Fluid Displacement and EOR Mechanisms

January 21, 2016

Prepared by

Rob Lavoie
EOR Topics to Discuss

- Early History of Waterflooding (First EOR Concept!)
- Why Primary Production Eventually Fails and What Makes Oil Displacement Work?
- Mechanisms of Oil Displacement
- Challenges
- Controllable Mechanisms of Oil Displacement
- Enhanced Oil Recovery Methods
  - Immiscible displacement
  - Mobility enhancement agents, Polymers
  - Residual oil saturation reducers, Miscibility, Surfactants
  - Miscible displacement
  - Surfactants and Polymers
  - Thermal methods
  - Poly Flood Concepts (Being Creative!)
1776 – Watt invents efficient “Steam Engine” – powered by wood and coal
1859 – Oil is discovered in America, Drake Well, Titusville, Pennsylvania
1871 – Bradford Field discovery – 10 bbls/day primary production
1880 – Geologist suggests waterflooding might improve oil production rate
1881 – Peak oil for Bradford field “Primary Production” – 23 mmbbl/yr
1881 – Bradford Field producing 77% of world oil production
1885 – Wells being artificially lifted – production falls to 10.5 mmbbl/yr
1890 – Operators observing oil rate increase adjacent to abandoned wells
1897 – Rudolf Diesel invents diesel engine – Based on Carnot Cycle
1906 – Bradford Field production drops to 2 mmbbl/yr
1910 – Wateflooding being practiced illegally – production increasing
1920 – Crude oil now selling at $5.97 per bbl, highest price in history
1921 – Waterflooding legalized by Pennsylvania State Legislature
1928 – “Five Spot Pattern” waterflooding underway
1937 – Bradford Field production increases to 17 mmbbl/yr (second peak)
Historic Bradford Oil Field, Pennsylvania - 1871
Fluid Displacement and EOR Mechanisms

From US Confederation, The Steam Engine, and Wealth of the Nations - to History of the Oil Industry - Bradford Field Example

- Oil Discovery in America - Drake Well, Pennsylvania
- 1871 - Bradford Field Discovered, Pennsylvania
- 1881 - Peak Primary Oil, 77% of World Oil Production, Geologist suggest possible waterflood
- 1885 - First artificial lift
- 1890 - Observing waterflood responses from offset wells
- 1899 - Five spot pattern invented
- 1910 - Illegal waterflooding
- 1920 - Crude oil selling at $5.97/bbl
- 1921 - Waterflooding legalized
- 1937 - Waterflood peak oil, Bradford field

Oil Rate, bbl/day

Year

1750 1800 1850 1900 1950 2000 2050

Oil Initial In-place (OIP) - 6.3 Billion BBL
Cumulative Recovered (Cum Rec.) - 681 Million BBL
Recovery Efficiency (Rec. Eff.) - 10.8%
Carbon Dioxide Enhanced Oil Recovery (CO2 EOR) Potential - 250 Million BBL
From US Confederation, The Steam Engine, and Wealth of the Nations - to History of the Oil Industry - Bradford Oil Field Example

1776 - Watt perfects steam engine, US Articles of Confederation written, Adam Smith writes "Wealth of the Nations", Coal and wood are primary energy source

1871 - Bradford Field Discovered, Pennsylvania

1881 - Peak Primary Oil, 77% of World Oil Production, Geologist suggest possible waterflood

1885 - First artificial lift

1890 - Observing waterflood responses from offset wells

1910 - Illegal waterflooding

1920 - Crude oil selling at $5.97/bbl

1921 - Waterflooding legalized

1928 - Five spot pattern invented

1937 - Waterflood peak oil, Bradford field

Oil Rate, bbl/day

Year

1750 1800 1850 1900 1950 2000 2050

Oil In Place (OIIP) - 6.3 Billion BBL
Cumulative Recovered (Cum Rec.) - 681 Million BBL
Recovery Efficiency (Rec. Eff.) - 10.8%

CO2 EOR Potential - 250 Million BBL
Fluid Displacement and EOR Mechanisms

From US Confederation, The Steam Engine, and Wealth of the Nations - to History of the Oil Industry - Brandford Oil Field Example

- **1776** - Watt perfects steam engine,
  - US Articles of Confederation written, Adam Smith writes "Wealth of the Nations",
  - Coal and wood are primary energy source

- **1859** - Oil Discovery in America - Drake Well, Pennsylvania

- **1860 to 1896** - Perfection of gas and gasoline engines

- **1871** - Bradford Field Discovered, Pennsylvania

- **1881** - Peak Primary Oil, 77% of World Oil Production, Geologist suggest possible waterflood

- **1885** - First artificial lift
- **1890** - Observing waterflood responses from offset wells

- **1886** - Karl Benz first patented "petrol" automobile engine

- **1897** - Rudolf Diesel invents diesel engine

- **1900** - Oil Rate, bbl/day

- **1910** - Illegal waterflooding

- **1920** - Crude oil selling at $5.97/bbl
- **1921** - Waterflooding legalized

- **1928** - Five spot pattern invented

- **1937** - Waterflood peak oil, Bradford field

- **1986** - CO2 EOR Potential - 250 Million BBL

**Key Data:**
- **OIIP** - 6.3 Billion BBL
- **Cum Rec.** - 681 Million BBL
- **Rec. Eff.** - 10.8%

**Graphical Data:**
- 1776 - Watt perfects steam engine,
- 1859 - Oil Discovery in America - Drake Well, Pennsylvania
- 1871 - Bradford Field Discovered, Pennsylvania
- 1881 - Peak Primary Oil, 77% of World Oil Production, Geologist suggest possible waterflood
From US Confederation, The Steam Engine, and Wealth of the Nations - to History of the Oil Industry - Brandford Oil Field Example

- 1776 - Watt perfects steam engine, US Articles of Confederation written, Adam Smith writes "Wealth of the Nations", Coal and wood are primary energy source
- 1789 - Oil Discovery in America - Drake Well, Pennsylvania
- 1810 - Peak Primary Oil, 77% of World Oil Production, Geologist suggest possible waterflood
- 1871 - Bradford Field Discovered, Pennsylvania
- 1881 - First artificial lift
- 1885 - Observing waterflood responses from offset wells
- 1886 - Karl Benz first patented "petrol" automobile engine
- 1897 - Rudolf Diesel invents diesel engine
- 1897 - Crude oil selling at $5.97/bbl
- 1900 - Illegal waterflooding
- 1906 - MAN AG Diesel Engine
- 1906 - Oil Rate, bbl/day
- 1921 - Waterflooding legalized
- 1928 - Five spot pattern Invented
- 1937 - Waterflood peak oil, Bradford field

Oil Rate, bbl/day:
- 1750 - 1800 - 1850 - 1900 - 1950 - 2000 - 2050
- OIIP - 6.3 Billion BBL
- Cum Rec. - 681 Million BBL
- Rec. Eff. - 10.8%
- CO2 EOR Potential - 250 Million BBL
From US Confederation, The Steam Engine, and Wealth of the Nations - to History of the Oil Industry - Brandford Oil Field Example

1776 - Watt perfects steam engine, US Articles of Confederation written, Adam Smith writes "Wealth of the Nations", Coal and wood are primary energy source

1859 - Oil Discovery in America - Drake Well, Pennsylvania

1871 - Bradford Field Discovered, Pennsylvania

1881 - Peak Primary Oil, 77% of World Oil Production, Geologist suggest possible waterflood

1885 - First artificial lift
1890 - Observing waterflood responses from offset wells

1886 - Karl Benz first patented "petrol" automobile engine

1887 - Rudolf Diesel invents diesel engine

1897 - Waterflood peak oil, Bradford field

1899 - Perfection of gas and gasoline engines

1906 - MAN AG Diesel Engine

1910 - Illegal waterflooding

1920 - Crude oil selling at $5.97/bbl
1921 - Waterflooding legalized

1928 - Five spot pattern invented

1937 - Waterflooding peak oil, Bradford field

CO2 EOR Potential - 250 Million BBL

OIIP - 6.3 Billion BBL
Cum Rec. - 681 Million BBL
Rec. Eff. - 10.8%
Primary production methods, Ultimate Recovery Efficiencies:

- Oil decompression, 0.1 to 5% OIIP
- Solution gas drive, 1 to 10% of OIIP
- Gascap drive, 1 to 20% of OIIP (size dependent)
- Compaction drive, 0 to 2% of OIIP
- Natural water drive is variable depending on the strength (size) of natural aquifer.
• From 1921 to Current Date – Waterflooding remains the most highly used enhanced oil recovery method worldwide.

• Waterflooding – mechanism of oil production support:
  – Provides pressure support for incompressible oil phase
  – Displaces oil towards production wells via viscous, gravity, and capillary forces.
Saturation Profile During a Waterflood

Saturation Profile

WATER BANK  OIL BANK  UNAFFECTED RESERVOIR

WATER  TRAPPED GAS  OIL

WATER  INITIAL FREE GAS

CONNATE WATER

Fluid Displacement and EOR Mechanisms
Stages or a Waterflood

Saturation Distributions During Different Stages of a Waterflood

- **a. Initial Conditions**
  - Initial Oil
  - Interstitial Water

- **b. Midpoint in Flood**
  - Residual Oil

- **c. At breakthrough**
  - Fluid Displacement and EOR Mechanisms

- **d. Late in the Flood**
  - X/L
Phases of a Waterflood

- Development Drilling
- Primary Depletion
- Production Incline
- Production Decline
- Begin Water Injection
- Water breakthrough

Fluid Displacement and EOR Mechanisms
Displacement: Secondary, Tertiary, or Quaternary

• Mobility Ratio
  – Viscosity Differences
  – Wettabillity

• Residual Oil Saturation

• Sweep Efficiency
  – Pore by Pore in Displaced Zone
  – Volumetric Sweep
    » Vertical
    » Areal
Fluid Displacement and EOR Mechanisms

Mobility Ratio

\[ M = \frac{k'_{rw}}{\mu_w} \cdot \frac{\mu_o}{k'_{ro}} \]

- Flood is stable at \( M \leq 1.0 \)
- Flood is unstable at \( M > 1.0 \)
Mobility Ratio - Viscous Fingering
(water displacing oil between glass plates – “x-ray shadow graphs”)

Viscous Fingering

(a) Vertical Cross-section

(b) Areal – one-quarter of a five spot pattern

\[ N_p = W_i = 6.0\% \]
\[ N_p = 20\%; W_i = 34\% \]
\[ N_p = W_i = 12\% \]
\[ N_p = 52\%; W_i = 650\% \]
Water Wet versus Oil Wet Behavior

Wettability of Oil / Water / Solid System

Water Wet

Oil Wet
Mobility Ratio – Relative Permeability

Water Wet Relative Permeability

Oil Wet Relative Permeability
Pore to Pore Sweep Efficiency

• What percentage of oil or hydrocarbon can we sweep out of the “average” pore?
• Applicable only to the volumetrically “Swept” portion of the reservoir where the displacing fluid has fully passed through the pores.
• The Maximum Theoretical Microscopic Sweep Efficiency is:

\[ E_{D_{\text{max}}} = \frac{S_{oi} - S_{orw}}{S_{oi}} \quad \text{Or} \quad E_{D_{\text{max}}} = 1 - \frac{S_{orw}}{S_{oi}} \]
Volumetric Sweep Efficiency - Illustration

Stratified Reservoir Showing Flood Front Banks before Reservoir Fillup

Stratified Reservoir after Reservoir Fillup
Areal Sweep Efficiency - Illustration

Water Flooding:

Mobility Ratio = 1.43

- Water Containing Area
- Water Invaded Area

Water Breakthrough

- Area Sweep Efficiency 65%
- WOR = 0.5
- 70.5%

WOR = 2
- 82.2%

Mobility Ratio = 0.4

- Water Containing Area
- Water Invaded Area

Water Breakthrough

- Area Sweep Efficiency 82.8%
- WOR = 0.6
- 87.4%

WOR = 4.7
- 95.6%

X-ray shadowgraphs of flood progress in scaled five-spot patterns

(after Craig, Geffen, Morse)
Waterflood Displacement Mechanisms

- Waterflood Recovery Efficiency
  \[ \text{Waterflood Recovery Efficiency} = \text{Microscopic Displacement Efficiency} \times \text{Vertical Sweep} \times \text{Areal Sweep} \]

- Maximum Moveable Oil Volume (MOV)
  \[ \text{Maximum Moveable Oil Volume (MOV)} = (1 - S_{wi} - S_{or}) \]

- Controlling parameters for reserves are:
  - Mobility Ratio \( M = \frac{k_{rw}}{\mu_w} \times \frac{\mu_o}{k_{ro}} \)
    - Stable for \( M \leq 1 \), Viscous Fingering for \( M > 1 \)
    - Heterogeneity
    - Pattern Shape

- Controlling Parameters for recovery time are:
  - Absolute Permeability
  - Well Spacing
  - Initial Gas Saturation
Fluid Displacement and EOR Mechanisms

Derivation of the Fractional Flow Equation

Velocity of Oil and Water in the Reservoir

\[
\frac{q_o}{A} = u_o = - \frac{k_o}{\mu_o} \left( \frac{\partial p_o}{\partial L} + g \rho_o \sin \alpha_d \right)
\]

Eq. 1

\[
\frac{q_w}{A} = u_w = - \frac{k_w}{\mu_w} \left( \frac{\partial p_w}{\partial L} + g \rho_w \sin \alpha_d \right)
\]

Eq. 2
Simple Derivation of the Fractional Flow Equation

\[ f_w = \frac{q_w}{q_w + q_o} \]

Divide this equation through by \( q_w \)

\[ f_w = \frac{1}{1 + \frac{q_o}{q_w}} \]

or

\[ 1 + \frac{\frac{1}{k_{ro}}}{\frac{1}{\mu_o}} \frac{\mu_w}{k_{rw}} \]

Given that the ratio of oil and water flow can be expressed as the ratio of oil and water transmissibility...

\[ f_w = \frac{1}{1 + \frac{k_{ro}}{\mu_o} \frac{\mu_w}{k_{rw}}} \]
Determination of average water saturation at breakthrough, $S_{wbt}$.
Effect of oil viscosity on fractional flow curve, strongly water-wet rock.
Effect of oil viscosity on fractional flow curve, strongly oil-wet rock.
Relative Permeability

Relative Permeability Curves - Water Wet

Water Wet Relative Permeability

Relative Permeability Curves - Oil Wet

Oil Wet Relative Permeability
Fractional Flow

**Water Wet Relative Permeability**
Fractional Flow Curve
Oil Viscosity – 2 cp

**Oil Wet Relative Permeability**
Fractional Flow Curve
Oil Viscosity – 2 cp

*Fractional Flow Curve - Water Wet - Light Oil Case*

*Fractional Flow Curve - Oil Wet - Light Oil Case*
Fractional Flow – Light Oil Versus Heavy Oil

Water Wet Relative Permeability
Fractional Flow Curve
Oil Viscosity – 2 cp

Oil Wet Relative Permeability
Fractional Flow Curve
Heavy Oil Case – 30 cp
Saturation Profile During a Waterflood
Pore to Pore Sweep Efficiency – Behind the Flood Front

• What percentage of oil or hydrocarbon can we sweep out of the “average” pore – as a summation behind the flood front?

• Applicable only to the volumetrically “Swept” portion of the reservoir where the displacing fluid has actually passed through the pores – behind the flood front.

• The Actual Theoretical Microscopic Sweep Efficiency (assuming 100% volumetric sweep) is based on the average residual oil saturation behind the flood front:

\[
E_D = \frac{S_{oi} - \bar{S}_{orwbff}}{S_{oi}} \quad \text{Or} \quad E_D = 1 - \frac{\bar{S}_{orwbff}}{S_{oi}}
\]
Application of the Welge graphical technique to determine the oil recovery after water breakthrough.

\[ f_w = 1 \]

\[ f_w = \frac{(1-f_{we})}{S_w - S_{we}} \]

\[ \frac{df_w}{dS_w} \bigg|_{S_{we}} = \frac{1-f_{we}}{S_w - S_{we}} \]
The shape of the fractional flow curve after breakthrough is used to predict both the watercut increase and oil recovery as follows:

- Watercut is predicted as a function of pore volumes injected, $W_{id}$

$$W_{id} = \frac{1}{\frac{df_w}{dS_w}|_{S_{we}}}$$  \hspace{1cm} Eqn. 1

- Pore volume of oil recovered is predicted from the estimate of average water saturation behind the flood front using the fractional flow curve

$$\bar{S}_W = S_{we} + (1 - f_{we}) \frac{1}{\frac{df_w}{dS_w}|_{S_{we}}}$$  \hspace{1cm} Eqn. 2
Substituting eqn. 1 into eqn. 2 gives:

\[ \bar{S}_w = S_{we} + (1 - f_{we})W_{id} \]

Subtracting Swc from both sides of the above eqn. Gives the dimensionless oil recovery equation:

\[ N_{pd} = \bar{S}_w - S_{wc} = (S_{we} - S_{wc}) + (1 - f_{we})W_{id} \]

Where

- \( W_{id} \) = Pore Volumes Water Injected
- \( N_{pd} \) = Pore Volumes Oil Produced

\[ N_{pd} = \frac{\text{oil production (rb)}}{\text{one pore volume (rb)}} = \frac{N_p B_o}{N B_{oi}} (1 - S_{wc}) \]

In conventional oil recovery terms, this is:

\[ RE = \frac{N_p}{N} = \frac{B_{oi}}{B_o} \frac{N_{pd}}{(1 - S_{wc})} \]

Where

- \( RE \) = Oil Produced (stb)
- \( STOIIP \) = STOIIP (stb)
Fractional Flow Curve Analysis/Diagnostics

Water Wet – Light Oil Case – Breakthrough

At Breakthrough of Layer:
- Watercut = 97%
- Average $S_w$ behind flood front = 76%
- Pore volumes injected = $(0.76 - 0.19)/1.0 = 0.57$
- Recovery Efficiency = $1 - 0.34/0.90 = 62\%$
  (assumes 100% volumetric Sweep)
Fractional Flow Curve Analysis/Diagnostics
Oil Wet – Slightly Heavy Oil Case – Breakthrough

At Breakthrough of Layer:
- Watercut = 30%
- Average $S_w$ behind flood front = 23%
- Pore volumes injected = $(.23 -.14)/(1.0 -.30) = 0.12$
- Recovery Efficiency = $1 - .77/.90 = 14%$
  (assumes 100% volumetric Sweep)
Fractional Flow Curve Analysis/Diagnostics
Oil Wet – Slightly Heavy Oil Case – Mature WF

Fractional Flow Curve - Oil Wet Heavy - 30 cp

Beyond Breakthrough:
- Watercut = 88%
- Average Sw behind flood front = 36%
- Pore volumes injected = (.36-.27)/(1.0-.88)=0.75
- Recovery Efficiency = 1 -.64/.90 = 29%
  (assumes 100% volumetric Sweep)
**Fractional Flow Curve Analysis/Diagnostics**

**Oil Wet – Heavy Oil Case – Breakthrough**

At Breakthrough of Layer:
- Watercut = 80%
- Average \( S_w \) behind flood front = 11%
- Pore volumes injected = \((0.11 - 0.105)/(1.0 - 0.80)\) = 0.025
- Recovery Efficiency = \(1 - 0.89/0.90 = 1.1\%\)

(assumes 100% volumetric Sweep)
Fractional Flow Curve Analysis/Diagnostics
Oil Wet – Heavy Oil Case – Mature WF

Fractional Flow Curve - Oil Wet Heavy - 3000 cp

Beyond Breakthrough:
- Watercut = 96%
- Average Sw behind flood front = 16%
- Pore volumes injected = (0.16 - 0.13)/(1.0 - 0.96) = 0.75
- Recovery Efficiency = 1 - 0.84/0.90 = 6.7%
  (assumes 100% volumetric Sweep)
Fractional Flow Curve - Oil Wet Heavy - 3000 cp with 3000 cp Polymer Flood

At Breakthrough of Layer:
- Watercut = 85%
- Average $S_w$ behind flood front = 54%
- Pore volumes injected = $0.54 - 0.47 / (1.0 - 0.85) = 0.47$
- Recovery Efficiency = $1 - 0.46 / 0.90 = 48\%$
  (assumes 100% volumetric Sweep)
Fractional Flow Curve Analysis/Diagnostics
Heavy Oil Case – W/Polymer – Mature WF

Fractional Flow Curve - Oil Wet Heavy - 3000 cp with 3000 cp Polymer Flood

Beyond Breakthrough:
- Watercut = 96%
- Average Sw behind flood front = 61%
- Pore volumes injected = (0.61-0.56)/(1.0-0.96)=1.25
- Recovery Efficiency = 1 - 0.39/0.90 = 56.7%
  (assumes 100% volumetric Sweep)
Fractional flow curve is tending to the higher water saturations for lower water rel-perm endpoints.
In a Corey function, the Relative Permeability for the phase x is expressed as:

\[ K_{rx} = E_x \times \left( \frac{S_x - S_{rx}}{S_{mx} - S_{rx}} \right)^{n_x} \]

where:
- \( E_x \) = end point for the phase x
- \( n_x \) = Corey Exponent
- \( S_x \) = phase saturation
- \( S_{rx} \) = phase residual saturation and
- \( S_{mx} \) = phase maximum saturation

The phase absolute permeability can then be expressed as:

\[ K_x = K \times K_{rx} \]

where:
- \( K \) = reservoir absolute permeability
- \( K_{rx} \) = relative permeability of phase x
Corey Curve Generated Relative Permeabilities

**Water Wet Relative Permeability**
- Kro Corey Exponent = 1.5
- Krw Corey Exponent = 2.9
- Sor = 24%
- Swi = 19.2%
- Kro end point = 1.0
- Krw end point = .15

**Oil Wet Relative Permeability**
- Kro Corey Exponent = 2.9
- Krw Corey Exponent = 1.5
- Sor = 30%
- Swi = 10%
- Kro end point = 1.0
- Krw end point = .60
Gas Drives:

Solution gas drive,
Gas cap drives,
Horizontal gas drives…

- Mobility ratio between gas and oil is very high
- As gas saturation increases, oil mobility decreases
- Gas tends to “Gravity Override” in a horizontal drive
- Gas is a compressible fluid, so maintaining drive pressure is more difficult
- Gas usually costs more than water on a reservoir volume basis
- Gas compression equipment is expensive to purchase and operate
Factors Impacting EOR Processes

• Recovery Efficiency is a product of three influences:
  – $E_D = \text{Microscopic Displacement Efficiency}$
  – $E_V = \text{Vertical Sweep}$
  – $E_A = \text{Area Sweep}$

• The Maximum Theoretical Moveable Oil Volume (Dimensionless)
  – $E_D_{\text{max}} = (1 - Swi - Sor)/ Soi$

• Mobility Ratio is the major controlling factor for the shape of the fractional flow curve:

$$M = \frac{k'_{rw} \mu_o}{\mu_w k'_{ro}}$$

Ratio of Displacing Phase Mobility to Displaced Phase Mobility
Viscous Fingering (water displacing oil between glass plates – “x-ray shadow graphs”)

- Injected fluids will “finger” through the oil
- The higher the Mobility Ratio, the more pronounced this effect becomes
- Lab flow experiments pictured here show viscous fingers at the point of breakthrough

5 cp oil
66 cp oil
412 cp oil
616 cp oil
2,000 cp oil
7,000 cp oil
Viscous Fingering for Radial Flow

- Injected fluids will “finger” through the oil
- The higher the Mobility Ratio, the more pronounced this effect becomes
- Higher Mobility ratio viscous fingers create much more contact area with the remaining oil
- **Can this effect be used to our advantage?**
Residual Oil – Interfacial Tension/Wettability Controlled

Water-Wet System

Oil Contacts Rock

Oil-Wet System

Water Surrounds Oil and Contacts Rock

Solid Grains
New Horizontal Well Paradigm

- Horizontal Injectors and Producers for secondary, tertiary, and quaternary, recovery displacement processes
- Displacing fluid combination possibilities:
  - polymer/ASP,
  - hot water/solvent,
  - hot water/CO$_2$
  - CO$_2$/foam
  - steam/miscible solvents…
- Requires determination of effects of both viscous fingers (mobility) and residual oil (interfacial tension) effects
  - Positive and/or negative effects
  - Methods of mitigating negatives
  - Methods of enhancing positives
• Enhanced Oil Recovery Methods
  – Immiscible displacement agents (Water, Gas, Steam, Polymer)
  – Mobility enhancement agents (Polymers, Foam, Heat)
  – Residual oil saturation reducers (Miscibility, Surfactants, Heat)
    • Miscible displacement agents
      – CO$_2$
      – Enriched hydrocarbon gas (ethane, butane, propane)
    • Surfactants
  – Poly Flood Concepts (Being Creative! Combination floods)
    • ASP (Alkaline, Surfactant, Polymer)
    • CO$_2$ foam
    • In situ combustion (Heat, CO$_2$)
CO₂ Flooding

- CO₂ flooding has been practiced commercially for over 40 years in Canada and the USA

- Current resurgence is related to the potential to sequester CO₂ while producing a valuable commodity

- Cost of CO₂ capture is at issue, however, scalability of CO₂ capture opportunities is unmistakable

- CO₂ capture costs are inline with alternative CO₂ neutral energy sources on a $ per tonne of CO₂ avoided basis
Quick Rules of Thumb

- Better with an API Gravity > 25 deg
- Better with an $S_{orw}$ of > 25%
- Better at a depth > 2500 ft
- 1 tonne CO$_2$ = 20 mcf

Expected Performance for CO$_2$ Flood (%OOIP)

- Primary Recovery Efficiency (RE) 5 to 15% (avg. 10%)
- Primary + Secondary RE 20 to 35% (avg. 25%)
- Incremental CO$_2$ Tertiary RE 8 to 18% (avg. 12%)
- Combined (Primary+Secondary+CO$_2$) 28 to 50% (avg. 37%)

- CO$_2$ utilization: Gross: 8 – 15 mcf/bbl, Net: 5 – 10 mcf/bbl
CO₂ Flooding Mechanisms

- Miscible (results in \( S_\text{or} \) reduction)
- Non-Miscible (still results in \( S_\text{or} \) reduction)
- Oil swelling
- Viscosity Reduction
- Viscous Displacement
- CO₂ Sequestration
Residual Oil – Interfacial Tension/Wettability Controlled
• Miscible hydrocarbon gas flooding has fallen out of favour in recent years because of the value/cost of NGLs

• However, recent over supply of NGLs derived from development of unconventional liquids rich gas plays will potentially reverse this trend

• Similar displacement issues as for CO$_2$ flooding example
ASP Flooding (Chemical Floods)

- Alkalines and Surfactants and Micellar Floods
  - Reduction of Residual Oil Saturation

- Polymers
  - Improvement of Mobility Ratio

- ASP
  - The whole is greater than the sum of the parts!!!
Thermal Floods

- CSS – Cyclic Steam Stimulation

- SAGD – Steam Assisted Gravity Drainage

- Hot Water Flooding
• In Situ Combustion
  – Complex high risk process: limited successful applications worldwide to date
  – Large base of performance information available
  – Very recent improvements in numerical and analytical methods along with high speed computer modeling that are enabling real time surveillance methods may result in a re-emergence of In Situ Combustion methods
• Foamy Oil Heavy Oil with Sand Production (Wormholes Enhance Heavy Oil Transmissibility)

• Thermal Heavy Oil EOR Methods (Poly displacements):
  – Steam over Miscible Solvent Injection
  – Steam Assisted Gravity Drainage (SAGD)
  – Hot Water and Solvent Drive Cycles

• Cold Heavy Oil EOR Methods (Poly displacements)
  – Polymer floods to control post CHOPS displacement mobility issues
    • i.e. “worm hole thief zones”
  – ASP floods to further reduce the matrix residual oil saturation
  – CO₂ flooding to swell remaining oil, reduce oil viscosity and residual oil saturation
Additional Cold Heavy Oil EOR Methods (Poly Floods)

- Water Alternate CO₂ (WACO₂) flooding
  - improves flood mobility ratio
  - Added benefits of oil swelling by CO₂ diffusion, reduced oil viscosity and reduced residual oil saturation

- CO₂ and WACO₂ foam flooding
  - where wettability changing surfactants are used to cause water to imbibe into the matrix (whether Sand or Carbonate)
Alternative Flooding Methods Proposed

- **Microbial EOR and Nano-Catalysts**
  - Industry resurgence for heavy oil applications
  - Potential upgrading of oil in-situ
  - Potential de-carbonization advantages
    - In-situ CO2 generation, with improved recovery benefits
    - Increase hydrogen content of produced oil
    - Reduced viscosity and swelling of heavy oil by CO2 dissolution
Rough Rules of Thumb for EOR Methodology

EOR Screening Chart

- **WATER FLOODING**
  - Chemical: Surfactant, Polymer, Micellar
  - CO₂, Hydrocarbon Gas, Miscible Floods (WAG, Foam)

- **Thermal, In Situ**
  - Combustion, Microbial, Nano-Catalysts

**Depth, m**

**Oil API Gravity**
Streamline Modeling for Waterflood Optimization

**repeated 5-spot**
- balanced rates

**repeated 5-spot**
- unbalanced rates

Streamlines colored by originating injector
Streamsim Technologies

• Founded in 1997
  – Based on research at Stanford University
  – 1997-2000 development funded by BHP, Elf, & Shell
  – +25 customers world-wide

• Products & Services
  – 3DSL (streamline simulator)
  – studioSL (GUI & workflow container)
  – Short courses & software training
  – Consulting

• Company Objectives
  – Promote SL-based workflows for Reservoir Engineering.
  – We are “simulator neutral” – workflows support 3DSL and other simulators.
• Heterogeneous rock properties (porosity, perm, NTG, rock regions, …).
• 3 dimensional flow and geological model.
• Multi-phase flow (immiscible, miscible).
• Changing well conditions.
• Gravity effects.
• Compressible or Incompressible Mode.

• To solve realistic problems we turn to numerical streamline methods and/or full finite difference gridblock numerical modeling.
Solve for Pressure

\[ \nabla \cdot \bar{K} \left( \lambda_t \nabla P + \lambda_g \nabla D \right) = q \]
Trace Streamlines

\[ \dot{v} = -\tilde{K} \cdot (\lambda_t \nabla P + \lambda_g \nabla D) \]

*Pollock’s Algorithm*
Transport along Streamlines

\[ \frac{\partial S_w}{\partial t} + \frac{\partial f_w}{\partial \tau} = 0 \]

\[ N_p = E_D \times E_V \times N \]
Fluid Displacement and EOR Mechanisms
For each time step do:

1. Pressure solution on the Eulerian grid
2. Trace SL’s to create “dynamic” grid
3. Solve transport along SL-grid
4. Map from SL’s to grid
5. Correct for gravity

Repeat

CPU time

\[ t^{psolve} \]

\[ t^{sl-grid} \]

\[ \sum_{streamlines} t^{sl-solver} \]

\[ \sum_{gravitylines} t^{gl-solver} \]
Well-Pairs and Heterogeneity

Grand Forks UMK Pool

Surveillance model

Detailed Flow Model

Fluid Displacement and EOR Mechanisms
Well-Pairs and Heterogeneity

Grand Forks UMK Pool

Surveillance model  Detailed Flow Model

Time 15248.0 days (2009/09/30 - 2009/10/31) - srv_wf  Time 15248.0 days (2009/09/30 - 2009/10/31) - inc_wf
The Pattern Efficiency Plot

- Snap-shot of current performance of patterns

Fluid Displacement and EOR Mechanisms
The Conformance Plot

- Overall performance of patterns

\[ N_o^{P9-7} = \sum Q_o^{P9-7} \Delta t \]
Streamline Modeling for CO$_2$ Sequestration Modeling – Displacement of Brine or Oil by CO$_2$
• Be creative! Try variations in displacement fluids to enhance oil recovery
  – Mobility Enhancement
  – Residual Oil Saturation Reduction
  – Areal and Vertical Sweep Efficiency Improvement
• Use modern streamline simulation methods for first approximations and faster evaluation of various displacement options!
• Tightly link static geological models with dynamic reservoir models (Streamline and Finite Difference) to fully assess opportunities for enhancing oil recovery!
• Be environmentally responsible! All the methods presented here are directly transferable to the development of SAFE! sequestration of CO$_2$ and EOR.