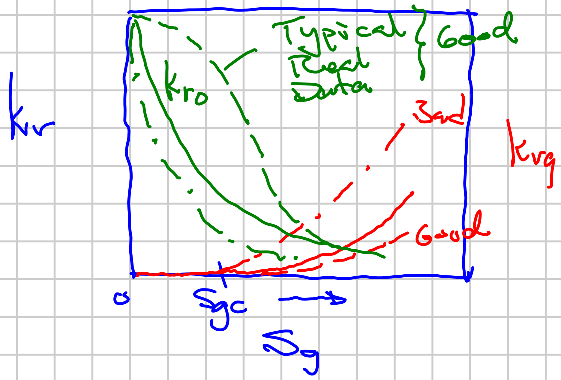
LNX Modeling of EOR Processes

└ Layered No-Crossflow

$k_v \approx 0$ $v_z \sim 0$

RP Bad RP Good

Depletion SGD Oil Reservoirs : 5 – (10 – 25%)



Carey : $k_{ro} \propto (1-S_g)^{n_o \sim 2-5}$

--- k_{ro} : Chierici Gerauld

EOR : Inject ⇒ $\underbrace{\text{Success | Failure}}$

KPI | Key Layer Permeability Variation

high-k , low-k layers

Distribution k (z)

horizontal x-y

depth (layer to layer) geological

1944 : Laws k distribution

1948 : ① Trans. AIME

Standing , Lindblad , Parsons : Gas Cycling Gas Condensate

"Charts" ② API : Dykstra & Parsons : Water Flooding

Leaky Piston Displ.

Analytical ③ Muskat : k = exponential

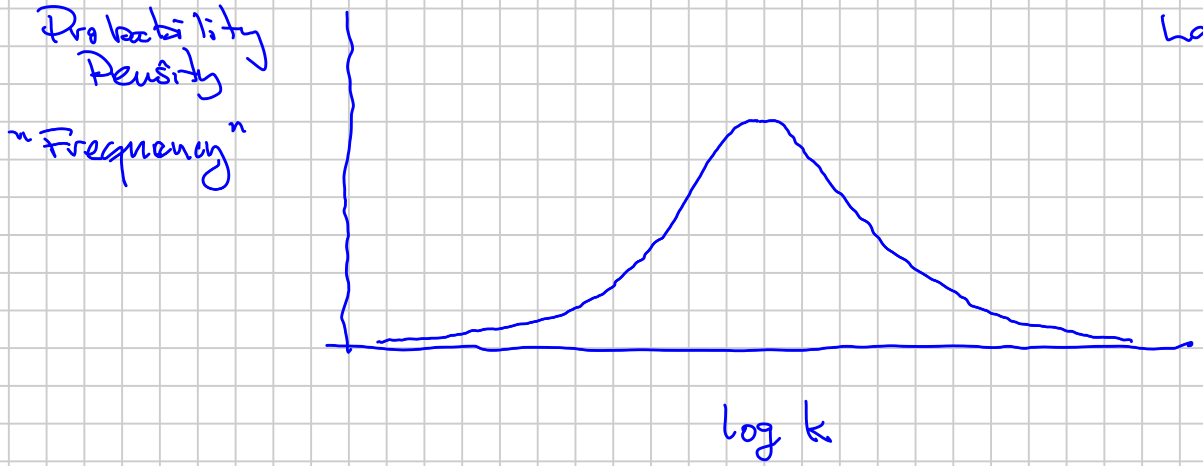
: Laws log-normal

Gas Cycling Gas Condensate

June 1948 (Trans AIME 1949)

k(z) using a log-normal permeability distribution

Laws 1944



Property
e.g. Grain Size / Porosity

ϕ : normal dist. $\qquad \bar{\phi} = \frac{1}{N} \sum \phi_i$

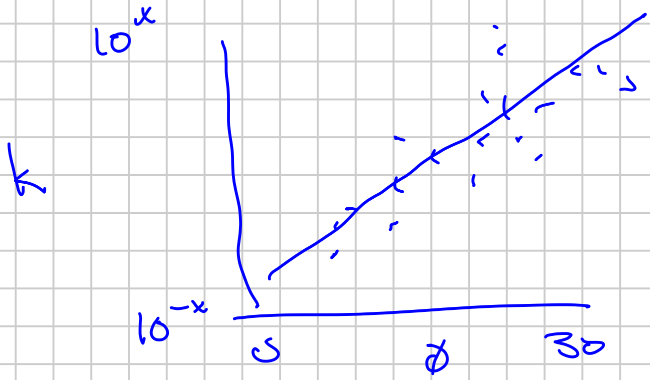
k : log-normal dist $\qquad \log \bar{k} = \frac{1}{N} \sum \log k_i$

$\Rightarrow$ Geometric Average

$$\bar{k}_G = \left(\prod k_i \right)^{1/N}$$

$\Rightarrow$ Approximation

$$\log k \sim a + b\phi$$



1949: • Muskat Trans AIME Gas Cycling

• Stiles WF EOR

Any k(z) distribution ⇒ Calculational Procedure N_{layers}

k, ϕ

Leaky Piston Displacement

1950 Muskat WF Analytical Solutions

k(z) linear
exponential
log-normal

Leaky Piston assumption

(1967) BL in each layer

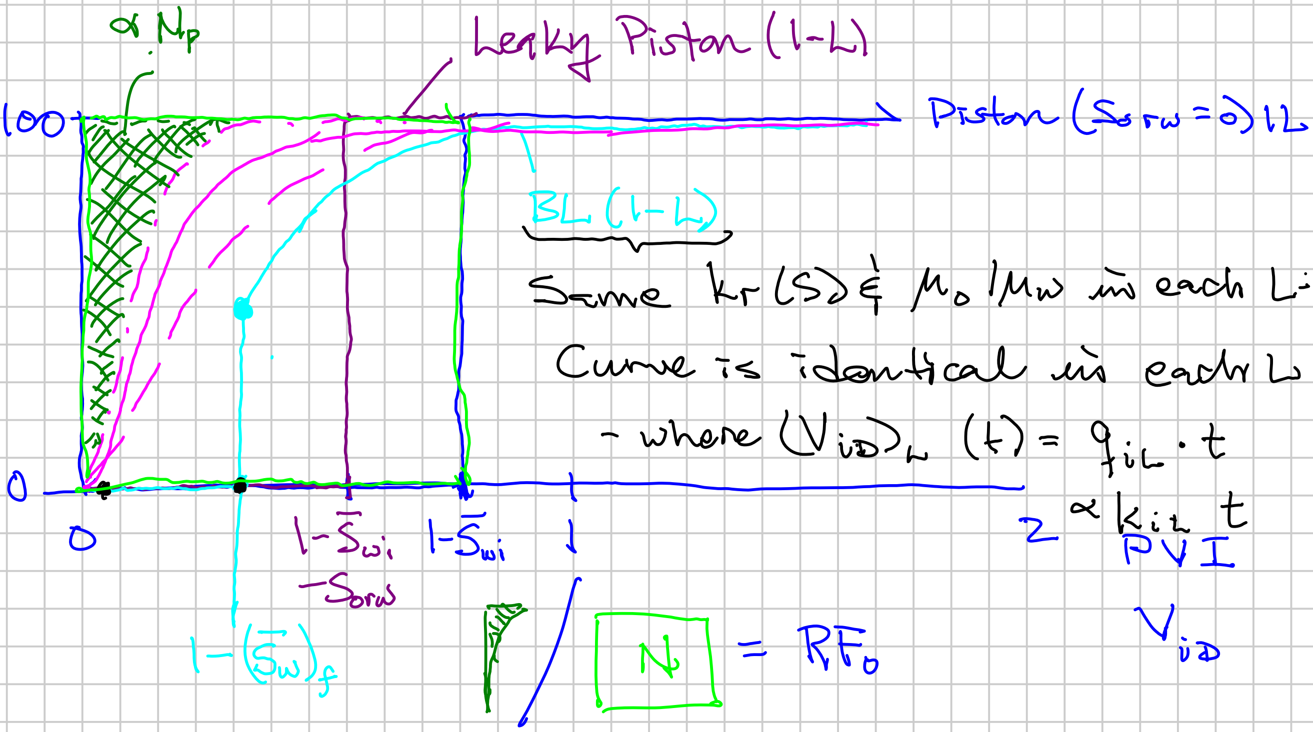
Snyder & Ramey : log-normal dist

LNX EOR Publications History

$\Rightarrow$ Production Performance of LNX Systems

"F_w" $= \left(\dfrac{q_w}{q_w + q_o}\right)_P$ $\dfrac{STB}{STB}$

~ f_w related



$\underbrace{\text{BL (1-L)}}$

Same $k_r(S)$ & μ_o/μ_w in each L:

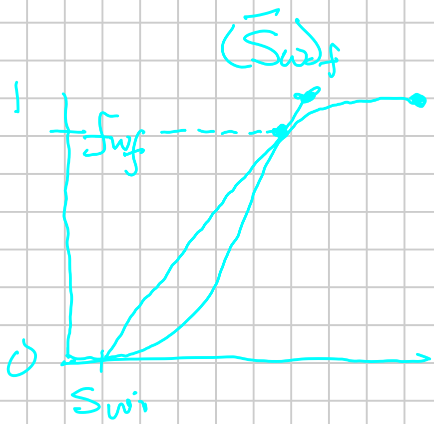
Curve is identical in each L

– where $(V_{iD})_L(t) = q_{iL} \cdot t$

$\propto k_{iL}\, t$

$$f_w = \left(\frac{q_{wR}}{q_{wR} + q_{oR}}\right)_P \qquad F_w = \frac{q_{oR}/B_o}{q_{wR}/B_w + q_{oR}/B_o}$$

B_w & B_o @ $\bar{P}_R$ in WF Unit



LNX

$$q_{wR}(t) = \sum_{L=1}^{N_L} f_w\left(V_{iD_L}(t)\right) \cdot q_{tL}$$

$f_w(V_{iD})$ same for all Layers

$\Leftrightarrow V_{iD}$ different for all Layers $\propto k_L$

q_{tL} may vary somewhat over time

$$V_{iDL} \cong V_{iDt} \cdot \frac{k_L}{\bar{k}}$$

$$\bar{k} = \frac{\sum k_L}{N_L}$$

LNX : ① Earlier BT

② Lower $RF_o = N_p(t) / N$

at a given time

} Larger the $k(z)$ Variation "V"

Laws (DP / Muskat / Standing ...)

$$"V" = \frac{|\bar{k}_G - k_{SD}|}{\bar{k}_G}$$

0 - 1

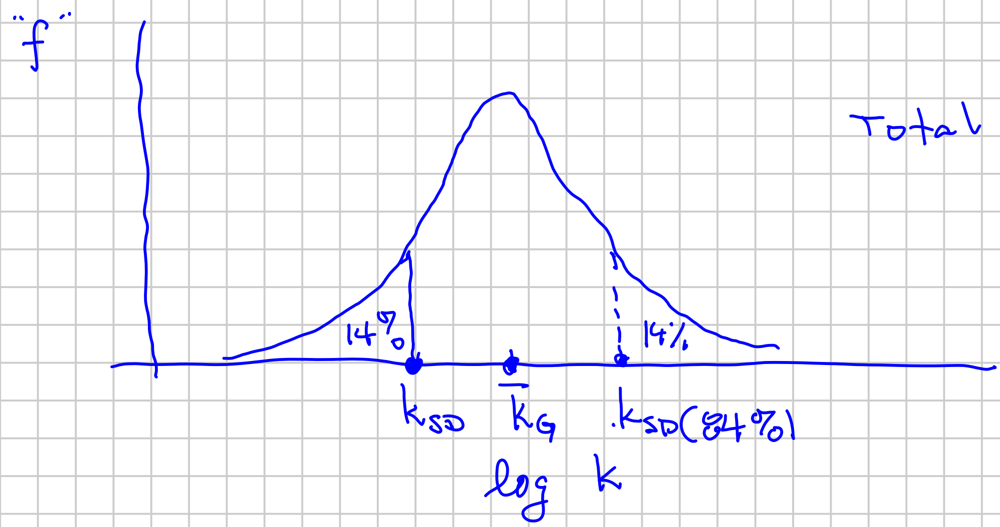
no max

(0.3 - 0.7)

real data

SD : standard deviation

Total Area = 1



Note Title 11/13/2018

Well Control and Management Considerations in EOR projects

① Well Controls: Practical & Reservoir Simulation

(a) Target Rate (volumetric)

- Surface Product Rates $\overbrace{q_g \quad q_o \quad q_w \quad q_L}^{④}$

$q_L = q_o + q_w$

- Reservoir Phase Rates

$q_{gR} \quad q_{oR} \quad q_{wR} \quad q_{LR} = q_{oR} + q_{wR}$ ⑤

(EOR) $q_{tR} = q_{gR} + q_{oR} + q_{wR}$

$(q_{\bar{g}})$ $$q_g = \underbrace{q_{gR} / B_{gd}(p)}_{q_{\bar{g}(gR)}} + \underbrace{(q_{oR} / B_o(p)) R_s(p)}_{q_{\bar{g}(oR)}}$$

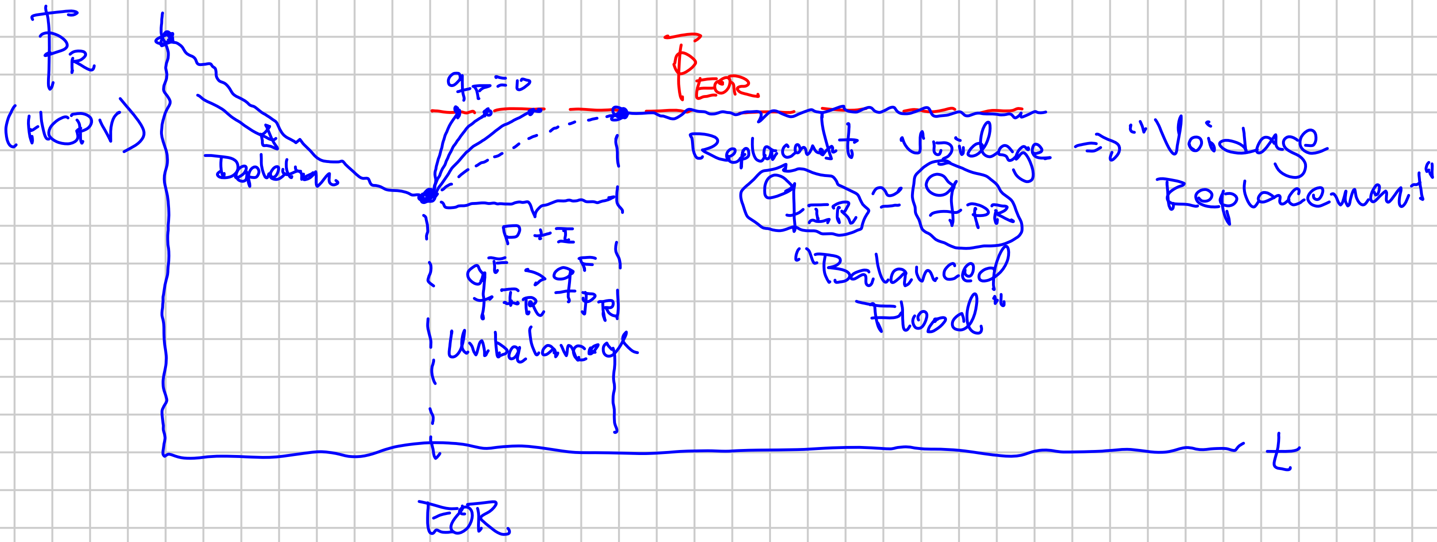
$(q_{\bar{o}})$ $$q_o = \underbrace{q_{oR} / B_o}_{q_{\bar{o}(oR)}} + \underbrace{(q_{gR} / B_{gd}) r_s}_{q_{\bar{o}(gR)}}$$

(b) Wellbore BH Pressure Constraints (alt. Wellhead Tubing Pressure Constraints)

Producer Well: $p_{wf,min}$ (= 1atm default)

Injector Well: $p_{inj,max}$

EOR Projects : ~ Target Average Reservoir Pressure $\bar{p}_{EOR}$



1980

CSD Petroleum Industry Course

Displacement Problem 1

(This problem pertains to the displacement of oil up-structure by an influxing aquifer. The problem is to be solved using the Buckley-Leverett method).

The sketches below illustrate a section of reservoir in which water is advancing up-structure as a result of pressure reduction in the oil band section. To simplify this problem two assumptions will be used : (1) the initial water in the oil zone amounts to 32% saturation and is constant with height. To say it differently, we will neglect any effects of the initial transition zone saturation. (2) water breakthrough into the 1st line well occurs when the front reaches the elevation of the well. In other words, we will neglect effects of "cusping" of water into the well.

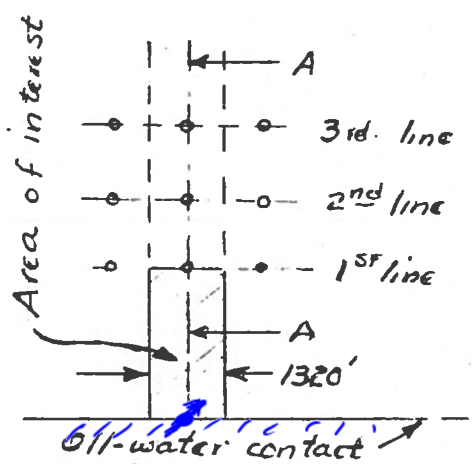


Figure 1
Plan View of "Window"

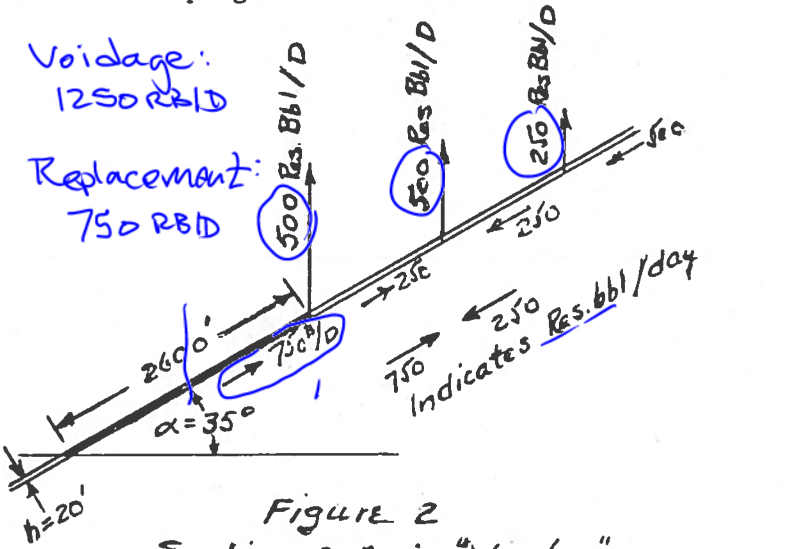


Figure 2
Section A-A in "Window"

"Window" Data

Window length = 2600'
Window width = 1320'
Formation thickness = 20'
Formation dip = +35°
Porosity = 0.235
Permeability (abs) = 100 md
Up-dip flow rate at oil-water contact = 750 Res.bbl/day

Fluid Saturations

S_{iw} = 0.30; S_{wi} = 0.32
S_{oi} = 0.68 S_{gi} = 0.00

Fluid Properties

B_o = 1.27 B_w = 1.02
μ_o = 1.16 cp μ_w = 0.38 cp
ρ_o = 45 lb/ft^3 ρ_w = 65 lb/ft^3

Relative Permeability Data

S_w	k_{ro}:imb	$k_{rw}/k_{ro}]$ imb	
0.30	0.725	0.0000	(S_{iw})
0.32	0.615	0.0195	
0.35	0.470	0.072	
0.40	0.315	0.280	
0.45	0.210	0.790	
0.50	0.133	2.000	
0.55	0.077	4.750	
0.60	0.036	11.85	
0.65	0.012	33.50	
0.67	0.007	55.53	

Displacement Problem 1 Cont.

The oil that is displaced up-structure by the influxing aquifer water will presumably be captured by the oil wells. When the water-oil front reaches the elevation of any well there will be an instantaneous jump in water-oil ratio (this is because we are considering only one layer - the jump would be more gradual if many layers were considered). We are, of course, interested in the amount of oil that can be recovered from the invaded volume (cross-hatched area in Fig 1) as we continue to produce the wells. The items to be calculated are:

(1) How many barrels of stocktank oil will be displaced from the invaded volume (and recovered) when the front first breaks through into the first line well ? What fraction of initial oil in this volume does this amount to ?

(2) What will be the surface producing water-oil ratio immediately after breakthrough ? Assuming that the well continues to produce at the same total fluid rate, what will the stocktank oil rate be ?

(3) When the first line well's cut reaches 95 %,what will be the amount of oil recovered from the invaded volume ? How long (years) will it take to reach this cut ? (Consider that the the aquifer influx rate into the window remains constant at 750 reservoir barrels per day.)

1980

M B Standing

CSD Petroleum Industry Course

Solution Displacement Problem 1

A. Calculation of fractional flow curve

$$f_w = \frac{1 - a\,k_{ro}}{1 + \frac{k_{ro}}{k_{rw}} \cdot \frac{\mu_w}{\mu_o}} \qquad a = \frac{7.84(10^{-6})\,k_{abs}(\rho_w - \rho_o)\sin\alpha}{q/A\ \mu_o}$$

$\alpha = 35°$

$$a = \frac{7.84(10^{-6}) \cdot 100\ (65-45)\ 0.5736}{750/20 \cdot 1320 \quad \cdot 1.16} = 0.2729$$

$S_{iw} = 0.30$

$S_{wi} = 0.32$

$$\mu_w/\mu_o = \frac{0.38}{1.16} = 0.3276$$

$$\therefore\ f_w = \frac{1 - 0.2729\,k_{ro}}{1 + \frac{0.3276}{k_{rw}/k_{ro}}}$$

S_w	k_{ro}	k_{rw}/k_{ro}	f_w	$\frac{f_w - f_{wi}}{S_w - S_{wi}}$	$\frac{\Delta f_w}{\Delta S_w}$
0.30 S_{iw}	0.725	0.0000	0	—	
0.32 S_{wi}	0.615	0.0195	0.0467 f_{wi}	—	
0.35	0.470	0.072	0.1571	3.680	
0.40	0.315	0.280	0.4212	4.651	
0.45	0.210	0.790	0.6664	4.767	4.904
0.50	0.133	2.000	0.8281	4.341	3.234
0.55	0.077	4.750	0.9158	3.779	1.754
0.60	0.036	11.65	0.9635	3.274	0.954
0.65	0.012	33.50	0.9871	2.850	0.472
0.67	0.007	55.53	0.9922	2.701	0.255

From plot of $\frac{f_w - f_{wi}}{S_w - S_{wi}}$ vs S_w the maximum occurs at $S_w = 0.430$. Maximum value is 4.80, which is slope of tangent line.

1. At break through at the first line well, the average saturation behind the front is

$$\bar{S}_w\Big]_{BT} = S_{wf} + \frac{1 - f_{wf}}{(f_w - f_{wi})/(S_w - S_{wi})_{max}} = 0.430 + \frac{(1 - 0.575)}{4.80} = 0.5185$$

05/15/12

Solution Displacement Problem 1 Cont

STB recovered @ BT

$$N_p = \frac{V_p[\bar{S}_w)_{BT} - \bar{S}_{wi})}{B_o} = \frac{(2600\cdot1320\cdot20)\cdot0.235}{1.27\cdot5.615}[0.5185-0.320]$$

$N_p = 449.0\ (10^3)$ STB. ans

$$\text{Rec. Fraction} = \frac{(0.5185-0.320)}{(1-0.320)} = 0.292 \quad \text{ans}$$

2. What will be surface water-oil ratio at B.T.

$$\text{Subsurface } w/o = \frac{f_w}{f_o} = \frac{0.5185}{(1-0.5185)} = 1.077 = WOR$$

$$\text{Surface water-oil ratio} = 1.077\cdot\frac{B_o}{B_w} = 1.077\cdot\frac{1.27}{1.02} = 1.34 \quad \text{ans}$$

$$q_o = \frac{q_t\cdot f_o}{B_o} = \frac{500(1-0.5185)}{1.27} = 189.6 \text{ STB/D} \quad \text{ans}$$

3 Cut @ first line well = 95%

$$\text{Cut} = 0.95 = \frac{q_w}{q_w+q_o} \quad \therefore F_{wo} = \frac{q_w}{q_o} = \frac{95}{5} = 19$$

$$WOR\ (\text{subsurface}) = F_{wo}\cdot\frac{B_w}{B_o} = 19\cdot\frac{1.02}{1.27} = 15.26 = \frac{q_w B_w}{q_o B_o}$$

$$\therefore f_w = \frac{15.26}{15.26+1} = \frac{q_w B_w}{q_w B_w + q_o B_o} = 0.9385; \quad S_{wc} = 0.569$$

$$\frac{\partial f_w}{\partial S_w} = 0.95$$

$$\therefore \bar{S}_w\Big]_o^c = S_{wc} + \frac{(1-f_{wc})}{\partial f_w/dS_w} = 0.569 + \frac{(1-0.9385)}{0.95} = 0.6337$$

$$\therefore \text{Recovery @ 95\% cut} = \frac{(2600\cdot1320\cdot20)0.235}{5.615\cdot1.27}(0.6337-0.320)$$

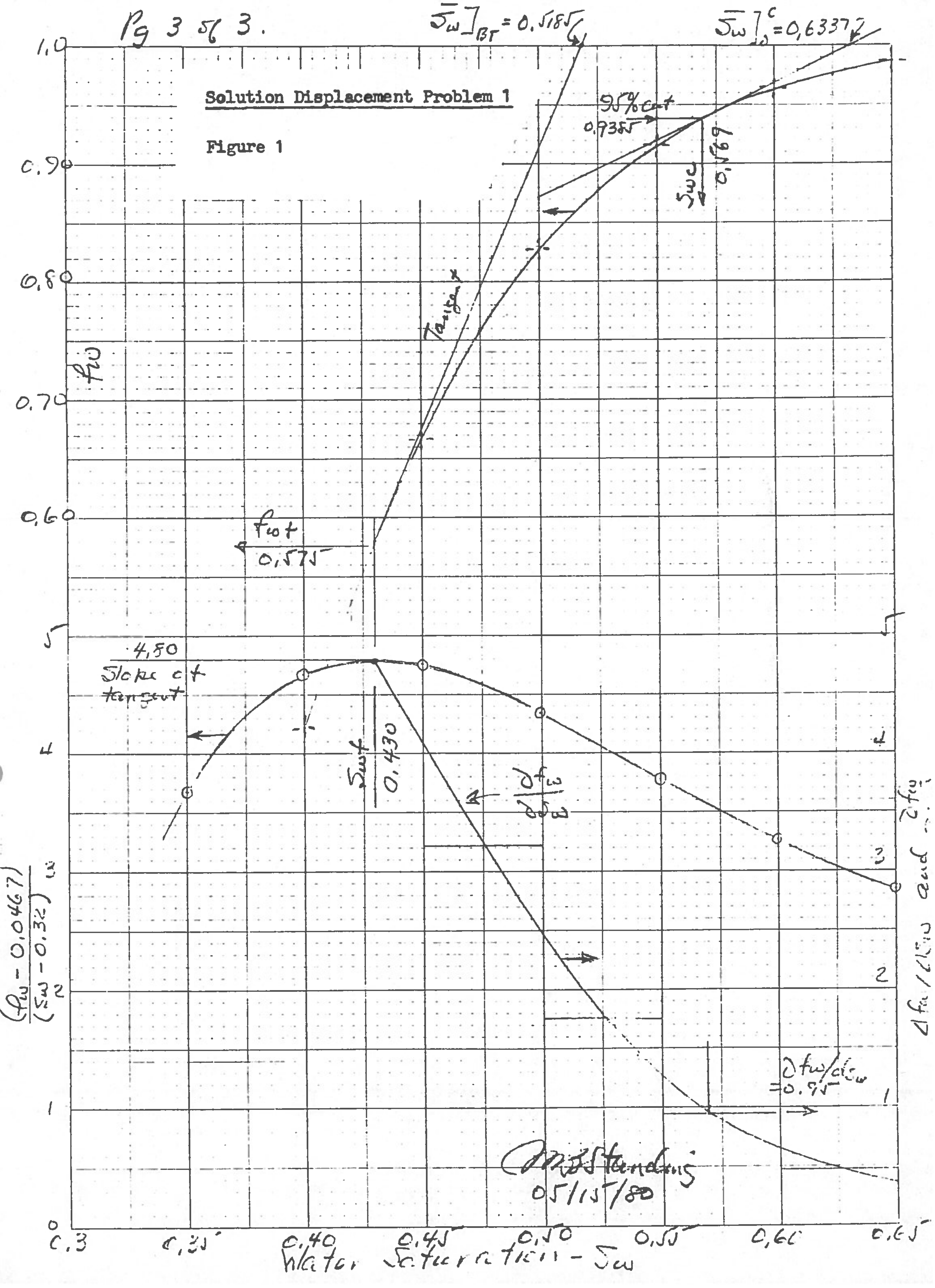
$$= 709.588\ (10^3) \text{ STB} \quad \text{ans}$$

$$\text{Pore Vol inj} = V_{iD} = 1/\partial f_w/dS_w = \frac{1}{0.95} = 1.053$$

$\therefore$ Time to reach 95% cut

$$t = \frac{W_i}{q_i} = \frac{(2600\cdot1320\cdot20)\cdot0.235\cdot1.053}{5.615\cdot750\cdot365} = 11.05 \text{ years} \quad \text{ans}$$

J... 05/15/93


Pg 3 of 3.
Solution Displacement Problem 1
Figure 1
1.0
0.90
0.80
0.70
0.60
5
4
3
2
1
0
0.3
0.35
0.40
0.45
0.50
0.55
0.60
0.65
Water Saturation - Sw
fw
Tangent
fwf 0.575
95% cut 0.9385
Swc 0.569
4.80 Slope at tangent
Swf 0.430
∂fw/∂Sw
∂fw/dSw =0.95
(fw - 0.0467)/(Sw - 0.32)
05/15/80