Note Title 10/22/2018

ENHANCED OIL RECOVERY (EOR)

"Enhanced"

- Recovery beyond what is expected by natural depletion: C_f, C_w, Aquifer, SGD, PVT (CVD), $\sqrt{s}$
- Inject $\underbrace{\text{water, gas}}_{\text{WAG}}$, (and/or chemicals)

N_{WD} + ΔN_{WEOR} = N_{Wt}

What is:

- EOR recovery?
- Depletion recovery?

What are:

- Depletion CAPEX & OPEX
- EOR CAPEX & OPEX

INCREMENTAL STO RECOVERY (%)

Initial STO In Place

$$N = \sum_{n=1}^{N_B} \Delta V_{pin} \left(\frac{S_{oi}}{B_{oi}} + \frac{S_{gi}\, r_{si}}{B_{gdi}} \right)_n$$

STO (RO)

"B": Block (e.g. RFU, simulator grid cells)

$$\Delta V_p = (\Delta x \cdot \Delta y \cdot \Delta z \; \phi)$$

Remaining STO in Reservoir at time after start of production

$$N_R = \sum_{n=1}^{N_B} \Delta V_{pn} \left(\frac{S_o}{B_o} + \frac{S_g\, r_s}{B_{gd}} \right)_n$$

$$N_p = N - N_R$$

$$= f\Big(\underbrace{S_o,\ S_g,\ \underset{(B_o,\, B_{gd},\, r_s)}{PVT}}, \ c_f \Big)$$

- $k_r(S)$: 2ϕ, 3-ϕ, f(PVT)
- PVT(p) : Depletion
- Injection (EOR)
  - Displacement $S(x, y, z)$
  - • Gravity
  - PVT $\underbrace{B_o \quad B_{gd} \quad r_s \quad S_o}_{V \mid C \mid M}$

Vaporization Condensation Miscibility

- Imbibition (Wettability)
- Diffusion
- Capillarity

EOR METHODS

All Methods – (Common Denominator)

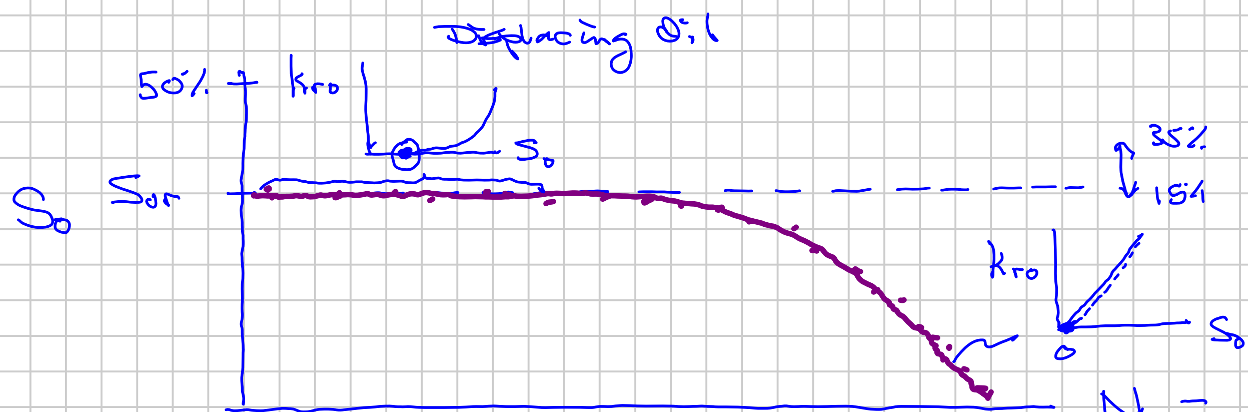
(a) Pore-Level: Drive "S_{oi}" → minimum → $\underbrace{S_{or}}_{\text{Many WF projects}}$ → 0

S_{orw}, S_{org}

$k_{ro} \to 0$ $\sigma \to 0$

$$\left(\frac{S_{oi}}{B_{oi}} + \frac{S_{gi} r_{si}}{B_{gi}}\right) \to \text{minimum}$$

- Buckley-Leverett (BL) flow theory $\underbrace{S_{oi} \to S_{or}}$
  Water & Gas



$$N_c = \frac{v}{\sigma} = \frac{(dp/dx)}{(P_c)}$$

$$\frac{P_{cgo}}{P_{cwo}} \propto \frac{\sigma_{go}}{\sigma_{wo}}$$

IFT

(b) CONFORMANCE – Volumetric Sweep

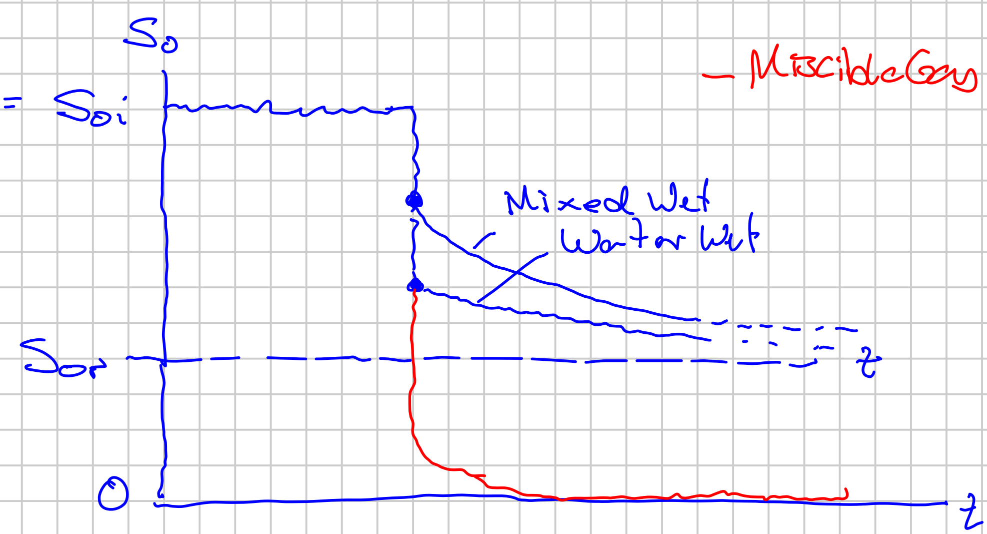
Composite
- Vertical (Layering) — z
- Areal (I-P well placement) "pattern" — x, y

* HCPV that has "seen" the injectant

- Usually the pore-level recovery $\left(\sim 1 - \frac{(S_o)}{S_{oi}}\right)$ at seeing

Microscopic Displacement Efficiency MDE

50% → 100%



EOR we use instead of time

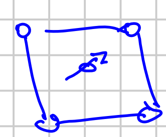
we use "pore volumes injected" PV_{inj} PV_i "PVI"

- "Small scale (core lab test)

Well defined, fixed, "pattern" "Volume"

$$PVI = \frac{Q_{inj}}{\text{"PV"}}$$

Core — Pattern



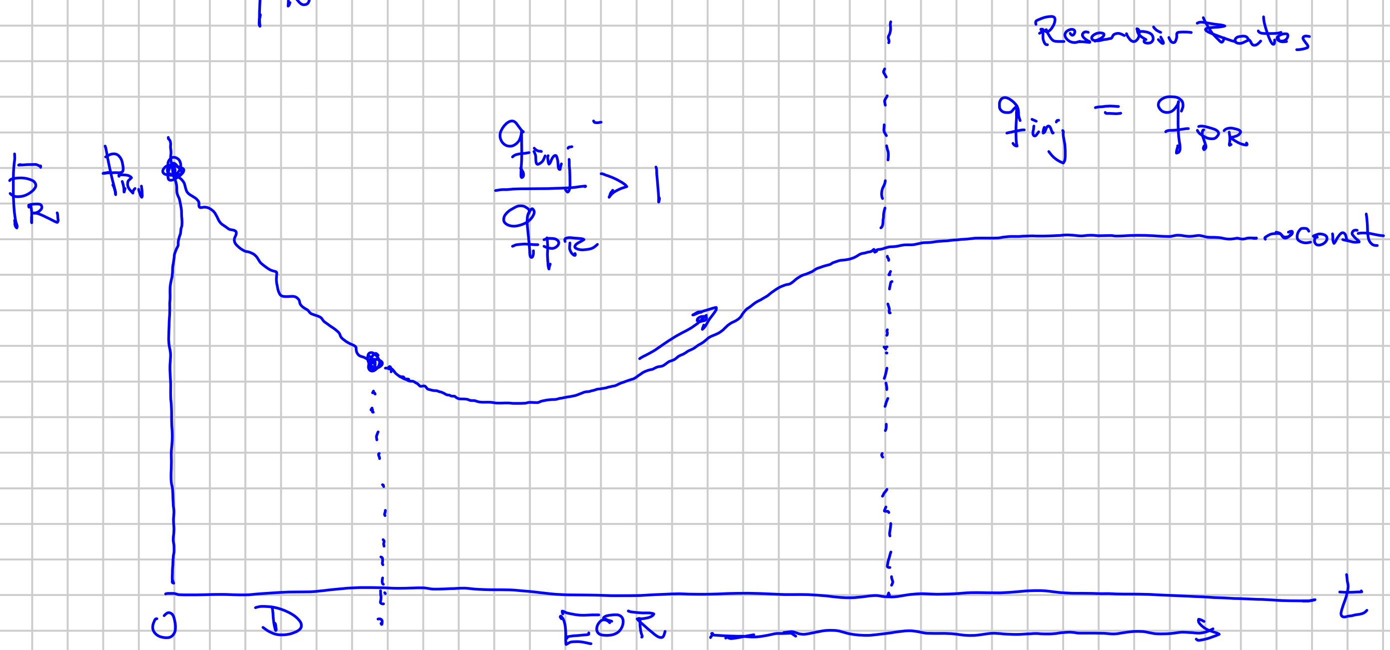
- Dynamic "PV" (t) – real fields/wells

nobody seems to talk about this...

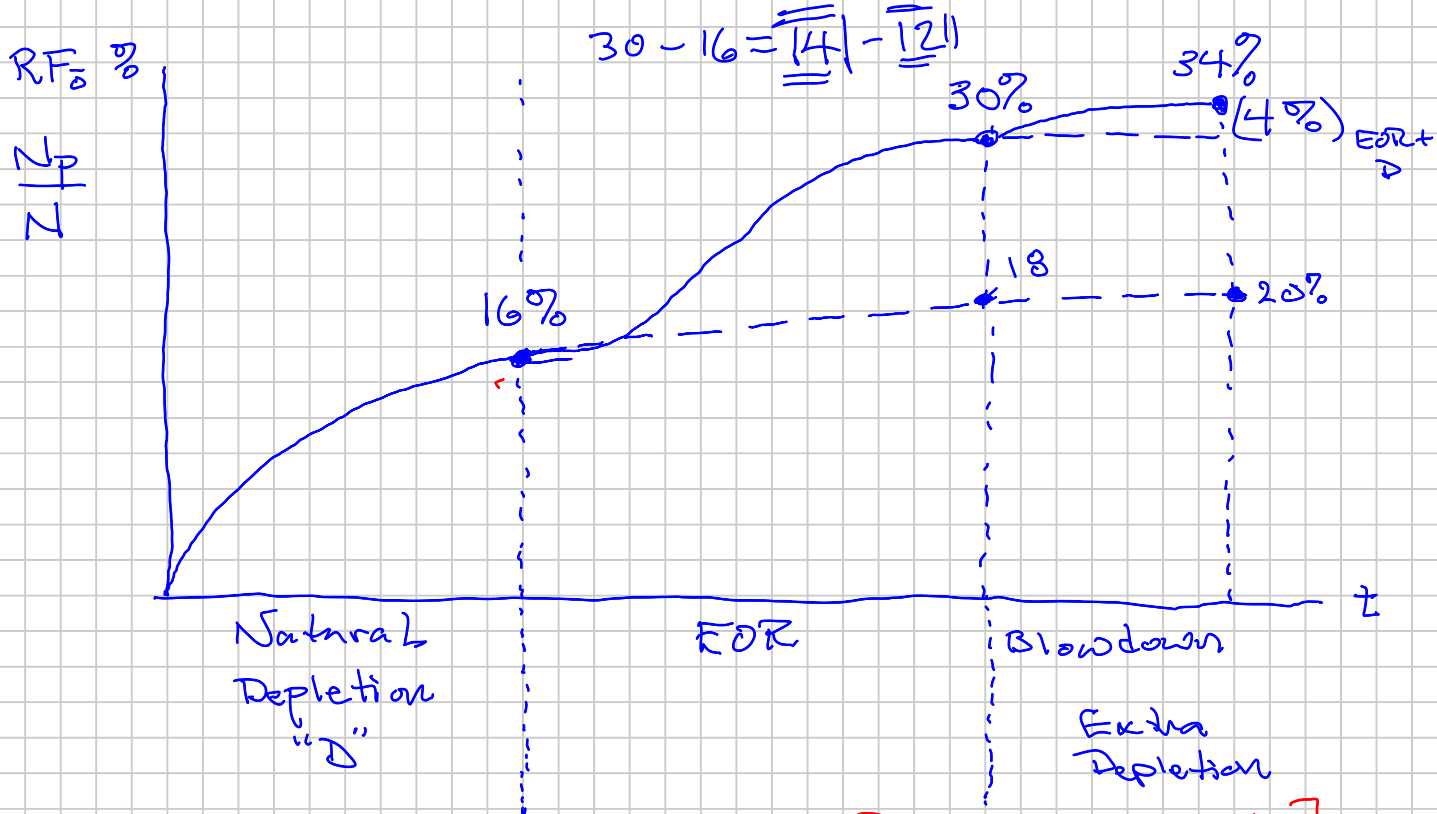
* VOIDAGE REPLACEMENT

$$q_{inj}(\bar{p}_R) \cong q_{tpR} = \underbrace{q_g B_g + q_o B_o + q_w B_w}_{@\ \bar{p}_R}$$

$\Rightarrow \quad \bar{p}_R(t) \sim$ constant



Note Title 10/23/2018



CW: D: 16 + 2 + 3 = 21
EOR: 34 − 21 = 13%

(EOR, Depletion)

(20, 15) | (30, 20) | (34, 16) | (30, 16) | (34, 15) |

(30, 18) | (25, 20) | (30, 20) | (35, 15) | (38, 15) |

(34, 20) | (14, 20) | (14, 20) | (32, 17) | (18, 31) |

(35, 20) | (21, 16) | (19, 18) | (20, 16) | (14, 20)

max EOR = 34 − 16 = 18%

MOBILITY ISSUES:

Effective — Relative

$$\lambda_p = \frac{k_p}{\mu_p} \bigg| \frac{k_{rp}}{\mu_p}$$

$\frac{md}{cp}$ $\frac{1}{cp}$

$$k_{rp} = \frac{k_p}{k} \leftarrow \text{Absolute}$$

Depletion

$$\lambda_g = \frac{k_{rg}}{\mu_g B_g}$$

$$\lambda_o = \frac{k_{ro}}{\mu_o B_o}$$

EOR: Two Phases

- Displacing Phase (Injecting)
- Displaced Phase (Usually oil)

$$\boxed{\lambda : f(\Delta p)}$$

$\Delta p = P_{inj} - P_{wf}$

λ_o (Displaced Phase)

$\underbrace{\lambda_w \quad \lambda_g}_{\lambda_D}$ (Displacing Phase

Mobility Ratio: M

Impacts directly ΔS_o (BL theory)

E_m E_p

Conformance

E_v

E_A

$$M \underset{\neq}{=} \frac{\lambda_{Displacing}\ \text{"w"}}{\lambda_{Displaced}\ \text{"o"}} = \frac{\frac{k_{rw}}{\mu_w}}{\frac{k_{ro}}{\mu_o}} = \frac{\frac{k_w}{\mu_w}}{\frac{k_o}{\mu_o}} = \frac{\overbrace{k_{rw}}\ \overbrace{\mu_o}}{\underbrace{k_{ro}}_{R}\ \underbrace{\mu_w}_{F}}$$

$\frac{1}{cp}$ $\frac{md}{cp}$

* After (?) 1950

Muskat 1950 Mobility Ratio $\bar{m} \equiv \dfrac{\lambda_{Displaced}}{\lambda_{Displacing}}$

Note Title 10/24/2018

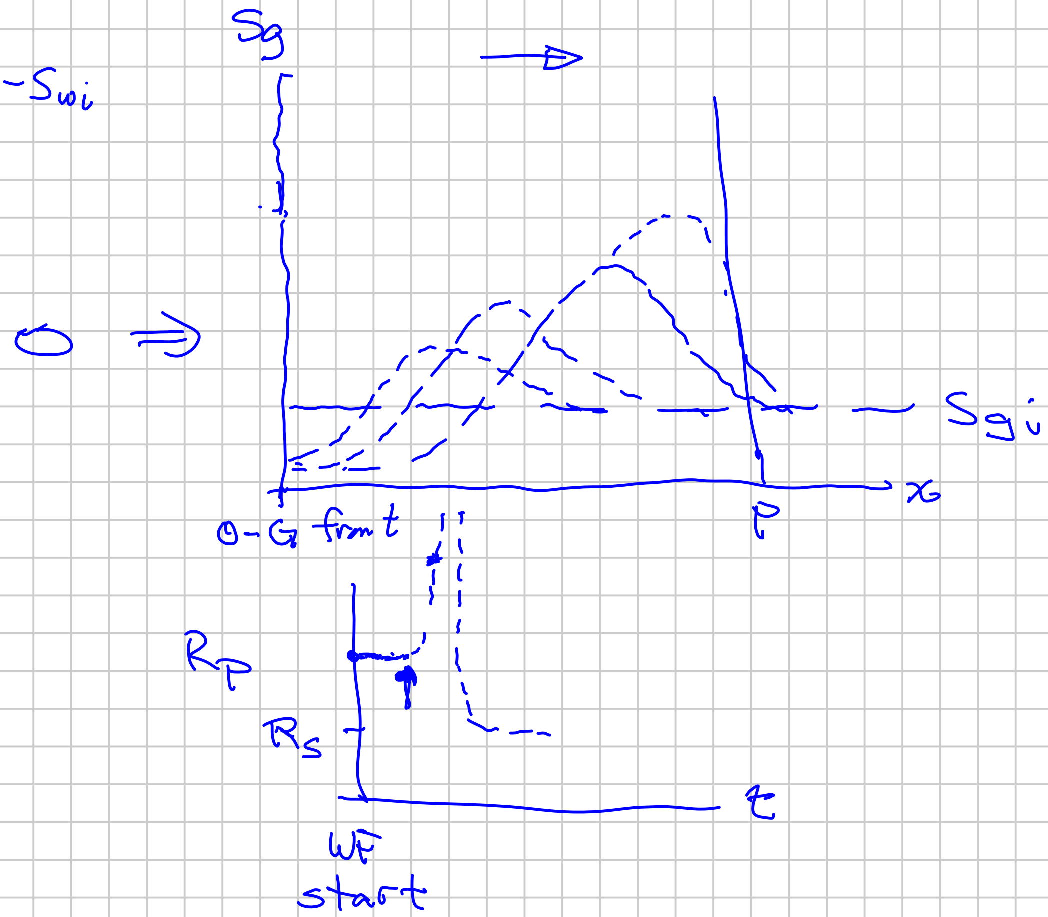
* Standing's Notes on Mobility

N.S. Oils $\mu_o < 2\ cp \rightarrow 0.3-0.2$

$\mu_w \sim 0.5\ cp$

(10-15 cp)

$S_o = 1 - S_g - S_{wi}$



BUCKLEY-LEVERETT THEORY

* Comments on Buckley-Leverett theory and Standing notes (all books...) discussion & presentation of BL theory.
  - When it may not "work"
  - How to check / verify
  - Why it might not work

$$\frac{q_w}{q} = f_w = \frac{1 + \frac{k_o}{q\mu_o}\left[\frac{\partial P_c}{\partial x} - \Delta\rho g \sin\alpha\right]}{1 + \frac{k_o}{k_w}\cdot\frac{\mu_w}{\mu_o}}$$

AS $k_o = k \cdot k_{ro}$ AND IGNORING $\frac{\partial P_c}{\partial x}$ BECAUSE SMALL

$$f_w = \frac{1 - a k_{ro}}{1 + \frac{k_{ro}}{k_{rw}}\cdot\frac{\mu_w}{\mu_o}} \quad = \frac{1 - a k_{ro}}{1 + M(S)}$$

WHERE

$$a = \frac{0.488\, k\, \Delta\rho \sin\alpha}{q\,\mu_o}$$

IF
$\Delta\rho$ = gm/cc
k = DARCY
q = BBL/DAY/FT^2
μ_o = cp

"q" $= v_D = q_R / A_\perp$; $A_\perp(x) =$ constant

f_w = fractional flow of displacing phase/fluid

$$= \frac{q_w}{q_w + q_o} = \frac{(v_D)_w}{(v_D)_w + (v_D)_o}$$

Simplify for Horizontal flow ($\alpha = 0$)

$$f_w = \frac{1}{1 + \frac{k_{ro}}{k_{rw}}\frac{\mu_w}{\mu_o}} = \frac{1}{1 + \frac{k_{rw}}{k_{ro}}(S_w)\left(\frac{\mu_w}{\mu_o}\right)} = f_w(S_w)$$

$$S_{wi} \le S_w \le 1 - S_{orw}$$

Inclined Flow: $$f_w = \frac{1 - a\,k_{ro}(S_w)}{1 + \frac{k_{rw}}{k_{ro}} \cdot \frac{\mu_w}{\mu_o}}$$

$$\underbrace{(a\,k_{ro})}_{\text{Gravity-Rate (Velocity) Term}} = \left(\frac{k_o}{\mu_o}\right) \cdot (\Delta\rho\, g \sin\alpha) \cdot \frac{1}{q}$$

R+F

F

λ_o

F

Controllable

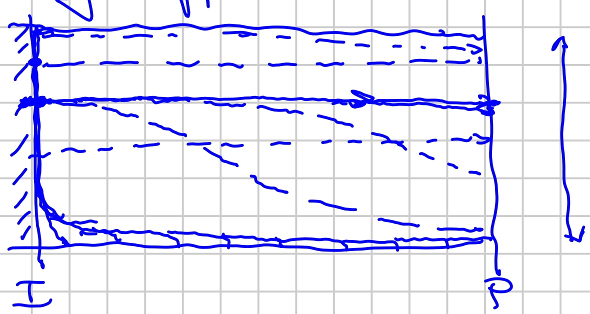
$$\Delta\rho = \rho_w - \rho_o$$

$\rho_o = 800\ kg/m^3$

$\rho_w = 1000\ kg/m^3$

Theory only applies to 1D flow

H:



1" Core

Layer 10 m

$$\begin{Bmatrix} q \\ v \end{Bmatrix} > \underbrace{\begin{Bmatrix} q \\ v \end{Bmatrix}^*}_{?} \Rightarrow \text{get 1D flow}$$

I:

Assuming 1D RL Theory Applies ... read & study notes ...

Notes on Mobility Ratios Used in Fluid Displacement Calculations.

All calculations that involve one fluid displacing a second fluid involve the ratio of the mobilities of the two fluids.

The mobility of a fluid is defined by me(MBS) as the ratio of effective permeability to viscosity.

Alternative: $\lambda_p \equiv \frac{k_{rp}}{\mu_p}$ $\left[\frac{1}{cp}\right]$

$$\lambda_o = k_o/\mu_o \quad \text{md/centipoise} \quad \text{md/cp} \qquad (1)$$
$$\lambda_g = k_g/\mu_g \quad \text{"} \qquad (2)$$
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Note that effective permeability in the above equations depend on saturation, saturation history (drainage or imbibition process) as well as the character of the porous rock.

In systems in which one fluid is displacing a second, it is common practice to call the fluid that is increasing in saturation the "displacing fluid" or "displacing phase". The fluid that is decreasing in saturation is called the "displaced fluid" or "displaced phase". The mobility ratio is the ratio of the mobility of the displacing fluid to that of the displaced fluid.

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For example, when water is displacing oil, as when aquifer water moves into an oil reservoir, the mobility ratio of the operation is written

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(F) ↳ ~ constant

Mobility pg 2 of 3

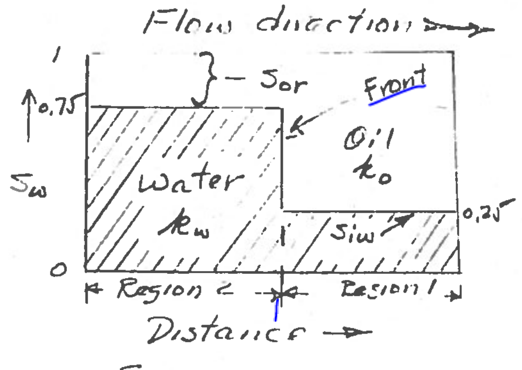

Figure 1.

Figure 1 illustrates partial displacement of oil by water. Only water is flowing in Region 2 behind the water/oil front, while only oil is flowing in Region 1 ahead of the front. In specifying the mobility ratio of this system, the effective water permeability in Region 2 is evaluated at the residual oil saturation, Sor. Sorw The effective oil permeability in Region 1 is evaluated at the irreducible water saturation Siw. The mobility ratio is,

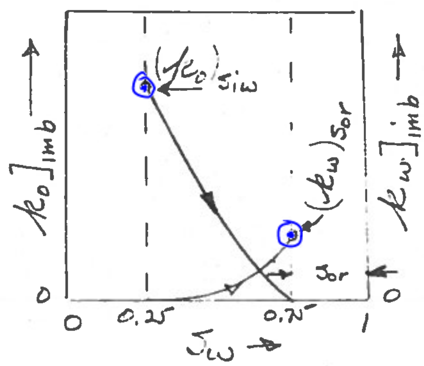

Figure 2

$$M = \frac{(k_w)_{Sor}}{(k_o)_{Siw}} \cdot \frac{\mu_o}{\mu_w} = \frac{k_{rw}(S_{orw})}{k_{ro}(S_{iw})} \qquad (6)$$

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$S_{oi} \to S_{orw}$ (not $S_{oi} \to 0$)

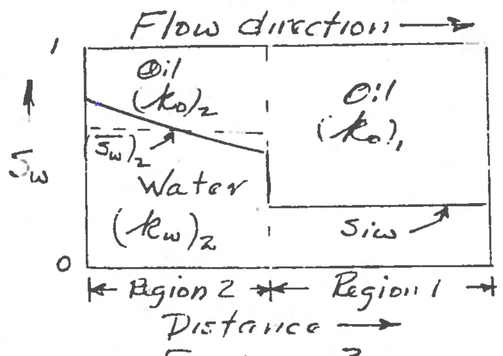

Figure 3

Figure 3 illustrates what is termed a "Buckley-Leverett" type displacement. With this type of displacement both oil and water are flowing in Region 2 (as the front advances). Only oil is flowing in Region 1. In specifying the mobility ratio of the system, the mobility of Region 2 can be ~~is~~ evaluated at the average saturation condition by the relationship.

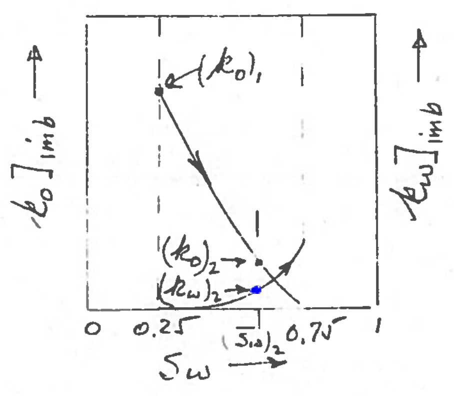

Figure 4.

$$\lambda_2 = \left(\frac{(k_w)_2}{\mu_w} + \frac{(k_o)_2}{\mu_o} \right) \quad @\bar{S}_{w2} \qquad (7)$$

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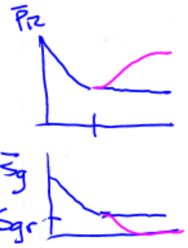
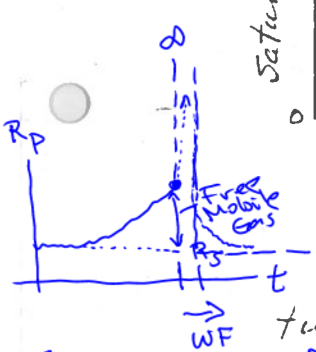
The above effective permeabilities are illustrated in Figure 4.





S_{Hcrw} = const 35%

S_{orw} (S_{gi} | S_{gr})?

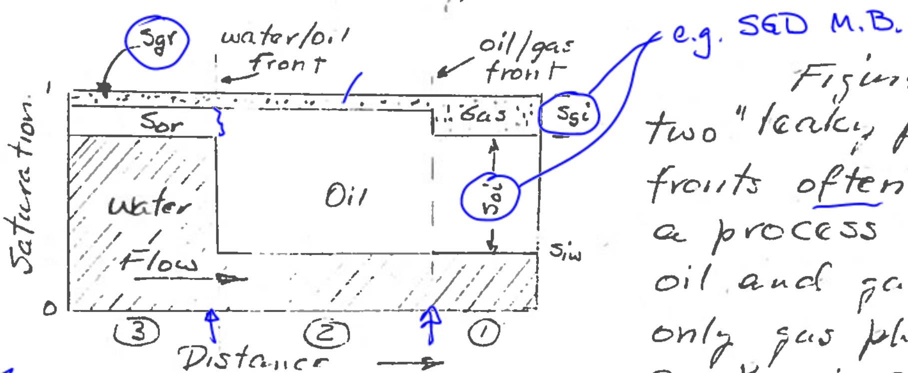


Figure 5

Figure 5 illustrates two "leaky piston" displacement fronts often used in calculating a process of water displacing oil and gas. In Region 1 only gas phase is flowing. In Region 2 only oil phase is flowing. And in Region 3 only water is flowing. The two mobility ratios would be written as.

$$M_{og} = \frac{\lambda_2}{\lambda_1} = \frac{(k_o)_{S_{iw},S_{gr}}}{(k_g)_{S_{gi}}} \cdot \frac{\mu_g}{\mu_o} \qquad (9)$$

and.

$$M_{wo} = \frac{\lambda_3}{\lambda_2} = \frac{(k_w)_{S_{or}+S_{gr}}}{(k_o)_{S_{iw},S_{gr}}} \cdot \frac{\mu_o}{\mu_w} \qquad (10)$$

Mobility ratios for most reservoir displacements lie between about 0.1 and 10. Mobility ratios less than 1 are generally considered as "favorable" in that the displacement front has fairly regular (smooth) features. This is illustrated by the front appearance at three successive times in Figure 6. Mobility ratios greater than 1 give more ragged displacement fronts as illustrated by Figure 7. The term "fingering" is often used to designate the erratic front behavior of high mobility ratio displacements.

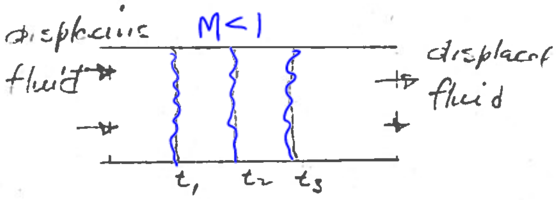
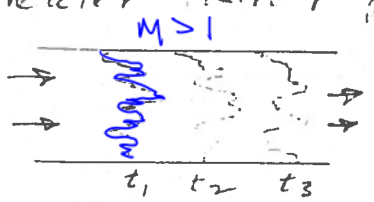


Figure 6



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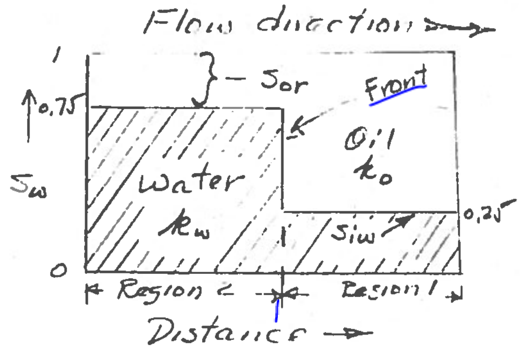

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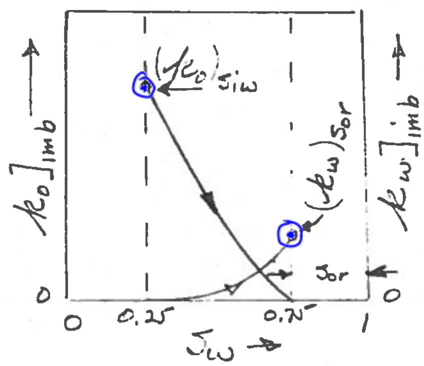

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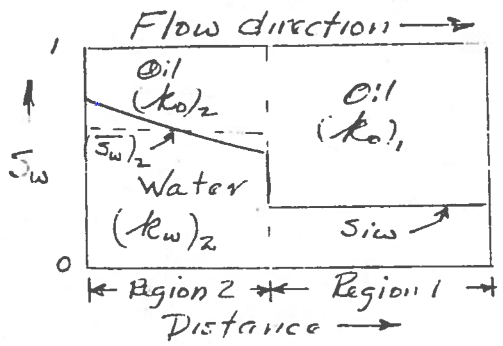
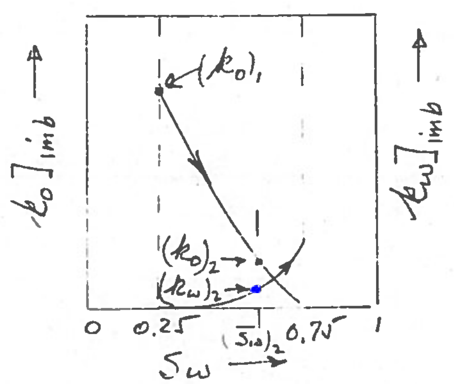


Figure 3



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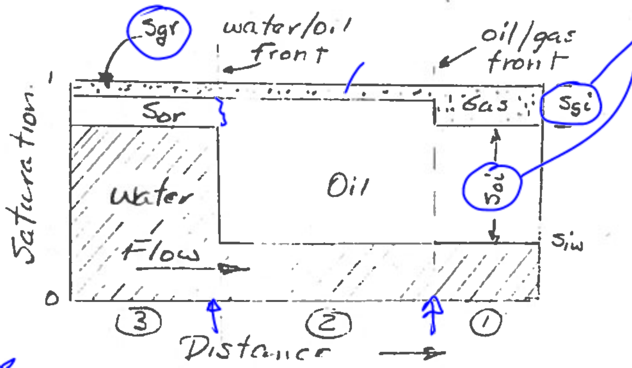
e.g. SGD M.B.



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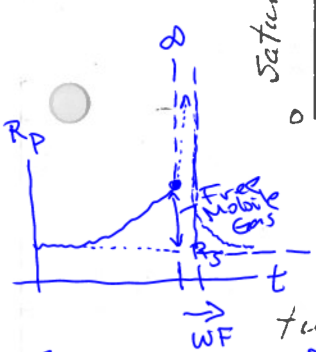

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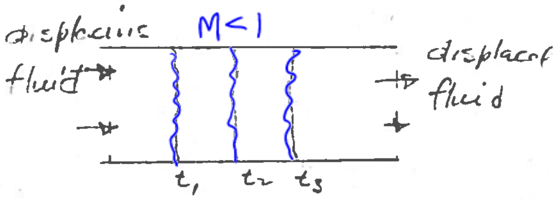

Figure 6

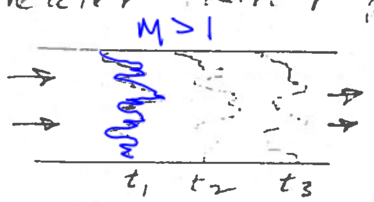

Figure 7