Field Units Oil Rate Eq. (Single Phase Oil: PSS)

$$q_o = \frac{kh\,(p_R - p_{wf})}{141.2\,\mu_o B_o\left[\ln\frac{r_e}{r_w} - \frac{3}{4} + \underset{\uparrow}{s}\right]}$$

$s = 0$ MBS notes

$p_b < p_w < p_R$

q_o [STB/D]
k [md]
h [ft]
p [psia]
μ_o [cp]
B_o [RB/STB]
r [ft]

$$\ln\frac{r_e}{r_w} - \frac{3}{4} \simeq \ln\frac{0.472 r_e}{r_w}$$

$$= \ln\frac{r_e}{r_w} + \underbrace{\ln 0.472}_{\sim -3/4}$$

$1 - \left(\frac{p_{wf}}{p_R}\right)^2$ Fetkovich Eq.

$$q_o = \frac{\bar{k}_o h \bar{p}\left[1-0.2(p_{wf}/\bar{p})-0.8(p_{wf}/\bar{p})^2\right]}{\underset{(141.2\times 2)}{254.2}\,\bar{\mu}_o \bar{B}_o (\ln 0.47\, r_e/r_w)} \qquad (19)$$

$254.2 = 141.2 \times \frac{9}{5}$

Field Units ✓

$\bar{p} = p_R$

$k_o = k \cdot k_{ro}$

Vogel:

$p_R \le p_b$

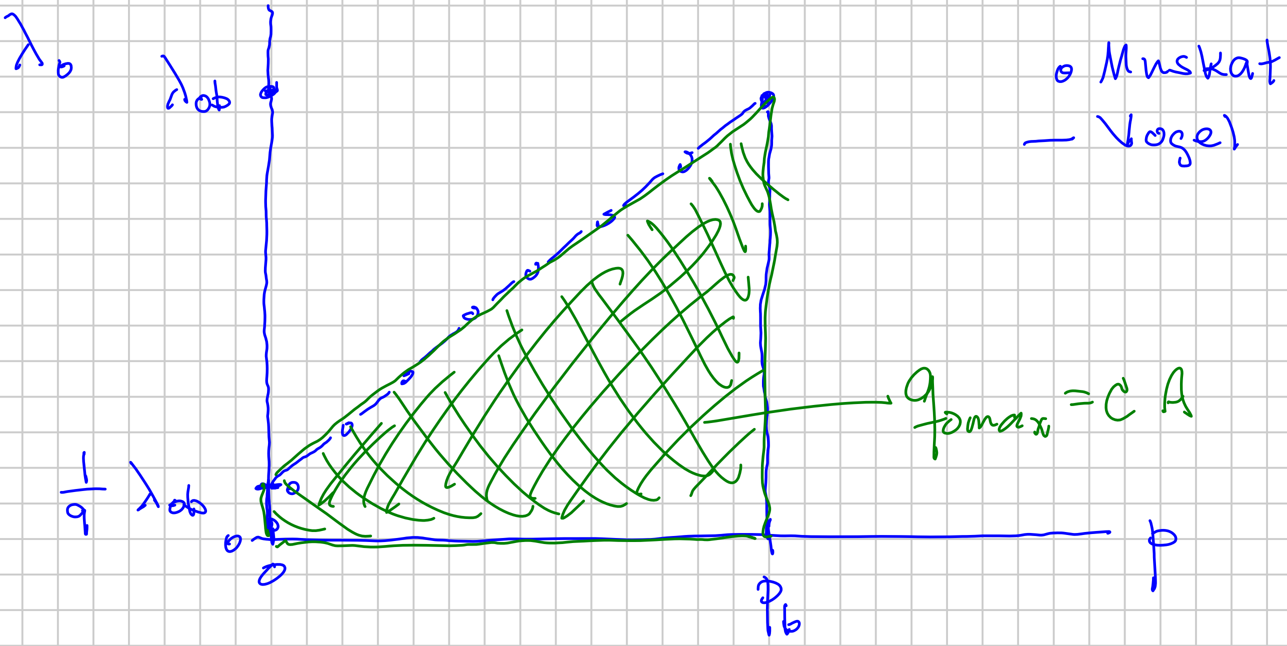
$\bar{k}_o$, $\bar{\mu}_o$, $\bar{B}_o$ @ $\bar{p} = p_R$

"Vogel" SGD saturated oil rate eq.

$$\frac{q_o}{\boxed{q_{omax}}} \cong 1 - 0.2\,\frac{p_{wf}}{p_R} - 0.8\left(\frac{p_{wf}}{p_R}\right)^2$$

$$= 1 - V\,\frac{p_{wf}}{p_R} - (1-V)\left(\frac{p_{wf}}{p_R}\right)^2$$

Fetkovich (197x) : $V = 0$



$k_{ro}(p)$!

Evinger - Muskat (1942)

$$q_o = \frac{kh}{\underbrace{141.2\left[\ln\frac{r_e}{r_w} - \frac{3}{4} + s\right]}_{C}} \cdot \int_{p_{wf}}^{p_R} \underbrace{\frac{k_{ro}}{\mu_o B_o}}_{\lambda_o}\, dp$$

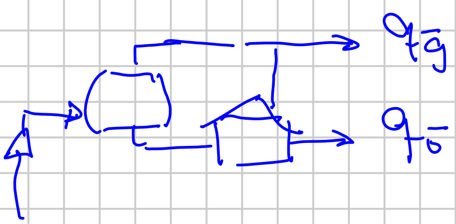
Foundation of Two-Phase Gas-Oil Flow

⇒ "Evinger-Muskat" methods (1942)
· SGD (Saturated Oil R)

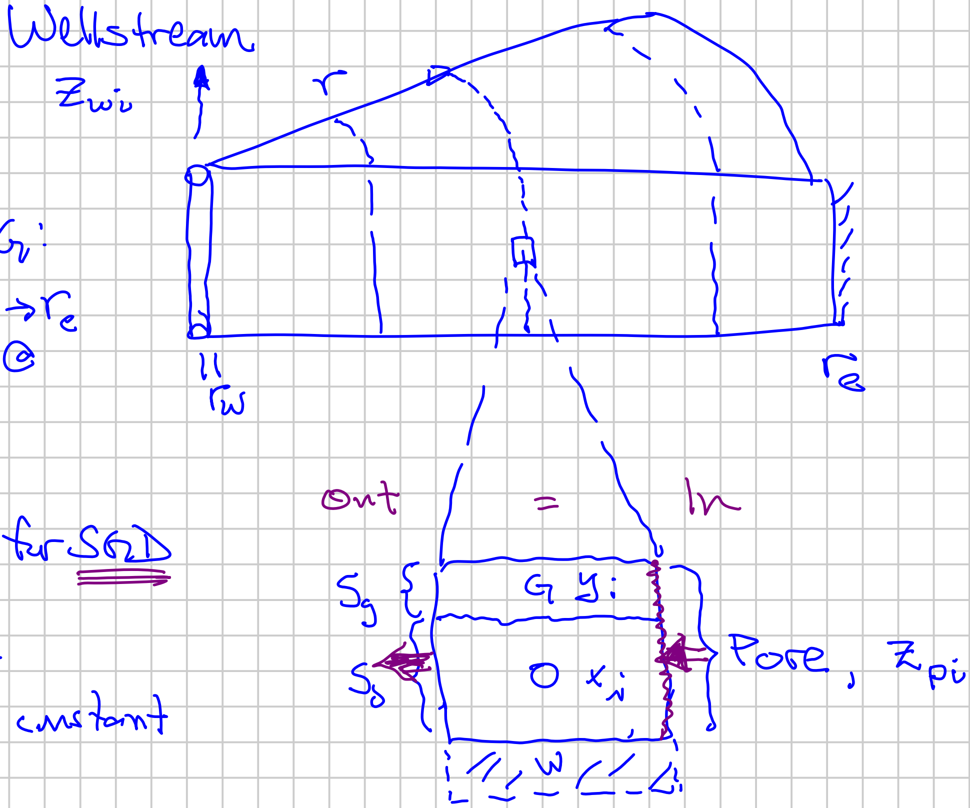
⇒ Fevang - Whitson
Gas Condensate R

E-M:

$p_R \doteq p_b$



$$\underbrace{R_p = \frac{q_{\bar{g}}}{q_{\bar{o}}}}$$



Steady State Flow Region } SGG: $r_w \to r_e$ @

E-M
Assumption for SGD

$\underbrace{r_w < r < r_e}$

$z_{wi} = z_{fi} = \text{constant}$

$R_p = R_{pf}$

$$\frac{S_o \frac{\rho_o}{M_o} x_i + S_g \frac{\rho_g}{M_g} y_i}{S_o \frac{\rho_o}{M_o} + S_g \frac{\rho_g}{M_g}} = z_{pi} \neq z_{fi} = \frac{\left(\frac{k_{ro}}{\mu_o}\frac{\rho_o}{M_o}\right) x_i + \left(\frac{k_{rg}}{\mu_g}\frac{\rho_g}{M_g}\right) y_i}{\left(\frac{k_{ro}}{\mu_o}\frac{\rho_o}{M_o}\right) + \left(\frac{k_{rg}}{\mu_g}\frac{\rho_g}{M_g}\right)}$$

Pore Composition

Flowing Composition

When SS Flow Region is Valid

$$\underset{r=r_w}{\overset{}{R_p\ @}} = \underbrace{R_s + \frac{k_{rg}}{k_{ro}} \frac{\mu_o B_o}{\mu_g B_g}}_{\text{any and all } p_{wf} < p \le p_R} = R_{pf}$$

$r > r_w \to r_e$

At given time, with $\underline{\underline{R_p}}$ known $\underbrace{(p_{wf}, p_R)}$ — SGD M.B.

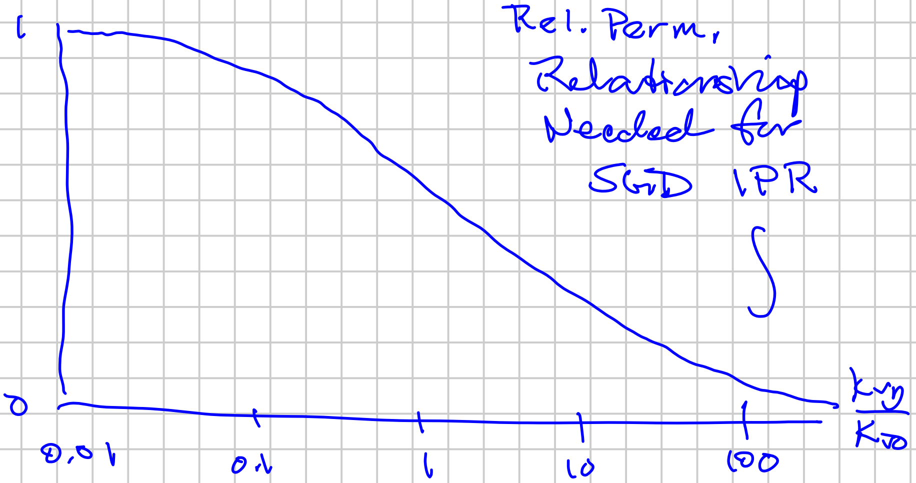
$$\frac{k_{rg}}{k_{ro}}(p) = \underbrace{\left(R_p - R_s(p)\right)\left(\frac{\mu_g B_g}{\mu_o B_o}\right)(p)}_{f(p)}$$

$p_{wf} < p < p_R$

$$\underbrace{\int \frac{k_{ro}(p)}{\mu_o(p) B_o(p)}}$$

Rel. Perm. (G-O) : S_{wc}

$$\underbrace{\cancel{S_o}\quad \cancel{S_g}\quad k_{rg}\quad k_{ro}}_{\text{Measure "SCAL"}} \qquad \boxed{k_{rg}/k_{ro}} \to \underline{\underline{k_{ro}}}\left(k_{rg}/k_{ro}\,(p)\right)$$



Rel. Perm. Relationship Needed for SGD IPR

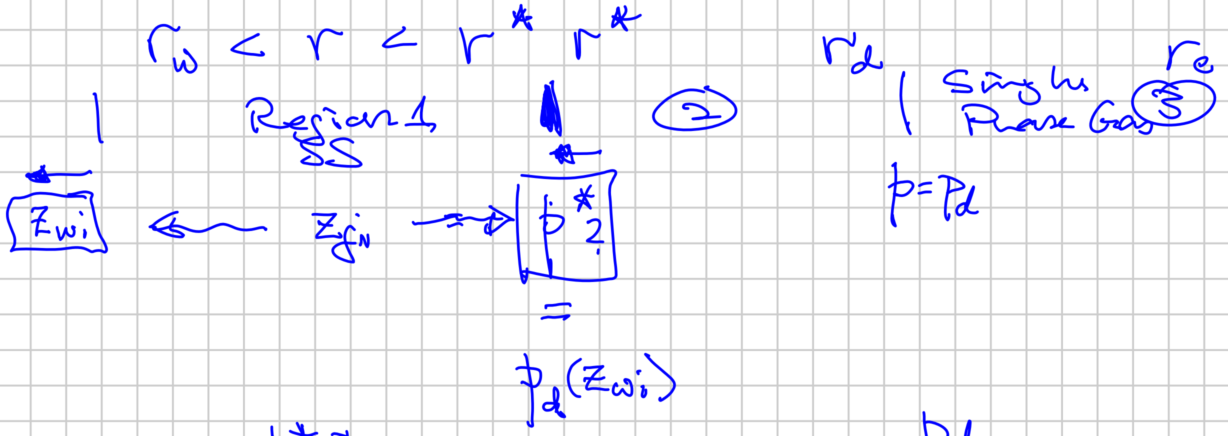
$\int$

Before 1994

Gas Condensates:

$$q_g = \frac{0.703 \quad kh}{T_R\left[\ln\frac{r_e}{r_w} - \frac{3}{4} + s\right]} \cdot \underbrace{\int_{p_{wf}}^{p_R}\left(\frac{k_{rg}}{\mu_g B_{gd}} + \frac{k_{ro}}{\mu_o B_o} R_s\right) dp}_{<1994\ ?}$$

SS Assumption:



$$\underbrace{\int_{p_{wf}}^{p^*=p_{dw}} \frac{k_{rg}(p)}{\mu_g B_g} + \frac{k_{ro}(p)}{\mu_o B_o} R_s}_{EM} + \underbrace{\int_{p^*}^{p_d} \frac{k_{rg}}{\mu_g B_g}} + \underbrace{\int_{p_d}^{p_R} \frac{1}{\mu_g B_g}}$$

$$k_{ro} = 0.5 - m\, S_g$$

Sat. Exponent to oil > 1

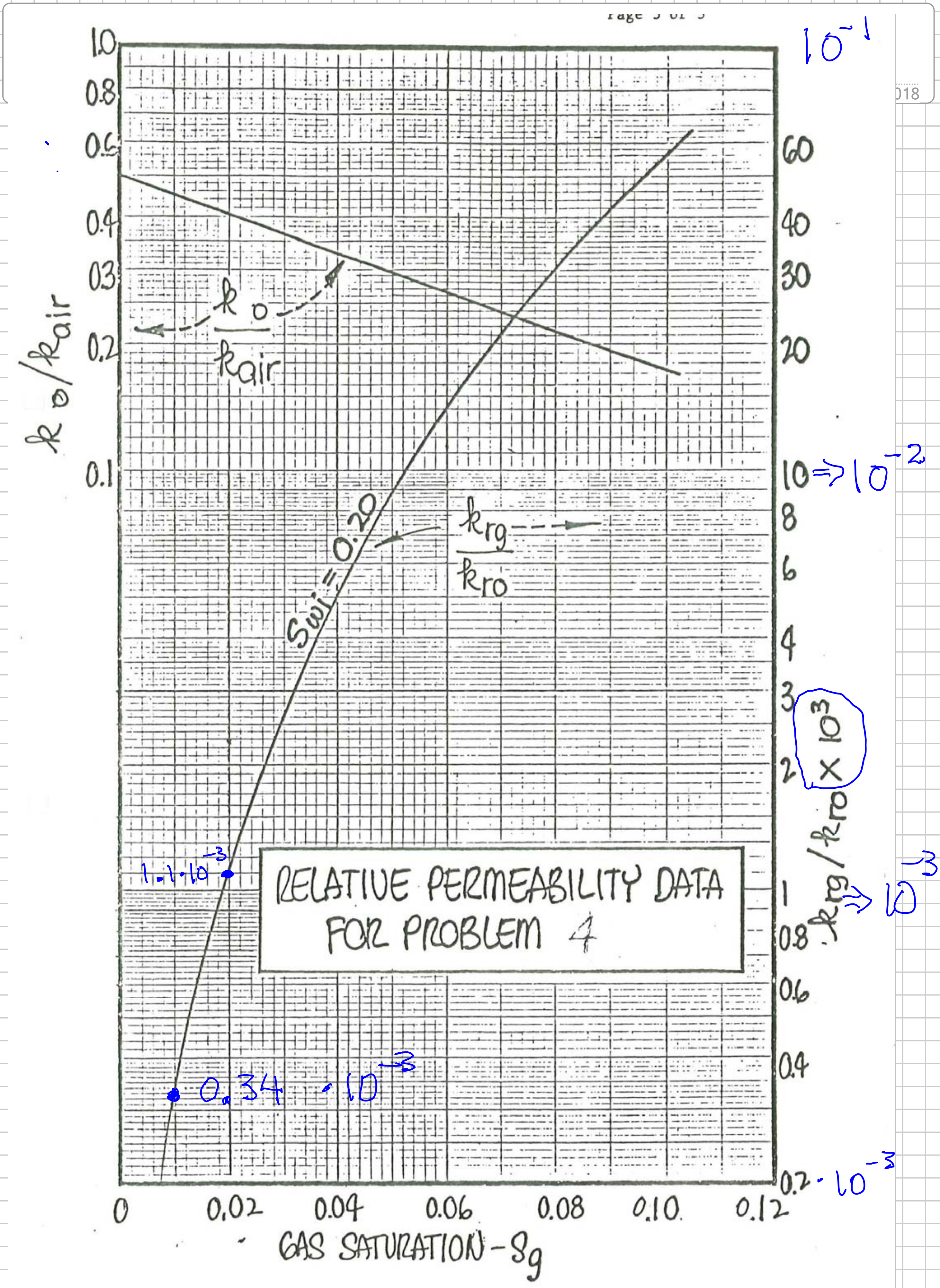
$$\boxed{k_{ro} \approx \overset{0.5}{k_{roi}} \cdot S_{on}^{\,n_o}}$$

k_{ro} @ S_{wi} @ $S_o = 1 - S_{wi}$

$$S_{on} \equiv \frac{S_o - S_{org}}{1 - S_{wi} - S_{org}}$$

Initially $S_o = 1 - S_{wi} \Rightarrow S_{on} = 1$

$S_o \to S_{org} \Rightarrow S_{on} = 0$


RELATIVE PERMEABILITY DATA
FOR PROBLEM 4
k_o/k_{air}
$\frac{k_o}{k_{air}}$
$\frac{k_{rg}}{k_{ro}}$
k_{rg}/k_{ro} × 10^3
Swi = 0.20
GAS SATURATION - S_g
1.0
0.8
0.6
0.4
0.3
0.2
0.1
60
40
30
20
10
8
6
4
3
2
1
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
0.08
0.10
0.12
10^{-1}
10 ⇒ 10^{-2}
⇒ 10^{-3}
0.2 · 10^{-3}
$1.1 \cdot 10^{-3}$
$0.34 \cdot 10^{-3}$

SGD MB : $p_R(Q_p)$: $\boxed{\text{Single RFU}}$

$$q_{RFU} = \frac{dQ_p}{dt} = \sum_{w=1}^{N_w} q_w \simeq \underbrace{N_w \bar{q}_w}$$

$\uparrow$ Single Well

$q_o = J(p_R^2 - p_{wf}^2)$ Fetkovich SGD

$$J_w = \frac{\bar{k}_{ro}(kh)\cancel{p_R}\cancel{\left[1-\left(\frac{p_{wf}}{p_R}\right)^2\right]}}{2(141.2)\mu_o B_o\left[\underbrace{\ln\frac{r_e}{r_w} - \frac{3}{4}}_{\sim 8} + s\right]}$$

All wells in a RFU ~ p_R same

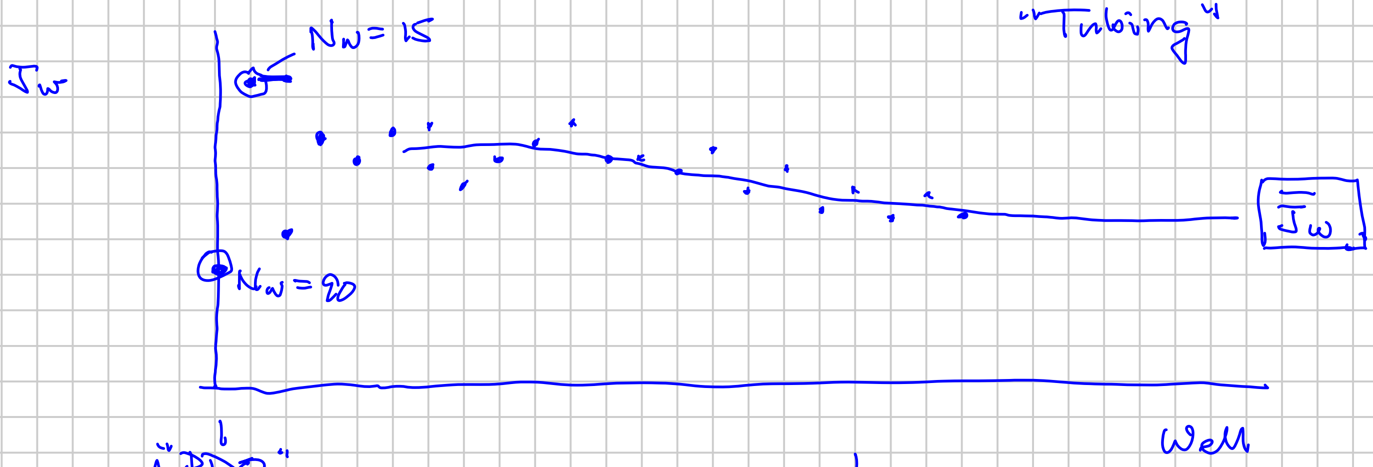
$\Rightarrow \simeq (\overline{k_{ro}/\mu_o B_o}), p_R$

Varies for each well in RFW ?

- $(kh)_w$
- s_w
- (p_{wf}) ~ similar

Artificial Lift

Production Pipe "Tubing"



"PDO"

$\Uparrow$

PUD : Plan for Utvikling og Drift

Development & Operation

(Production)

Rate-Time Forecasting $\quad q_F(t) \Rightarrow$ Revenue (t)

vs

Cost & Expenditures

Prof. Milan Stanko : Field Development Course

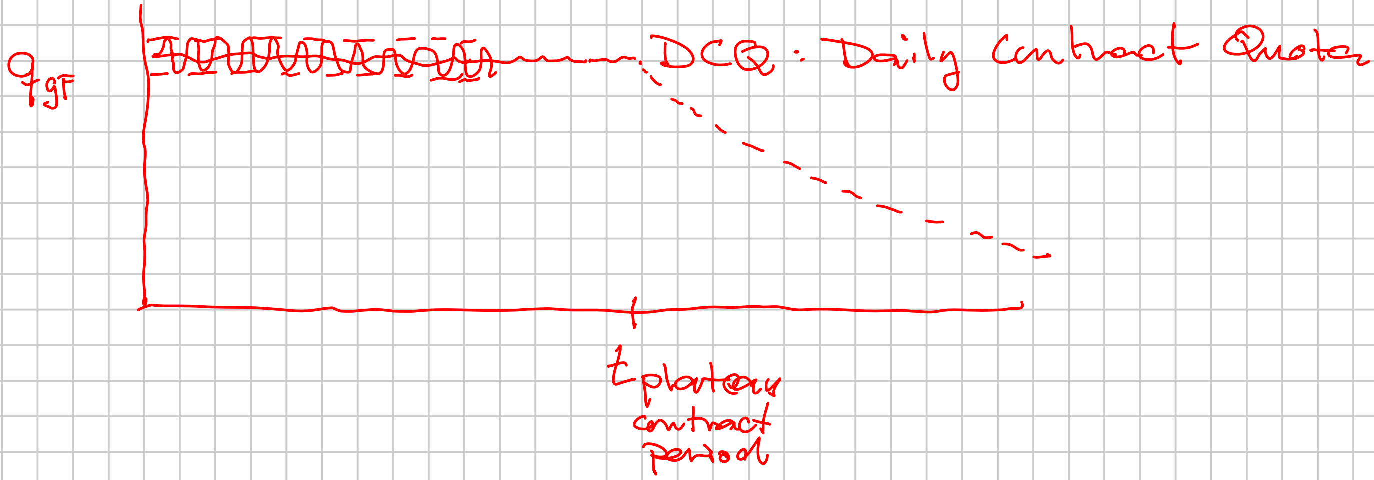
$$q_F(t) = \sum_{w=1}^{N_w} q_w\Big(\overset{\Delta p_R \ \text{"R"}}{\underset{\uparrow \ (kh)_w,\, S_w}{J_w}} \ ; \ \overbrace{\underset{\uparrow \ \text{Gas}}{d_t}, L_w, TVD, \ldots}^{\Delta p_T \ \text{"T"}} \ ; \ \underset{\substack{\uparrow \\ p_{sp} \\ p_{pipeline} \\ p_{atm}}}{p_{\substack{surface \\ constraint}}}\Big)$$

oil : Artificial Lift

M.B. $\begin{cases} p_R(t) \\ Q_p(t) \end{cases} \rightarrow q_F$

Frigg:	ΔP_R	ΔP_t
	<5%	>95%

* Gas Field Development : Offshore (Large Onshore)



Oil Field Development :

* (a) - Huge (Giant) Fields - $q_F \sim$ const $\quad t_p$

(b) - Other : Produce what you can $\quad p_{wf,min}$

$q_F(t)$: Given

$(MB + IPR)$?

$$\text{Define}\left\{\begin{array}{l}\underline{p_{wf,\min}}\\ \underline{\bar{J}_w}\end{array}\right\} \quad \text{at any time } \bar{p}_R \text{ (M.B.)}$$

$$q_{w,\underline{\max}}\,(\bar{p}_R)$$

$$\underline{\min} \quad \underbrace{N_w(t)}_{\text{First Order Cost}} = \frac{q_F\ (=DCQ)}{q_{w,\max}(\underset{\overset{\uparrow}{t}}{p_R})}$$