flooding of sandstone with crude oil at room temperature

**BS 3 (WP Crude Oil)**

No Aging

$T_d = 22^\circ C$ ($\mu_{\text{crude oil}} = 111.2$ cP)

$R_{wf}$ (%OOIP) vs. PV Brine Injected

- R1/C1: $S_{wi} = 23\% : S_{or} = 36\%$
- R1/C2: $S_{wi} = 20\% : S_{Or} = 35\%$

$k_g = 708$ md
Recovery of crude oil – No Aging

Conclusion

• Aging of the rock with crude oil is needed for increased recovery by sequential flooding.
Recovery of refined oil from a mixed-wet Berea core

- $T_a = 75^\circ\text{C}$
- $t_a = 14$ days
- $T_d = 60^\circ\text{C}$
- WP Crude Oil / Refined Oil
Recovery of refined oil from a mixed-wet Berea core

Preparation

• The core is aged at $S_{wi}$ with crude oil
• The crude oil is displaced by an intermediate solvent (to avoid destabilization of asphaltenes)
• The solvent is displaced by mineral oil to leave an adsorbed oil film
  - a mixed-wet condition referred to as MXW-F
Preparation of MXW-F cores

MXW → Decalin → S220 → MXW-F
Recovery of refined oil by sequential flooding of MXW-F Berea

BS 8 (MXW-F : HVO)

$T_a = 75^\circ C$

$T_d = 60^\circ C$

$R_{wf} (\% OOIP)$

$S_{wi} = 21\% : S_{or} = 19\%$

$S_{wi} = 18\% : S_{or} = 19\%$

PV Brine Injected
Oil recovery from MXW-F core

Observations
• Characteristically high recovery for the first flood (nearly 80% OOIP).  
• There was no change in recovery from the first to the second flood.

Conclusions
• For MXW-F cores, the adsorbed film in the presence of mineral oil is more robust with respect to stability of wetting.  
• In addition to adsorption, the crude oil brine interface and/or bulk crude oil is needed.
Comparison of saturation profiles at breakthrough & final distribution ($S_{or}$) by MRI imaging

- $T_a = 75^\circ C$
- $t_a = 14$ days
- $T_d = 60^\circ C$
- WP Crude Oil
1D NMR Profiles of oil distribution

Breakthrough oil distribution

Final oil distribution

R1/C1
PVl = 0.48 4.7

R1/C2
PVl = 0.48 4.4

R1/C3
PVl = 0.48 4.4

Core

1D profiles of oil distribution at water breakthrough and at residual oil saturation
Change in MRI saturation profile and oil recovered after breakthrough

Observation

- Increase in proportion of oil recovered after breakthrough for consecutive floods implies that there is a change in wettability* after exposure of the core to increased water saturation.

* the crude oil/brine/rock interactions that determine oil recovery
Spontaneous imbibition before and after aging a core at high water saturation

- $T_a = 75^\circ$C
- $t_a = 65$ days
- $T_i = 75^\circ$C
- $T_d = 80^\circ$C
- WP Crude Oil
Effect of aging at $S_{or}$ on subsequent spontaneous imbibition of brine into Berea sandstone
Spontaneous imbibition before and after aging a core at high water saturation

- Increase in water wetness after aging at \( S_{or} \) and elevated temperature
- After increase in water saturation by spontaneous imbibition and aging at elevated temperature, a subsequently measured imbibition curve showed increased water wetness as indicated by:
  - decreased induction time for onset of imbibition,
  - higher rate,
  - higher recovery
These and numerous other observations indicate that:

- Wettability is not a fixed crude oil/brine/rock property determined solely by initial aging conditions. Increase in water saturation results in increased water wetness.

- Wettability and direction of wettability change depend primarily on the direction of change of water saturation.
• The wettability at the onset of a waterflood is not regained by re-flooding the core with crude oil. Each waterflood affects the outcome of a subsequent waterflood.

• Increase in recovery of crude oil by sequential water flooding results from a favorable form of increase in wettability to water that arises from increase in water saturation during each waterflood. The change is only partially reversed by decreasing the water saturation by displacement with crude oil.
Single-Well Tests of Sequential Floods

Calculations are based on a simple piston-like displacement model

$\phi = 20.9\%, \ 30\ ft\ reservoir\ oil-zone\ thickness$
Increased Oil Recovery by Oil Injection Followed by Water Injection

- $S_{or}$ reduction taken from laboratory data.

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<thead>
<tr>
<th></th>
<th>Bth 01</th>
<th>3D MRI</th>
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<tbody>
<tr>
<td>WF1</td>
<td>50</td>
<td>36</td>
</tr>
<tr>
<td>WF2</td>
<td>37</td>
<td>29</td>
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<tr>
<td>WF3</td>
<td>20</td>
<td>24</td>
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Reservoir at residual oil saturation after waterflood (WF1)

$S_{OR}$ (WF1) = 36.2%

target zone radius = 45 ft

Day 0
Injection of oil into the target zone

$S_{OR} (WF1) = 36.2\%$

Target zone radius = 45 ft

Oil injected = 100 bbl

$S_O = 64.9\%$

Day 1
START WATER INJECTION

$S_{OR}$ (WF1) = 36.2%

inner radial distance

oil bank radial length

oil bank minimum radial length = 4.5 ft

oil bank volume = 406 bbl

Day 2
Continuation of oil bank displacement by injection of brine (WF2)

$S_{OR} (WF1) = 36.2\%$

$S_O = 64.9\%$

$S_{OR} (WF2) = 28.8\%$

Oil bank radial length = 6.9 ft

Oil bank volume = 1,149 bbl
The well is put on production and the oil bank grows in volume and radial length.

$S_{OR\ (WF1)} = 36.2\%$

Day 0
The well is put on production and the oil bank grows in volume and radial length.

$S_{OR}$ (WF1) = 36.2%
$S_{OR}$ (WF2) = 28.8%
$S_{OR}$ (WF3) = 24.0%
Single Well Field Test

100 bbl oil + 2,000 bbl brine → 900 bbl oil in 14 days
(as high as 3200 bbl optimistically)

100 bbl oil + 10,000 bbl brine → 4,000 bbl oil in 62 days
(as high as 15,000 bbl optimistically)
Many possibilities exist for other approaches to improved recovery by injection of small volumes of oil

- **Example 1**: Inject multiple oil banks
- **Example 2**: Improve recovery of sequential floods by displacing injected oil with low salinity brine.
- **Example 3**: Pre-injection of oil will convert a tertiary mode low salinity flood into a much more effective secondary mode low salinity waterflood.
- **Example 4**: Pre-inject low salinity brine
Discussions were held with six major companies in Oct/Nov 2009 to suggest that they test sequential flooding in their production research laboratories and/or perform field tests. 

(Response was encouraging)
Field test: advantages/diagnostics

• Low cost: Injected brine and oil are directly available: Required oil volume is small
• Single well test gives direct volumetric measure of oil production
• Tracers added to the injected oil and brine will allow monitoring of mixing of injected oil and brine with reservoir oil and brine
• Oil/brine production ratios will indicate heterogeneity and viscous fingering
• Flow reversal will tend to counteract rock heterogeneities and phase distribution effects
Further Laboratory Work
1. Core Floods and Imbibition Tests

• test different crude oils and rocks including Minnelusa, Tensleep, Cottonwood Creek, WP etc
• tests with longer cores
• monitor wettability by imbibition tests between sequential waterfloods
• re-age the core at initial water saturation between each sequential flood (to see if the sequential flooding effect is diminished)
• run additional MRI corefloods for sandstone and limestone cores
2. Pore scale mechanism – Micro X-ray CT –
(Joint Wettability Project with Australian National Univ.)

- Change in pore-scale distribution by of initial brine and residual oil before and after each sequential waterflood:
  - 1st tests are planned for Bentheim sandstone (low clay content will give excellent density contrast for discrimination between quartz, oil, and brine at the pore scale – 2 μ resolution)
  - Changes with low salinity flooding for Tensleep and Minnelusa are also under investigation
Conclusions

• Each flood causes change in wetting properties; water wetness increases with water saturation

• Sequential waterflooding *without* change in salinity and *without* cleaning or re-aging between cycles showed reductions in residual oil saturation

• NMR imaging confirmed the effect of sequential waterflooding

• Single-well field testing of sequential waterflooding is justified
Manuscripts in preparation

• Detailed Account of Mechanism: 11th Int. Symp. on Reservoir Wettability, Sept., Calgary, Alberta

• Additional results (since Abu Dhabi 2008) and field test approach: SPE 2010 (Oct) Annual Meeting,

• MRI results (Joint with ConocoPhillips): SCA Sept 2010

Note: draft copies should be available for the next EORI Meeting
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Thank You!