TPG4145 Fluid Flow & PVT

Note Title 2014-09-03

CURTIS HAYS WHITSON

Ideal Gas Law:

$$pV = nRT$$

Videos – Youtube : Khan Academy

① Conversion from mass (moles) to Volume

$$\left(\frac{V_{\bar{g}}}{n}\right) = \left(\frac{\overset{\checkmark}{R}\ \overset{\text{abs. temp.}}{T_{sc}}}{p_{sc}}\right)$$

= constant ANY gas

$\bar{g}$: gas at STC

STC @ T_{sc} = 60°F (15.56°C)

p_{sc} = 1 atm
(1.01325 bara)
(14.696 psia)

Sellable gas quantities

App. A :	R = 8314.3	0.083143
Units :	p [Pa]	[bar]
	T [K]	[K]
	n [kg-mole]	[kg-mole]
	V [m^3]	[m^3]

10^5 Pa / bar

$$= \frac{0.083143(\overset{K}{15.56+273.15})}{1.0135} \qquad \bar{g}$$

$$\left(\frac{V_{\bar{g}}}{n_g}\right) = 23.68 \ \text{Sm}^3/\text{kg-mole}$$

$$= 379.48 \ \text{scf}/\text{lb-mole}$$

Cheat-Sheet Numbers for Conversion

P $\quad \underbrace{14.5}0377 \quad \frac{psi}{bar}$ ✓

T $\quad 1.8 \quad 32 \qquad T_F = T_c \cdot 1.8 + 32$

$459.67 \quad (460) \qquad T_R = T_F + 460$

$$T_c = (\underbrace{312}°F - 32)/1.8 = 150\ °c$$

V $\quad 35.31\ \frac{ft^3}{m^3} \quad 5.6146\ \frac{ft^3}{bbl} \quad 6.28\ \frac{bbl}{m^3} = 35.31/5.615$

42 gal/bbl

m (n) $\quad 2.204\ \frac{lb}{kg}$

R $\quad$ App. A $\quad$: 10.7315 $\qquad$ "8314" $\cdot\ 10^{\overset{\swarrow}{x}}$

L $\quad$ 2.54 cm/in $\qquad$ 12 in/ft

A $\quad$ 43560 ft^2/acre

$\rho \quad 62.428\ (lb/ft^3)/(g/cm^3)$

$\quad 0.06248\ (lb/ft^3)/(kg/m^3)$

"G" $\quad \frac{dp}{dh}$ = constant $= \rho g \qquad$ psi/ft

$\nabla P \qquad\qquad$ bar/m

$$\rho\,[lb_m/ft^3] \Rightarrow \nabla P = \frac{dp}{dh} = \frac{\rho_m\,[lb/ft^3]}{144\,[in^2/ft^2]} = \left[\begin{array}{c}\left[\frac{lb_f/in^2}{ft}\right] \\ \left[psi/ft\right]\end{array}\right]$$

$$\mathrm{SI}: \quad \underbrace{\rho\,[\mathrm{kg/m^3}] \cdot 9.8\ \mathrm{m/s^2}}_{\mathrm{Pa/m}} \cdot \frac{\mathrm{bar}}{10^5\ \mathrm{Pa}} \qquad \frac{\mathrm{bar}}{\mathrm{m}}$$

REAL GAS LAW & GAS PVT PROPERTIES

Real Gas Law : $pV = nRT \cdot Z$ $\boxed{Z_g}$

Z-factor

Deviation Factor

$Z \equiv$

Actual Data : p, V, n, T

Ideal Gas Law Applies

Test	✓ p	✓ T	✓ n	V	$\left(\frac{pV}{nTR}\right)$
1					1
2					1
3					[0.5 2] max
4					[0.95 1.05
5					⋮
⋮					
100					

Estimate : $Z(p, T, \text{gas})$

van der Waals Corresponding States Theory

All gases behave similarly if correlated using "reduced" p & T

p_r T_r

✓ $p_r \equiv \frac{p}{p_c}$

✓ $T_r = \frac{T}{T_c}$

gas

$\boxed{Z_g(p_r, T_r)}$

"Generalized Relationship"

any gas

Gas 1 : $p_{c_1} = 600$ psia Gas 2 : $p_{c_2} = 700$ psia

$T_{c_1} = 300\ ^\circ R$ $T_{c_2} = 250\ ^\circ R$

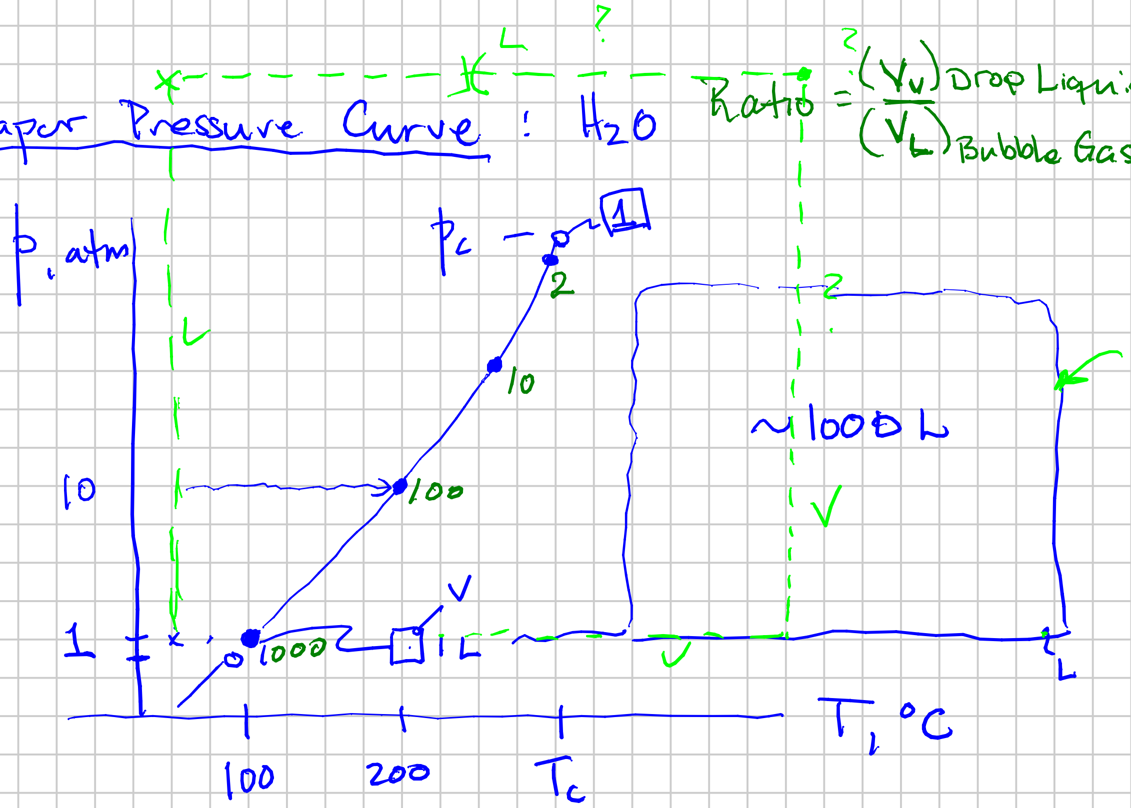
$$\frac{pV}{nRT} = Z_{g1} @ \begin{matrix} 6000 \text{ psia} \\ \& \\ 600\ ^\circ R \end{matrix} = Z_{g2} @ \begin{matrix} 7000 \text{ psia} \\ \\ 500\ ^\circ R \end{matrix}$$

$$p_{r1} = \frac{6000}{600} = 10 \qquad p_{r2} = \frac{7000}{700} = 10$$

$$T_{r1} = \frac{600}{300} = 2 \qquad T_{r2} = \frac{500}{250} = 2$$

Vapor Pressure Curve : H_2O

$$\text{Ratio} = \frac{(V_v)_{\text{Drop Liquid}}}{(V_L)_{\text{Bubble Gas}}} = \frac{\rho_L}{\rho_v}$$



Generalized Z-factor Chart $Z_g(T_r, p_r)$

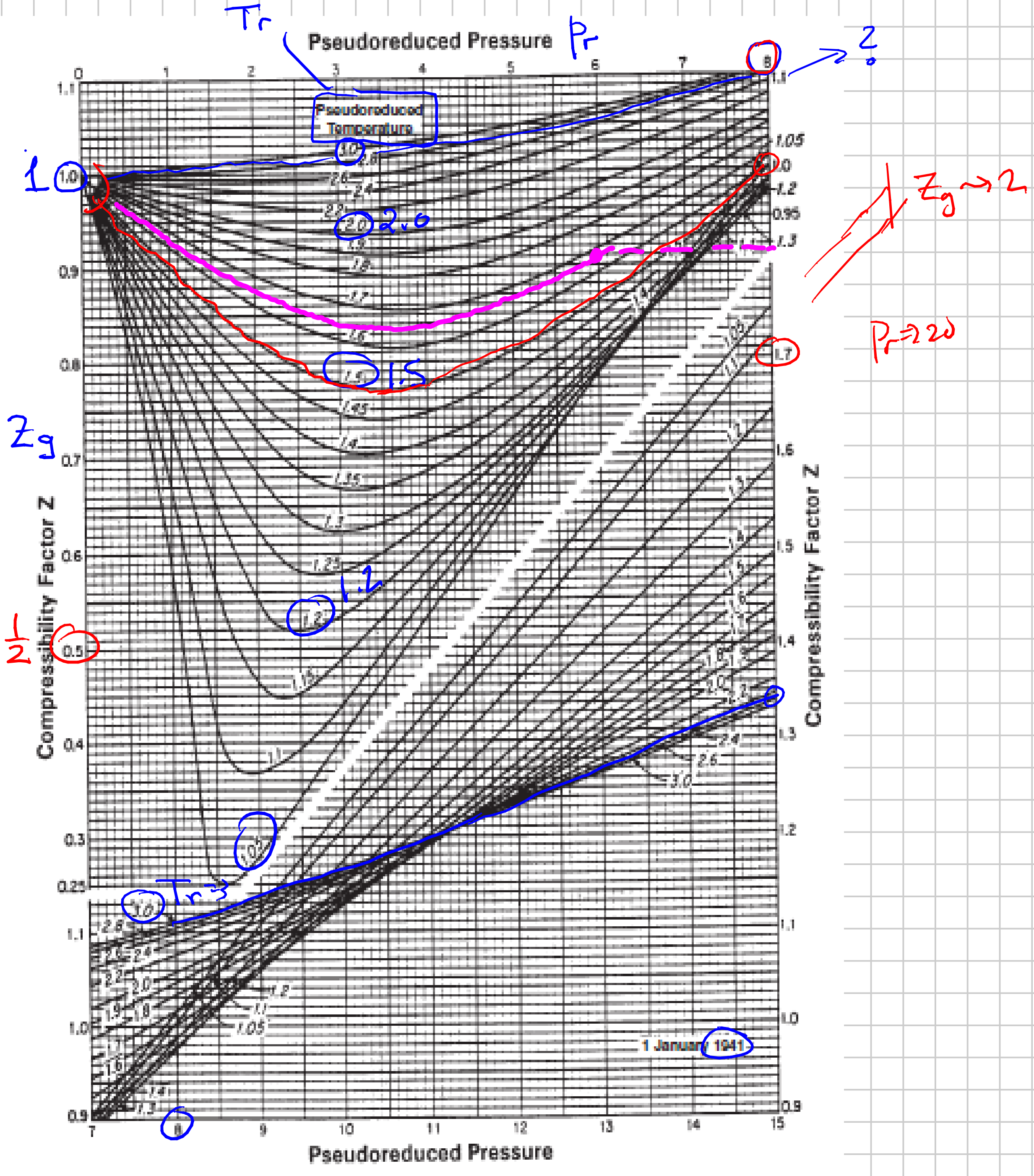


Fig. 3.6—Standing-Katz[4] *Z*-factor chart.

All Petroleum Reservoirs, at any (P,T, gas)

{ Marchall B. (Muz) Standing } { Donald Katz }

U. Michigan

Yarborough (Amoco) : Fit BWR EOS to the Standing-Katz chart

Using $Z_g(\underset{\uparrow}{T_r}, \underset{\uparrow}{p_r})$ Petroleum Gases:
App. A

"T_c"
"p_c" } for mixtures:

in Surface (Pipeline) Gases & Reservoir

N_2 CO_2 H_2S non-HCs

{ C_1 C_2 C_3 $i\text{-}C_4$ $n\text{-}C_4$ } "Gas" HCs

$i\text{-}C_5$ $n\text{-}C_5$ | C_6 | C_7 C_8 ...

in Reservoir

{ C_{10} ... C_{20} ... C_{30} ... C_{50+} }

"$\underline{\underline{C_{7+}}}$" ⇒ Makes up most of Sales Oil

Mixtures $\bar{T}_r$ $\bar{p}_r$

$\underbrace{\text{gas mole fraction}}$ average
y_i

$$y_i \equiv \frac{(n_i)_{\text{in gas}}}{(n_{\text{total}})_{\text{in gas}}}$$

Known, use the Mixing Rules — exception: H_2S, CO_2

Ch. 3

Wichert & Aziz

$$\left.\begin{aligned} \boxed{T_{pc}} &= \bar{T}_c = \sum_{i=1}^{N} y_i \cdot T_{ci} \\ \boxed{p_{pc}} &= \bar{p}_c = \sum_{i=1}^{N} y_i\, p_{ci} \end{aligned}\right\} \text{Mixing Rules}$$

pseudo-critical "average"

C_{7+} $\underbrace{T_{c7+} \quad p_{c7+}}$?

Matthews: $T_{c7+}(M_{7+}, \gamma_{7+})$ Liquid Specific Gravity

$p_{c7+}(\underset{\uparrow}{M_{7+}}, \underset{\uparrow}{\gamma_{7+}})$

Measured w/ $\textcircled{y_i}$

Ch. 3

$$T_{pr} = \frac{T}{T_{pc}}$$

$$p_{pr} = \frac{p}{p_{pc}}$$

$$\boxed{Z_g(T_{pr}, p_{pr})}$$

SK Chart
Petroleum Mixtures

$$T_{pc} = \sum_{i=1}^{N} y_i T_{ci}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.50b)$$

$$\text{and } p_{pc} = \sum_{i=1}^{N} y_i p_{ci}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.50c)$$

where the pseudocritical properties of the C_{7+} fraction can be estimated from the Matthews *et al.*[32] correlations (**Fig. 3.8**),[3]

$$T_{cC_{7+}} = 608 + 364 \log\left(M_{C_{7+}} - 71.2\right)$$

$$+ \left(2{,}450 \log M_{C_{7+}} - 3{,}800\right) \log \gamma_{C_{7+}} \quad \ldots\ldots \quad (3.51a)$$

$$\text{and } p_{cC_{7+}} = 1{,}188 - 431 \log\left(M_{C_{7+}} - 61.1\right)$$

$$+ \left[2{,}319 - 852 \log\left(M_{C_{7+}} - 53.7\right)\right]\left(\gamma_{C_{7+}} - 0.8\right).$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.51b)$$

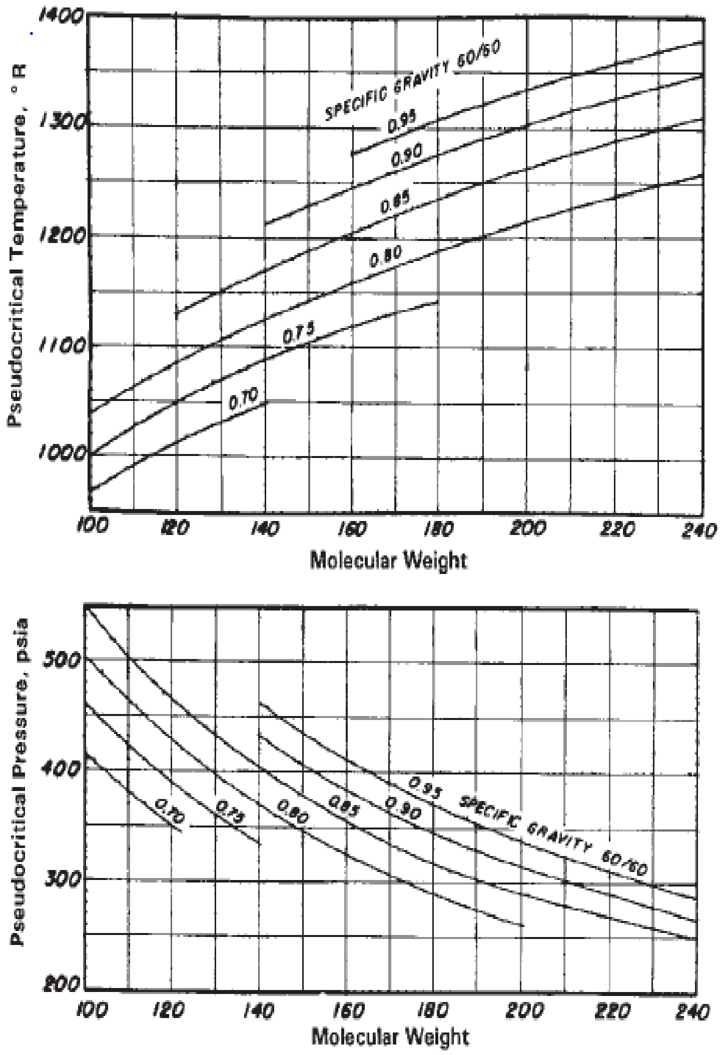


Fig. 3.8—Heptanes-plus (pseudo)critical properties recommended for reservoir gases (from Standing,[33] after Matthews *et al.*[32]).

If y_i is not known, estimating T_{pc} & p_{pc}

Measure $\bar{M}_g$

Express $\gamma_g \equiv \left(\frac{\rho_g}{\rho_{air}}\right)$ at STC (1 atm, 60°F) $\boxed{z \cong 1}$

Ideal Gas Law

$$\frac{n_g}{V_g} = \frac{p}{RT}$$

$$\rho_g = \frac{m_g}{V_g} = \frac{n_g M_g}{V_g} = \frac{n_g}{V_g} M$$

$$\frac{\boxed{\rho_g = \frac{p_{sc} M_g}{R T_{sc}}}}{\boxed{\rho_{air} = \frac{p_{sc} M_{air}}{R T_{sc}}}} \Rightarrow \boxed{\gamma_g = \frac{M_g}{M_{air}}}$$

Mixture y_i

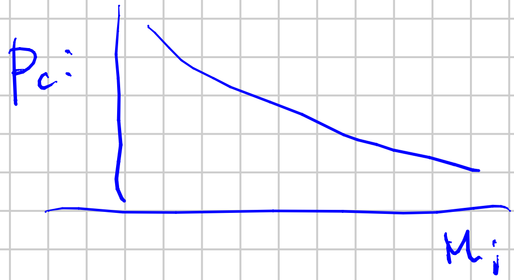
$$\bar{M}_g = \frac{(\sum y_i M_i)}{\sum y_i} \qquad \frac{\text{Total Mass}}{\text{Total Moles}} \qquad y_i \propto n_i$$

$$\sum y_i = 1$$

✓ $\bar{M}_g = \sum y_i M_i$

$T_{pc} = \sum y_i T_{ci}$

$p_{pc} = \sum y_i p_{ci}$



Correlations Developed

$T_{pc}(M_g)$ $T_{pc}(\gamma_g)$

$p_{pc}(M_g)$ $p_{pc}(\gamma_g)$

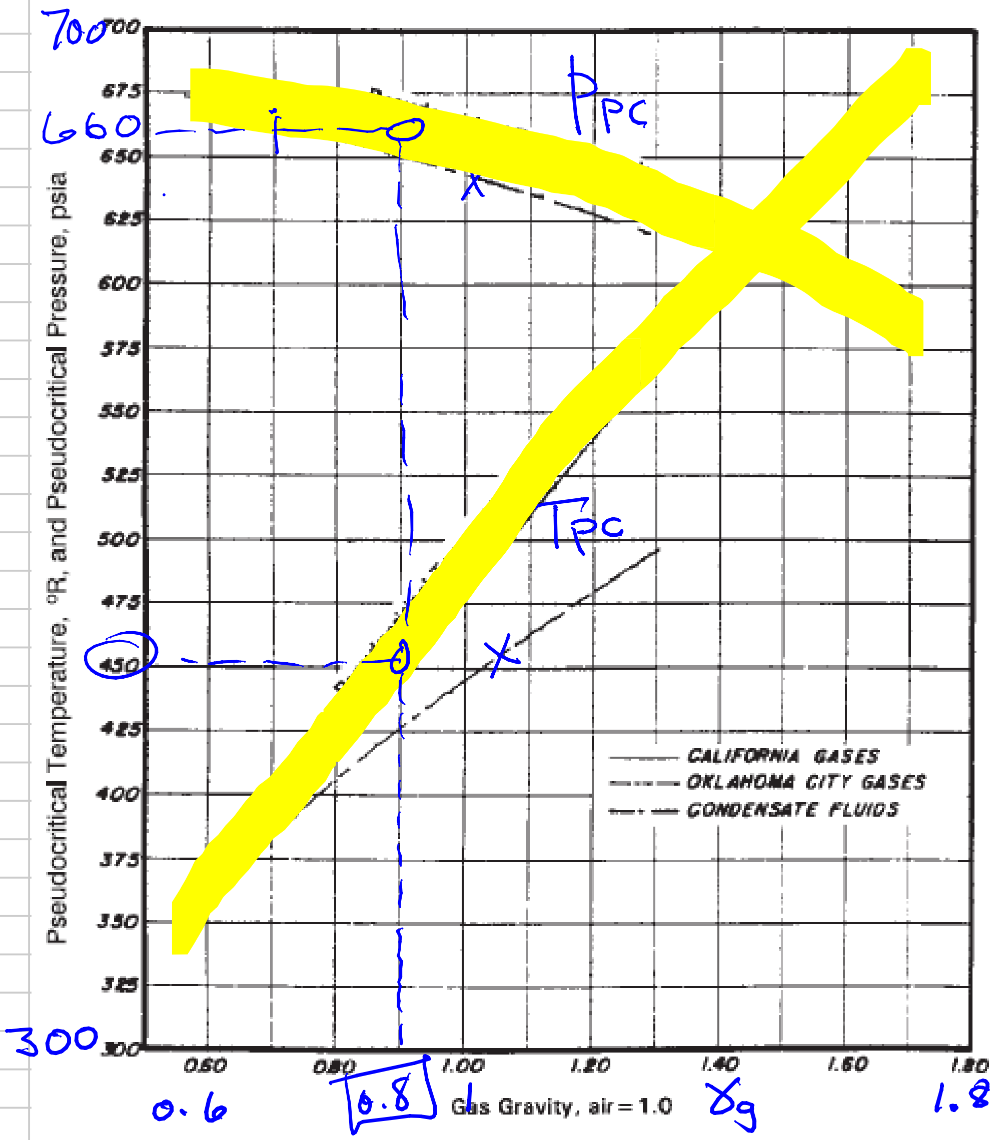


Fig. 3.7—Gas pseudocritical properties as functions of specific gravity.

Sutton Eqs.

Aksel
Lydersen

U. Wisconsin, Madison

Group Contribution Theory

$Z(p, T, \overset{\overset{y_i}{\downarrow}}{\gamma_g})$ App. B.

Frigg ~7 Tcf T: 10^{12}

cf scf

$7 \cdot 10^{12}$ scf

$T_R = 180°F$ $p_R = 4000$ psia $\gamma_g = 0.7$ (air = 1)

Z_{Ri} ?

$T_{pc} = 390\ °R$

$p_{pc} = 670$ psia

$$T_{pr} = \frac{\overset{°R}{(180°F + 460)}}{390} = 1.64$$

$$p_{pr} = \frac{4000}{670} = 5.0$$

$$\boxed{Z_g \simeq 0.91}$$

Problem 1 – Units Conversion Example in Excel with Gas PVT Properties

- Take existing Excel File → MODIFY
- (Any Excel) Modification Process :

⇒ (*) ALWAYS – Get familiar w/ File (What's Input / Calc'd)

(1) What to Modify

(2) How to Modify

(3) How to QC Modifications

e-notes : Get going !

(1) Download (2013)

(2) Create appropriate Directory

TPG4145 / e-notes

(might try Total Commander)

(3) Unzip all

(4) Gas-PVT.ppt

- Study
- Use
- Identify (IT) problems

Unit Conversion Constants

p	bara ⇔ psia	14.50377 psi/bar
T	°C ↔ °F	32 1.8
	K ⇔ °R	
ρ	g/cc ⇔ lb/ft³	62.4... (lb/ft³)/(g/cc)
μ	mPa·s ⇔ cp	1 mPa·s ≡ 1 cp

FLUID PHASE BEHAVIOR – "PVT"

FLUIDS: Hydrocarbon Mixtures (& Water)

PHASES: Gas (Vapor) Oil $\left\{\begin{array}{l}\text{(Aqueous)}\\ \text{(Solids) Wax}\\ \quad\quad\quad\ \text{Asphaltenes}\\ \quad\quad\quad\ \vdots\end{array}\right.$

BEHAVIOR: VOLUMETRIC:

Gases: $pV = nRT\,Z_{(p,T,gas)}$

$\underline{|\text{EQUILIBRIUM}|}$:

$\left.\begin{array}{l}\to \text{1-phase}\\ \to \text{2(more)-phases}\end{array}\right\}$ Map out $f(p,T,z_i)$ $\uparrow$

Component (i) "Partitioning"! (betweening phases) $\Leftarrow$

$z_i \equiv \left(\frac{n_i}{n}\right)$ overall molar Composition

OTHER: Viscosity (μ)

$\nu = \mu/\rho$

μ: $0.01 \overset{\text{mPa.s}}{\text{cp}} \longrightarrow 10 \rightsquigarrow \underline{10{,}000}$

Gas NCS

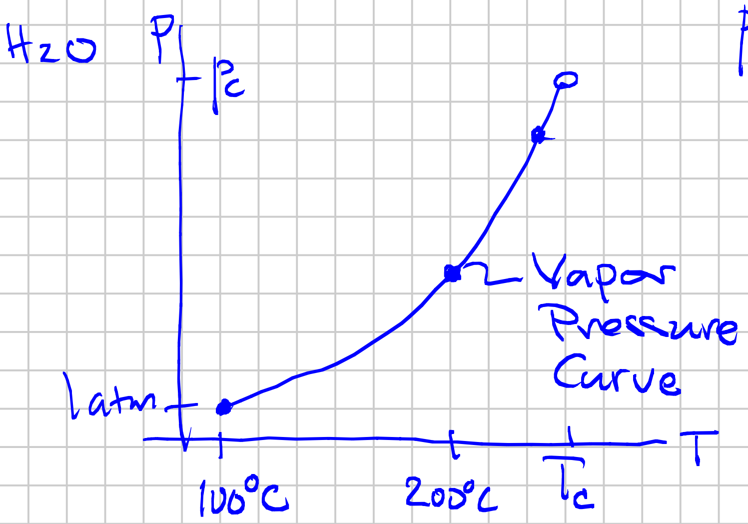
SURFACE (INTERFACIAL) TENSION (σ)

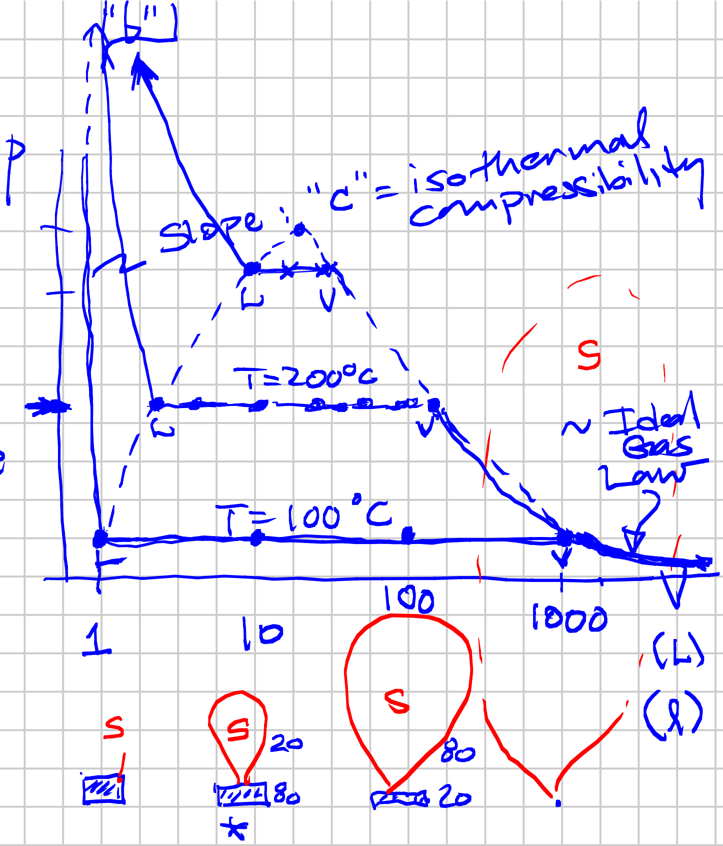
$\Rightarrow$ Gas-Oil, Gas-Water, Oil-Water

(G,O,W)– Rock

DIFFUSION COEFFICIENTS (D_i)

Single Component:

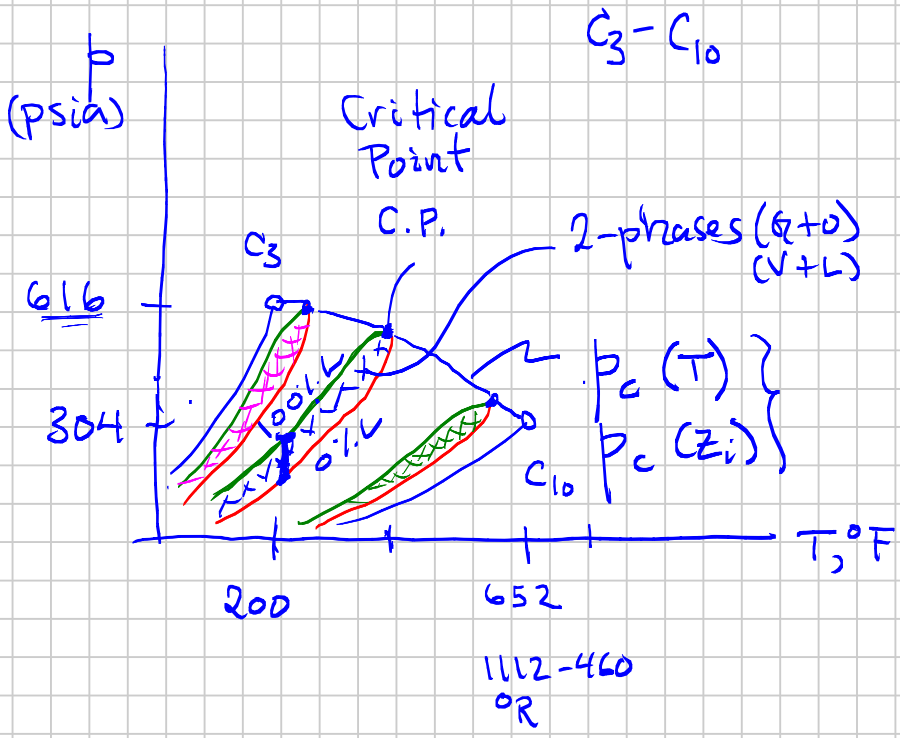


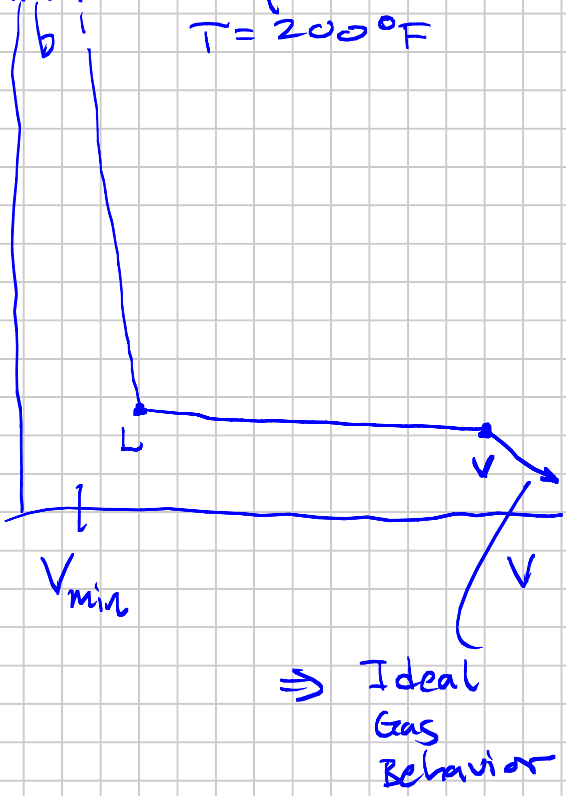


$$c \equiv -\frac{1}{V}\underbrace{\left(\frac{dV}{dp}\right)}_{\text{small for } L}$$

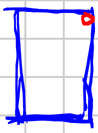
* 2-Component (Binary) Systems

P-T Phase Diagram : Mapping out 1-phase vs 2-phase



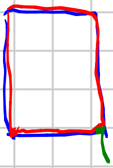


$p_b(T, z_i)$ $p_d(T, z_i)$



$\left\{ \begin{matrix} 0.5 \text{ kg } C_3 \\ 0.5 \text{ kg } C_{10} \end{matrix} \right\}$ 0.9 kg C_3 / 0.1 kg C_{10} 0.1 kg C_3 / 0.9 kg C_{10}

$p_b(T)$



"Dew"

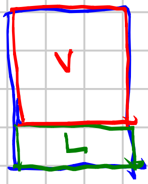
$p_d(T)$

Two Phases (Binary) Mass (Mole) Conservation

"f_v" $= n_v/(n_v+n_L)$

n = total moles of mixture z_i

$\left\{ \begin{matrix} n_v \\ n_L \end{matrix} \right\}$



y_i

x_i

n_v = moles of Vapor phase

n_L = — " — Liquid — " —

(p, T, z_i)

$*\quad n = n_v + n_L$

$\left\{ \$ \propto \frac{1}{\Delta p} \right\}$

Engineering:

n_i = total moles of i in the mixture

$\left.\begin{matrix} \rho_v \\ \mu_v \end{matrix}\right\} = f(p, T, \underline{\underline{y_i}})$

n_{vi} = — " — in the Vapor phase

n_{Li} = — " — Liquid

$\left.\begin{matrix} \rho_L \\ \mu_L \end{matrix}\right\} = f(p, T, \underline{\underline{x_i}})$

$*\quad n_i = n_{vi} + n_{Li}$

✓ $\Delta p_G = f(\rho_v, \rho_L, f_v)$

$\underline{z_i} \equiv \frac{n_i}{n}$ total mole frac

✓ $\Delta p_\mu = f(\underset{\mu_v}{\rho_v}, \underset{\mu_L}{\rho_L}, f_v)$

$y_i \equiv \frac{n_{vi}}{n_v}$ vapor mole frac

$\underline{x_i} \equiv \frac{n_{Li}}{n}$ liquid mole frac

L

Value (Economics)

$\$\quad y_i(f_v) \times \underline{1}$

$\$\quad x_i(1-f_v) \times \underline{\underline{10}}$

$F_v \quad f_v \equiv \frac{n_v}{n}$

$$\boxed{z_i = f_v \cdot y_i + (1-f_v)\, x_i}$$

$$n_i = n_{vi} + n_{Li}$$

Bubblepoint : $f_v = \epsilon$

$$\Rightarrow z_i = \epsilon\, y_i + (1-\epsilon)\, x_i = x_i$$

$$\boxed{z_i = x_i}_{BP}$$

Dewpoint : $f_L = 1 - f_v = \epsilon$

$$\Rightarrow \boxed{z_i = y_i}_{DP}$$

Partioning Ratio

$$K_i \equiv \frac{y_i}{x_i}$$

Petroleum Reservoirs
@ P_R T_R

$\underline{\underline{y_{C_1}}} = 0.95 \rightarrow 0.6$ (0.7)

$\underline{\underline{x_{C_1}}} = 0.05 \rightarrow 0.6$ (0.5)

"Equilibrium Ratio"

"K-value"

$K_{C_1} = 1.x \rightarrow 3\,(10)$

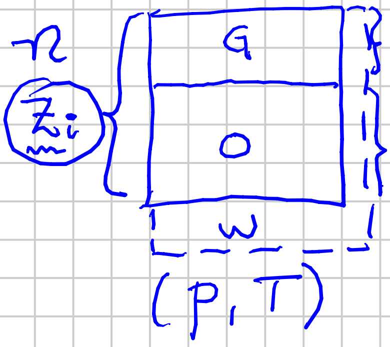
$$\boxed{K_i\,(p, T, z_i)}$$

Key to understanding thermodynamics

PHASE EQUILIBRIUM (K-values) K_i Equilibrium Ratios

Note Title 2013-09-06

GAS-OIL



Molar Compositions

n_g $y_i = \dfrac{n_{ig}}{n_g}$

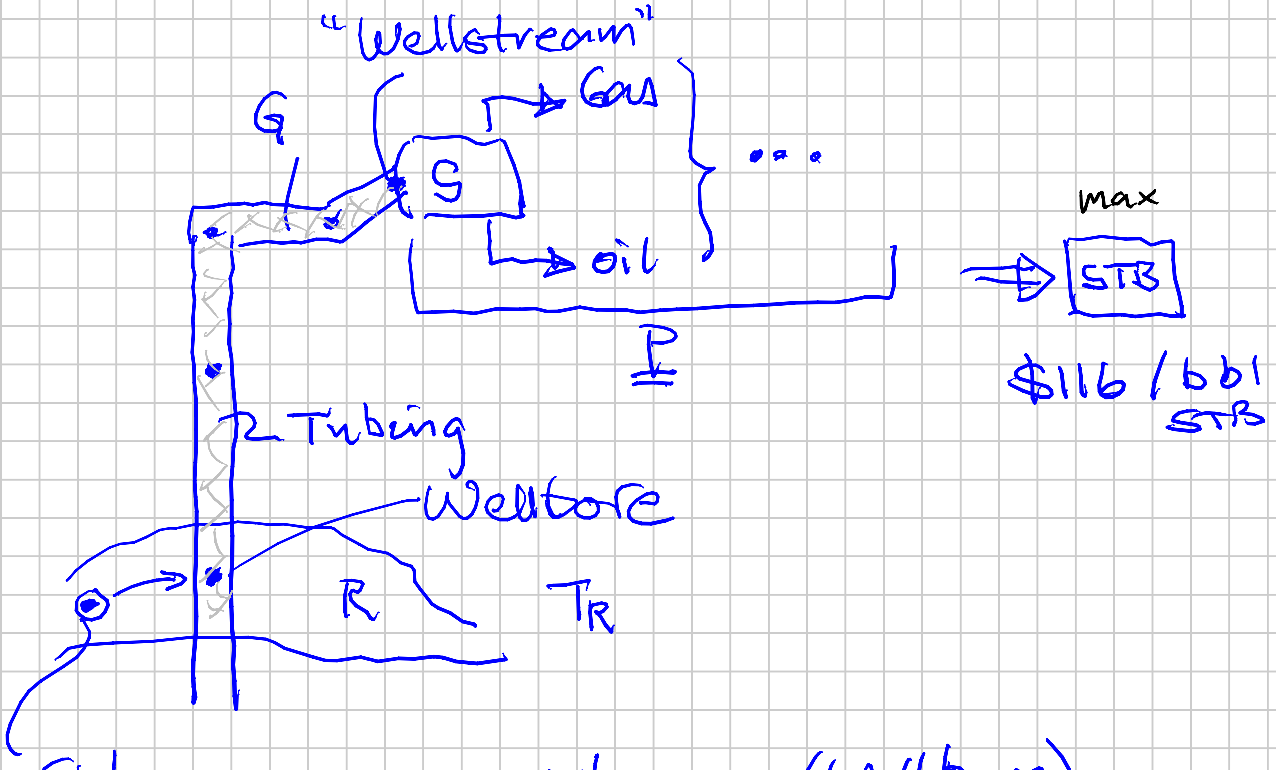
n_o $x_i = \dfrac{n_{io}}{n_o}$

$$K_i \equiv \frac{y_i}{x_i}$$

$$\uparrow$$

$$\boxed{K_i(p, T, \underline{z})}$$

Know @ Reservoir, Production Pipe, Surface Gathering Lines, Separator Unit



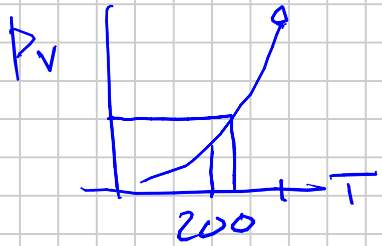
In-Situ Reservoir $\substack{= \\ \neq}$ Wellstream (Wellbore)

Behavior of K_i

K_i represents (in lay terms) the relative preference of component i to "be" in the $\underbrace{\text{gas phase}}_{K_i > 1}$ or $\underbrace{\text{oil phase}}_{K_i < 1}$:

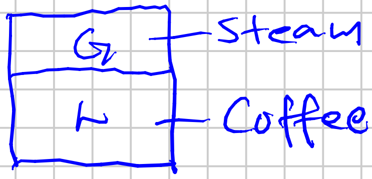
We can make more money by selling component i as part of the liquid phase (ultimate processed surface)

5-10 times the value



@$p_v(T)$

H_2O



$y_{H_2O} = 1$

$x_{H_2O} = 1$

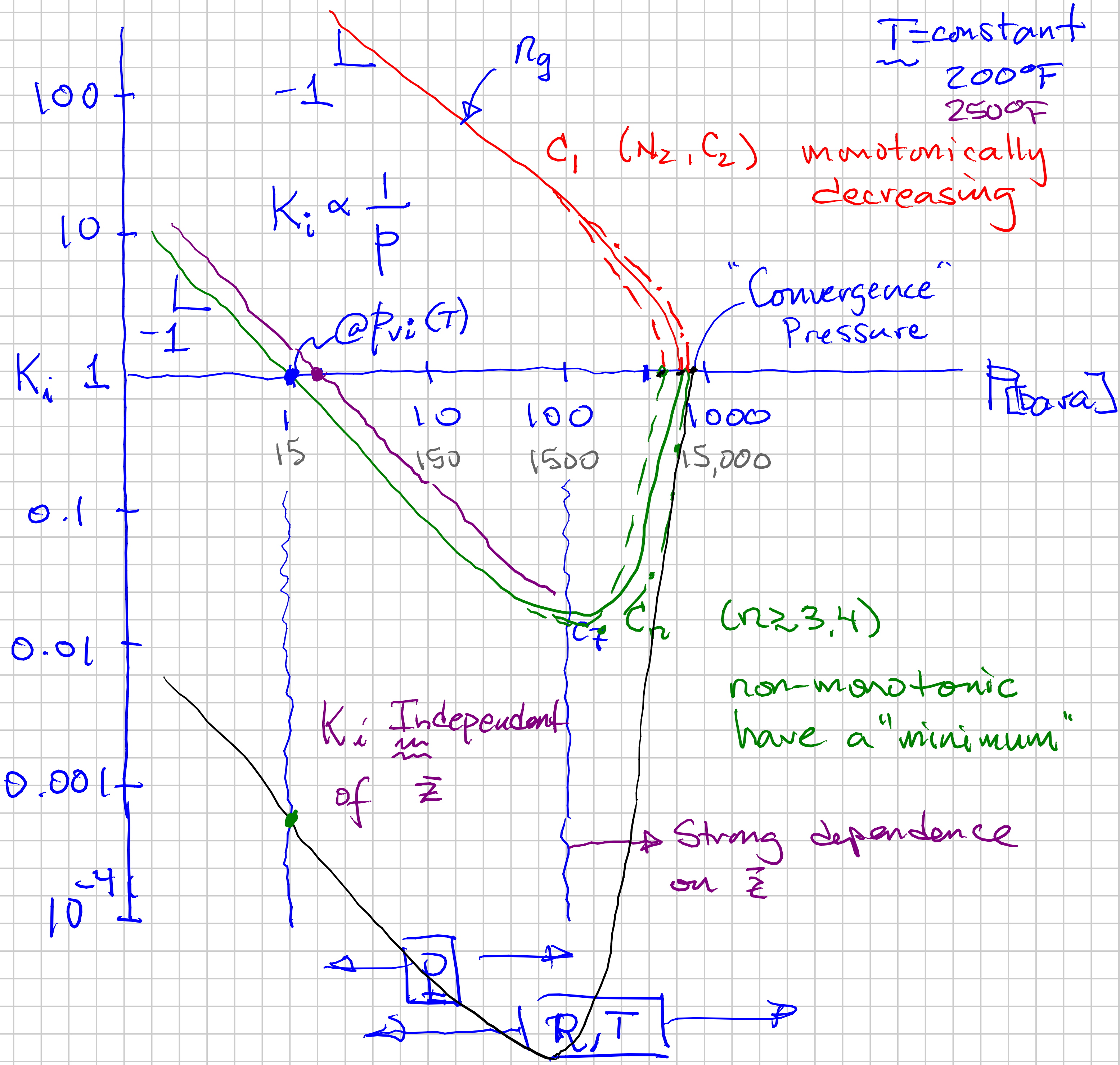
$K_{H_2O} = \frac{1}{1} = 1$

100°C

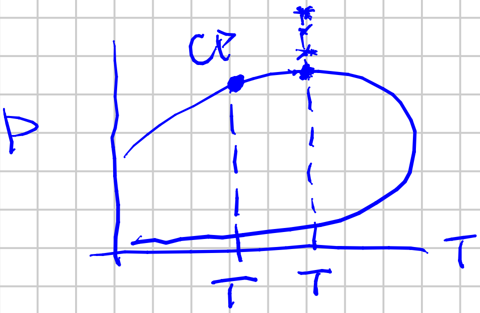
1 atm

$p_{vi}(T) \Rightarrow K_i(p \leq 100 \text{ bara}, T)$

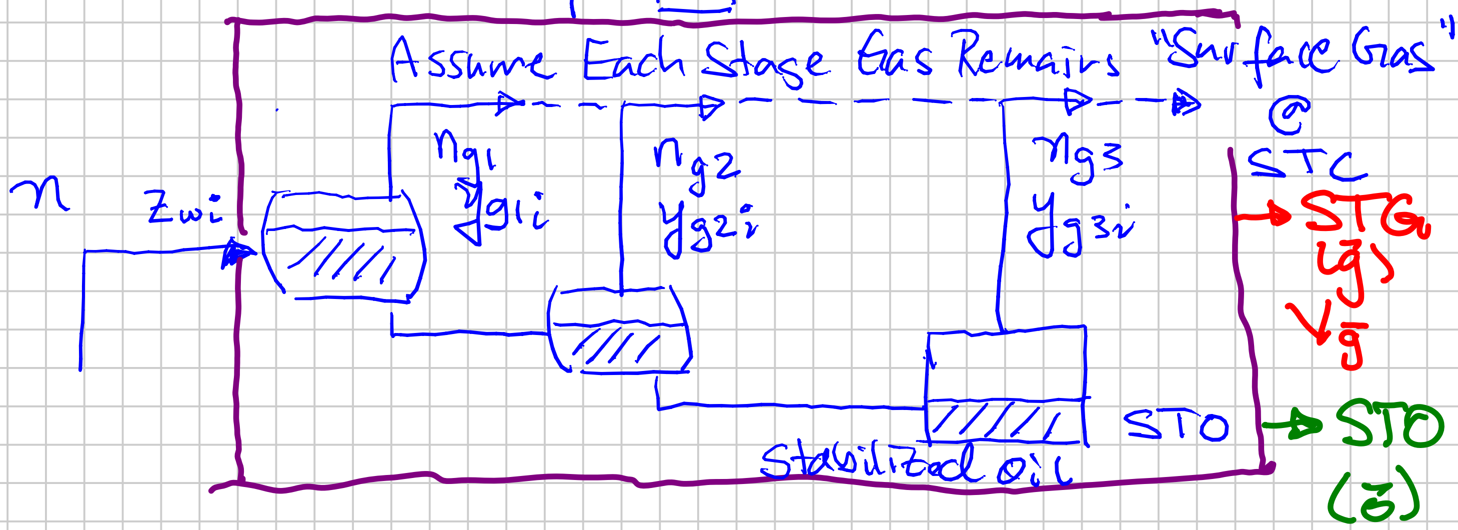
$$K_i = \frac{p_{vi}(T)}{p}$$



$\underset{\sim}{K_{i\,min}}$ @ ~ $\underline{50\text{-}120 \text{ bara}}$



SURFACE PROCESSING "$\boxed{P}$"



Stage 1 $\begin{Bmatrix} P_{sp1} \\ T_{sp1} \end{Bmatrix}$ Stage 2 $\begin{Bmatrix} P_{sp2} \\ T_{sp2} \end{Bmatrix}$ Stage N $\begin{Bmatrix} P_{sp3} \\ T_{sp3} \end{Bmatrix}$

$V_{\bar{o}}$ max

$n_{\bar{o}}$

$K_{1i}(p,T)$ $K_{2i}(p,T)$ $K_{3i}(p,T)$

Controls the ultimate MOLES of i => STO

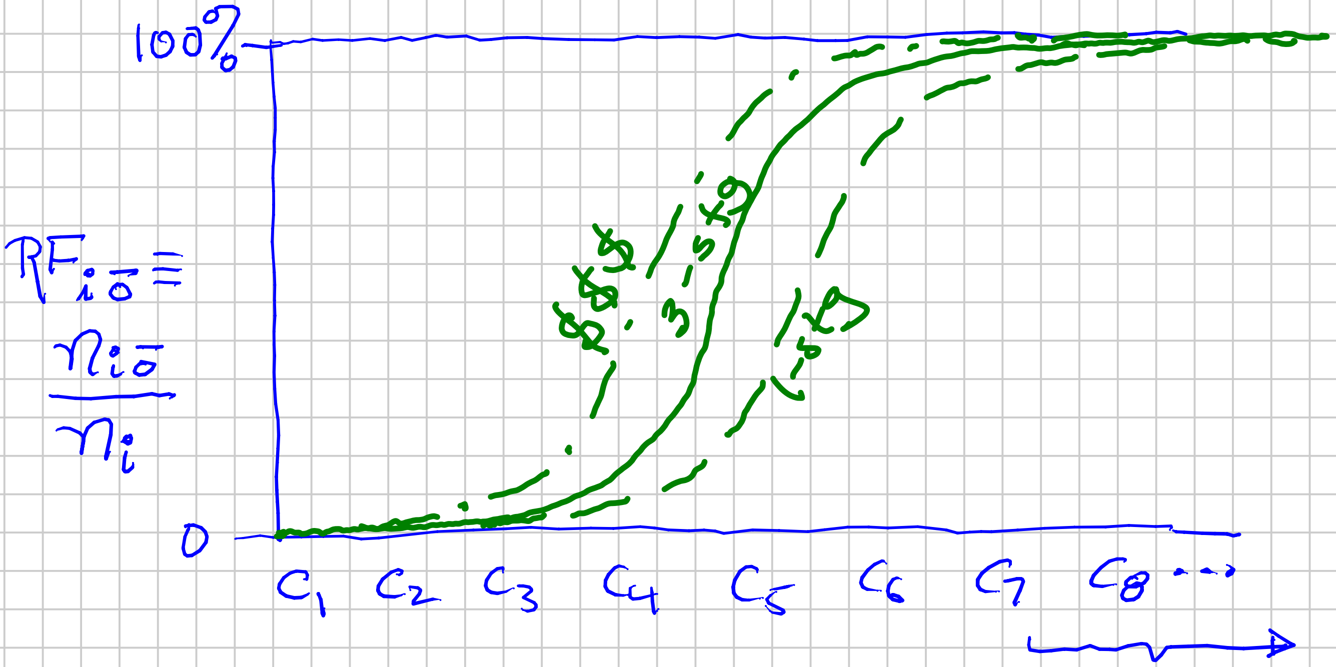
$$\begin{tikzcd} K_i \arrow[d, "\bar{K}_{all}"'] \arrow[dr, bend left, "(K_i)"] & \\ (n_g) & y_i \end{tikzcd}$$

$$n_{ig} = \underset{\uparrow\ \text{max}}{\underline{(n_g)}} \cdot \underset{\uparrow\ \text{max}\ K_i}{\underline{y_i}}$$

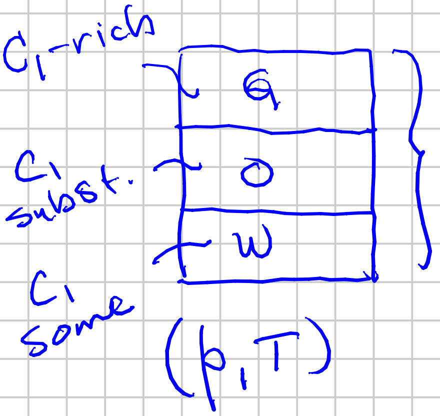
$\underline{1949}$

1-stg

$$V_{\bar{o}} \propto \left(1 - \sum_{k=1}^{3} n_{igk}\right)$$



Water – Gas-Oil Phase Equilibria



N_2
CO_2
C_1
C_2
C_3
⋮
C_7
⋮
C_{20}
⋮
C_{36+}
H_2O

- Pore In-Situ
- Production Pipes
- Separator
- Ocean (Leakage Blowout)

In general

Rigorous

Gas-Oil $K_i(p, T, \vec{z}) \simeq K_i(p, T, \vec{z}^*)$

No H_2O — H_2O Included

Engineering Guideline

⇒ We can ignore H_2O component and aqueous phase when doing gas-oil phase equilibria calculations.

$$K_{wgi} \equiv \frac{y_i}{x_{wi}} \; \underbrace{\gg}_{} 1$$

$$K_{woi} \equiv \frac{x_i}{x_{wi}} \; \underbrace{\gg}_{} 1$$

$\underbrace{\text{all } i \text{ except } H_2O}_{\text{Limited Solubility in the Aqueos Phase}}$

$\underbrace{\ll}_{} 1$ for H_2O ⇒

CO_2

Methane

⋮

HCs

$\Big\downarrow$ Decreasing Solubility

$$K_{wgC_1} < K_{wgC_2}$$

$H_2O - G - O$

When is solubility important?

① Gas production ⇒ water production

0.1 – 5 mol-% wellstream H_2O

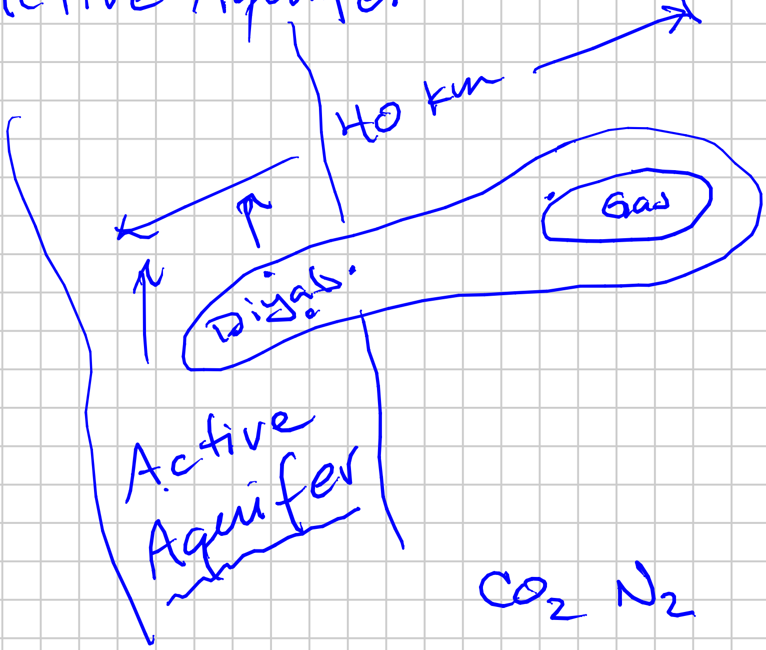
→

- $T_R > 300°F$
- $P_{wf} < 500$ psia

② When oil & gas "sees" (mixes) with larger amounts of water that has no yet equilibrated ("seen") oil & gas yet.

- Injecting water (water flood)
- Offshore blowout situation

- Active Aquifer



Dakhan

CO_2 N_2

Gaseous Components (C_1 C_2 C_3 ; Aromatics)

PHASE EQULIBRIUM CALCULATIONS (& APPLICATIONS)

Note Title 2013-09-12

① Select Student Course Evaluation Group
'Reference' Groups

Lisbeth Hultmann

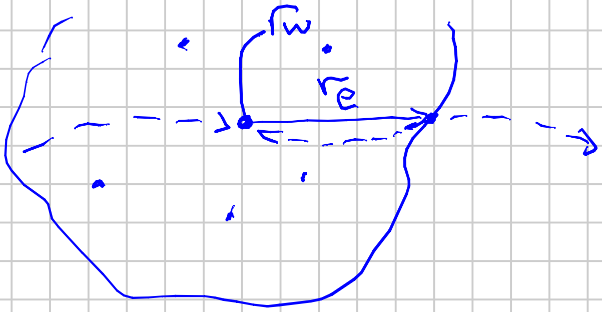
3 students:

1 - 5-yr Norsk : Carl Ivar Klovning
1 - 2-yr MS Norsk : Vinh Vuong Tran
1 - 2-yr MS International : Allan Katende

Darcy's Law:

$$v = \underbrace{\frac{k}{\mu}}_{\uparrow} \cdot \underbrace{\frac{\Delta p}{\ln(r_e/r_w)}}$$

"Well Spacing"



Higher v : fewer wells

	Quantity		Magnitude	# orders of Magnitude
God-Given	k	[md]	(10^{-4}) $(0.1-1)$ — 10,000 shale Low	[5]
	μ	[cp]	0.01 – 0.1 – 100 Gas } Oil	[5]
	Δp	[bar]	10 — 1000	[2-3]
	$\ln\frac{r_e}{r_w}$		5 – 10	
	$\frac{k}{\mu}$	"Mobility"		[→10]

The well spacing is (in reality) most dependent – for a given well type – on (k/μ)

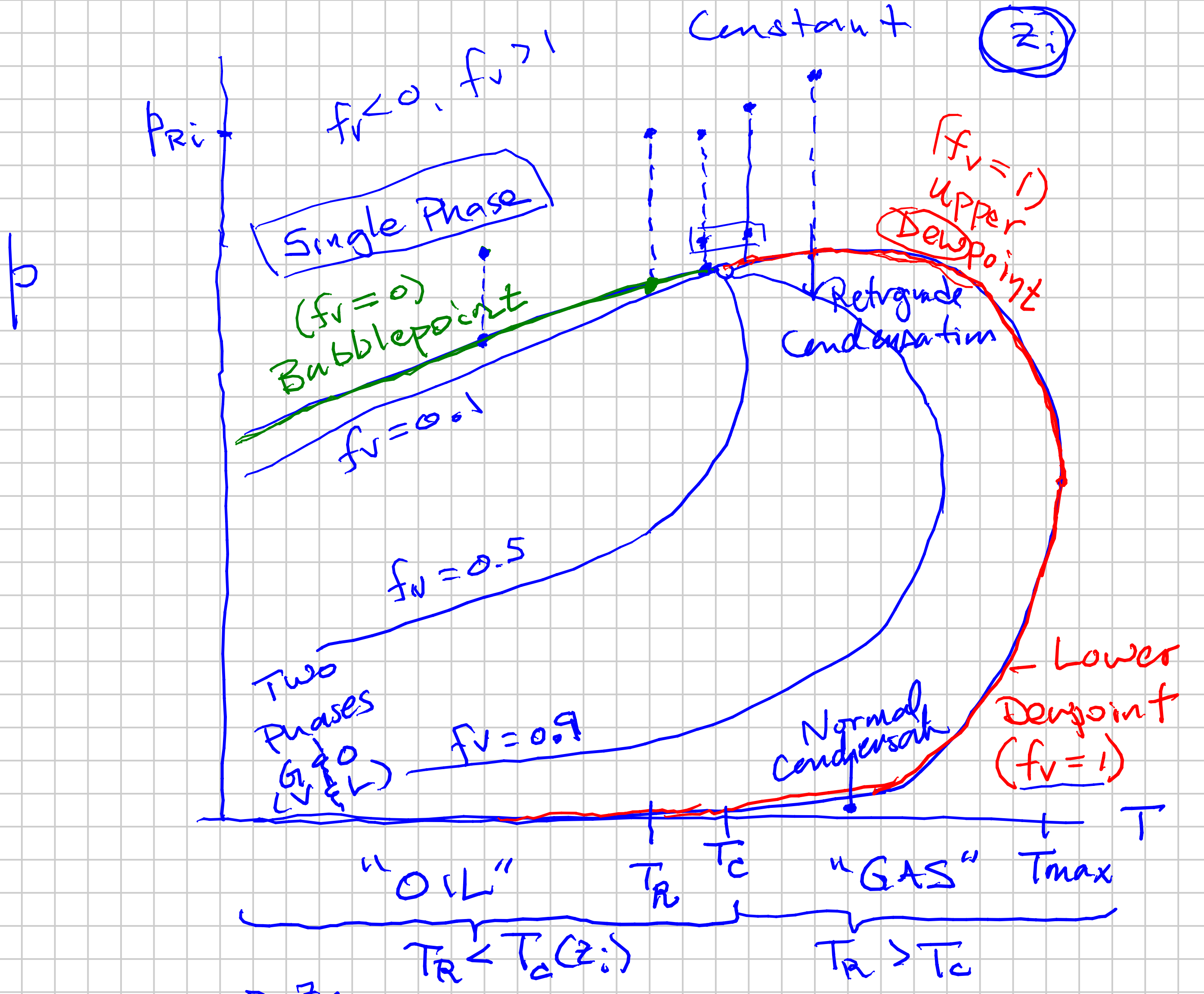
High Lower Spacing (fewer wells)

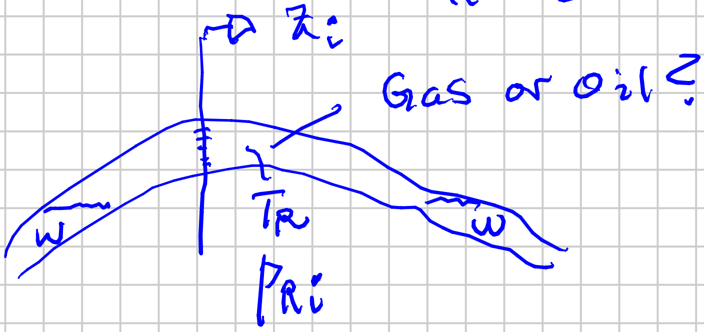
Low Higher Spacing (more wells)
(More Dense)

i.e. How many wells (per area) are needed to "drain" within a "reasonable" period of time (20-30 yr)

Formal / Scientific Fluid Type Definition (Reservoir)

Mixture z_i





$$\underbrace{T_c < T_R < T_{max}}$$

Gas Condensate

"Retrograde" G.C.

$T_R > T_{max}$ (No Cond. inside Reservoir)

Wet Gas $\boxed{I}$ Dry Gas

Surface Condensation

No Surf. Condensation

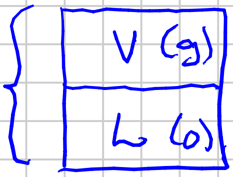
9o $115/STB

Phase Equilibrium Calculations

Simplified "Isothermal FLASH"

n

z_i



$n_V \quad y_i \qquad n_{iV} = n_V \cdot y_i$

$n_L \quad x_i \qquad n_{iL} = n_L \, x_i$

(p, T)

Know: $\underbrace{z_i \quad (p, T)}_{\text{estimate}} \Rightarrow \underline{z_i \quad K_i(p,T)}$

$K_i = \frac{y_i}{x_i}$

Requirement:

$\Sigma z_i = 1$

$$\left.\begin{aligned} n &= n_V + n_L \\ \Rightarrow \frac{n_i}{n} &= \frac{n_{iV}}{n} + \frac{n_{iL}}{n} \end{aligned}\right\} \text{Material Balances}$$

Definitions: $K_i \equiv \frac{y_i}{x_i}$

$$\begin{cases} f_V \equiv \frac{n_V}{n} \\ z_i \equiv \frac{n_i}{n} \end{cases} \qquad y_i = \frac{n_{iV}}{n_V} \qquad x_i = \frac{n_{iL}}{n_L}$$

$z_i = f_V \, y_i + (1 - f_V) \, x_i \Leftarrow$ Solve for x_i

Constraint: $\underbrace{\Sigma y_i = 1 = \Sigma x_i}$

$$\sum_i y_i - \sum_i x_i = \underbrace{\boxed{0 = \sum_i y_i - x_i}}_{\text{Constraint}}$$

MM

Solving this equation $\Rightarrow \boxed{f_v \,,\, y_i \,,\, x_i}$

Muskat - McDowell 1949

$$K_i = \frac{y_i}{x_i} \Rightarrow y_i = K_i x_i$$

$$\sum y_i - x_i = \sum K_i x_i - x_i = \sum x_i (K_i - 1)$$

$$z_i = f_v K_i x_i + (1 - f_v) x_i$$

$$= f_v K_i x_i + x_i - f_v x_i$$

$$= x_i \left(f_v (K_i - 1) + 1 \right)$$

$$\Rightarrow x_i = \frac{z_i}{\left[f_v (K_i - 1) + 1 \right]}$$

$$0 = \sum y_i - x_i = \boxed{\sum_i \frac{z_i (K_i - 1)}{\left[f_v (K_i - 1) + 1 \right]} = 0} \quad h_v(f_v)$$

One unknown: f_v

Once f_v solved, calc. x_i & y_i

Rachford-Rice Equation $\boxed{\text{Ch. 4}}$

Muskat-McDowell: $c_i = \dfrac{1}{K_i - 1}$

(1949)

$$h(f_v) \quad \sum_{i}^{N} \frac{z_i}{f_v + c_i} = 0 \qquad ; \; c_i = \infty$$

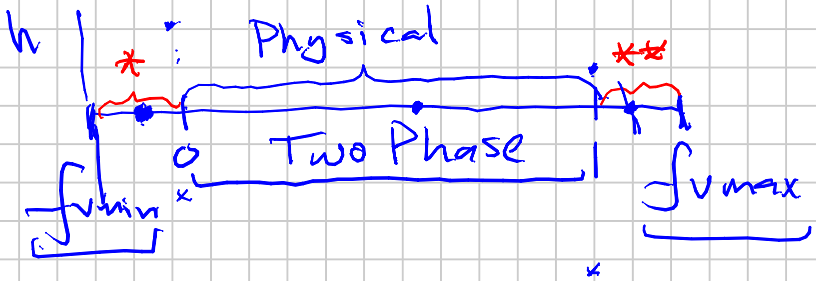
$$K_i = 1$$

N−1 (N−2) solutions

Only <u>one</u> solution that yields PHYSICAL values of y_i & x_i $\underline{(\geq 0)}$

A priori we know which solution — i.e.

$$\underset{\underset{\displaystyle\frac{1}{1-K_{\max}}}{\uparrow}}{\underline{f_{v\min}}} < f_v^* < \underset{\underset{\displaystyle\frac{1}{1-K_{\min}}}{\uparrow}}{\underline{f_{v\max}}}$$



We know K_i

⇒ $K_{\min}$, $K_{\max}$ ✓

$f_{v\max}$ $f_{v\min}$ ✓

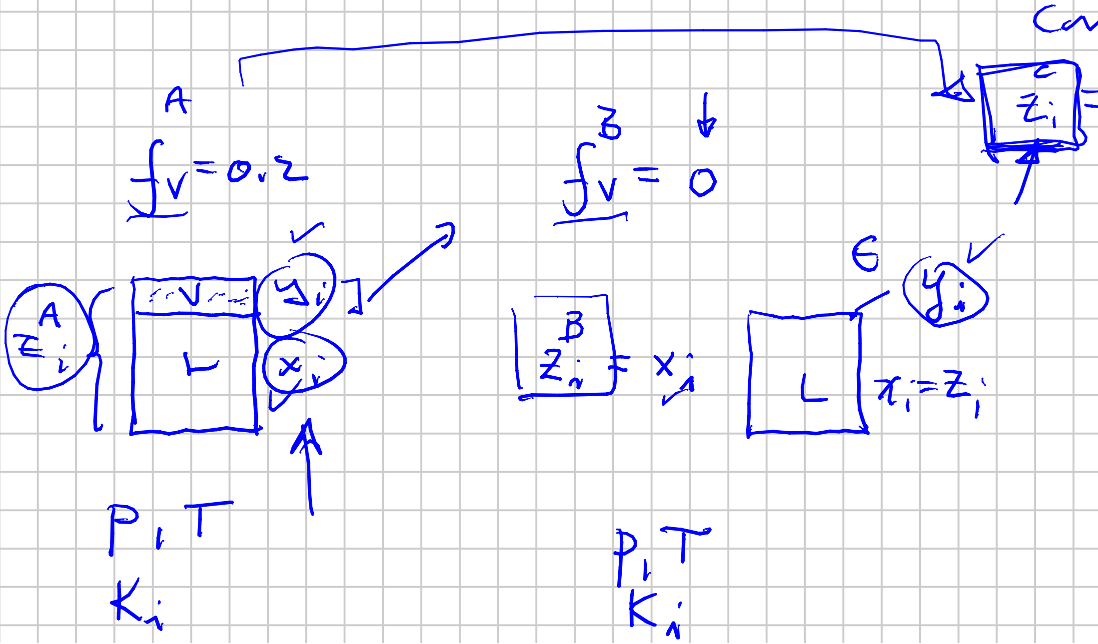
$h(f_v)$ is monotonic

* Single Phase "L-like"

** Single Phase "V-like"

Constructed

$$\boxed{z_i^C} = -0.1\, y_i + 1.1\, x_i$$



Solve :

$f_v^C = \boxed{-0.1}$

✓ y_i
✓ x_i

Equilibrium Phases

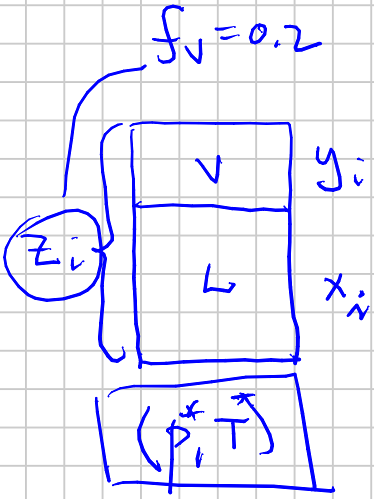
When two phases exist & are in equilibrium:

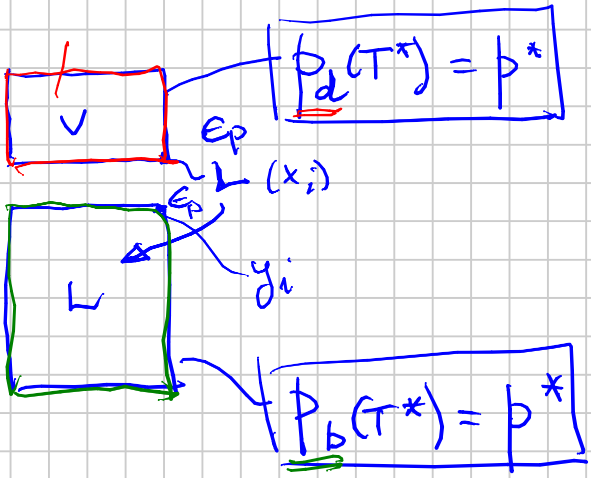
Gas (Vapor) Phase is "Saturated"

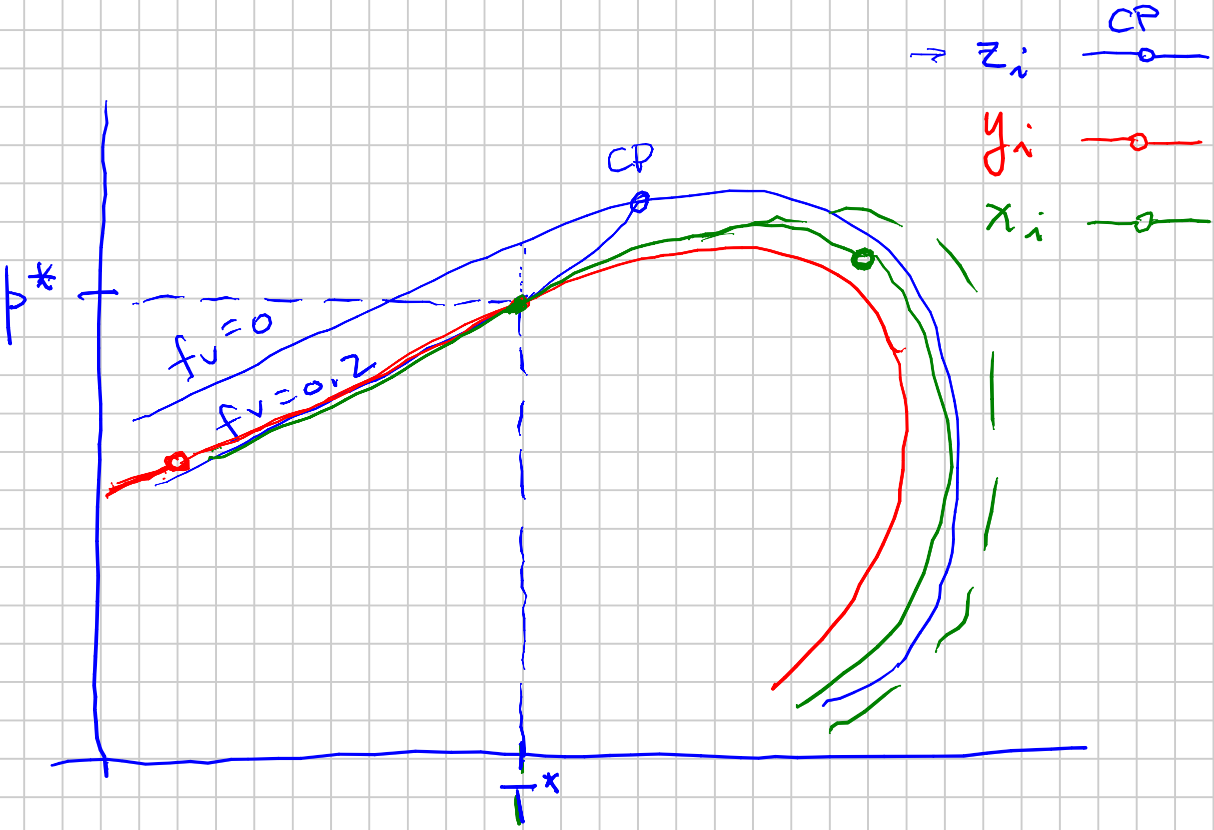
Oil (Liquid) Phase is "Saturated"

⇓

with the equilibrium phase(s)







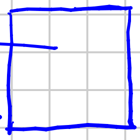
ISOTHERMAL FLASH CALCULATION (Rachford-Rice)

PROBLEM Statement: (1) How many phases (V L)

: 1 or 2 $\quad$ 0 $\quad$ 9

Under-saturated $\quad$ Saturated: 2 phases

$1-\epsilon \quad \epsilon$



Overall Composition z_i Known

(p, T) Fixed, Known, Specified

(2) How much of each phase (moles or mole fraction)

n_v / n_L $\qquad$ $f_v \equiv \frac{n_v}{n}$

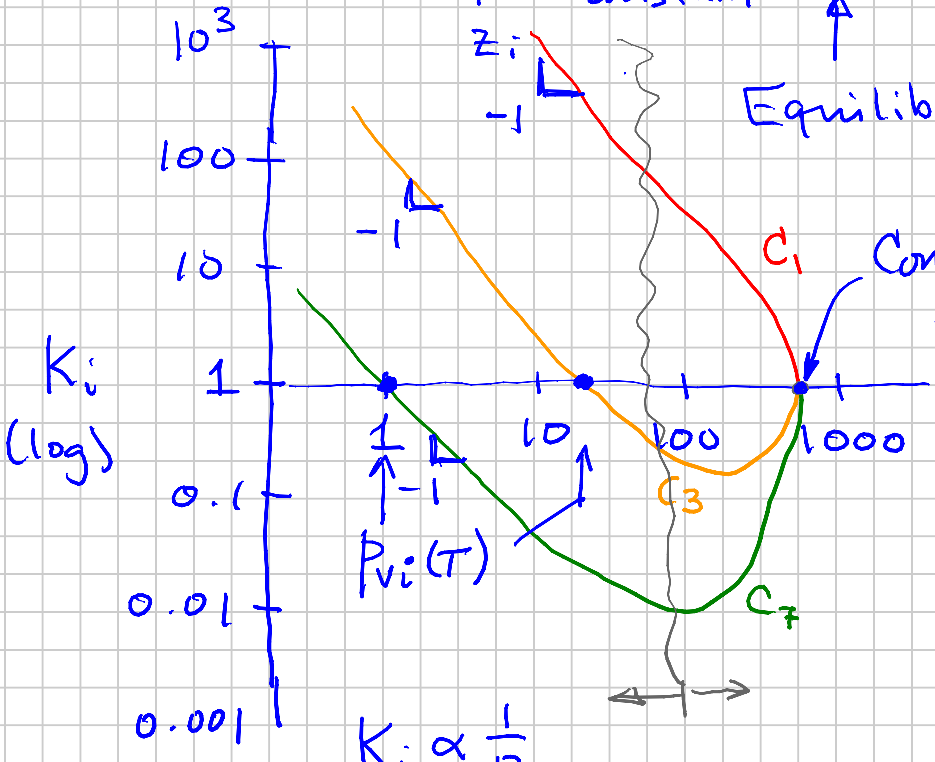
(3) Molar composition of each phase V: y_i

L: x_i

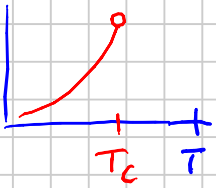
SOLUTION:

Requires estimate of $K_i = \frac{y_i}{x_i}$ @ (p, T, z_i)

T = constant



Equilibrium Ratio



Convergence Pressure p_K

$K_i \to 1$

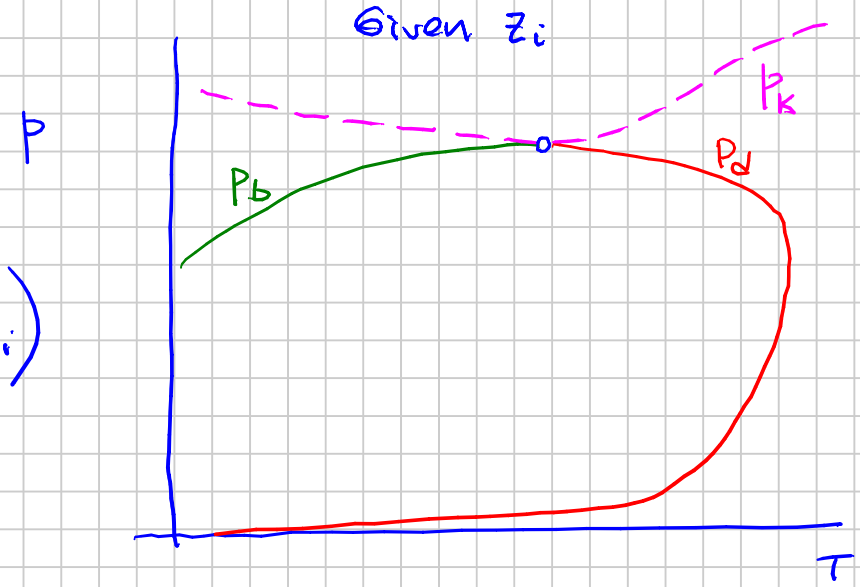
$p_{(\log)}$ [bara]

$p_K(T, z)$

If $T = T_c$ of z_i

$\Rightarrow p_K = p_c$ of z_i

SPE PBM



* Modified Wilson Eq.

$$K_i\left(p, T, p_K ; \underline{\underline{p_{ci}}}, \underline{\underline{T_{ci}}}, \underline{\underline{\omega_i}}\right)$$

Component Material Balance:

$$\left\{\begin{array}{l} n_i = n_{Li} + n_{vi} \qquad \leftarrow \\ \text{Total Material Balance} \\ n = n_L + n_V \end{array}\right.$$

$$n = \sum_{i=1}^{N} n_i \qquad n_L = \sum_{i=1}^{N} n_{Li} \qquad n_V = \sum_{i=1}^{N} n_{Vi}$$

Define:

$$z_i \equiv \frac{n_i}{n} \qquad y_i \equiv \frac{n_{Vi}}{n_V} \qquad x_i \equiv \frac{n_{Li}}{n_L}$$

$$f_V \equiv \frac{n_V}{n} \qquad ; \quad f_L = \frac{n_L}{n} = 1 - f_V$$

Also show:

$$\sum z_i = 1 = \sum y_i = \sum x_i$$

$K_i \equiv \dfrac{y_i}{x_i}$ know

$$\left.\begin{array}{l} \boxed{z_i = f_V\, y_i + (1 - f_V)\, x_i} \\ n_i = n_{Vi} + n_{Li} \end{array}\right\} \text{same thing}$$

$$K_i = y_i / x_i$$

$$\Rightarrow \quad y_i = K_i x_i$$

$$\underset{\checkmark}{z_i} = f_v \cdot (\underset{\checkmark}{K_i} x_i) + (1-f_v)\, x_i$$

Solve this for x_i

$$z_i = x_i \left[f_v K_i + (1-\overset{+}{f_v}) \right]$$

$$z_i = x_i \left[f_v (K_i - 1) + 1 \right]$$

✓ $$x_i = \frac{\overset{\checkmark}{z_i}}{\underset{\checkmark}{f_v}(\underset{\checkmark}{K_i}-1)+1}$$ ✓ ←

✓ $$y_i = K_i x_i = \frac{z_i K_i}{f_v(K_i-1)+1}$$ ✓ ←

1949: Muskat - McDowell

$\sum y_i = 1$ $\qquad$ $\sum x_i = 1$

$$\sum y_i - \sum x_i = 1 - 1 = 0$$

$$\sum_{i=1}^{N} (y_i - x_i) = 0$$

"Rachford-Rice":
195x

$$h(f_v) \equiv \sum_{i=1}^{N} \left[\frac{\overset{\checkmark}{z_i}(\overset{\checkmark}{K_i}-1)}{f_v(\underset{\checkmark}{K_i}-1)+1} \right] = 0 \qquad (1)$$

if $f_v = \frac{-1}{K_i - 1}$

1949: M-M

$c_i = \frac{1}{K_i - 1}$; $c_i = 0$ if $K_i = 1$

$$h(f_v) = \sum_{i=1}^{N} \left[\frac{z_i}{f_v + c_i} \right] = 0 \qquad (1')$$

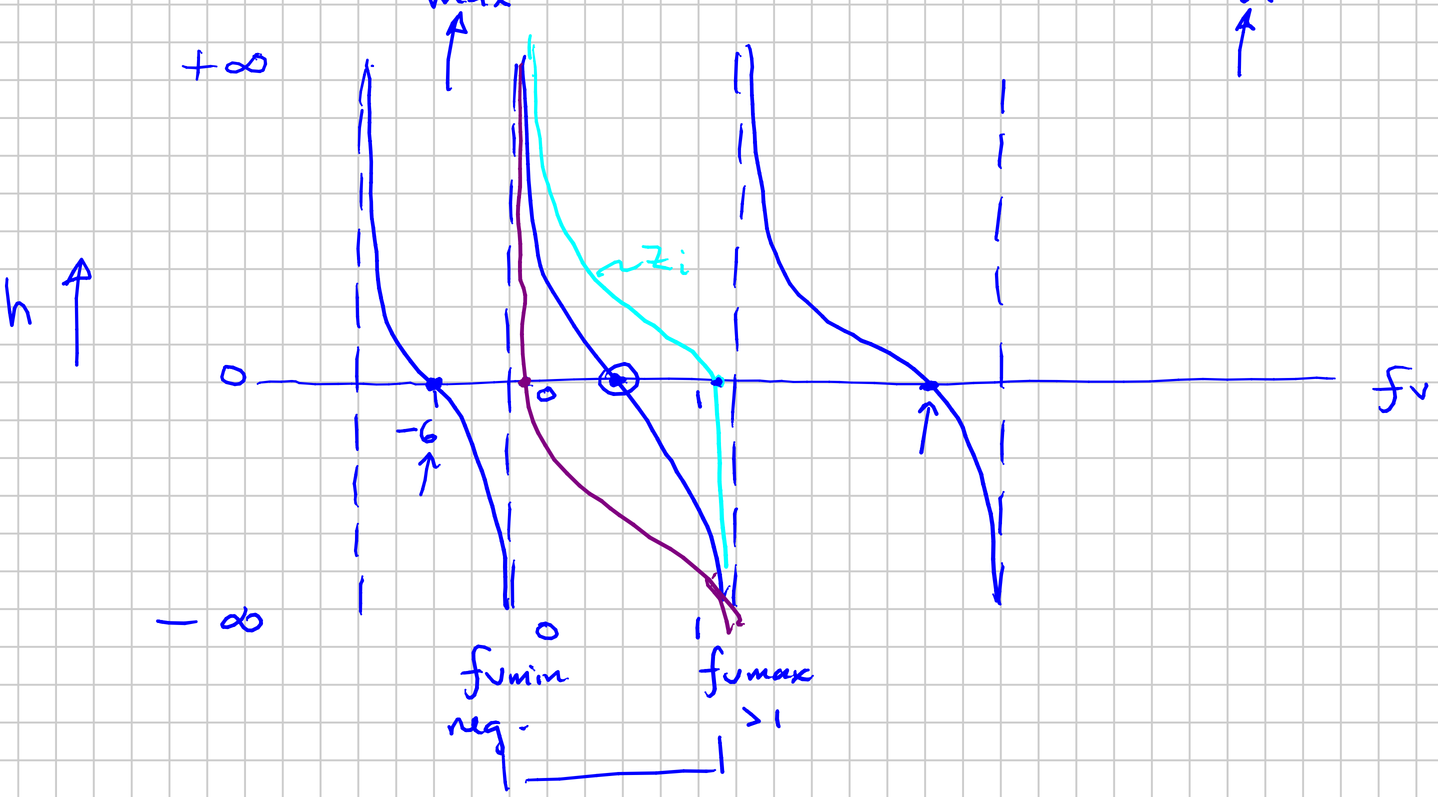
(1) $h(f_v)$ is a monotonic function → NR

(2) N−1 solutions

− Only one of these yields $\underbrace{\text{physical solution}}$

$x_i \geq 0$ }
$y_i \geq 0$ }

$$0 > \frac{1}{1-K_{max}} = f_{v\,min} < f_v < f_{v\,max} = \frac{1}{1-K_{min}} > 1$$



: Solved f_v^*

L + V $0 < f_v^* < 1$: two phase solution

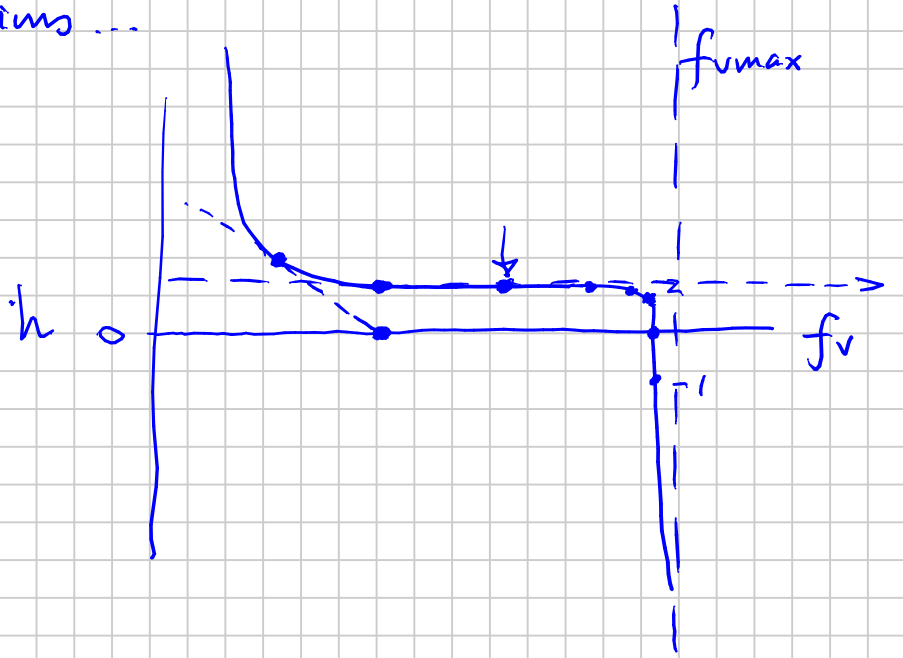
Liquid $f_v^* = 0$ }
Vapor $f_v^* = 1$ } : saturated single phase

Liquid-Like $f_v^* < 0$ }
Vapor-Like $f_v^* > 1$ } : undersaturated single phase

< 1% of calculations ...

$z_i \rightarrow \epsilon$

$K_i \rightarrow \epsilon$ or huge



Setup for Solution:

p, T, z_i Given

Guestimate
Estimate

1. Estimate $K_i(p, T, p_K)$: Wilson Ch. 3 or 4

Guess $\boxed{f_v}$

Calc $\boxed{f_{v\min}}$ $\boxed{f_{v\max}}$

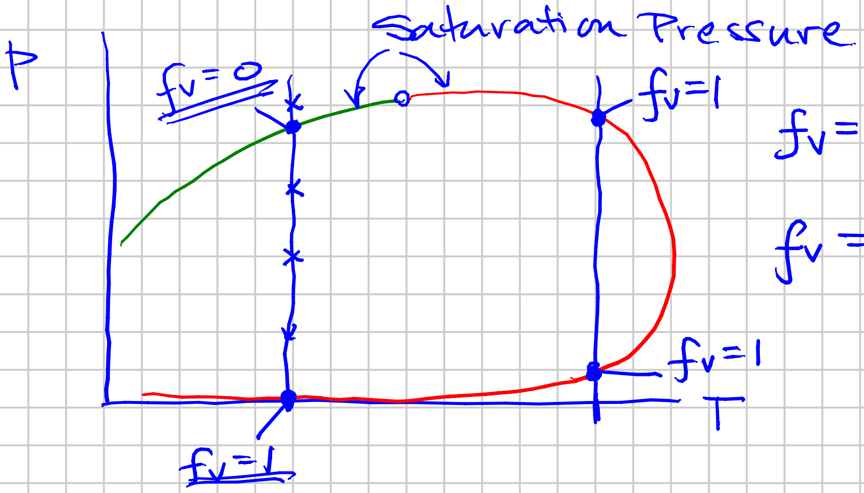
2. Setup a Table

i	z_i	K_i	$c_i = \frac{1}{K_i - 1}$	Term_i	y_i	x_i
1						
2		$K_{\max}$				
⋮						
N		$K_{\min}$				

$\boxed{h}$ ← drive this to $\rightarrow 0$ (ϵ)

sum

Special Cases of Flash Calculation:



$f_v = 0$: Bubblepoint

$f_v = 1$: Dewpoint

Bubblepoint : $f_v = 0$

"Bubble"

$\Rightarrow \quad \sum y_i = 1$ equation

$$\boxed{h_{BP}(p_b) = 1 - \sum_{i=1}^{N} z_i \left(K_i(p_b)\right) = 0}$$

$$y_i = x_i K_i$$

$$y_i = z_i K_i (p ; \underbrace{T, p_K}_{\text{fixed}})$$

search

Dewpoint : x_i ∈ phase $\qquad f_v = 1 - \epsilon$

$$\sum x_i = 1$$

$$x_i = y_i / K_i$$

$$x_i = z_i / K_i (p ; T, p_K)$$

?

Fixed T, p_K

$$\boxed{h_{DP} = 1 - \sum x_i = 0 = 1 - \sum \frac{z_i}{K_i(p)}}$$

Two Solutions:

Upper DP

Lower DP

$$h(f_v) = \sum_i \frac{z_i}{f_v + c_i} = 0 \qquad MM$$

$$= \sum_i \frac{z_i(K_i - 1)}{f_v(K_i - 1) + 1} = 0 \qquad RR$$

Given z_i $\quad K_i(p, T, \underset{\uparrow}{z})$

p_K = convergence pressure

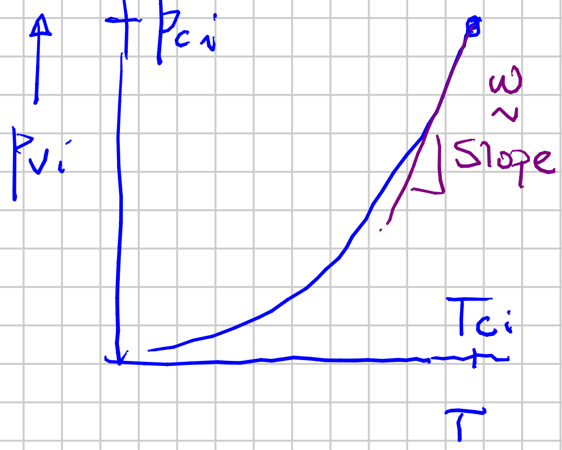
p where all $K_i \to 1$

Solution. Table B-19 gives component properties taken from Appendix A needed to calculate *K* values from the modified Wilson *K*-value equation. $A_0 = 0.7$ is used in the modified Wilson *K*-value correlation, where $\boxed{A_1 = 1 - (p/p_k)^{0.7}}$ in Eq. 3.159. For example, the *K* value for methane is given by

$$K_i = \underbrace{\left(\frac{p_{ci}}{p_k}\right)}_{f(\text{mixture } z_i,\, T)}^{\overset{\searrow}{A_1} - 1} \frac{\exp\left[5.37\, A_1 (1 + \overset{\text{Acentric Factor}}{\overset{\downarrow}{\omega_i}})\left(1 - T_{ri}^{-1}\right)\right]}{p_{ri}}, \qquad (3.159)$$

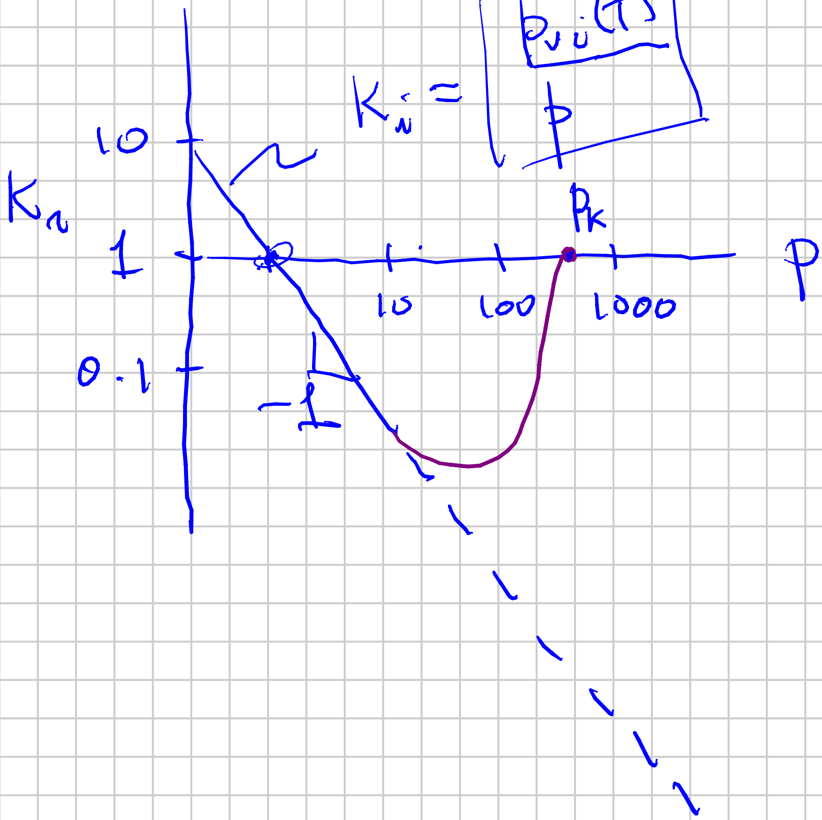
$$T_{ri} = \frac{T}{T_{ci}} \qquad p_{ri} = \frac{p}{p_{ci}}$$

Component i : $\underset{\sim}{T_{ci}}$ p_{ci} $\underset{\sim}{\omega_i}$



Original Wilson Eq.

$$K_i = \boxed{\frac{p_{vi}(T)}{p}}$$



SOLVER SOLUTION:

Options
- maximize
- minimize
- set a value = 0

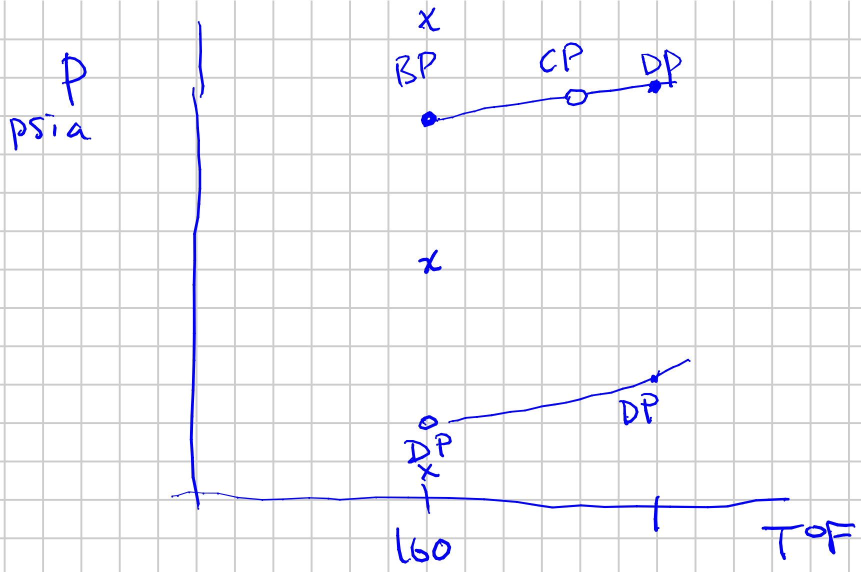
① Set Target Cell — $h = \sum \frac{z_i}{f_v + c_i}$

② Set variable(s) to change to reach Target — f_v

③ Constrain the changes in variable(s) — $f_{v\,min} < f_v < f_{v\,max}$

④ Run Solver

* Try Solver using various initial estimates



Bubblepoint: Searching p where calculated $\sum y_i = 1$

$$K_i(p) = \frac{y_i}{x_i} = \frac{y_i}{z_i} \Rightarrow y_i = z_i K_i$$

$$\sum y_i = 1 = \sum z_i K_i(p)$$

Dewpoint: $\sum x_i = 1 = \sum z_i / K_i(p)$

$p = p_K \Rightarrow K_i = 1 \Rightarrow$ Automatically converge

DP $\sum x_i = 1$

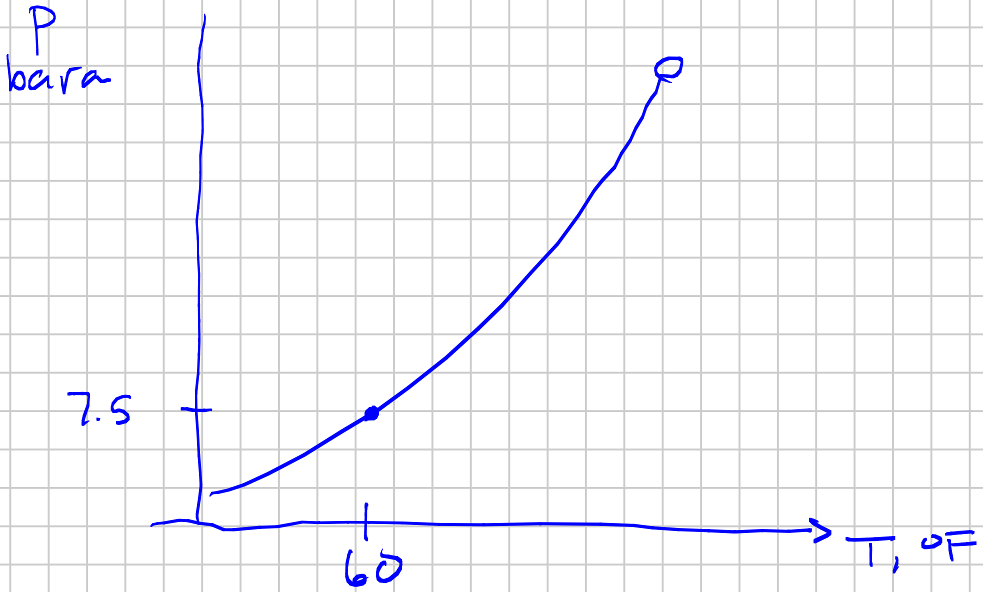
BP $\sum y_i = 1$

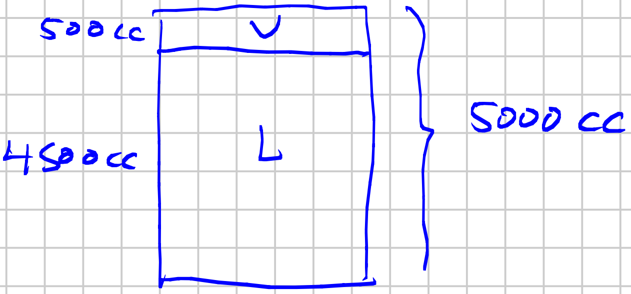
$$\rho \equiv \frac{m}{V} \quad (1) \qquad M \equiv \frac{m}{n} \quad (2)$$

$$Z \equiv \frac{pV}{nRT} \quad (3)$$ definition (gas or liquid)

$$\boxed{\rho = \frac{p M}{R T Z}}$$

Gas & Liquid





$$\left[m = V_L \cdot \rho_L + V_v \rho_v \right]$$

(a) $4500 \cancel{cc} \times 0.5 \frac{g}{\cancel{cc}} + 500 \cancel{cc} \times 0.016 \frac{g}{\cancel{cc}}$

$= \qquad g$

(b) $m = 0 \cdot 0.5 + \overset{\checkmark}{5000} \cdot \overset{\checkmark}{0.016}$

(c) $p = 1$ atm $\quad T = 60°F \quad Z_g \cong 1$

$$(\rho_{C_3})_v \;@\; STC = \frac{p_{sc} M_{C_3}}{R T_{sc} (1)}$$

$$m = 0 \cdot \rho_L + 5000\ cc \cdot (\rho_{C_3})_v$$

$M \left[\frac{g}{g\text{-mole}} \right] \qquad \left[\frac{lb}{lb\text{-mole}} \right]$

44 $\qquad$ 44

Phase Equilibria

- Know: P, T, z_i

FLASH – Want: # Phases, Amount of each phase &
(K_i) Phase composition, $\underbrace{\text{phase properties } (\rho\ \mu)}_{\text{Not Flash results / Other Equations}}$

Applications:

- Engineering ΔP (Darcy, Reynolds +++)
- Sales Products $(\bar{g}, \bar{o}$, NGLs) $

$$\underbrace{\overset{\uparrow}{\underset{=}{\bar{g}}} \quad \overset{\text{STO}}{\Uparrow} \quad \overset{\uparrow}{\text{Refrigeration } \$}}_{(P, T)\ \text{Surface Facilities (Separators)}}$$

{ Maximize Net Revenue $

$$GOR \equiv \frac{V_{\bar{g}}}{V_{\bar{o}}} \quad \frac{\$}{\$}$$

Maximize Gross Sales Revenue

100 $/bbL

[[5 $/Mscf]]

BTU J

boe barrel oil equivalent (energy)

6 Mscf ≃ 1 STB

Troll:

45 Tcf $\quad \underbrace{45\cdot10^{12}\ \text{scf}} \times \frac{\text{boe}}{6000\ \text{scf}} = 7\cdot10^{9}$ boe

Value $ $\qquad \frac{\text{Value}}{7\cdot10^{9}} \qquad \frac{\$}{\text{boe}}$

$$\underline{45\cdot10^{9}\ \text{Mscf} \times \$5/\text{Mscf}}$$

$\sim \$\,225\cdot10^{9}$

$$\frac{\$225\cdot10^{9}}{7\cdot10^{9}\ \text{boe}} = \$32\ /\text{boe}$$

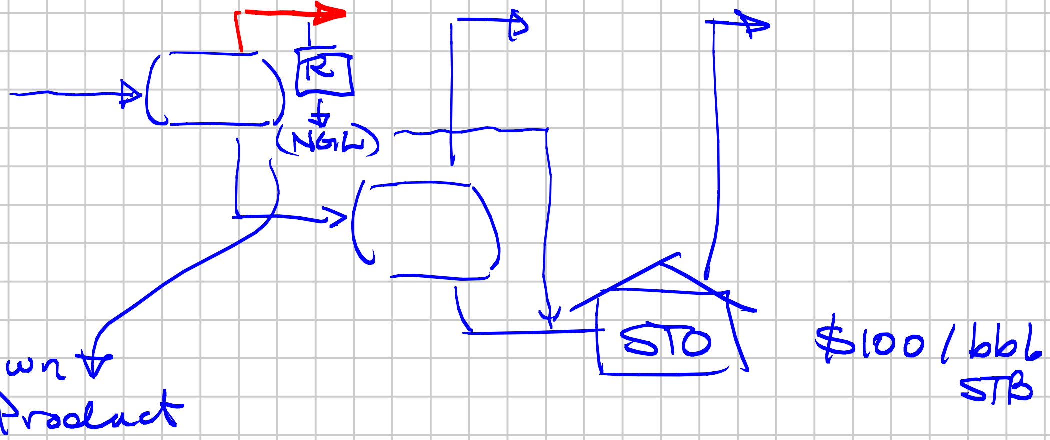
LNG = gas to (p, T) ~ Liquid-like for transportation

$$\left\{ \text{GTL} \qquad C_1 \xrightarrow{\$\$} C_n \right\}$$

C_n / 6 – 15 HC

NGL

Mscf $\quad \boxed{y_i}$



Liquid yield (L_i)

Shrunken Gas
Dried Gas $\downarrow$ $0.9 \times \text{Mscf} \times \underline{\underline{\$5}}$

+

1 Mscf y_i NGL $\rightarrow$ C_3 gallons or bbls $50
$\rightarrow$ C_4 — " — $60
$\rightarrow$ C_5 — " — $75

$$L_i \left[\frac{\text{gallons of } i}{1 \text{ Mscf}} \right] =$$

Ch. 6

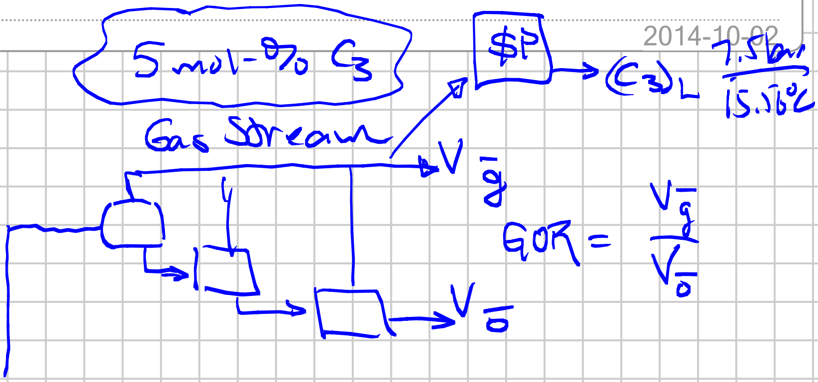
$80/bbL

CLASS PROBLEM:

$100 / bbL

$ 5 / Mscf

5.615 ft³/bbL } Unit
35.31 ft³/m³ } Conversions



$$GOR = \frac{V_{\bar{g}}}{V_{\bar{o}}}$$

What producing GOR [Sm³/Sm³] – Gas-Oil Ratio – yields equal $ Revenue from gas product ($\bar{g}$) and (stock-tank) oil product ($\bar{o}$)?

Basis: sell 100 bbl oil = $V_{\bar{o}}$

Oil revenue = $100/bbL × 100 bbl = $10,000

Gas revenue = Oil revenue = $10,000

⇒ Gas Volume $V_{\bar{g}}$ = $10,000 / ($5/Mscf)
= 2,000 Mscf = 2 MMscf

$$GOR = \frac{V_{\bar{g}}}{V_{\bar{o}}} = \frac{2\cdot 10^6\ \text{scf}}{100\ \text{STB}} \qquad = 2\cdot 10^6\ \text{scf}$$

$$= 20{,}000\ \cancel{\text{scf}}/\text{STB} \times \left(\frac{\text{bbL}}{5.615\ \cancel{\text{ft}^3}}\right) \times = 3{,}570\ \frac{\text{Sm}^3}{\text{Sm}^3}$$

$$OGR = 1/GOR = \underbrace{50\ \text{STB/MMscf}}_{\sim\text{Lean ``GC''}}$$

Gas Condensate System "Gas Phase" In-Situ Initially

50% from "oil"

L_i = Liquid yield from a gas stream of a particular component

✓ $\rho_{LC3} = 0.5$ g/cc ~ 31 lb/ft^3

✓ $M_{C3} = 44$ lb/lb-mole

379 scf/lb-mole $\quad \frac{RT_{sc}}{p_{sc}} = \frac{V}{n}$ $\quad$ (23.67 Sm^3/kg-mole)

New revenue C_3 as a "Propane Tank" Liquid

C_3 in Gas stream $\underline{\text{5-mol-\%}}$

$$V_{\bar{g}} = 2 \cdot 10^6 \text{ scf}$$

$$n_{\bar{g}} = \frac{2 \cdot 10^6}{379} \frac{\text{scf}}{\text{scf/lb-mole}} = \underline{52{,}77} \text{ lb-mole}$$

$$n_{C3} = 0.05 \; n_{\bar{g}} = \underline{263.8} \text{ lb-mole}$$

$$m_{C3} = n_{C3} \cdot M_{C3} = \underline{11{,}610} \text{ lb}$$

$$(V_{C3})_L = m_{C3} / (\rho_{C3})_L = \underline{375} \text{ ft}^3$$

$$= \underline{67} \text{ bbl}$$

$$= \boxed{+\$\,5330}$$ C_3 NGL

Lost Revenue in Gas

$$\boxed{-\$\,500}$$ C_3 "Loss" in Gas 'Shrinkage'

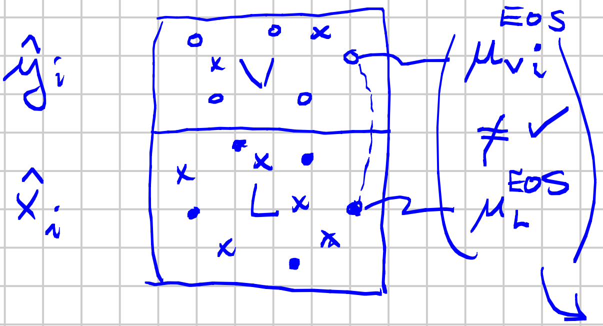
Net Gain $= \boxed{+\$\,4830}$ Extracting C_3 from Gas Stream

Net Revenue \$24,830 vs \$20,000

$C_3 + C_{10}$

vdW
RK
PR

Will Rogers



Gibbs ✓ : How to calculate μ
Helmholtz

↳ New set of K_i

pVT

Ch. 4

$p = 7.5$ bara
$T = 60\,°F$

μ_{Total} = minimum

Ch. 4

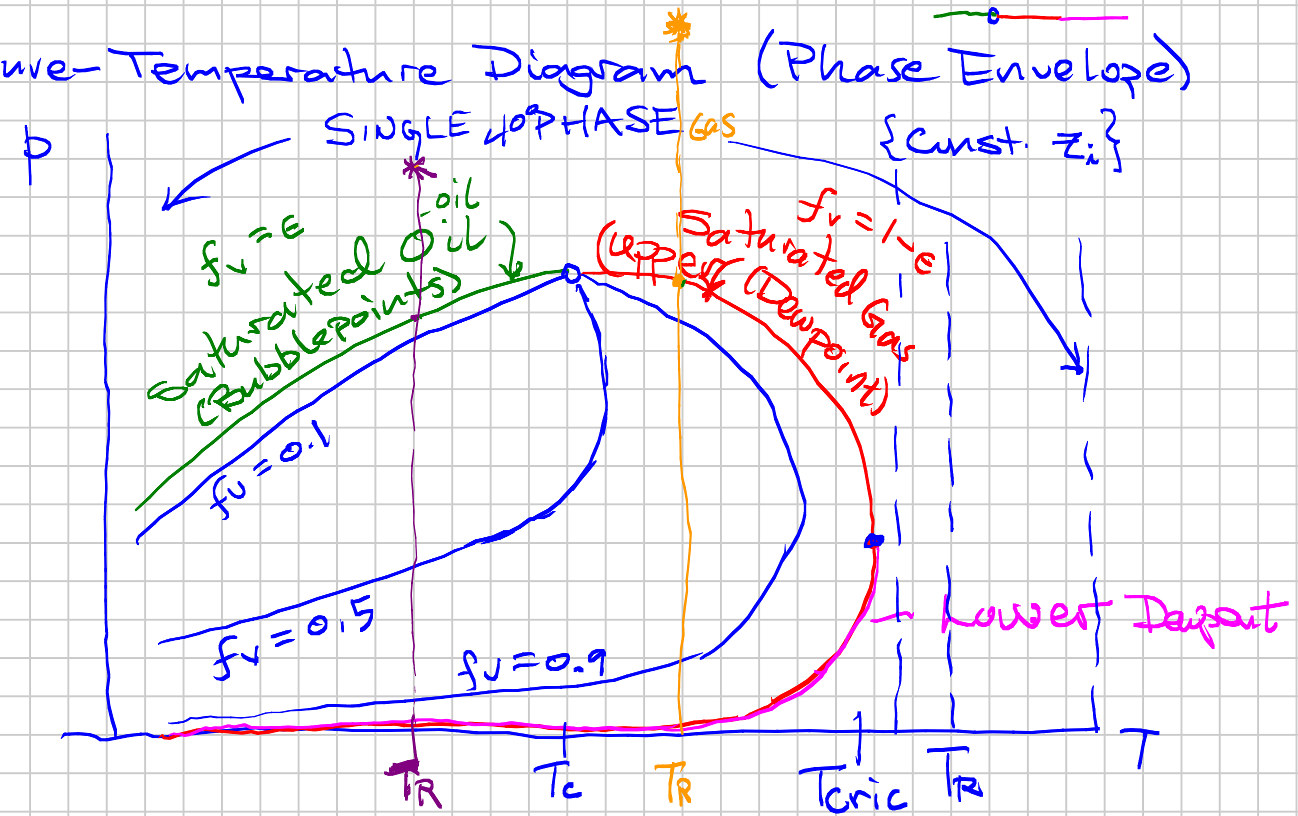
{ Michelsen (DTU) Mollerup ⇐ }

Wilson $K_i(p, T, p_k)$ ⇒

$f(z, T)$

Applications:

① Pressure-Temperature Diagram (Phase Envelope)



Flash (RR, MM) : $f_v \equiv \dfrac{n_v}{n}$

Same $(z_i)_R$ Same ρ_{Ri}

Different T_R

Oil : $T_R < T_c$

Gas : $T_R > T_c$

} Define formally Oil Reservoir, Gas Reservoir

FLUID TYPES:

* Gas Condensate

⟵ OILS ($T_R < T_c$) ⟶ ⟵ GASES ($T_R > T_c$) ⟶

(Near-Critical)

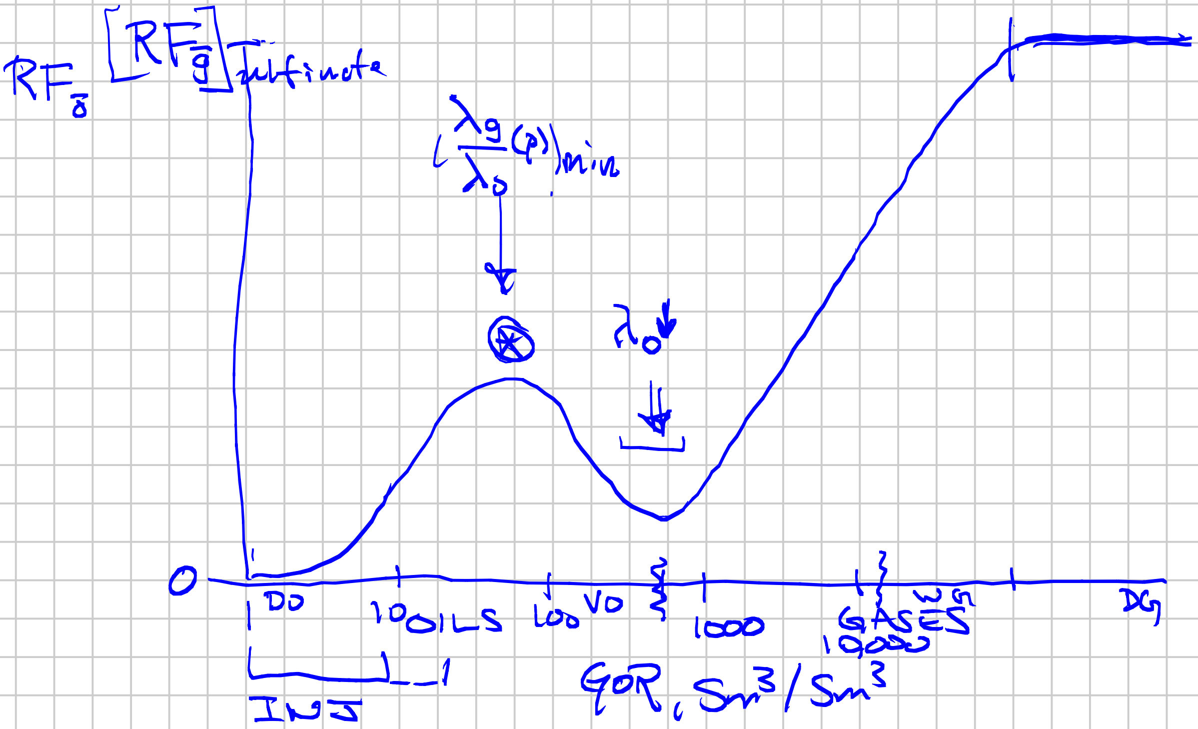
	Dead Oil	Low-GOR Oil	Oil	Volatile Oil	Rich GC*	Lean GC	Wet Gas	Dry Gas
							$T_R > T_{cric}$	
GOR [Sm³/Sm³]	< 1	→ 20		> 300	700 →	3500	< 20 000	∞

500–700

Wet Gas, Dry Gas: No "L" in Reservoir

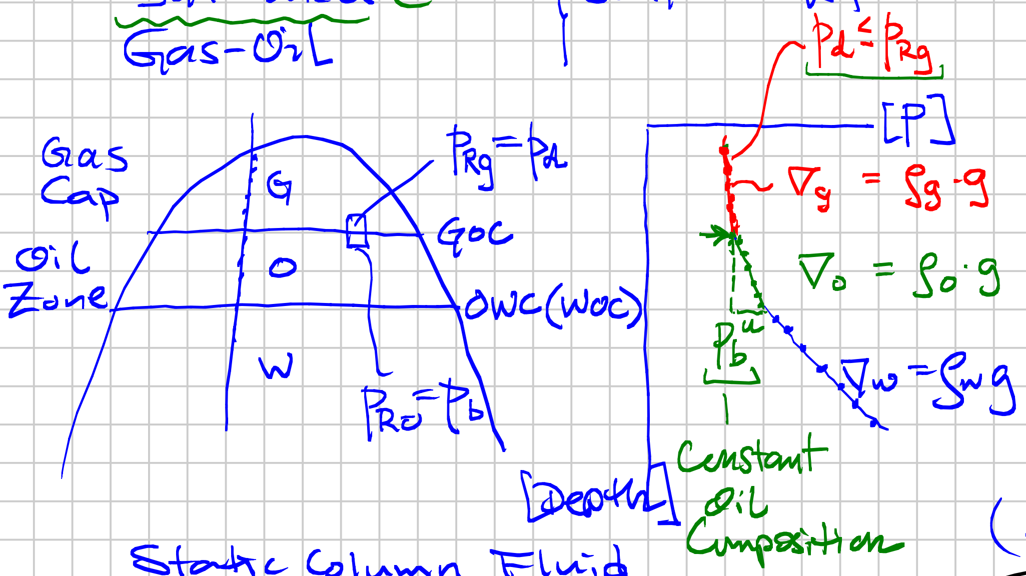
$$\lambda_p \equiv \left(\frac{k_p}{\mu_p}\right) \sim \frac{k \cdot k_{rp}}{\mu_p}$$

$$\underbrace{k_r \sim S^{n \sim 3-4}}$$



Reservoirs With Heterogeneous In-Situ Fluids

Saturated @GOC | Simplest Equilibrium Systems
Gas-Oil



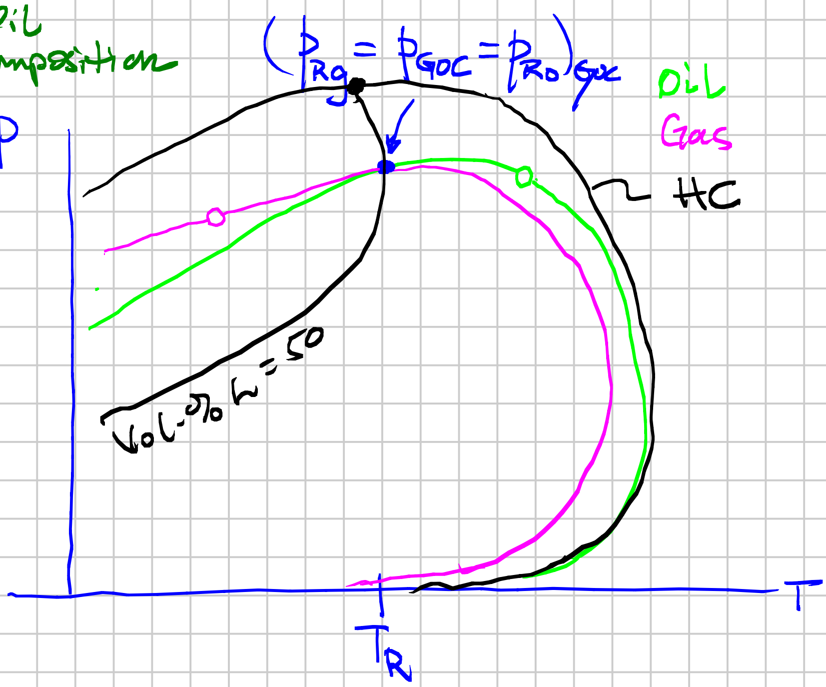
$\rho_g \sim 100-350 \text{ kg/m}^3$

$\rho_o \sim 350-950 \text{ kg/m}^3$

$\rho_w \sim 1000 \text{ kg/m}^3$

Static Column Fluid

$$\nabla \equiv \frac{dp}{dD} = \rho g$$



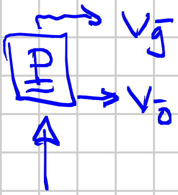
LABORATORY PVT TESTS

Measuring:

- Saturation Pressures @ T_R
- ρ_o μ_o ρ_g (μ_g calc.)
- $V_o (p < p_s)$: $\lambda_o = \dfrac{k \cdot k_{ro}(S_o^{n \sim 3-4})}{\mu_o}$

$S_o \propto V_o$

- Surface Products



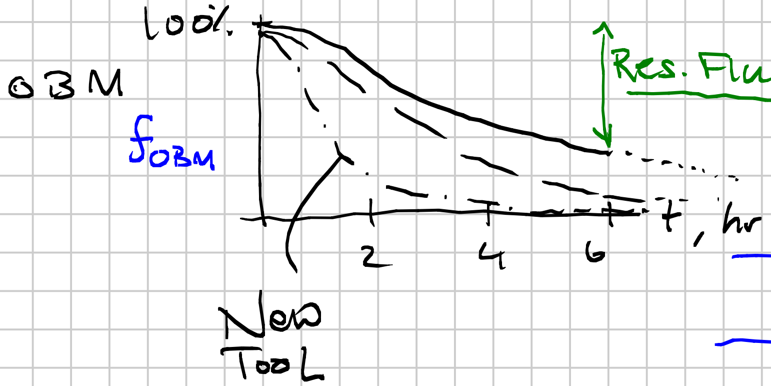
V_g \$3-5/Mscf

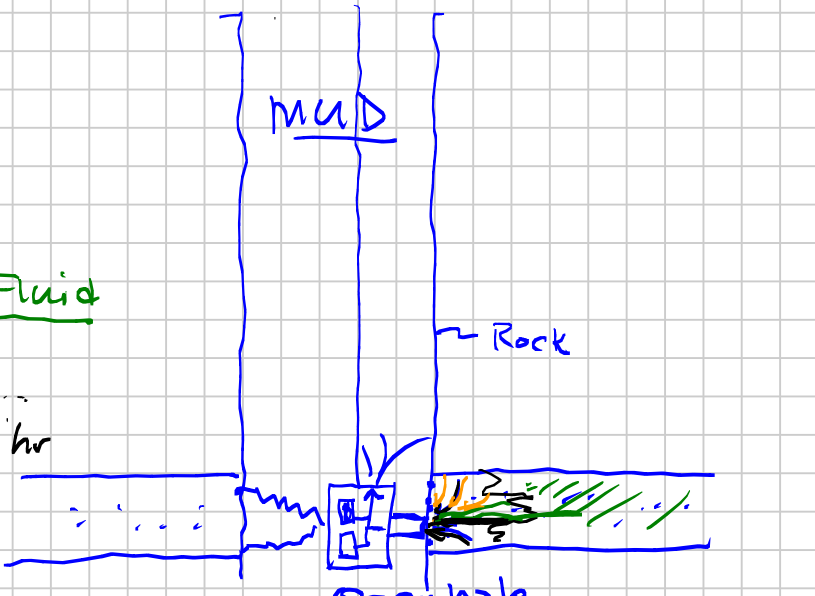
V_o \$100/bbl

① Collect Samples

I – Openhole Formation Testing Tool

- OBM contamination





Openhole Formation Testing Tool

MDT (SLB)

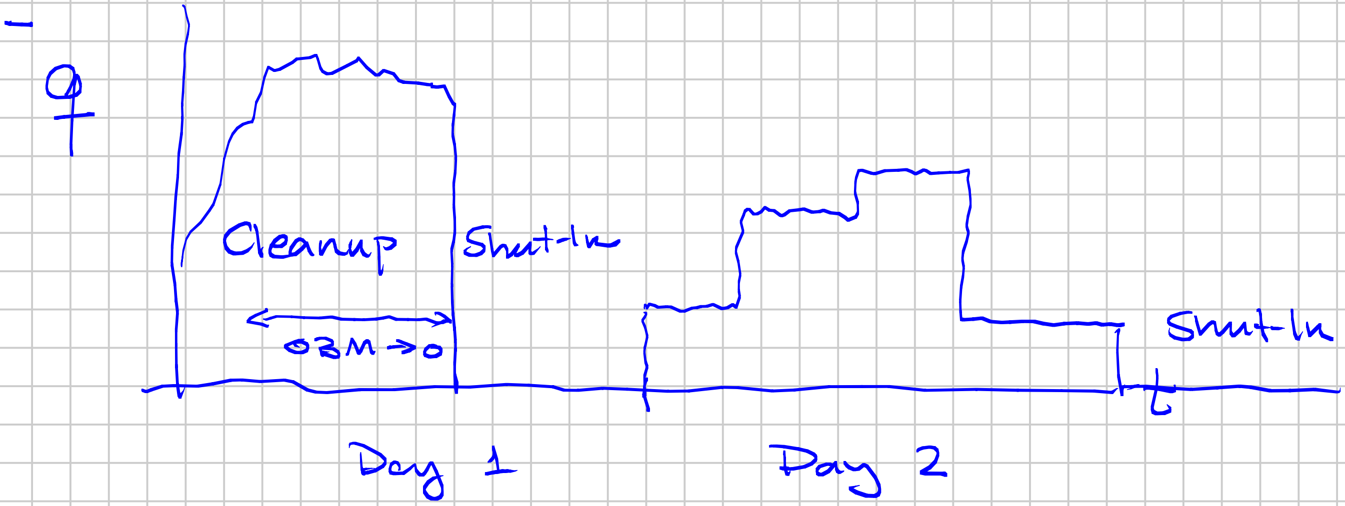
RCI

RDT

$$\overset{\checkmark}{z_{Tool,i}} = z_{Ri}(1 - f_{OBM}) + \underset{\checkmark}{z_{OBMi}} \cdot f_{OBM}$$

Guess / Know $f_{OBM} \Rightarrow z_{Ri}$ ✓

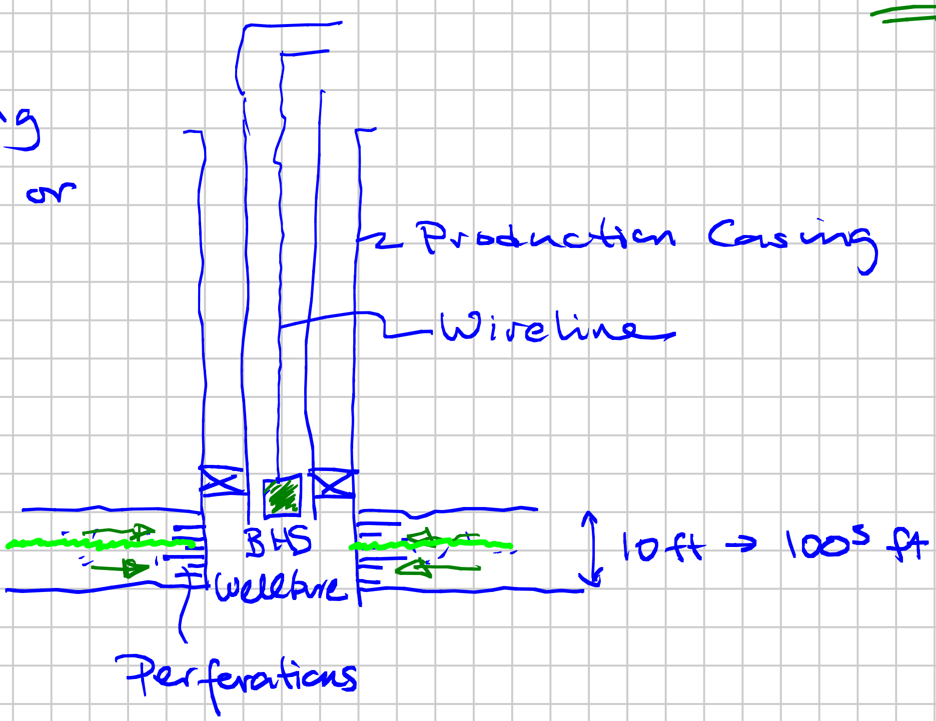
After Casing Set and During Production Testing



II – Wireline Bottomhole Samples ("BHS") - OILS only

Collected during low flow rates or During Shut-In

Mobility-Averaged Sample

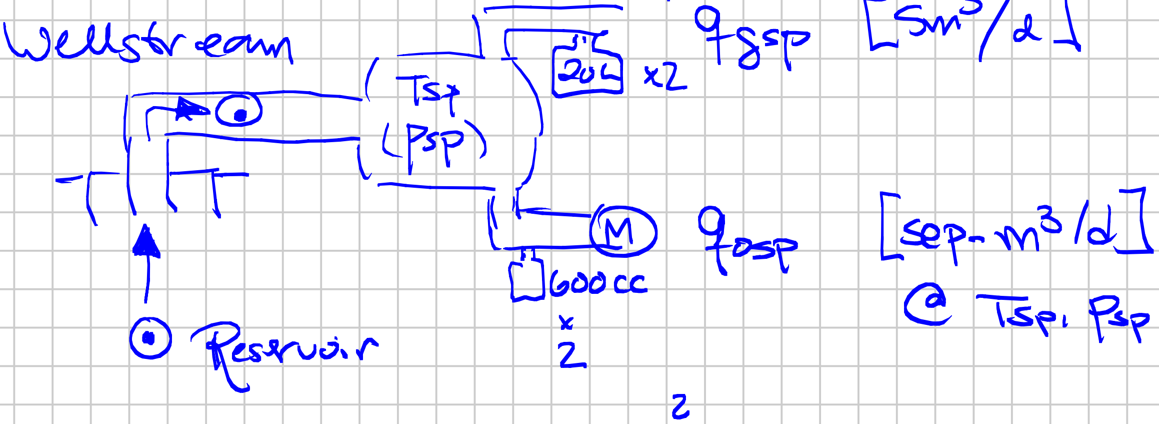


(a) OBM cont.

(b) Wax Precipitation = $f(T_R \rightarrow T^*)$

(c) Asphaltene —"— = $f(p \rightarrow p_b)$

III. Surface Separator Samples



~ In-flow from Reservoir ($\overset{?}{\approx}$ In-Situ Fluid)

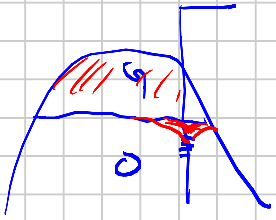
- Relatively inexpensive
- — " — Simple
- Large amounts of sample
- Getting "right" wellstream mixture
  (~ Reservoir insitu mixture)

requires accurate measurement of
q_{gsp} & q_{osp} i.e. $R_{sp} \equiv \frac{q_{gsp}}{q_{osp}}$

Why might Wellstream (Wellbore) Mixture ≠ In-Situ Reservoir Fluid (z_{Ri})

① Variation of z_{Ri}(depth) : Average

②



③ $p_{wf} < p_s$ ⇒ Producing GOR ≠ Solution GOR

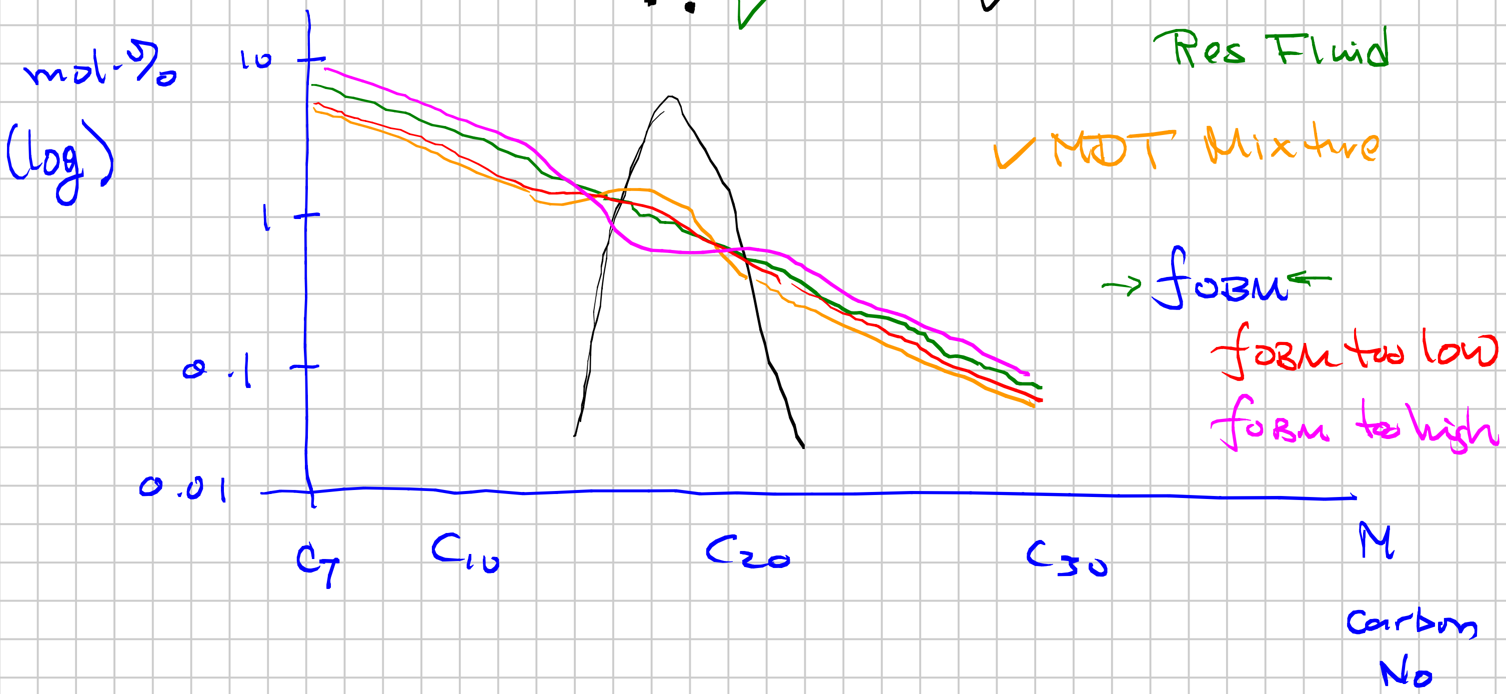
BHFP

$$\left(\begin{matrix}\lambda_g y_i \\ + \\ \lambda_o x_i\end{matrix}\right) / \lambda_t \neq z_{Ri}$$

z_{wi}

Decontamination of OBM sample to estimate In-Situ $\boxed{z_{Ri}}$ ∴ ✓

z_{OBMi} ✓
- (a) Fang
- (b) "Diesel"



But the OBM-contaminated sample itself will have WRONG PVT properties — e.g. p_b, ρ, GOR, ...

PVT Lab Tests (Ch. 6)

① Get Sample

@ T> P> STC

- Openhole Formation Test (MDT, RCI,) } OILS & GAS COND.
- Surface Separator / } Cased hole / Production Test
- Wireline Bottomhole (BHS) — OIL
- Stock Tank Oil } Crude Assay (Product Value, Refinery)

② Compositional Analysis

- Quantifying amounts (mass and/or moles) of compounds:

non-HC : N_2 CO_2 H_2S

Light HCs : C_1 C_2 C_3 $i\text{-}C_4$ $n\text{-}C_4$ $i\text{-}C_5$ $n\text{-}C_5$

Heavier : C_6 C_7 C_8 … C_9 C_{10} C_{11} C_{12} C_{13} … C_{36+}

C_{7+} pre-1980 C_{12+}

1985-90s Now

Gas Chromatograph (GC)

Since 1990s:

C_6 isomers → $\bar{C}_6$

C_7 isomers "$\bar{C}_7$" (e.g. benzene)

C_8 isomers $\bar{C}_8$ toluene

C_9 isomers $\bar{C}_9$

C_{10}

C_{11}

C_{12}

Today: $N \sim 50$

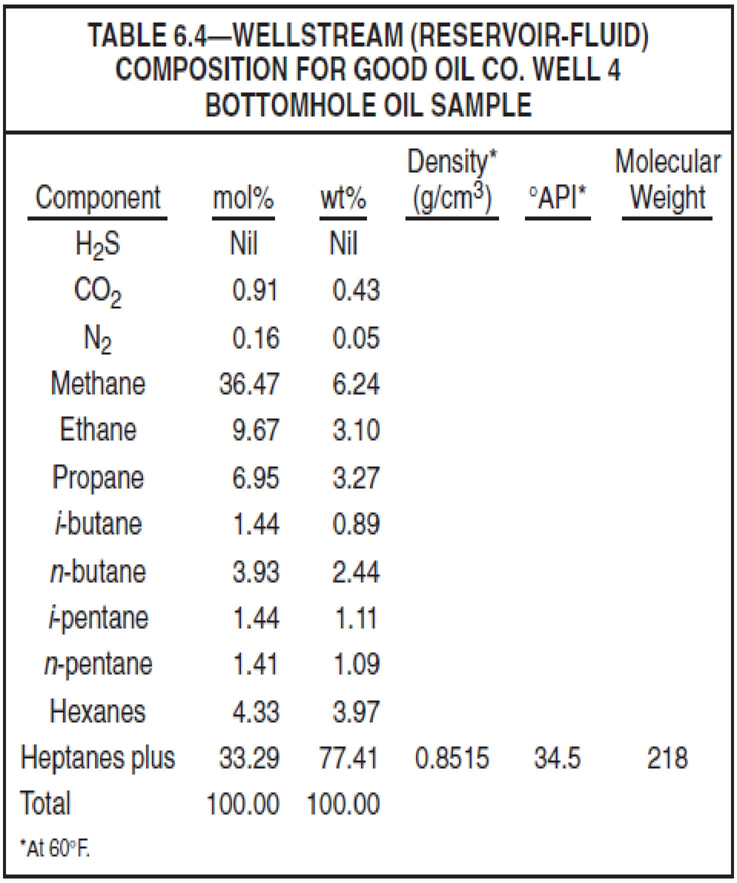
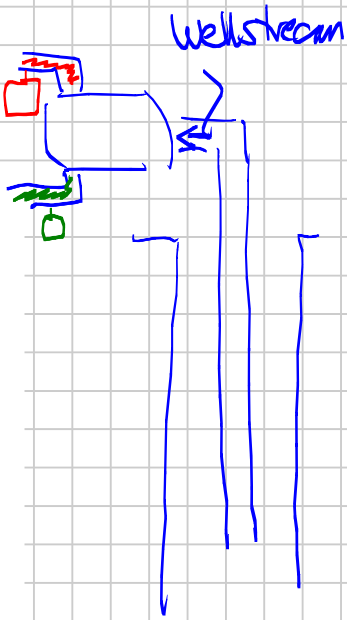


TABLE 6.4—WELLSTREAM (RESERVOIR-FLUID) COMPOSITION FOR GOOD OIL CO. WELL 4 BOTTOMHOLE OIL SAMPLE

Component	mol%	wt%	Density* (g/cm³)	°API*	Molecular Weight
H_2S	Nil	Nil			
CO_2	0.91	0.43			
N_2	0.16	0.05			
Methane	36.47	6.24			
Ethane	9.67	3.10			
Propane	6.95	3.27			
i-butane	1.44	0.89			
n-butane	3.93	2.44			
i-pentane	1.44	1.11			
n-pentane	1.41	1.09			
Hexanes	4.33	3.97			
Heptanes plus	33.29	77.41	0.8515	34.5	218
Total	100.00	100.00			

*At 60°F.

Example Oil BHS



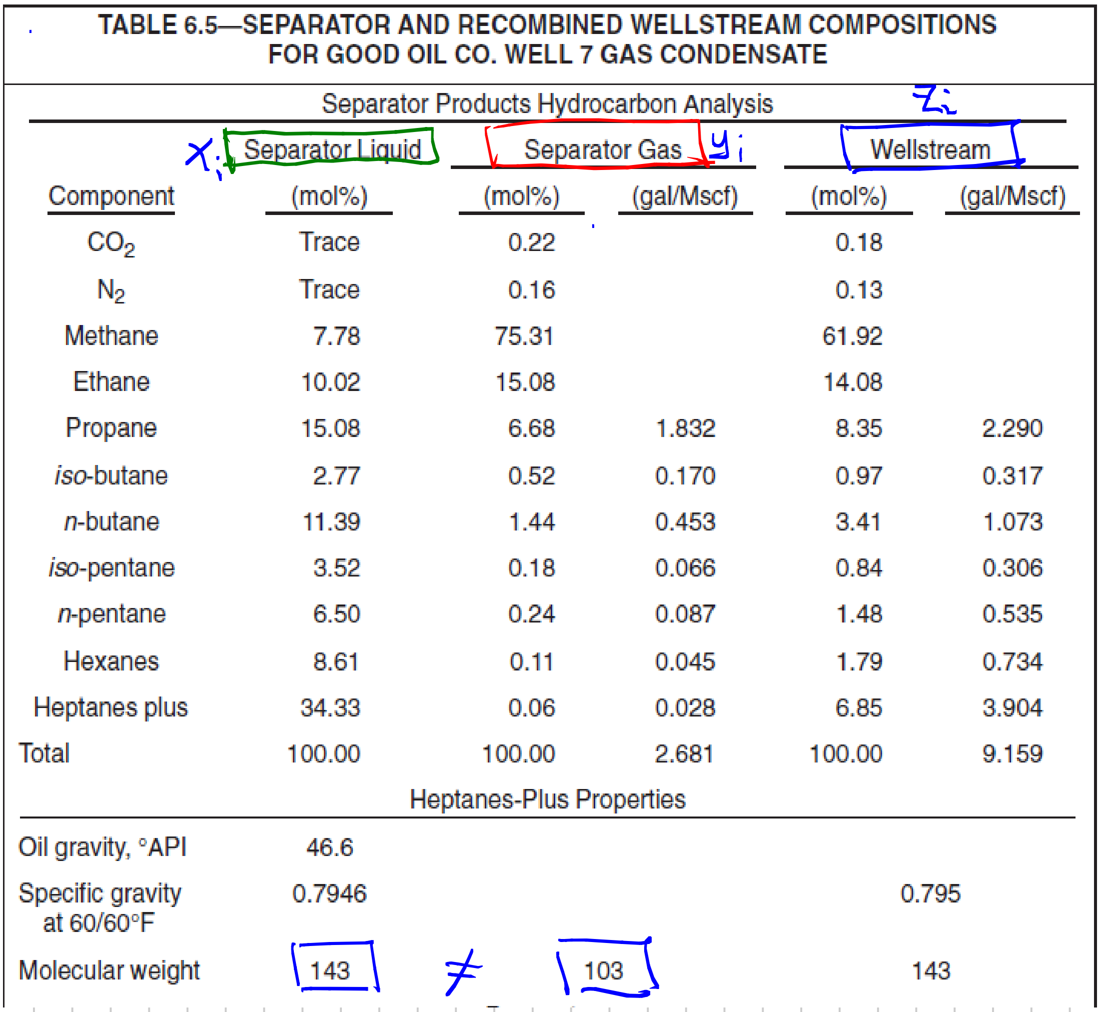


TABLE 6.5—SEPARATOR AND RECOMBINED WELLSTREAM COMPOSITIONS FOR GOOD OIL CO. WELL 7 GAS CONDENSATE

Separator Products Hydrocarbon Analysis

	x_i Separator Liquid	y_i Separator Gas		z_i Wellstream	
Component	(mol%)	(mol%)	(gal/Mscf)	(mol%)	(gal/Mscf)
CO_2	Trace	0.22		0.18	
N_2	Trace	0.16		0.13	
Methane	7.78	75.31		61.92	
Ethane	10.02	15.08		14.08	
Propane	15.08	6.68	1.832	8.35	2.290
iso-butane	2.77	0.52	0.170	0.97	0.317
n-butane	11.39	1.44	0.453	3.41	1.073
iso-pentane	3.52	0.18	0.066	0.84	0.306
n-pentane	6.50	0.24	0.087	1.48	0.535
Hexanes	8.61	0.11	0.045	1.79	0.734
Heptanes plus	34.33	0.06	0.028	6.85	3.904
Total	100.00	100.00	2.681	100.00	9.159

Heptanes-Plus Properties

Oil gravity, °API	46.6				
Specific gravity at 60/60°F	0.7946			0.795	
Molecular weight	$\boxed{143}$	$\boxed{103}$		143	

$\boxed{143} \neq \boxed{103}$

High GOR (R)

$\Rightarrow F_g \rightarrow 1$

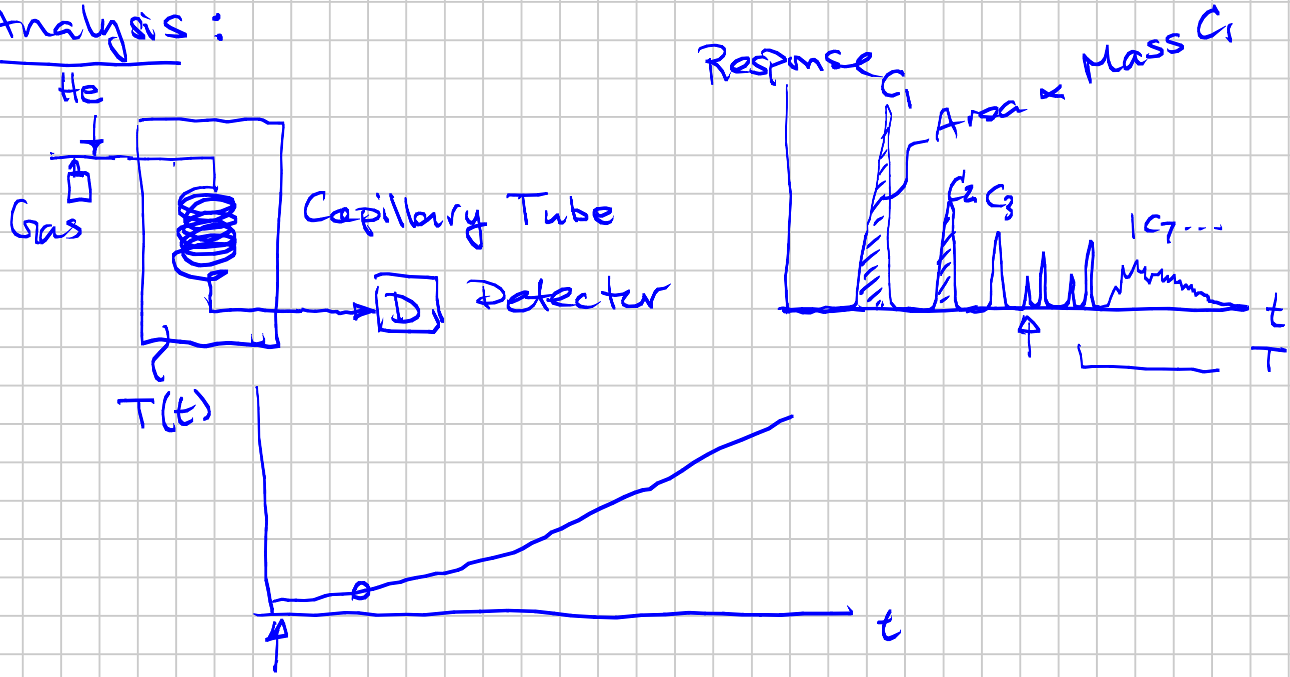
$z_i \sim y_i$

$$F_g\left(\frac{V_g}{V_o} = R, \rho_o, M_o\right)$$

$$F_g = \frac{n_g}{n}$$

$$\frac{n\, z_i}{n} = \frac{n_g\, y_i}{n} + \frac{n_o\, x_i}{n} \Rightarrow \overset{\downarrow}{z_i} = F_g \overset{\downarrow}{y_i} + (1-F_g)\, x_i$$

GC Analysis:



⇒ w_i weight fractions

$$n_i = \frac{w_i}{M_i}$$

$$[y_i] = \frac{n_i}{n} = \frac{w_i/M_i}{\left(\sum_{j=1}^{N} w_j/M_j\right)} \Bigg\} \quad \text{Ch. 5}$$

mole fractions of all i depend

Known | Estimate

M_i of N_2 CO_2 H_2S . . . nC_5 C_6 C_7 C_{N+}

on all M's M_{C_6} M_{N+}

GC can accept

*- Atmospheric (dead) oil

*- Somewhat pressurized gas

* NOT RESERVOIR FLUIDS DIRECTLY

* NOT SEPARATOR OIL

SEPO/RF ⇒ Create STO STG by Flashing @ ~1 atm

$$\underbrace{\overset{\downarrow}{GC_1} \qquad \overset{\downarrow}{GC_2} \qquad \overset{\downarrow}{GOR}}$$

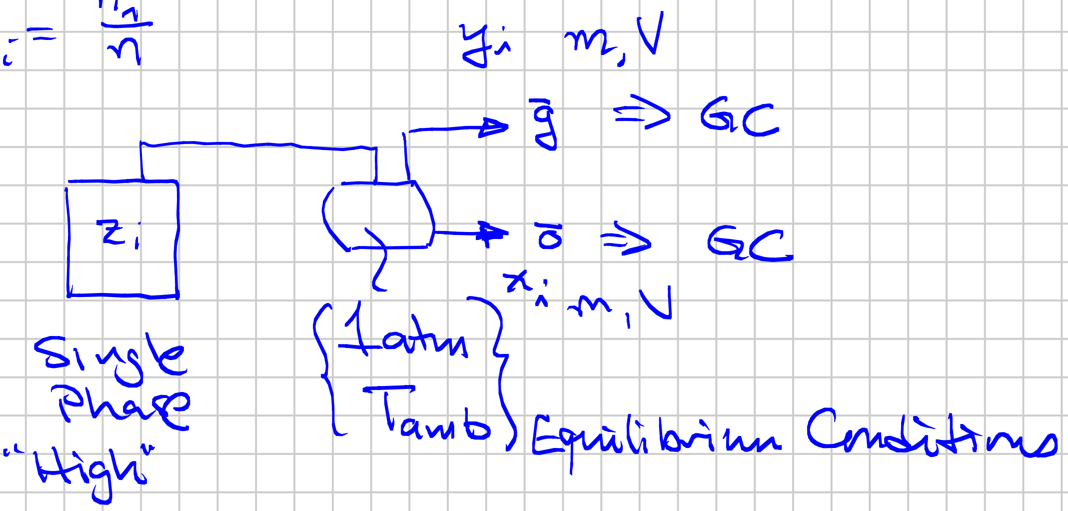
$\Rightarrow$ RF z_i

SEPO $(x_i)_{osp}$

Equilibrium

Flash / GC / Recombination

$z_i = \frac{n_i}{n}$



Gases (RG or rich sep. gas or higher-GOR oils)

① Freeze w/ Liquid N_2 in a glass container

② Heat-off the light components into a gas bottle (metal)

③ Left with a $\underbrace{\text{oil (condensate) and some gas}}_{\text{not in equilibrium}}$

✓ $\boxed{z_i = F_g y_i + (1-F_g) x_i}$

Component

$F_g = \frac{n_g}{n}$.

$$F_g = \left\{ \frac{1}{1 + \underline{GOR}^{-1} \cdot \left(\frac{RT_{sc}}{p_{sc}}\right)\left(\frac{\rho_o}{M_o}\right)} \right\} \qquad \frac{GOR}{GOR + \rho/M}$$

consistent units

GOR $[m^3/m^3]$

ρ $[kg/m^3]$

M $[kg/kgmole]$

$$F_g = \frac{n_g}{n_g + n_o}$$

Basis: $1\ m^3$ oil(o) $= V_o$

$V_g = GOR \cdot V_o = GOR$

$n_g = \left[V_g \Big/ \left(\frac{RT_{sc}}{p_{sc}}\right) \right]$

$n_o = V_o \cdot \frac{\rho_o}{M_o} = \frac{\rho_o}{M_o}$

PVT Lab Measurements of Res. Fluid

- p_{sat} & BP or DP @ T_R ✓
- ρ @ $p \geq p_s$ @ T_R ✓
- $V_g(p<p_s)$ & $V_o(p<p_s)$ | $V_t(p<p_s)$ ✓

{ - $\mu(p>p_s)$ }

CONSTANT COMPOSITION EXPANSION (CCE)

— " — MASS — " — (CME) $\lesssim 250\ \mathrm{Sm^3/Sm^3}$ Lower-GOR OILS

High-P, -T Cell

I. "Blind" Cell ($V_t(p)$)

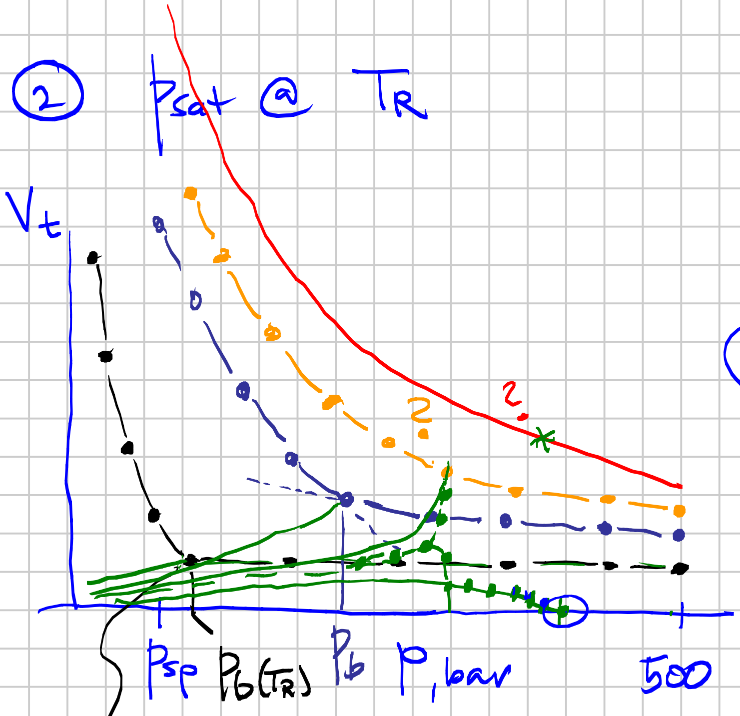
II. Windowed Cell ($V_g(p)$ $V_o(p)$)

① Charge (Fill) with RF : "z_i" in the Cell

(a) Transfer directly single phase MDT or BHS to the cell

⇒ (b) Physically recombine sep. oil & sep-gas in the cell in the CORRECT proportion (ratio) as was producing when samples collected.

② p_{sat} @ T_R



Clear Discontinuity in $V_t(p)$ @ p_b

z_i → (
— V_{osp} (no SepGas)
=
— V_{osp} V_{gsp1}
=   ∧
— V_{osp} V_{gsp2}
=   ∧
— V_{osp} V_{gsp}
)

Higher-GOR Systems ($\gtrsim 250\ \mathrm{Sm^3/Sm^3}$)

Visual measure of $V_o(p)$

extrapolate to ↗ $= V_t$ (BP)
↘ $= 0$ (DP)

CCE Summarize Measurements

$\boxed{T_R = \text{const.}}$ (sometimes $T < T_R$ $T \to 100°F \to$)

Measured

p	V_t	$\{V_o\}$	$\{V_g\}$
p_{Ri}			
		Not Reported	
$\boxed{p_s}$	$\boxed{V_s}$		
$[p_{low}]$			

Reported ✓ ✓ OR

p	$\frac{V_t}{V_s}$	$\left\{\frac{V_o^{(p)}}{V_s}\right\}$ | $\left\{\frac{V_g^{(p)}}{V_t^{(p)}}\right\}$	ρ	Z_g
	< 1		Single Phase	
p_s	1.00	>	↑	
	> 1			
	~ 4			

DEPLETION TESTS

* Remove Gas at each new pressure step → Cryogenic Flash Process y_i

* Start test at p_s

* How the two phases change in amount and properties as $p \to$ drops.

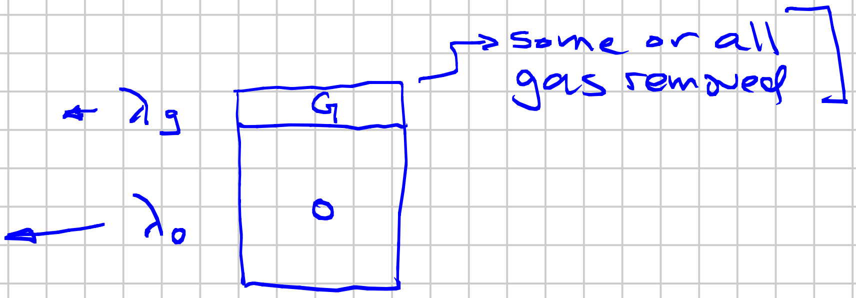
$(V_o \quad V_g) \neq S_o \quad S_g$

$\rho_o \quad \rho_g \quad = f(p < p_s)$

$\mu_o \quad \mu_g$

$\{x_i\} \; [\underline{\underline{y_i}}] \rightsquigarrow$ Liquids ($\underline{\text{STO}}$ + $\underline{\text{NGL}}$) $= f(p)$

} ≈ actual gas & oil in Res. as it depletes



CCE: $\lambda_g = 0$

Other Two : $\lambda_g >> \lambda_o$

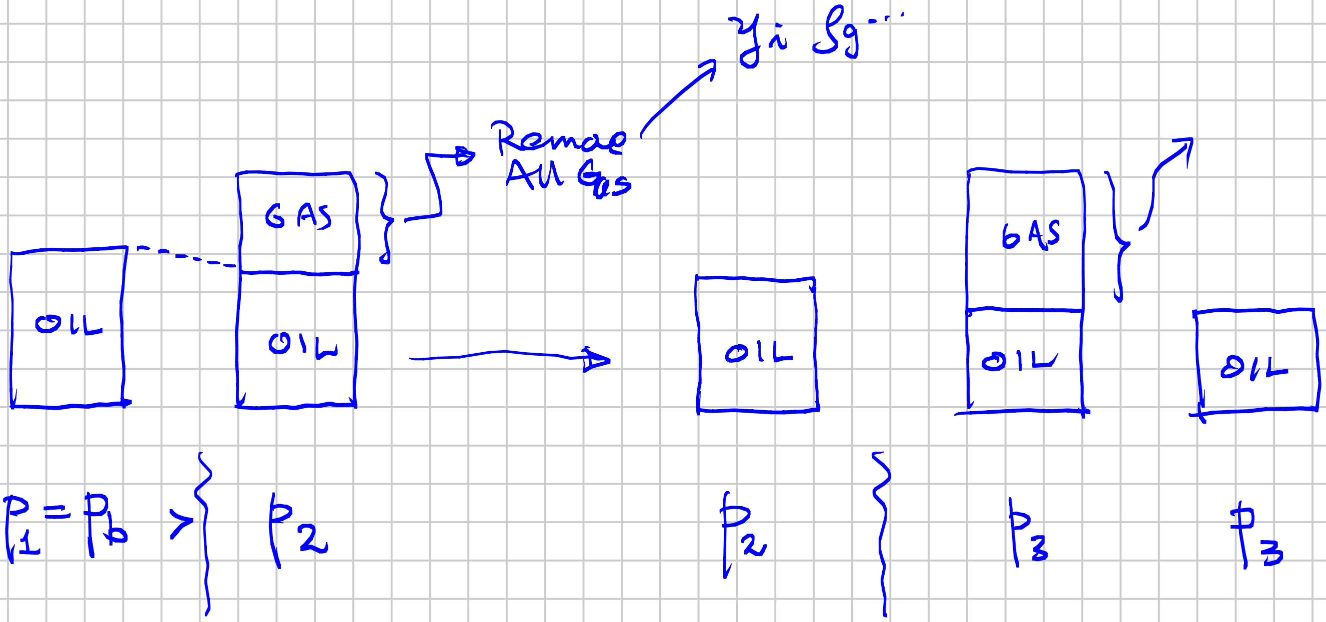
PVT Test

@ p

Depletion Process where ALL Gas Removed each step

Differential Liberation Experiment (DLE)

=> Only used for Reservoir <u>OILs</u>



6 – 10 stages

PVT "DEPLETION" LABORATORY TESTS (Ch. 6)

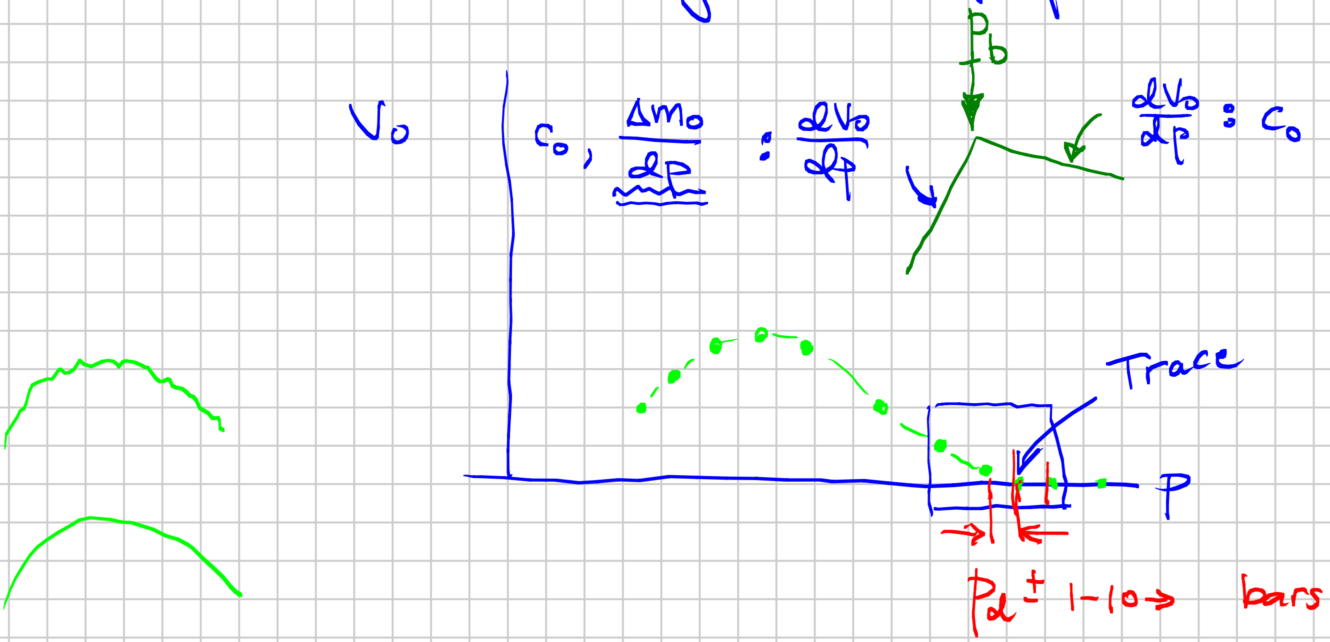
- CCE : ✓ p_s & BP or DP
  - ✓ $\rho\,(p \geq p_s)$ and/or $Z_g\,(p \geq p_d)$
  - ✓ $V_t\,(p < p_s\,;\, p > p_s)$

  } "Blind" PVT Cell

  $\{ V_o\,(p < p_s) \}$ visual PVT cell*

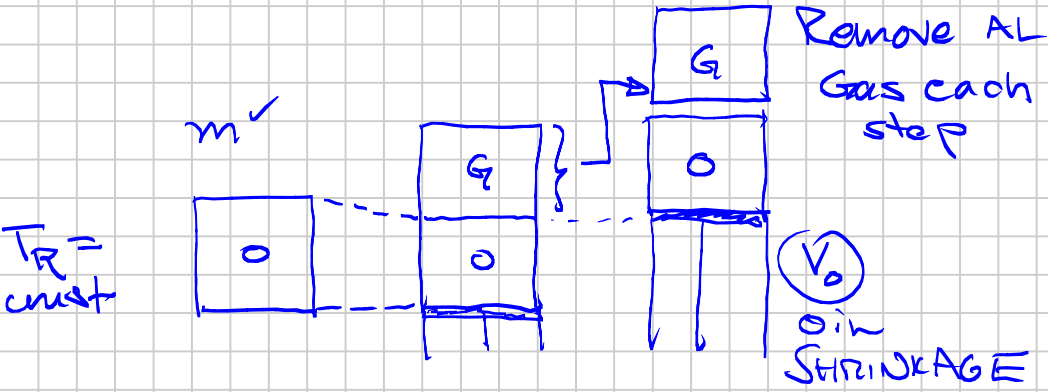
$\underset{\sim\sim}{p \geq p_s}$ $\qquad \underset{\checkmark}{\rho(p)} = \frac{m}{V(p)} = \frac{p\overset{\checkmark}{M}}{RTZ}$ ⇒ Calc. Z_g

* Discontinuity in $V_o\,(p = p_s)$



Depletion Test: Traditionally Used (Only) for OILS

Differential Liberation Test (DLE)



M_g (γ_g) ✓ (y_i)

(ΔV_g) $\underline{(\Delta n_g)}$ @ (p_2, T_R)

$\Rightarrow$ $pV = nRTZ$ ✓ ✓ ✓ ✓ ✓ ↑

Z_g ± 2-4%

$p_1 = p_b$ > p_2 .... p_2

$\Downarrow$

$$\rho_o = \frac{(m_o)_{M.B.}}{V_o}$$

±1-2%

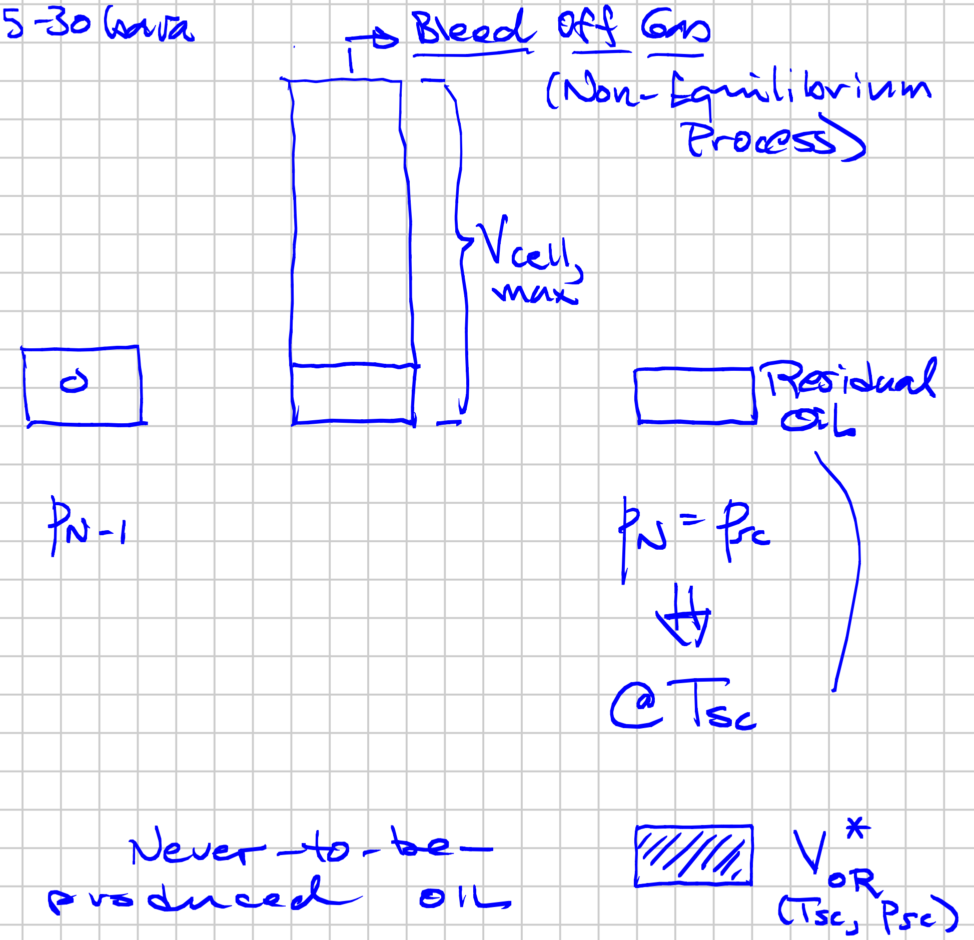
Repeated p...

(5) 7-10 ( )

Appendix D. DLE (& Multi-Stage Separator Test)

Final Step (N): $p_{N-1} \rightarrow p_N = p_{sc}$

@ T_R 15-30 bara



Lab Reports DLE test results

$\Delta V_{\bar{g}} = \Delta n_g \cdot 23.68$

RELATIVE to V^*_{oR}

p	$B_{od} \equiv V_o/V^*_{oR}$	ΔR_{sd} $\left(\frac{\Delta V_{\bar{g}}}{V^*_{oR}}\right)$	$R_{sd} = (\Delta R_{sd})_{max} - \Delta R_{sd}$	ρ_o	Z_g	γ_g	DLE (2) μ_o
p_b		0	132				
⋮		Cumulative ↓					
$p_N = p_{sc}$		132 Sm^3/Sm^3	0				

Sm^3 Residual Oil @ T_{sc}

✓ { NEVER use these #s directly in any engineering calculation

---

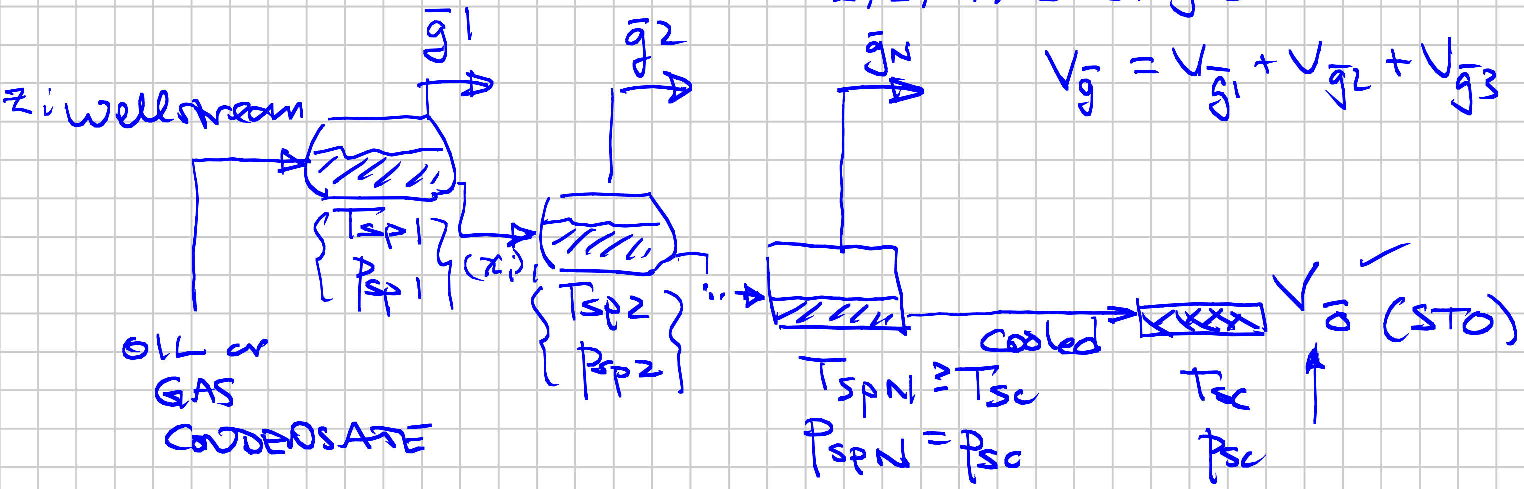
(Only for GORs ≲ 5000 $\frac{scf}{STB}$ 1000 $\frac{Sm^3}{Sm^3}$)

MULTI-STAGE SEPARATOR TEST:

~ Approximate a Realistic Surface Process of creating sellable products $\bar{g}$ & $\bar{o}$

2, 3, 4, 5 stages

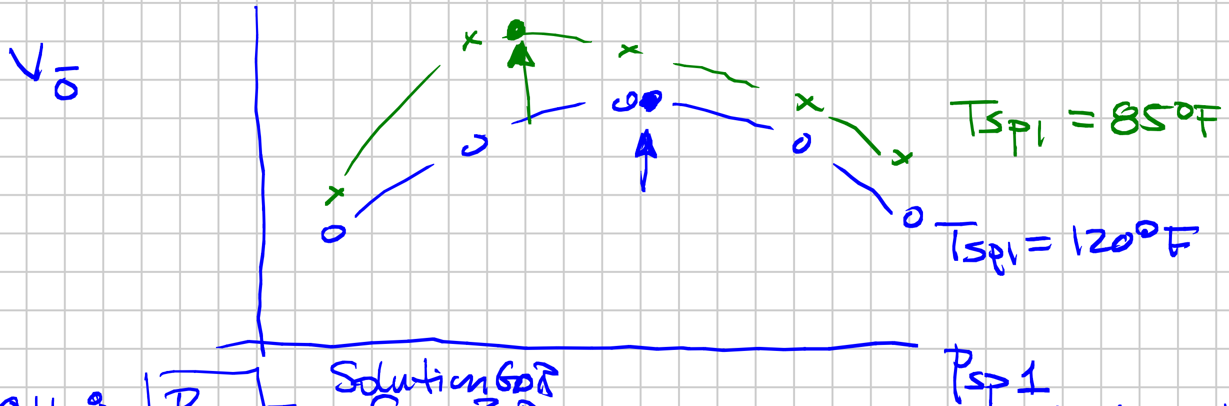
$V_{\bar{g}} = V_{\bar{g}1} + V_{\bar{g}2} + V_{\bar{g}3}$



Continuous Oil Shrinkage ⇒

Minimize — " — STO Shrinkage

by changing $(T_{sp}, \underline{\underline{P_{sp}}})$ ...



$\underline{\text{OIL}}$: $\boxed{R_{sb}}$ = Solution GOR from B.P. Oil

Gas Condensate:

$\Rightarrow$ $GOR = \dfrac{V_{\bar{g}}}{V_{\bar{o}}}$; $OGR = \dfrac{V_{\bar{o}}}{V_{\bar{g}}} = \boxed{r_{sd}}$ = Solution OGR from DP Gas

$\{\rho_{\bar{o}} \quad \gamma_{API}, \gamma_{\bar{o}}\}$

Oil FVF @ BP

$\boxed{\underline{\underline{FVF}}}$ $\dfrac{V_s(T_R, P_s)}{V_{\bar{o}}}$ OILS $\dfrac{V_{ob}(T_R, P_b)}{V_{\bar{o}}} = \boxed{B_{ob}}$

GASES $\dfrac{V_{gd}}{V_{\bar{g}}} = \boxed{(B_{gd})_d}$

"dry"

dewpoint

Each Stage Gas: $\overset{\checkmark}{V_{\bar{g}}}$ $\overset{\checkmark}{\gamma_g}$ $\overset{\checkmark}{(y_i)}$ $\underline{(V_{\bar{g}}/V_{\bar{o}})}$ OR $\underline{(V_{\bar{g}}/V_{osp})}$

Oil: $[V_{osp}(p_{sp}, T_{sp})] / V_{\bar{o}} = B_{osp}$

Separator Oil Volume Factor

App. D (also Ch. 6) Multistage Sep. Test

How to combine DLE data & "SEP" data
⇒ Black-Oil PVT properties for
① engineering calculations.

using a simplified method that is often OK,
sometimes not.

DEPLETION PVT LAB TESTS

- CCE (Oils & Gas Condensates)
- DLE (Oils)
- SEP (O & GC)

} Oils ⇒ ~ Black-Oil PVT Tables

- CVD : Constant Volume Depletion (GC & higher-GOR Oils)

$\gtrsim 400-500$ Sm^3/Sm^3

↓

GENERAL BLACK-OIL PVT (Ch. 7)
(Modified)

CVD : Mainly Gas Condensates

Start @ p_s

Remove Gas @ each stage of depletion
(not all of it)

{ "STO" ($\bar{o}$) Carrying capacity of Reservoir Gas
AS A FUNCTION OF RESERVOIR PRESSURE

"C_{n+}"

→ $y_i(p, T_R)$ $i \in$ "C_{5+} C_{6+} C_{7+}"

←

High Low

Surface Process Efficiency

$\boxed{y_{n+}} \propto$ Surface Oil Rate

6

DLE : Could measure y_i : $\underbrace{y_{n+}}(p)$ $\underline{\pm}$

└ Oils releasing gas out of solution ⇒

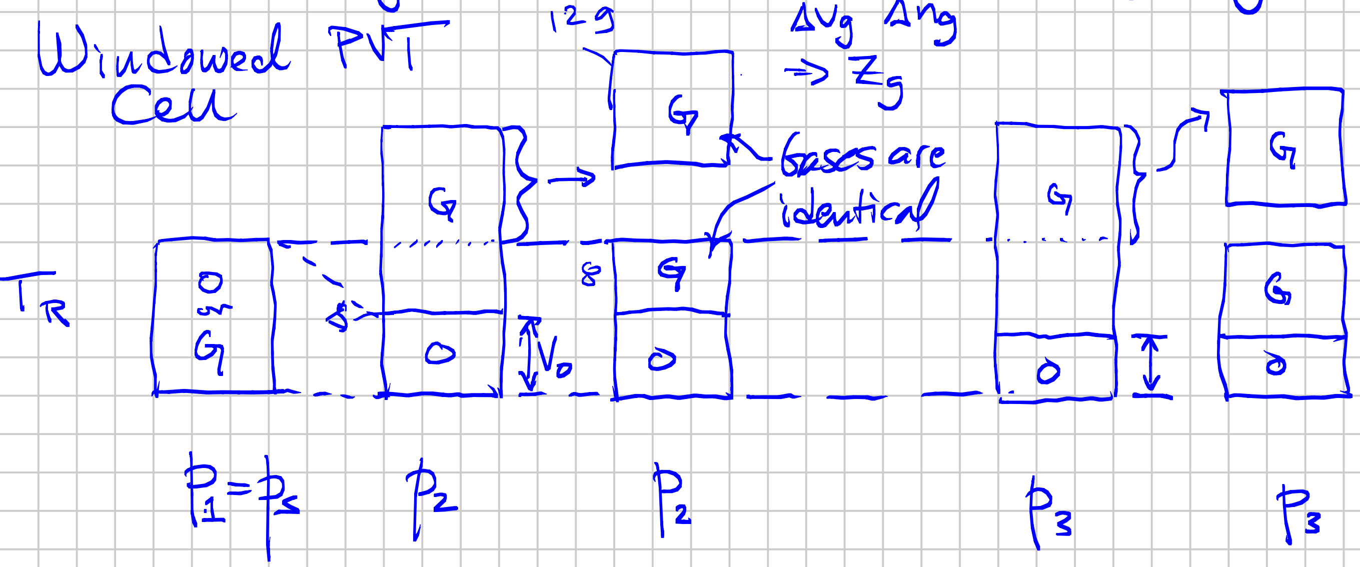
1950s - 1960s → early 1970s $\underbrace{q_{\bar{o}g} \sim 0}$ ✓✓

surface oil from gas

Lab techniques for measuring $y_{n+}(p)$ accurately are BAD.

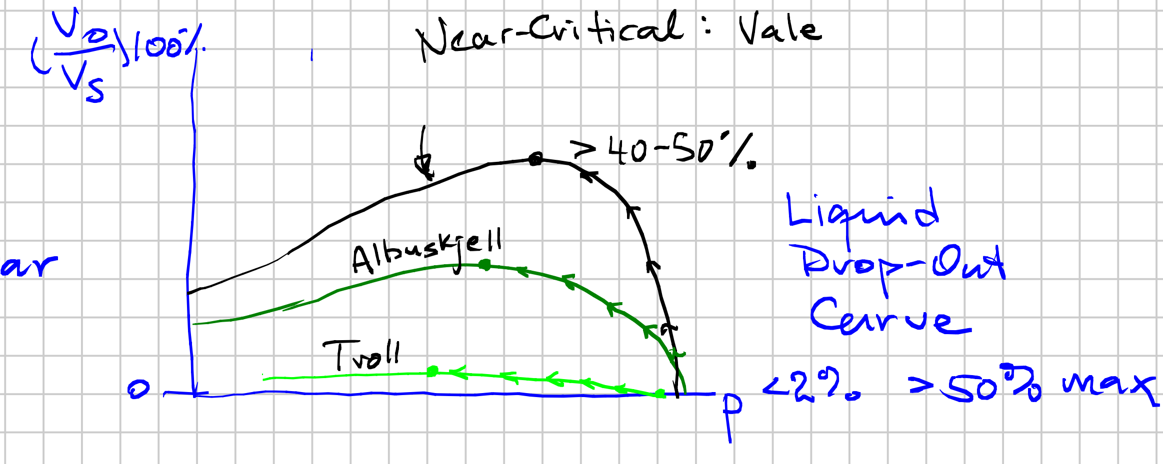
CVD : y_{n+} measured more diligently (accurately)

Windowed PVT Cell



N = 6 − 10 stages

					Calc Lee et al	Cumulative
p	y_i	(y_{n+})	V_o/V_s	Z_g	$\mu_g(M_g, \rho_g, T)$	$\Delta n_g/n$ %
p_s						



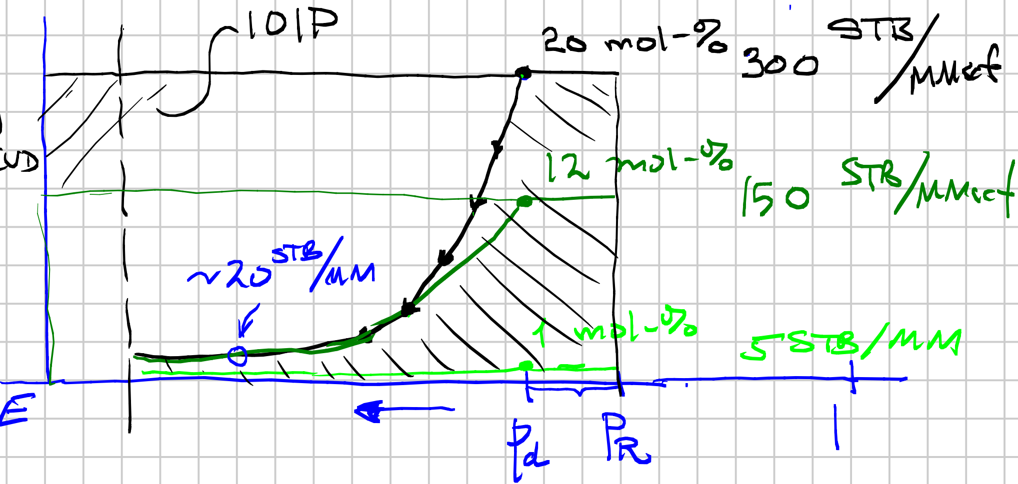
$p_N \sim$ 40-50 bar

$$\underbrace{\text{"}r_s\text{"} = \frac{q_{\bar{o}}}{q_{\bar{g}}}} \propto \left(\frac{y_{n+}}{1-y_{n+}}\right)_{CVD} \checkmark$$

CVD y_{n+}

$\Downarrow$

OIL REVENUE RECOVERY



Example: Field $q_{gF} = 10^9/\text{day} = 1\ \text{bcf/D}$

$$OGR = \frac{300\ \text{STB}}{\underline{\text{MMscf}}} \Rightarrow GOR \sim 3300\ \frac{\text{scf}}{\text{STB}} \sim 500\ \frac{\text{Sm}^3}{\text{Sm}^3}$$

$$\text{Initial Oil Rate: } 300\ \frac{\text{STB}}{10^6\ \text{scf}} \cdot 10^9\ \frac{\text{scf}}{\text{D}}$$

$= 300\,000$ STB/D ←

$= 150\,000$ STB/D

$= 5\,000$ STB/D

BLACK-OIL PVT PROPERTIES:

Compositional Analogy

OIL PHASE:

✓ R_s = solution gas-oil ratio (GOR) } "x_i" ✓

✓ B_o = oil FVF } ρ_o ✓

μ_o = oil viscosity

(V_o, V_g) "F_g" ⇐ $\boxed{GOR}$ + $\underline{\underline{(z_i)}}$

GAS PHASE:

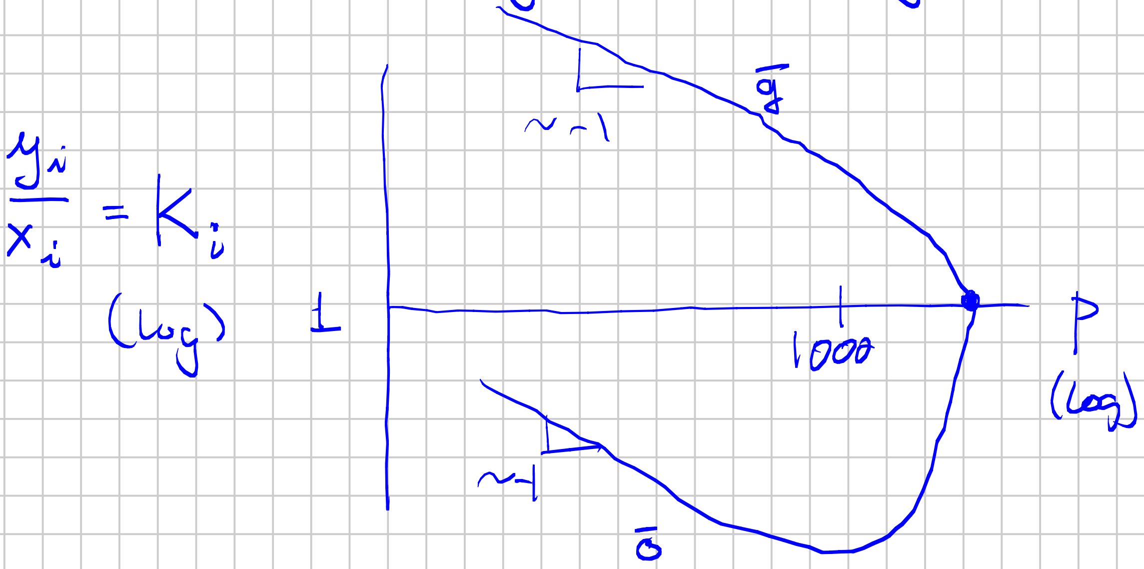
✓ r_s = solution oil-gas ratio (OGR) } "y_i" ✓

✓ B_{gd} = "dry" gas FVF } ρ_g ✓

μ_g = gas viscosity

$i \in \{\bar{g}, \bar{o}\}$

r_s = "STO carrying capacity of the Res-gas"



$\boxed{@\ p}$

① Saturated BO PVT: 2 equilibrium phases:

$\boxed{\begin{array}{l} p = p_d \text{ GAS} \\ p = p_b \text{ OIL} \end{array}}$

$$\underline{\frac{1}{r_s(p=p_d)}} \geq \underset{\checkmark}{GOR} \geq R_s\,\underline{(p=p_b)}$$

$$y_i \geq z_i \geq x_i$$

$$1 \leq F_g \leq 0$$

② Undersaturated BO PVT $\quad p > p_s \begin{cases} \text{Gas} \\ \text{Oil} \end{cases}$?

Gas: $GOR > \frac{1}{r_s(p=p_d)}$

Oil: $GOR < R_s(p=p_b)$

HOW TO CALCULATE BO PVT?

① Traditional "Old School" BO PVT

- DLE $B_{od}(p)$ $R_{sd}(p)$ $\mu_o(p)$ ✓
- SEP B_{ob} R_{sb} multistage sep. test

② Use a Compositional Model

⇒ * z_i

(e.g. z^o_{Ri} = initial reservoir composition) ← $(p_s)_i$

* Equilibrium "Flash" model

{ - Modified Wilson $K_i(p, T, p_K)$ } Never used
+ density correlations

⇒ ⊛ - Cubic EOS (equation of state)

PR : Peng Robinson (1976)

SRK : Soave Redlich-Kwong

1970 1949

⇒ * Define the surface process "$\underline{P}$"

- 1-stage flash to STC
- N-stages (p_{sp}, T_{sp}) each stage

⋮

⇒ * Define the range of pressures where you want BO PVT properties

p_{low} ~ 10 bar → p_{Ri} ++ (Account for Injection)

⇒ * Strategy to create a wide range of saturated conditions $\underline{(p_s)_i}$ → p_{low} (10 bar)

Depletion

- May also need @ $\underbrace{p > (p_s)_i}$

Injection of Gas

and/or

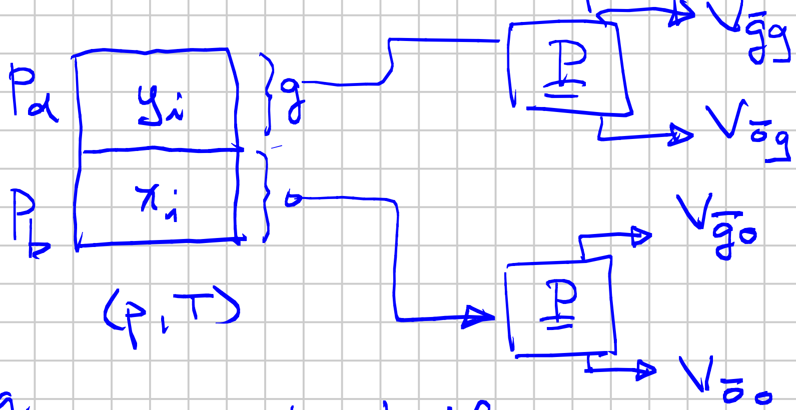
p_s (spatially)

Procedure to get Sat. & Undersat. BO PVT :

① Flash @ p, T

⇒ 2-phases gas+oil equilibrium

Phase Amounts Don't matter



↑↑

②

Take Eq. Oil away by itself :

(a) Calc (e.g. per 1 mole) $\underbrace{V_o(p,T),\ \rho_o(p,T),\ \mu_o(p,T)}$

all $p \geq p_b$ of x_i

(b) Take oil composition x_i, feed this to the surface process : $V_{\bar{g}}$ $V_{\bar{o}}$

③

Take Eq. Gas away by itself :

(a) Calc (e.g. 1 mole) $\underbrace{V_{\bar{g}}(p,T)\ \rho_g(p,T)\ \mu_g(p,T)}$

$p \geq p_d$ of y_i

(b) Take gas composition y_i feed this to surface process $V_{\bar{g}}$ $V_{\bar{o}}$

OIL Phase: x_i @ p_b, T

$\underset{s}{\checkmark}\quad R_s(p_b) = \dfrac{V_{\bar{g}o}}{V_{\bar{o}o}}$

$\underset{s}{\checkmark}\underbrace{\checkmark\checkmark\checkmark\checkmark}_{u}\quad B_o\,(p \geq p_b \text{ of } x_i) = \dfrac{V_o\,(p \geq p_b \text{ of } x_i)}{V_{\bar{o}o}}$

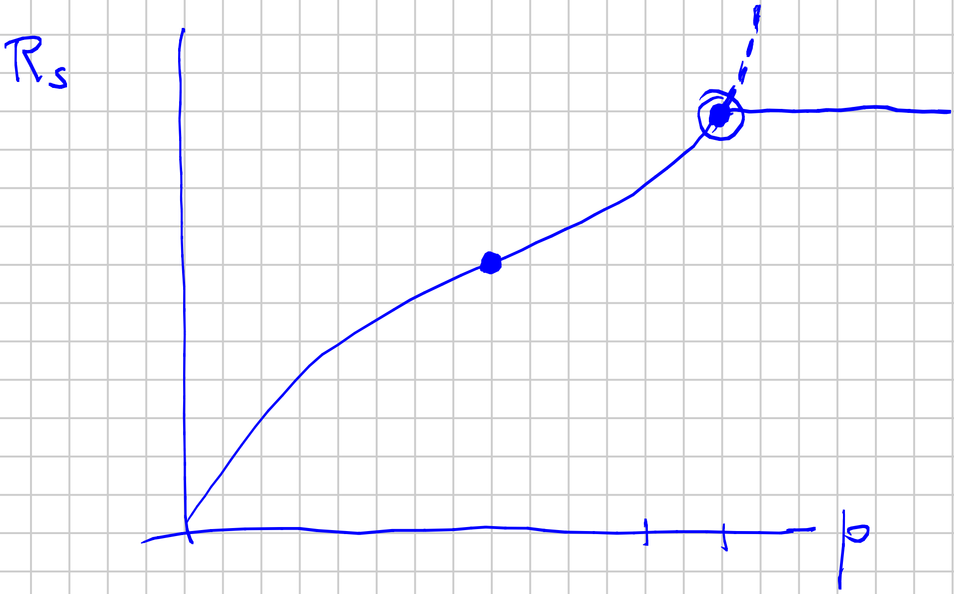
$\underset{s}{\checkmark}\ \underbrace{\checkmark\checkmark\ \checkmark}_{u}\quad \mu_o\,(p \geq p_b \text{ of } x_i)$

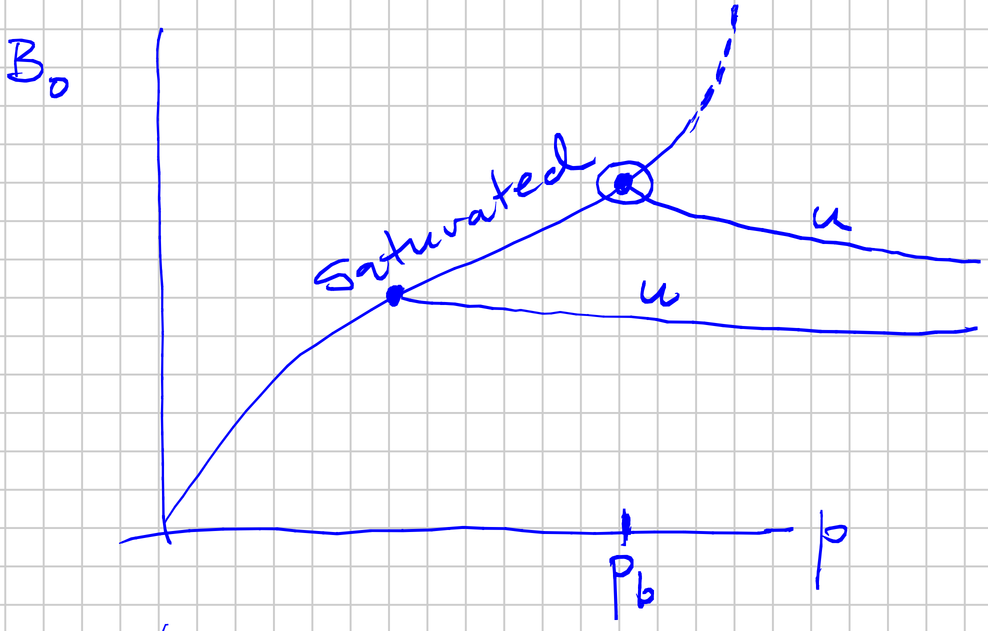
GAS PHASE: y_i @ p_d, T

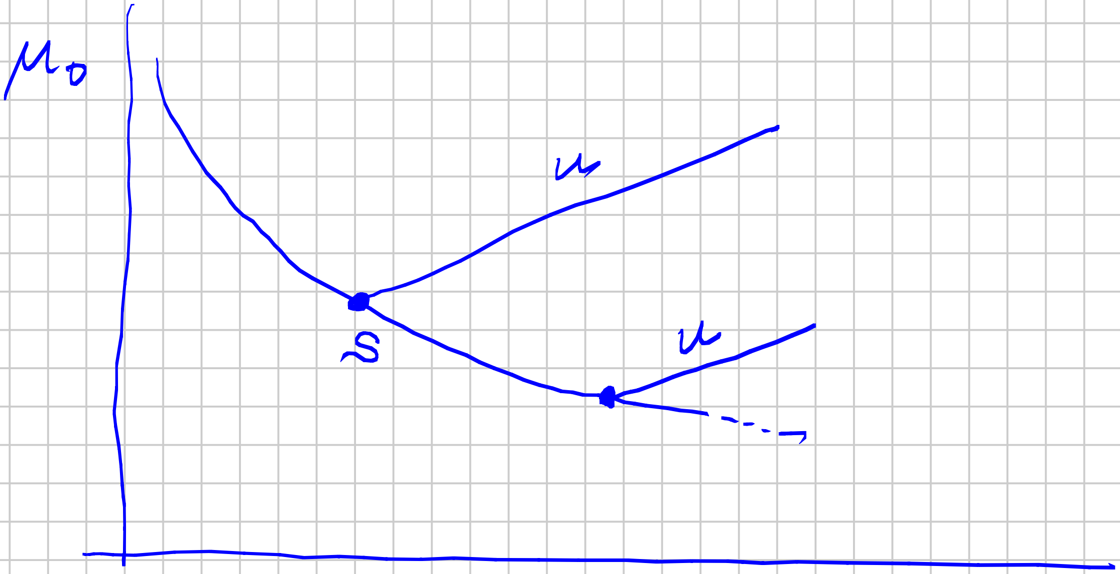
$\underset{s}{\checkmark}\quad r_s(p_d) = \dfrac{V_{\bar{o}g}}{V_{\bar{g}g}}$

$\underset{s}{\checkmark}\ \underbrace{\checkmark\checkmark\checkmark}_{u}\quad B_{gd}\,(p \geq p_d \text{ of } y_i) = \dfrac{V_g\,(p \geq p_d \text{ of } y_i)}{V_{\bar{g}g}}$

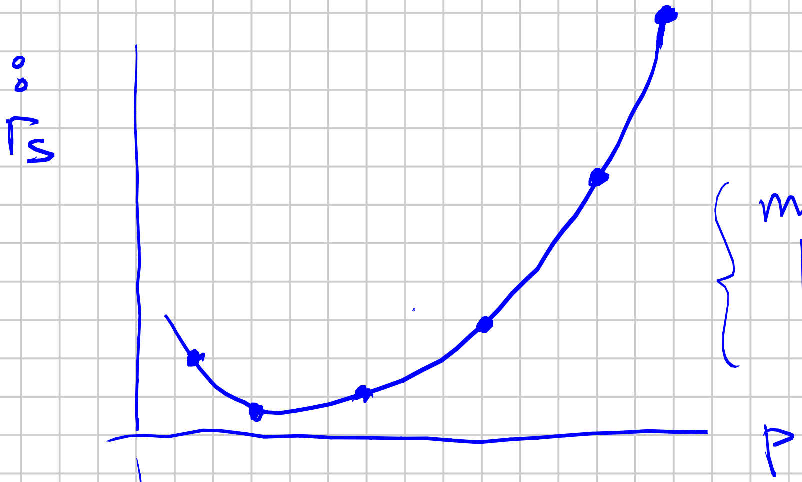
$\underset{s}{\checkmark}\ \underbrace{\checkmark\checkmark\checkmark}_{u}\quad \mu_g\,(p \geq p_d \text{ of } y_i)$





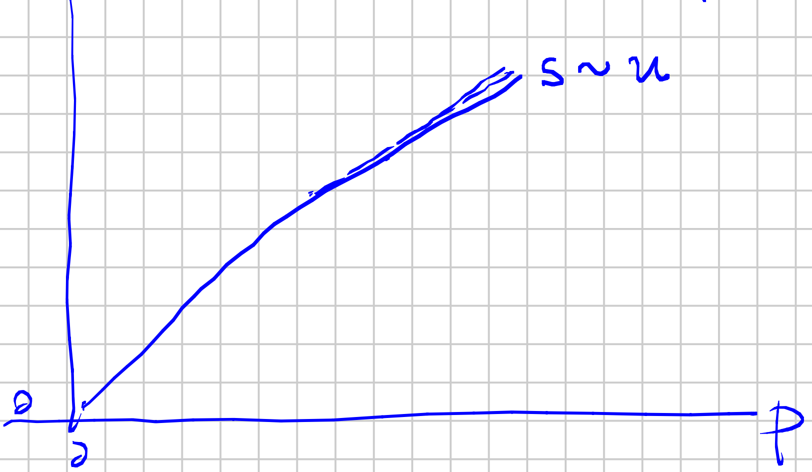


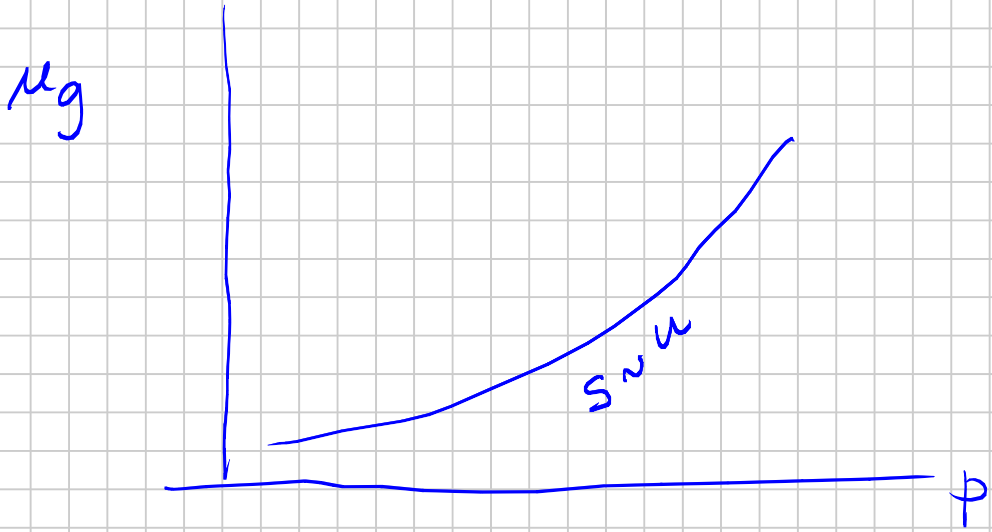
GAS PHASE :



{ mimics the K-value of C_{7+} }

$$b_{gd} = \frac{1}{B_{gd}}$$




μ_g
s~u
p

PVT SUMMARY w/ Q&A's

- Components in Petroleum Reservoir Fluids ✓
- VLE (Phase Behavior) 1- 2- n-component systems
- Gas PVT: $Z(p,T,y)$ ρ μ c B_g
- Surface Products & Processing $\underbrace{\text{GOR} \quad \text{OGR}}$ ✓
- Fluid Types: Gas & Oil (p-T ; & GOR)
- Sampling }
- PVT Lab Tests: CCE, DLE, CVD, SEP
- Black-Oil PVT: $\underbrace{\underset{\text{Oil Phase}}{B_o \quad R_s \quad \mu_o} \;\Big|\; \underset{\text{Gas Phase}}{B_{gd} \quad r_s \quad \mu_g}}_{\text{Saturated \& Undersaturated}}$

Traditional $r_s = 0$

$$B_g = \frac{p_{sc}}{T_{sc}} \cdot \frac{T_R Z}{p} \quad X$$

$$\underbrace{n_{\bar g} = n_{gR}(p,T)}_{r_s = 0}$$

$$\underline{r_s > 0 \Rightarrow \underbrace{n_{\bar g} < n_{gR}}}$$

$$\boxed{B_{gd}} = \frac{p_{sc}}{T_{sc}} \cdot \frac{T_R Z}{p} \cdot \frac{1}{(n_{\bar g}/n_{gR})}$$

"dry" by condensate removal $r_s > 0$

$$\underbrace{0.8x < \frac{n_{\bar g}}{n_{gR}} < 1}_{2020 \leftarrow 0?}$$

- PVT Correlations (Ch. 3)

  - Gas Z-factor chart ✓

  - Oils:

    (1) Bubblepoint Pressure p_b

Standing

Lasater

Glasø

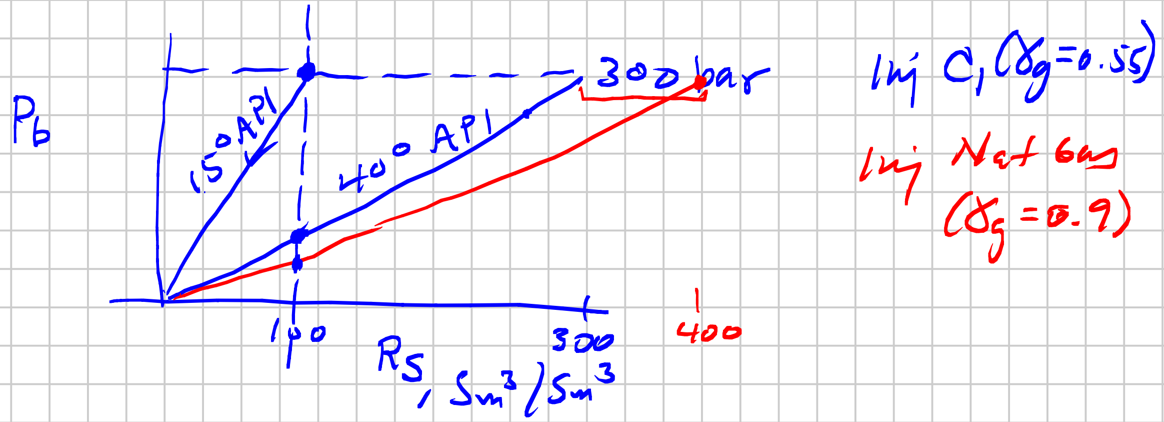
⋮

$$p_b\underbrace{(R_s,\ T,\ \rho_{\bar{o}}\,(\gamma_{API}),\ \gamma_g)}_{}$$

Always Available

↑ ↑ ↑ ↑ ↓ ↓

R_s = const
γ_{API} =
γ_g =
✓



±2-15%

$$\underset{[psia]}{p_b} = 18.2\,[A - 1.4]$$

$$A_{(p_b)} = \left(\frac{\overset{\text{scf/STB}}{R_s}}{\gamma_g}\right)^{0.83} \cdot 10^{(0.00091\overset{\text{°F}}{T} - 0.0125\gamma_{API})}$$

Standing:

Saturated Oil FVF

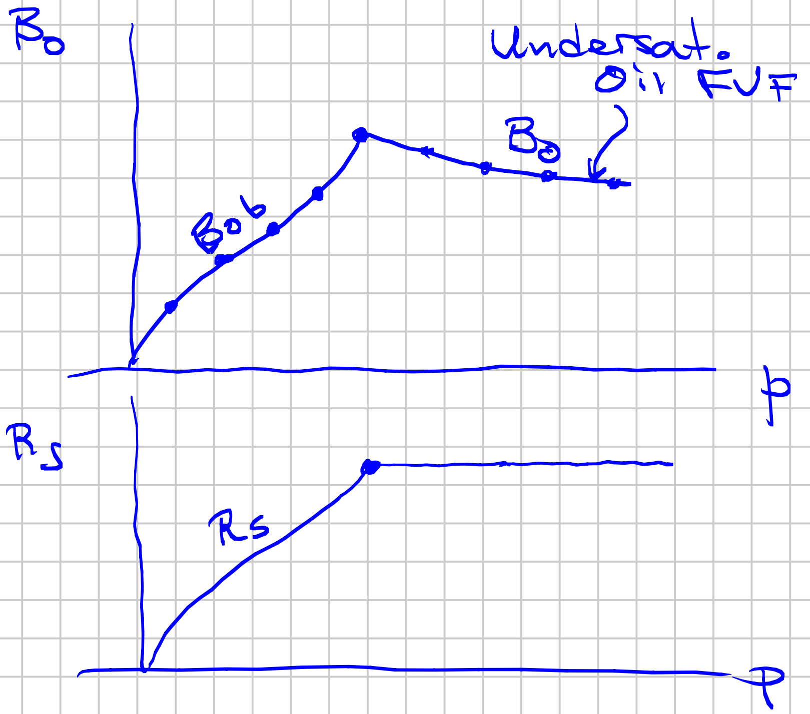
$$B_{ob}(R_s,\ T,\ \gamma_{API},\ \gamma_g)$$

$$= 0.9759 + 12\cdot10^{-5}\cdot A_{(B_{ob})}^{1.2}$$

$$A_{(B_{ob})} = \underset{\text{scf/STB}}{R_s}\left(\frac{\gamma_g}{\gamma_o}\right)^{0.5} + 1.25\,\overset{\text{°F}}{T}$$

±1-2% (3)

B_o $(p > p_b)$



$c_o \sim A/p$, $p \ge p$

$$c_o = -\frac{1}{B_o}\left(\frac{\partial B_o}{\partial p}\right)$$

$$\Rightarrow B_o = B_{ob}\cdot(p_b/p)^A$$

Vazquez:

$A(R_s, T, \gamma_o, \gamma_g)$

Ch. 6 & 7: $\rho_o = \dfrac{\rho_{\bar{o}} + \rho_{\bar{g}} R_s}{B_o}$ ✓ $p \ge p_b$

Oil Viscosity: Very difficult to get accurate (± 5 – 50+ %)

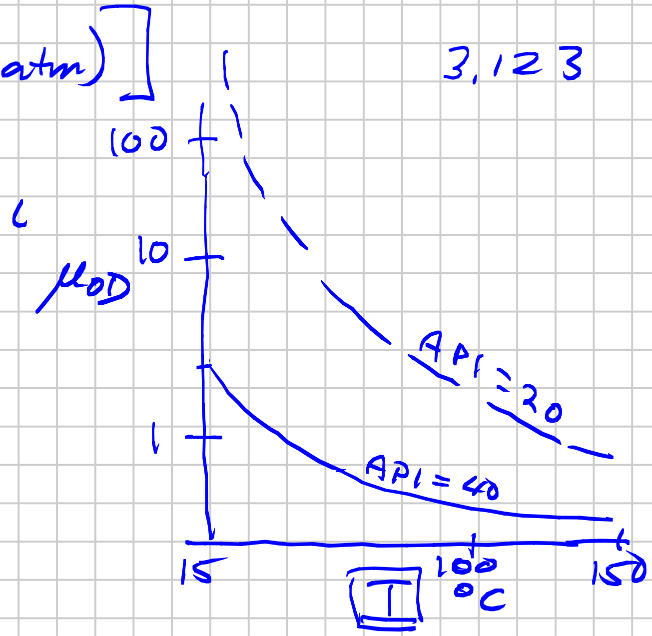
Most Correlations don't take into account "P" or "A"

@ T

$$\mu_{ob} = A\cdot\left[\mu_{OD}(T, 1atm)\right]^B$$ 3,123

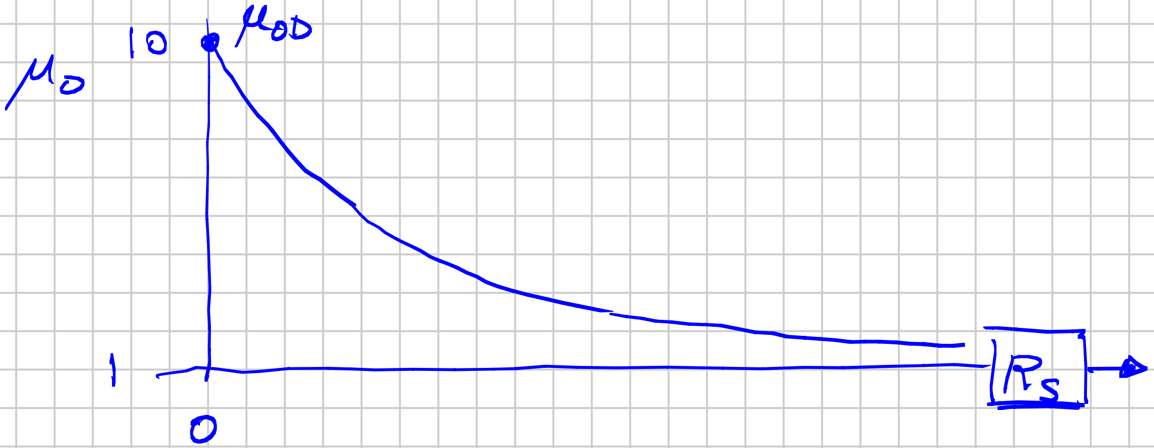
$R_s = 0$

Dead Oil

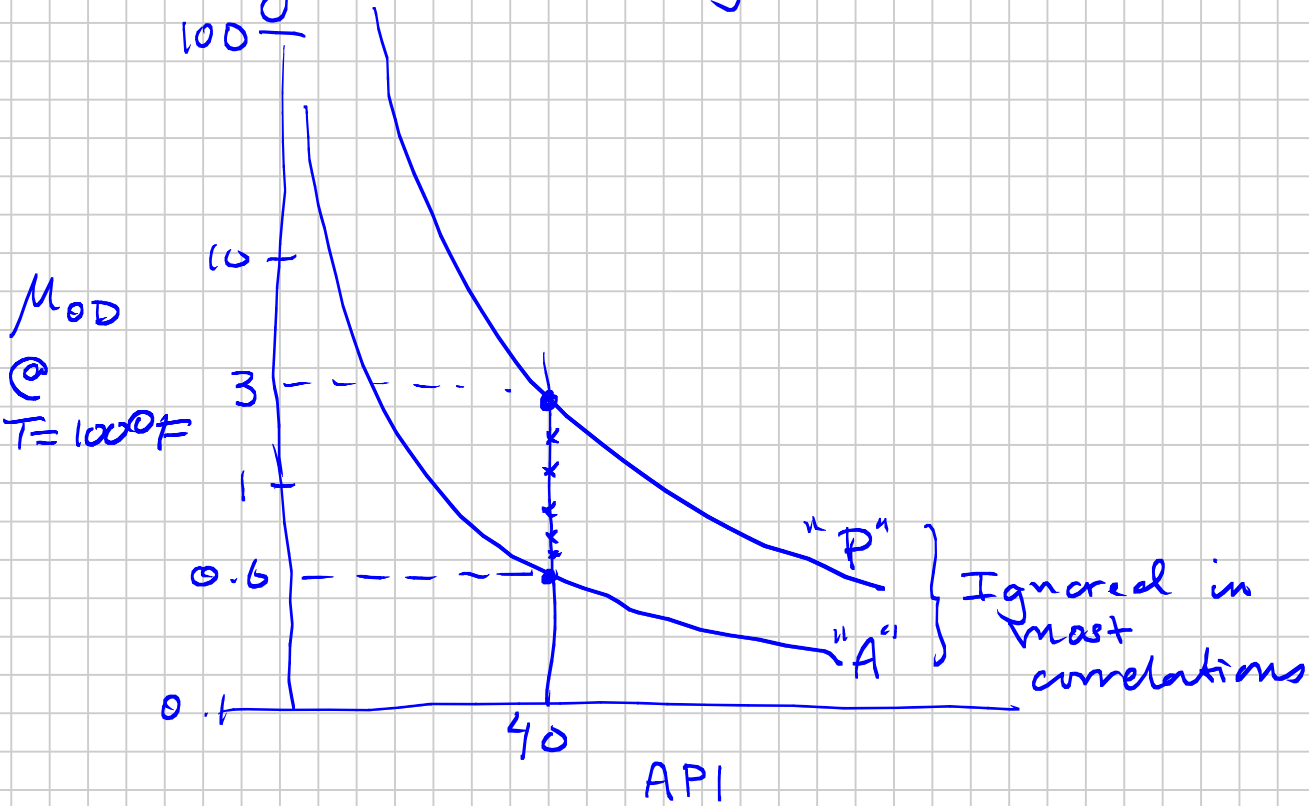


$A(R_s)$

$B(R_s)$



Paraffinicity - Aromaticity



$$\mu_o(T, R_s, \rho_{\bar{o}}, P\text{-}A)$$

Natural Gas Petroleum Engineering ⟷ "FLOW"

TASK (DRY)

① GAS RATE EQ Well $q_g \longleftrightarrow \Delta p$ Reservoir → Pipeline

@ STC

1 atm 60°F

SPE:

MMscf/D Mscf/D scf/D

Sm^3/d standard m^3 / d

std m^3

$f(t)$

$\downarrow$

$\bar{p}_R$

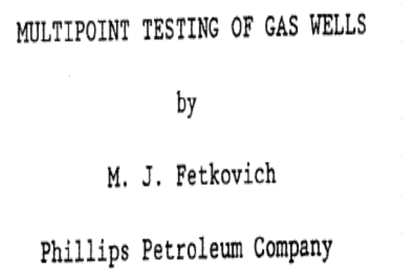
(a) Reservoir Δp_R — q_g Given Today's p_e

(b) "Tubing" Δp_T — q_g Calc q_{gw}

q_{gR} gas rate in the reservoir @ p, T_R

Mike J. Fetkovich

Mscf/D



MULTIPOINT TESTING OF GAS WELLS

by

M. J. Fetkovich

Phillips Petroleum Company

List our pressures

Darcy +

③ p_{wf} = wellbore flowing pressure

② $\bar{p}_R$ = volumetric average reservoir pressure

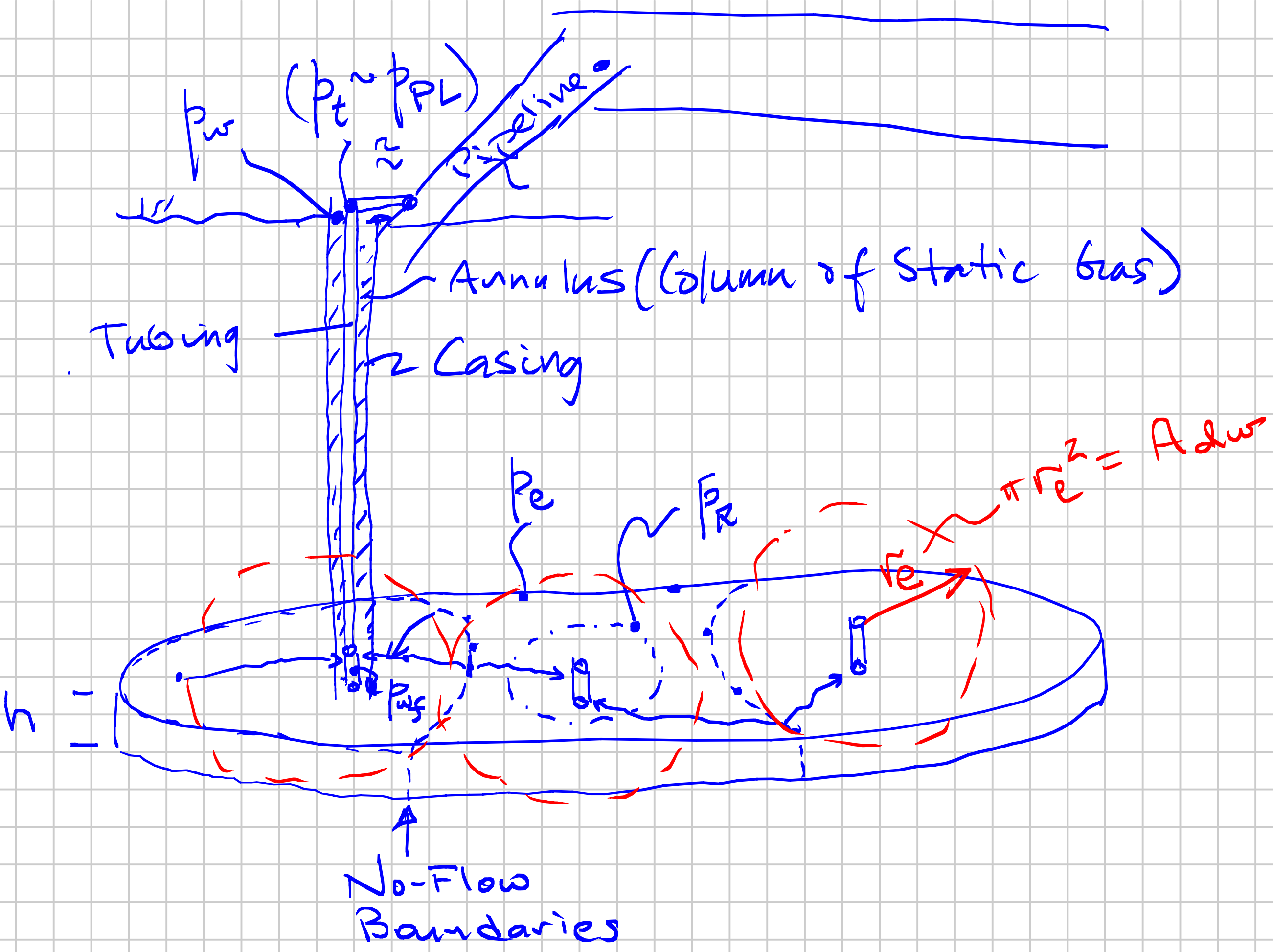
$$= \int_{V_{dw}} p(V)\, dV$$

① p_e = pressure at the external outer boundary

p_t = tubing flowing pressure

p_w = annulus pressure flowing @ surface

$p_{wf} \to p_t$: Tubing (Friction + Gravity) | $p_{wf} \to p_w$ Annulus (Gravity)



Homogeneous (φ, Sw, k) Reservoir

$$V_{dw} \propto \frac{q_{fw}}{\sum_{u=1}^{3} q_{fu}} = \frac{q_{fw}}{q_{fF}} = \frac{V_{dw}}{V_{dF}}$$

#1 Job of a Petroleum Engineer is

Forecast q(t) G&O => Revenues, NPV, Company Value

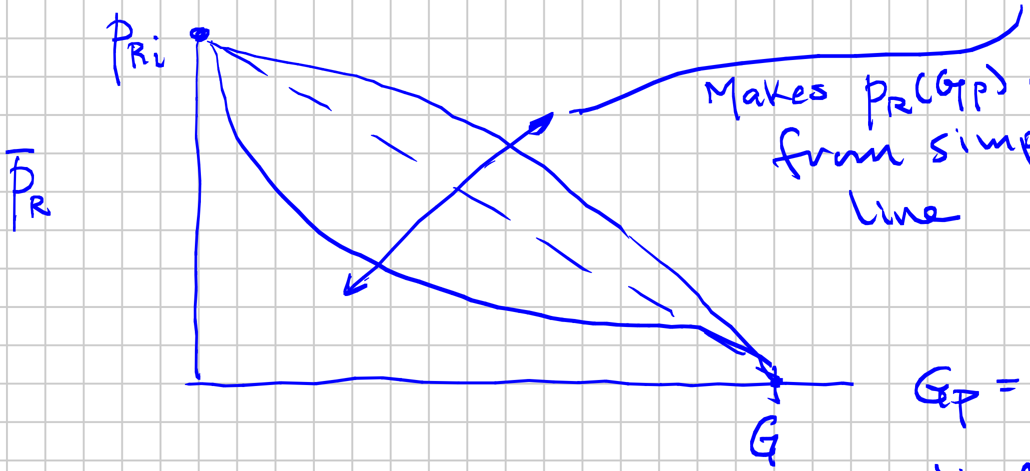
TASK

②

$$\underline{\underline{p_R(t)}} = f\left(\underbrace{\int_0^t q_{gF}\,dt}_{\underline{\underline{G_p}}}\right)$$

$\underline{\underline{G_p}}$ = cumulative gas production

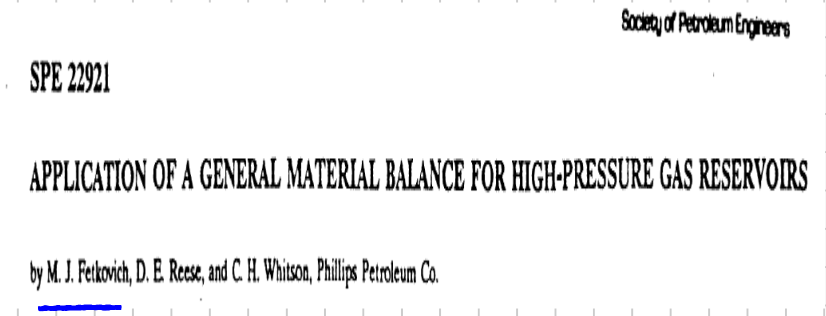
Gas Material Balance: $p_R(G_p, \dots)$



Makes $p_R(G_p)$ deviate from simple straight line

G_p = Cum. Gas Produced

IGIP = Initial Gas ($\bar{g}$) in Place



Society of Petroleum Engineers

SPE 22921

APPLICATION OF A GENERAL MATERIAL BALANCE FOR HIGH-PRESSURE GAS RESERVOIRS

by M. J. Fetkovich, D. E. Reese, and C. H. Whitson, Phillips Petroleum Co.

TASK ③ PRODUCTION DECLINE PERFORMANCE

- of individual wells and/or
- Entire Field

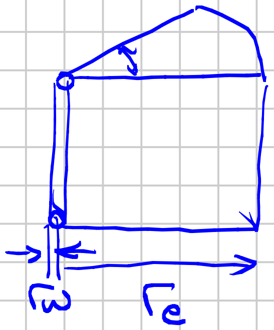
"DECLINE CURVE ANALYSIS" (DCA)

Father of DCA : MJ Fetkovich

Reservoir Gas Rate Equation

$q_g \leftrightarrow p_{wf} \cdot p_R \; (p_e)$

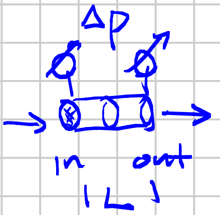
$$\boxed{q_g = \frac{(kh)\overset{PVT}{(p_{pR} - p_{pwf})}}{T_R \cdot \underbrace{\left[\ln\frac{r_e}{r_w} - \frac{3}{4}\right]}_{\sim 8-10}}}$$



Darcy Velocity

Darcy's Law: $v = \frac{k}{\mu} \cdot \frac{\Delta p}{L}$

≠ pore velocity



$q = v \cdot A$

bulk Area ⊥ to flow

$A = \pi\left(\frac{d_{core}}{2}\right)^2$

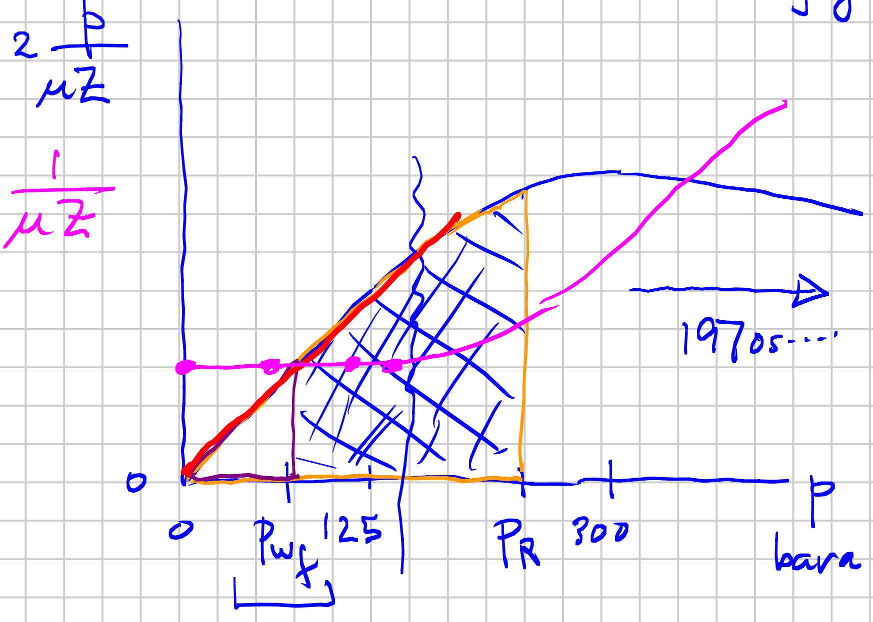
$$p_{pR} \equiv 2 \cdot \int_0^{p_R} \frac{p'}{\mu Z}\, dp'$$

$\left(\frac{\rho}{\mu}\right)$

$-$

$$p_{pwf} = 2 \cdot \int_0^{p_{wf}} \frac{p}{\mu Z}\, dp$$

Given Gas (γ_g, y_i)



$p_{pR} - p_{pwf}$ = Driving Potential for Darcy

WE Control

History Lesson 1966: Al-Hussainy Ramey & Crawford

<1960s+ $p_{Ri} \le 150$ bara

$\frac{p}{\mu Z} = m \cdot p$ straight line

$\boxed{p_p} = 2\int_0^p \frac{p}{\mu Z}$

$m(p)$: OLD SPE

Low-Pressure Gas Rate Equation

$$q_g = \frac{(kh)\cdot 2\cdot(p_R^2 - p_{wf}^2)}{\underbrace{T_R\,(\mu Z)^*}_{\text{const}}\left[\ln\frac{r_e}{r_w} - \frac{3}{4}\right]}$$

T_R &

$*$ At p_{Ri}

or

p_{sc}

$$q_g = C\,(p_R^2 - p_{wf}^2)$$

MJF : $\displaystyle\int \frac{1}{\mu_g B_g}\,dp = \frac{T_{sc}}{\underbrace{p_{sc}T_R}}\int \frac{p}{\mu Z}$

ARC : $\displaystyle 2\int \frac{p}{\mu Z}\,dp$

$$B_g = \frac{p_{sc}}{T_{sc}}\cdot\frac{Z T_R}{p} \qquad \frac{1}{B_g} = \frac{T_{sc}}{T_R\,p_{sc}}\,\frac{p}{Z}$$

Field Units:

q_g	scf/D
k	md
h	ft
p	psia
T	°R
μ	cp

$$q_g = \frac{0.703\,kh\,(p_R^2 - p_{wf}^2)}{T_R\,(\mu Z)^*\left[\ln\frac{r_e}{r_w} - 3/4\right]}$$

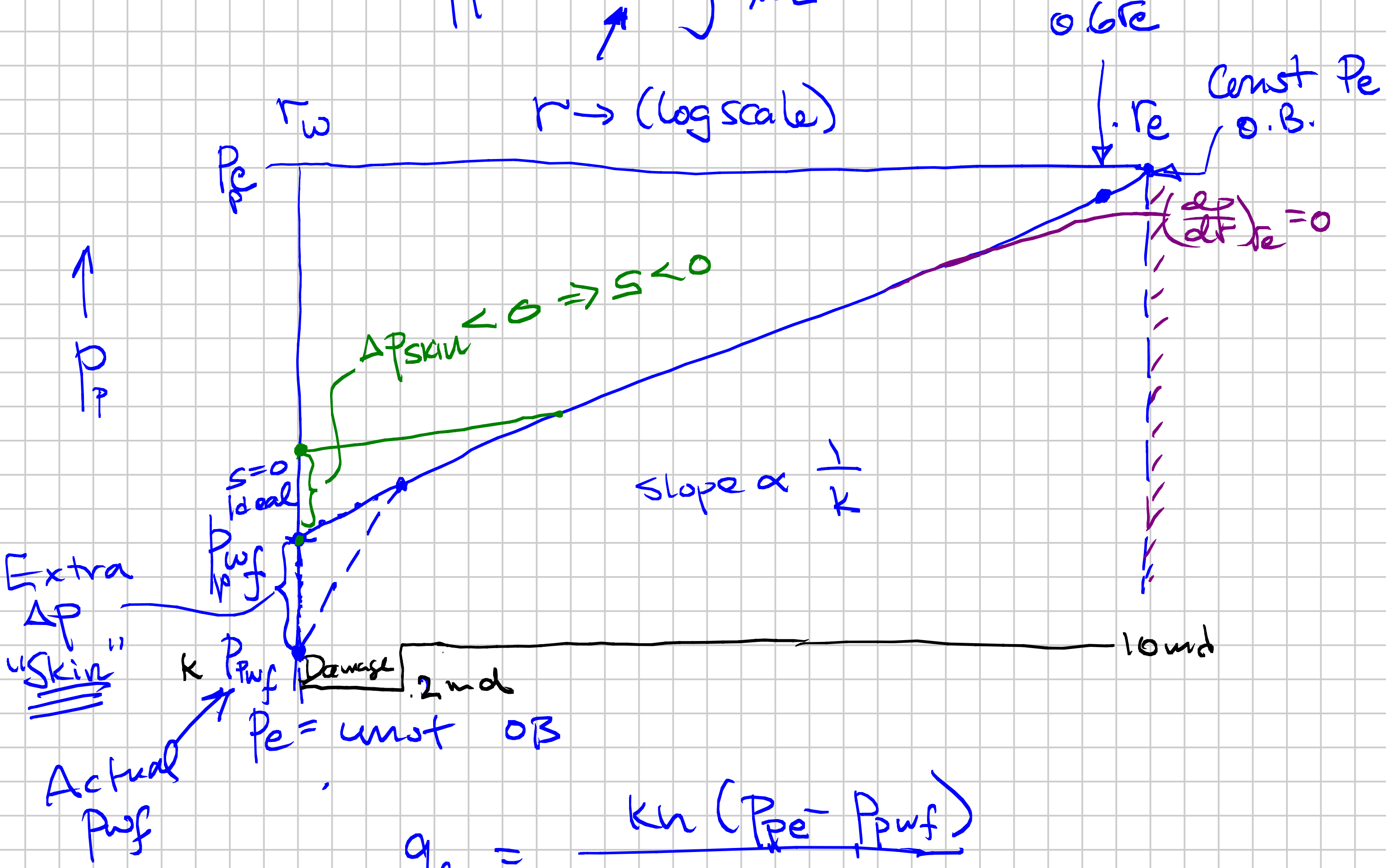
Assuming Steady State Flow : q_{mass} = const @ all r

$$q_g = \frac{0.703\, kh\,(\overset{\checkmark}{p}_{pR} - p_{pwf})}{T_R\left[\ln\frac{r_e}{r_w} - \underbrace{\frac{3}{4}}_{\text{because}}\right]}$$

No-Flow O.B.

"p_{pR}"

$$p_p = 2 \cdot \int \frac{p}{\mu Z}\, dp$$



$$q_g = \frac{kh\,(p_{pe} - p_{pwf})}{T_R\left[\ln\frac{r_e}{r_w}\right]}$$

$$q_g = \frac{kh\,(\overset{\checkmark}{p}_{pR} - p_{wf})}{T_R\left[\underbrace{\ln\frac{r_e}{r_w} - 0.60}\right]}$$

Physically Δp_{skin} damage $\quad r_d \rightarrow r_w$

Rate Equation, Δp_{skin} occurs. AT r_w

$$q_g = \frac{0.703\ kh\ \overbrace{(p_{pR} - p_{pwf})}}{T_R\left[\underbrace{\left(\ln\frac{r_e}{r_w} - \frac{3}{4}\right)}_{\sim 8} + s\right]}$$

$\updownarrow$ Dimensionless Quantity "Skin"

(Assume Pseudopressure p_p)

$$s = \Delta p_{p_{skin}} \cdot \left(\frac{0.703\ kh}{q_g T_R}\right)$$

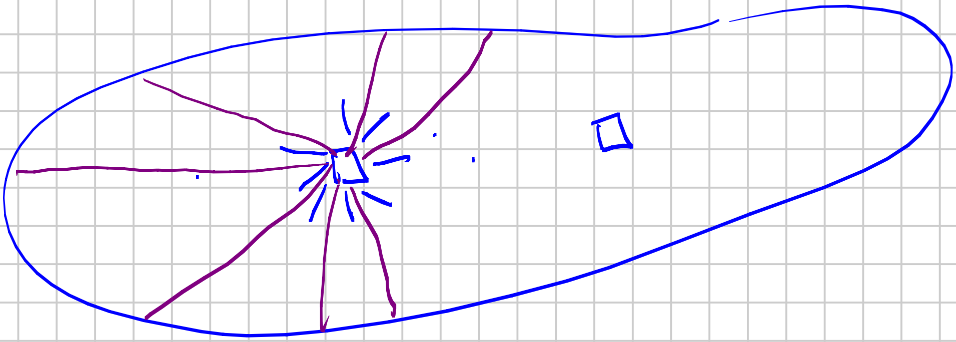
$$\Delta p_{p_{skin}} = \overset{\text{Ideal }(s=0)}{p_{p_{wf}}} - p_{p_{wf,\ actual}}$$

Magnitude of (Driller's) Damage Skin

$$s \sim 0 \rightarrow 5 \rightarrow 10 \rightarrow 50^{+}$$

Skin Effects:

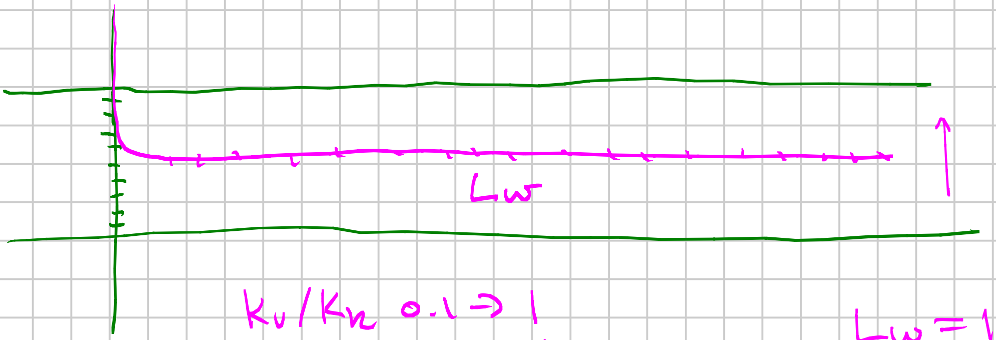
- (Driller's) Damage $s > 0$] →10–100
- (Completion) Damage $s > 0$]
- Flow Geometry Damage $1 - 10$
  $\underbrace{\sim 1 - 2 - 3}$
- ⋮



- Stimulation Skin $\sim -1 \rightarrow -5$
- Stimulation Flow Geometry Skin

$$10^6\ Sm^3/d = \frac{1}{8+\underset{\overset{\uparrow}{0}}{s}} \cdot C \cdot \frac{1}{8}$$

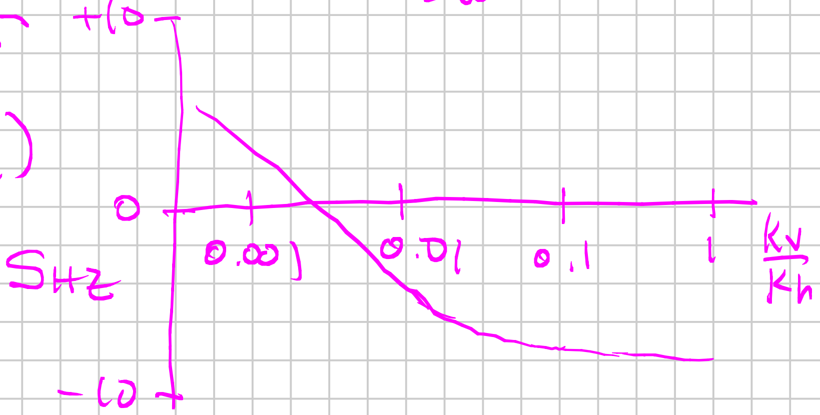
$$2\cdot 10^6\ Sm^3/d = C \cdot \frac{1}{8-4} = \frac{C}{4}$$



$$S_{HZ} \rightarrow \overbrace{-5 \rightarrow -8}^{k_v/k_h\ 0.1 \rightarrow 1}$$

$$S_{HZ} = f(L_w,\ k_v/k_h)$$

$L_w = 1000\ m$



$$q_g = \frac{kh\left[\overset{\overset{p_R(t)}{\downarrow}}{p_{pR}} - \overset{\overset{\text{Control}}{\swarrow}}{p_{pwf}}\right]}{T_R \cdot \left[\ln\frac{r_e}{r_w} - 3/4 + s\right]}$$

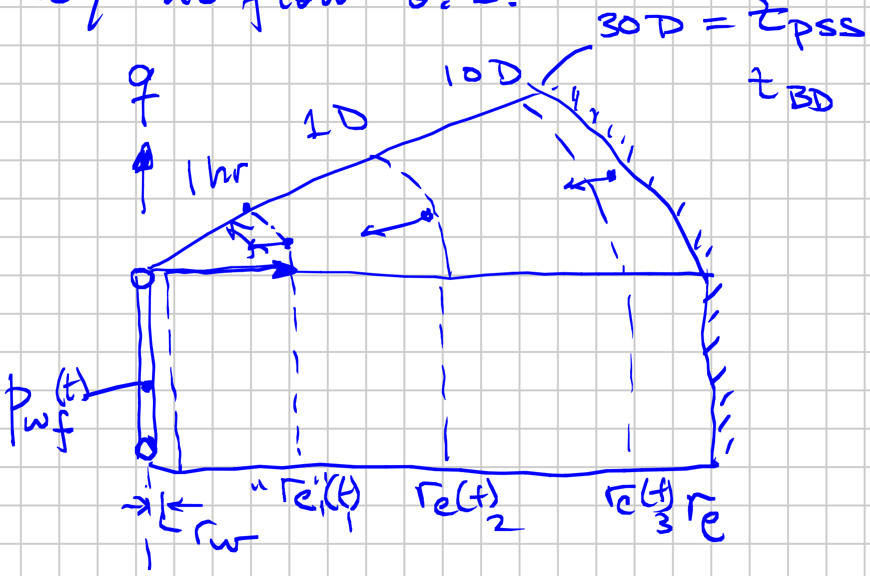
scf/D

Fix p_{wf}: $q_g(t) \downarrow$

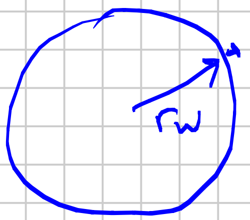
$$p_p \equiv 2 \cdot \int_0^p \frac{p}{\mu Z}\,dp$$

PseudoSteady State (PSS) Flow

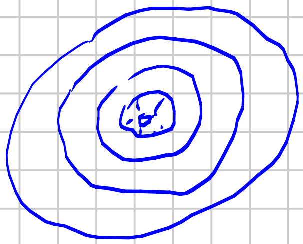
w/ no-flow O.B.



$\underline{\Delta p(r) > \epsilon}$ (mbar)
(1 psi)



$\frac{r_e(t)}{r_w} \gtrsim 1$



"Transient" Before reaching PSS

Boundary Dominated

$\underbrace{\hspace{6cm}}$

Infinite Acting

"Well Testing" ⟶ PTA (Pressure Transient Analysis)

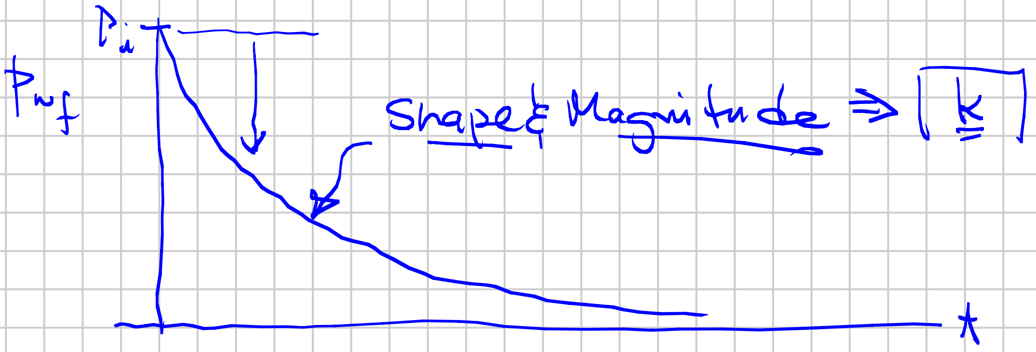
Hank Ramey
↓
↓
↓

[q = constant (controlled)]

"study" $p_{wf}(t)$ ⇒ Estimate k, s, $\bar{p}_R$, ... r_e, shape

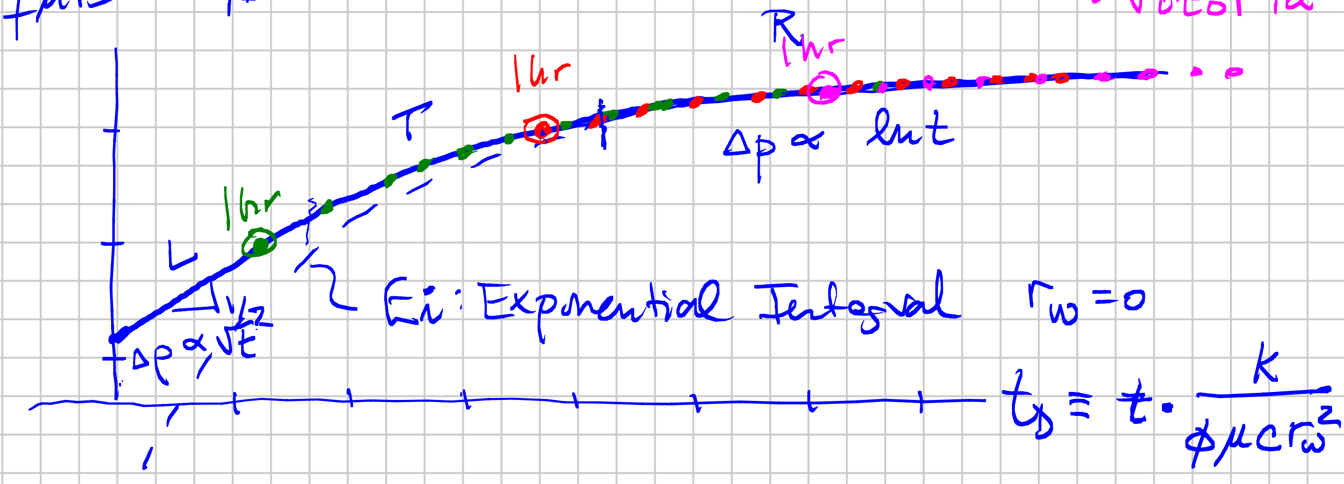
Single Phase "Slightly (constant)" Compressibility System

$$\underset{\text{constant}}{q} = \frac{kh\,[p_i - p_{wf}(t)]}{\mu B\,\left[\ln \frac{r_e(t)}{r_w}\right]}$$



Every well w/ h = const, q = const, ... (assumptions)
Same shape of $p_i - p_{wf}(t) \equiv \Delta p(t)$

$$\Delta p \cdot \frac{kh}{q\mu B} \equiv p_D = \text{dimensionless pressure drop}$$



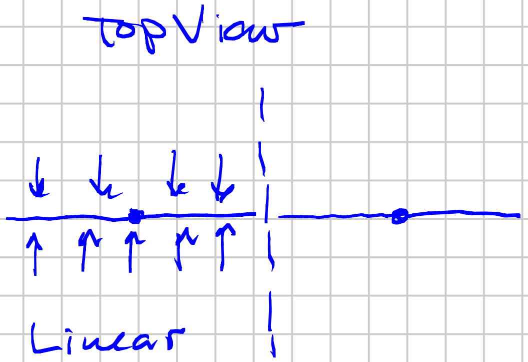
Ei: Exponential Integral $r_w = 0$

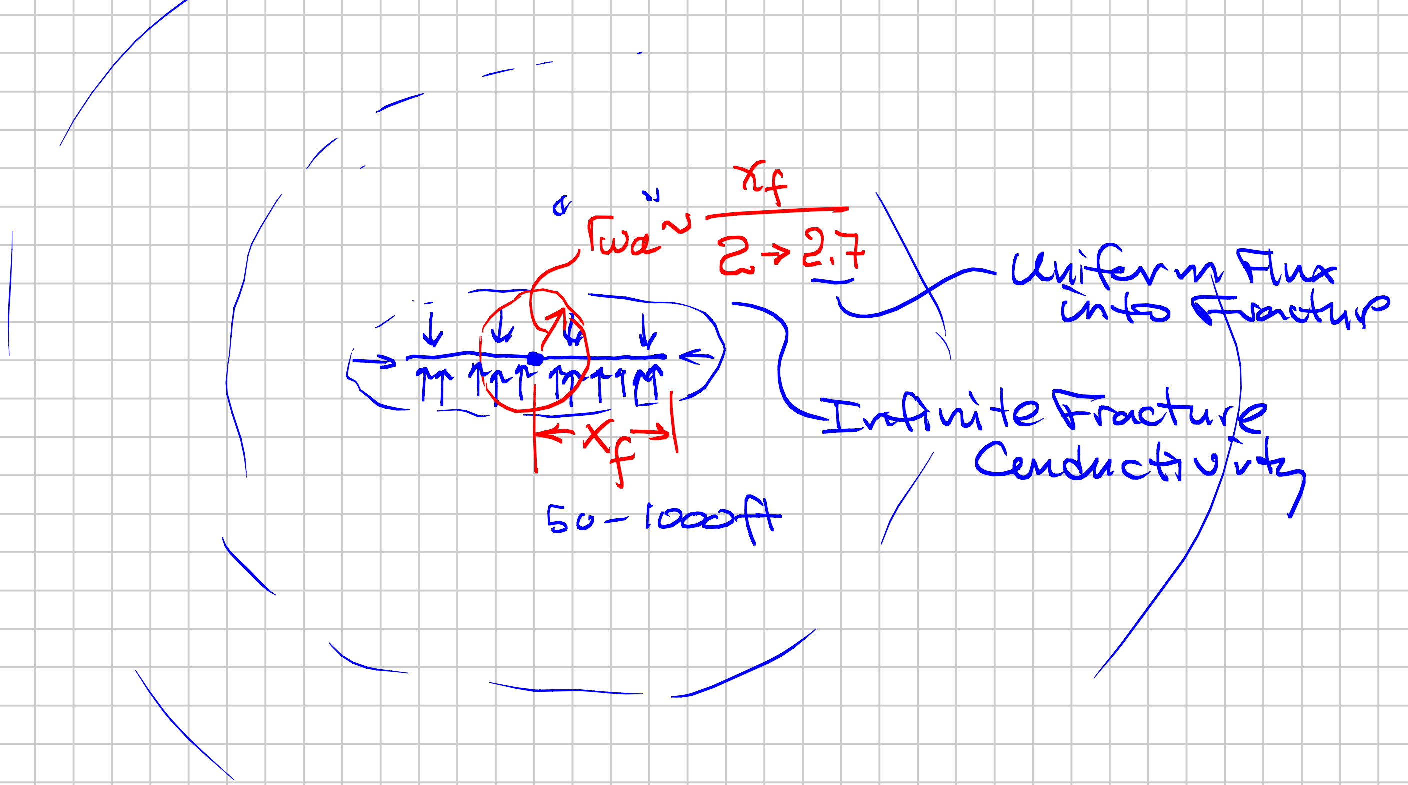
$$t_D \equiv t \cdot \frac{k}{\phi \mu c r_w^2}$$

Dimensionless Time

van Everdingen - Hurst

$$\frac{kh\,\Delta p}{\mu B q}$$





p_{wf} = constant (instead of q)

IA Flow

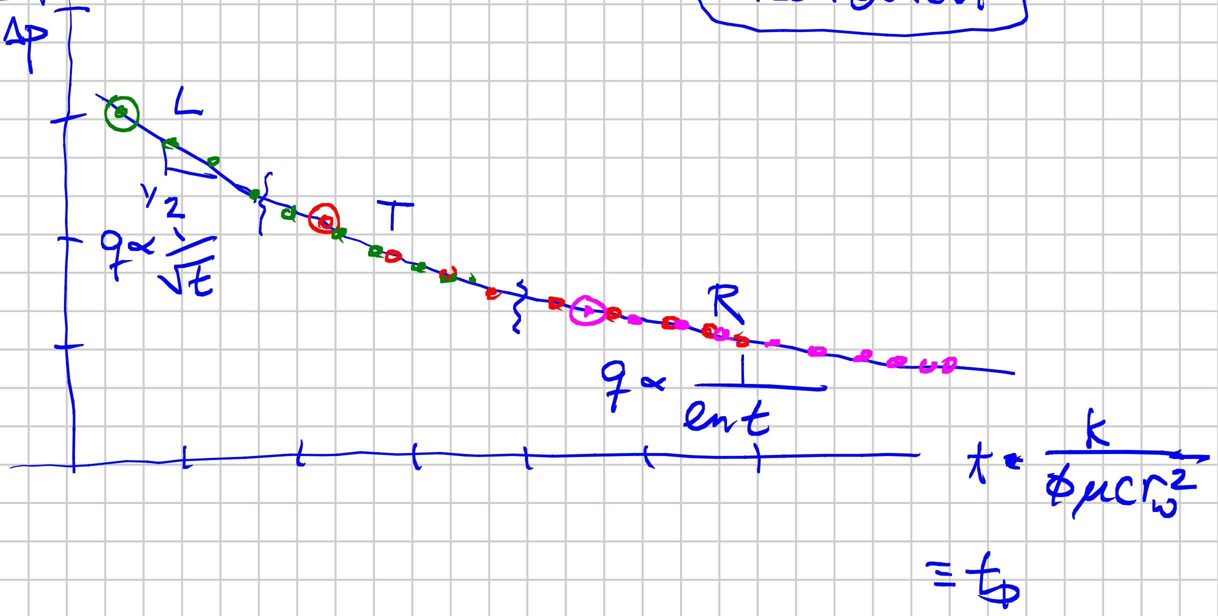
DCA

Decline Curve Analysis (Mike J. Fetkovich)

$$q(t) = \frac{kh\left[p_i - p_{wf}\right]}{\mu B\left[\ln \frac{r_e(t)}{r_w}\right]}$$

$$q_D = q \cdot \frac{\mu B}{kh\Delta p}$$

Tsarovich



$$q_D^{IA}(t_D) \simeq \frac{1}{p_D(t_D)^{IA}}$$

q_D ~ same for radial well & vertically fractured well

L T R

$\sqrt{t}$ ⟶ $\ln(t)$

PTA Experts:

- Hank Ramey (Stanford)
- Raj Raghavan (Al Reynolds ++ U. Tulsa)
- Alain Gringarten (Imperial College)

→ Leif Larsen (U. Stavanger)

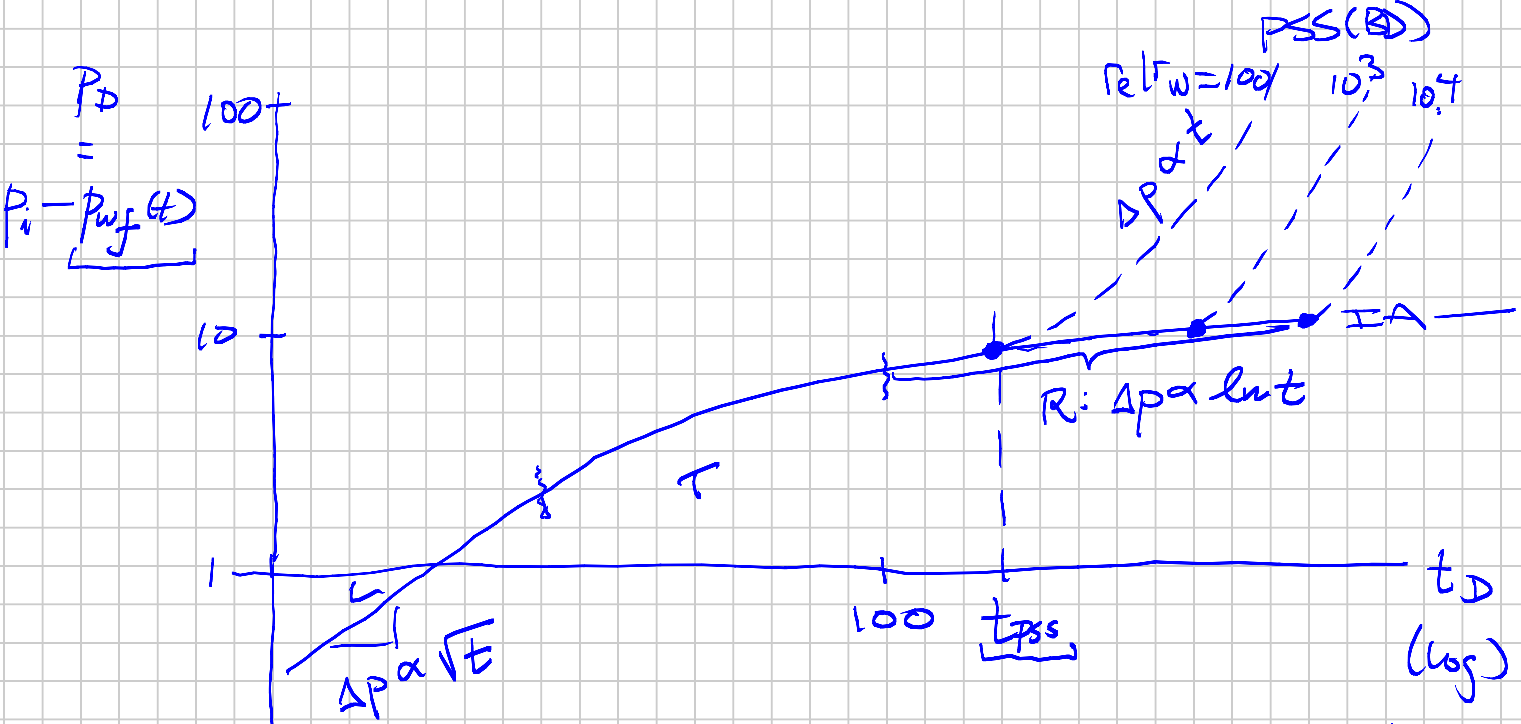
- Cinco-Ley
- Christine Economides (& Michael Economides)
- Earlougher (book)
- Mathews & Russel (book)

→ George Stewart (book)

- Roland Horne
- John Lee
- Kabir
- Bourdet (d(Δp)/d logt)

DCA:

1st. IA → PSS (BD) PTA



$$t_{pss} = f\left(r_e/r_w, \frac{k}{\phi \mu c r_w^2}\right)$$

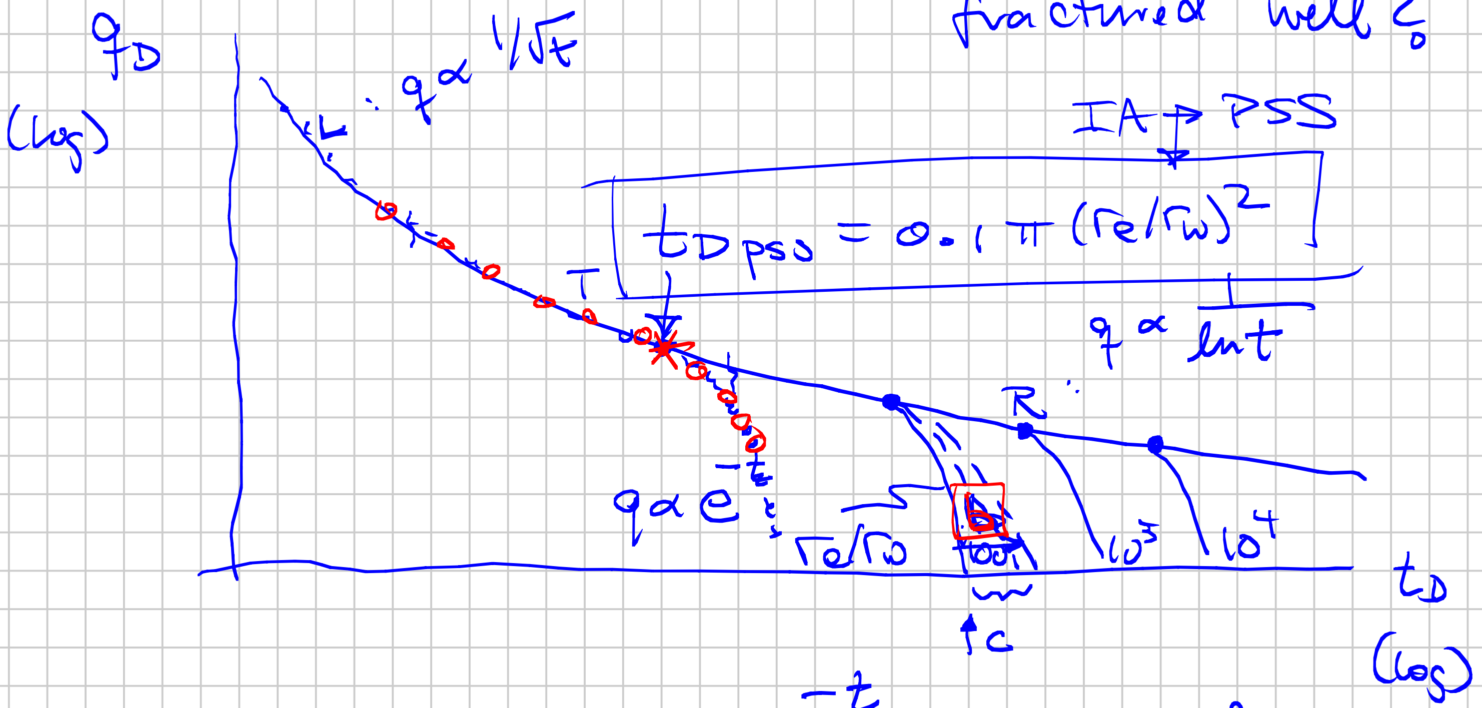
$$\uparrow$$

$$f\left(\frac{k}{\phi \mu c r_e^2}\right)$$

p_{wf} = const ⇒ DCA ⇒ Δp = constant

IA : PSS (BD)

Radial solution for a vertically fractured well ?



PSS (BD) : $q \propto e^{-t}$ Exponential

c : ~~small & constant~~ ($b = 0$)

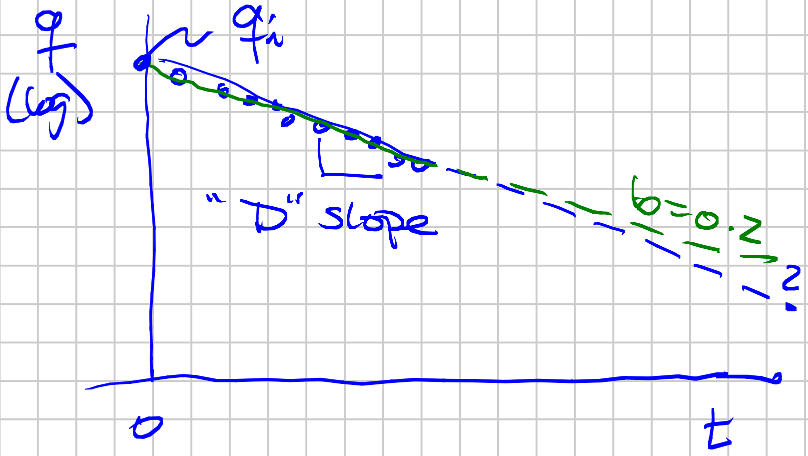
∴ Decline is less severe if higher compressibility during depletion.

Gas , SGD oil

DC Equations by ARPS's (Before Fetkovich)

$$q = \frac{q_i}{[1 + bDt]^{1/b}}$$

b & q_i & D were best fit to data



$b = 0$: Exponential

$$\left. q = q_i e^{-Dt} \right] \left(\begin{array}{l} \text{Analytical} \\ \text{Solution to} \\ q_D(t_D) \text{ PSS} \end{array} \right)$$

Fetkovich: $b \sim$ "Recovery Efficiency"

$= 0$: lowest ($c \sim$ small)

$\downarrow$

$\rightarrow 0.5$ e.g. SGD very favorable k_{rg} / k_{ro}

$\uparrow$ high S_{gc}

@ p_{wf} = const

$$q_i = \left[\frac{kh\, \Delta p}{\mu B \ln(r_e/r_w) + s} \right]$$

$$D = \frac{1}{1-b} \cdot \frac{q_i}{Q_{p\,ultimate}} \sim \text{similar for all wells}$$

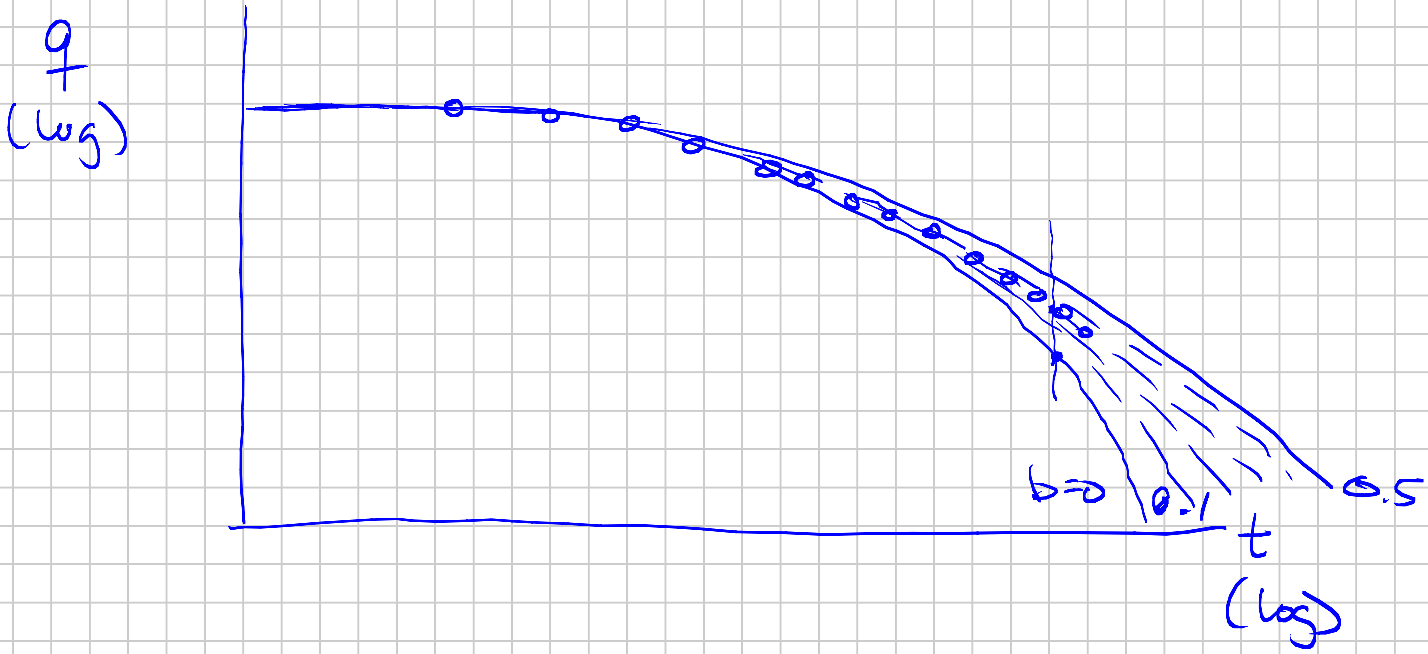
$$Q_p = \text{cum. production} = \int_0^t q\, dt$$

$Q_{p\,ult}$ @ $t = \infty$ $(q \rightarrow 0)$

$$= N \cdot RF_{ult} \qquad \frac{k}{\phi \mu c r_e^2}$$

$$\uparrow$$

$$\left[\frac{\bar{h} \bar{\phi} A (1 - \bar{S}_w)}{B_{oi}} \right]$$



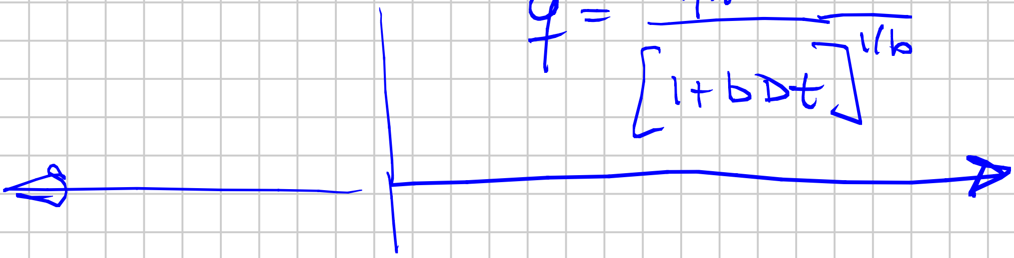
$t_D \sim t_{Dd} \sim D$

$q_i \quad q_D$

Fetkovich Generalized DC Analysis:

$\underline{\underline{IA}} \longrightarrow t_{pss} - \text{Arps DC} \longrightarrow$

$$q = \frac{q_i}{\left[1+bDt\right]^{1/b}}$$



$$\left\{\begin{array}{cc} q_i & D \\ \updownarrow & \updownarrow \\ q_D & t_D \end{array}\right\}$$

b: Recovery Efficiency

Proponent and Used :

Rate Normalization (IA)

Winestock & Colpitts

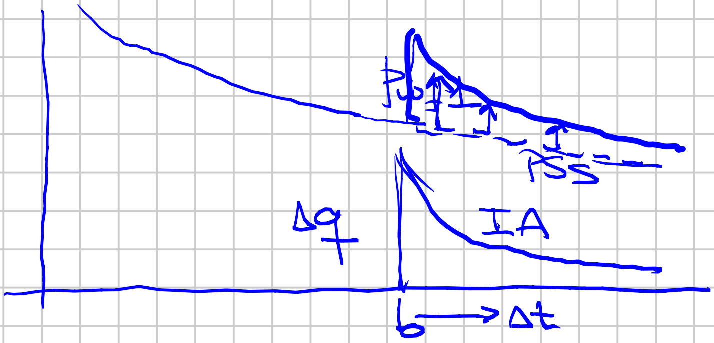
$p_{wf}(t)$ smoothly varying

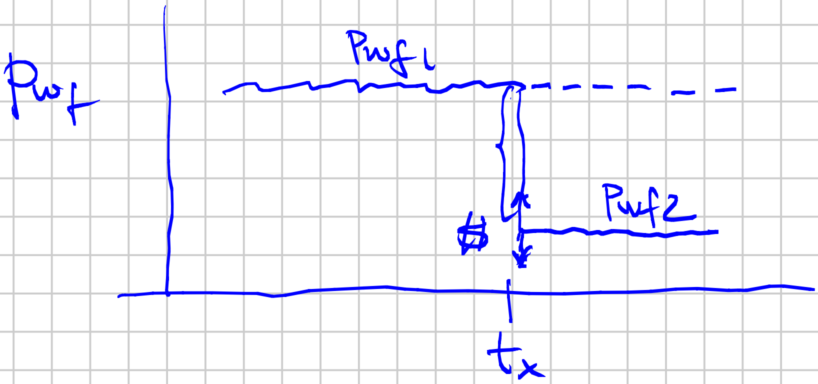
$$\frac{q(t)}{p_i - p_{wf}(t)} \Rightarrow \text{Behave according } \underset{\substack{\uparrow \\ p_{wf} = \text{const}}}{q_D(t_D)}$$

$$q_D(t_D) \propto \frac{1}{p_D(t_D)}$$

PTA using $\dfrac{p_i - p_{wf}(t)}{\underset{\substack{\nearrow \\ \text{smoothly varying}}}{q(t)}} : p_D(t_D)$

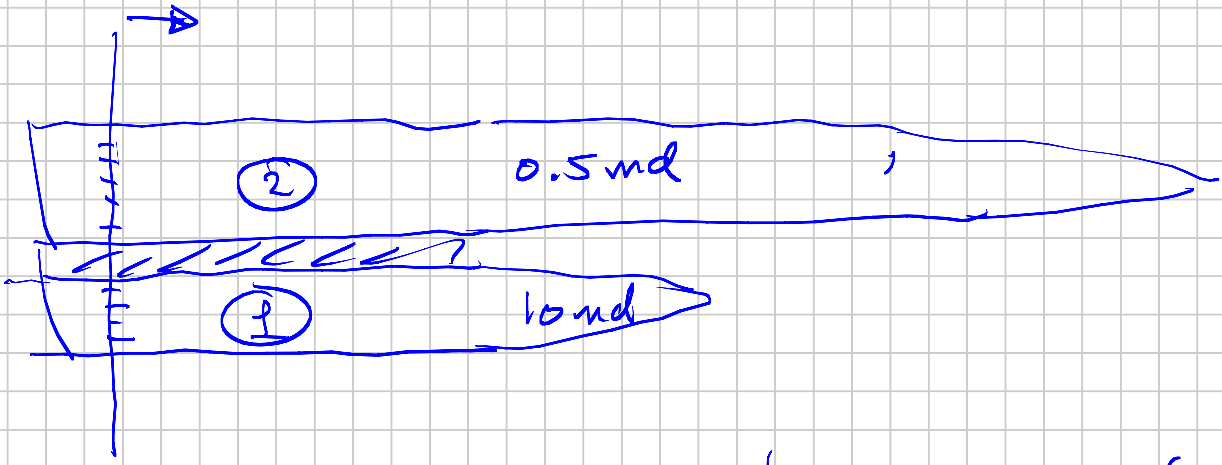
Proposed & Used Superposition of $q_D(t_D)$ for step changes in p_{wf} : compression in gas wells





$$q = \frac{kh}{\mu B} \left\{ q_D(t_D) \cdot (p_i - p_{wf1}) \right.$$
$$\left. q_D(t-t_x)_D \, (p_{wf1} - p_{wf2}) \right\}$$

Layered No-Crossflow Systems



$b_{①} = 0.2$

$b_{②} = 0.35$

Arp's $b_{well} > \underline{0.5 \to 0.9}$ (1)

PSS
(BD)

$$\overset{f}{\downarrow}$$

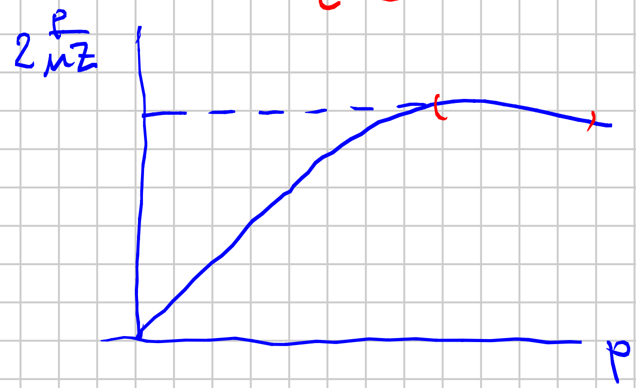
$$q_g^{(t)} = \frac{\boxed{\circ{kh}\,(p_{pR}^{(t)} - p_{pwf})}}{\boxed{T_R \cdot \left[\ln \frac{r_e}{r_w} - \frac{3}{4} + s\right]}} \quad (1)$$

Darcy's Law

— Constant
t > 0 ....

t > tpss
(k > 1-10md)

$$p_p \equiv 2 \cdot \int_0^p \frac{p}{\mu Z}\, dp$$



"IA":
Radial Flow

Const.

$$q_g = \frac{\boxed{kh}\,(\overset{\text{cnst}}{\overset{\downarrow}{p_{pi}}} - \overset{\downarrow}{p_{pwf}^{(t)}})}{T_R\left[p_D^{(t)} + s\right]} \quad (2)$$

Darcy's Law

— f(t) until tpss

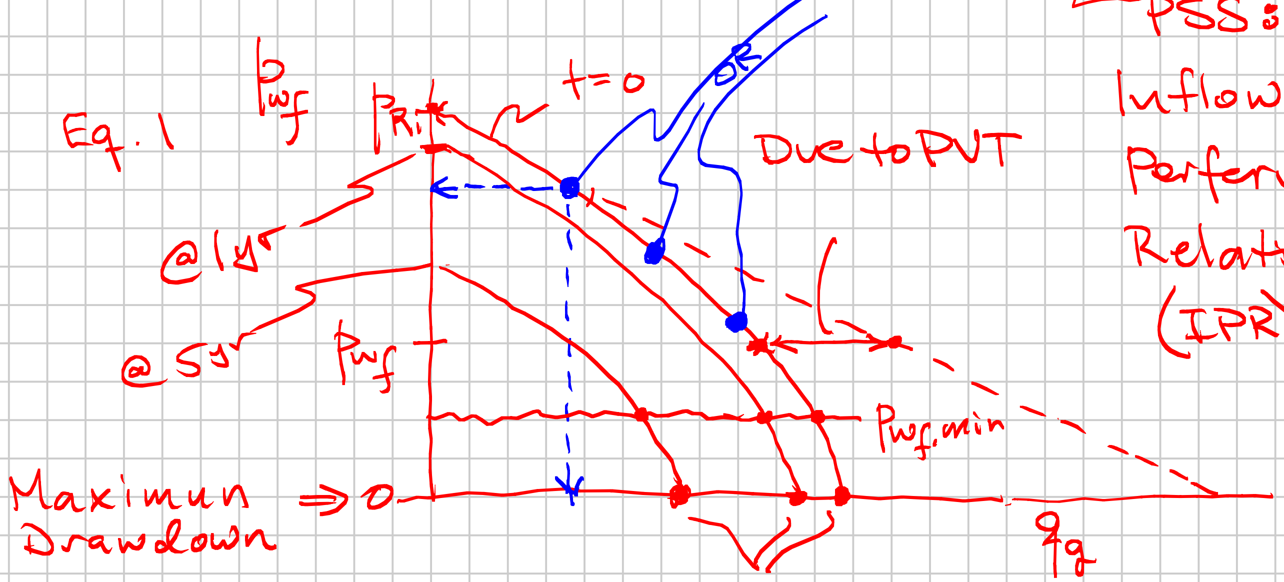
$$p_D = \frac{1}{2}\left[\ln t_D + 0.809\right]$$

Single-Rate Test

$$\frac{kh}{T_R\left[\ln \frac{r_e}{r_w} + s\right]}$$

Constant

PSS : BD



Inflow
Performance
Relation
(IPR)

$p_{wf} \to 0$

AOFP

Absolute Open Flow Potential

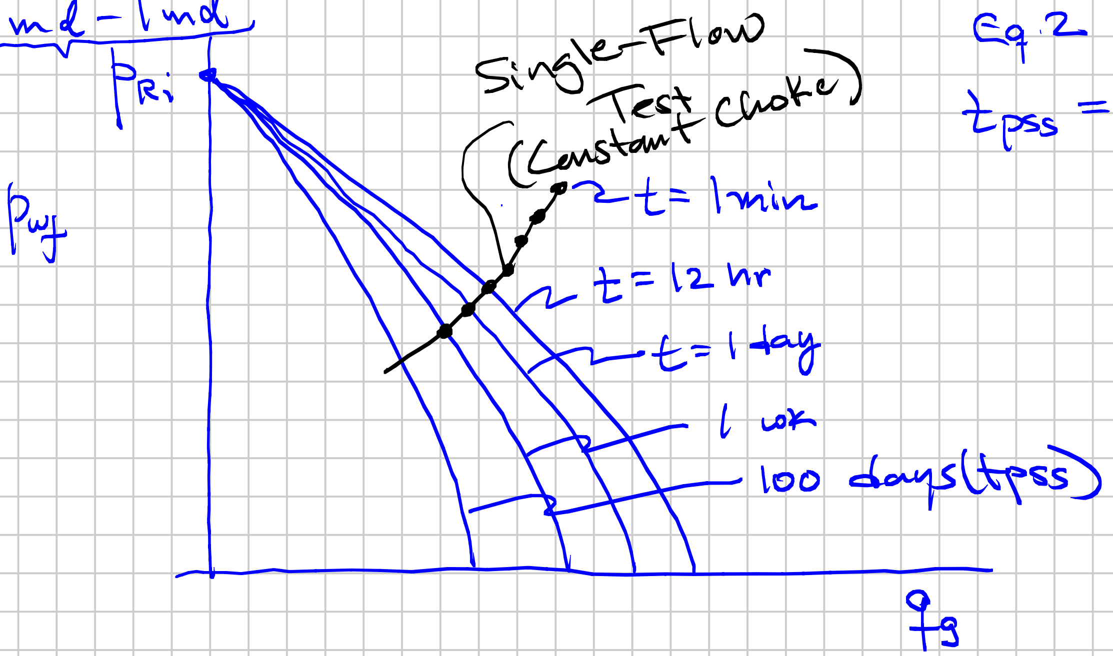
$q_{g\max}$

Lower Perm: t_{pss} can be "Large" (days-wks.-months)

$k \lesssim 0.1$ md - 1md

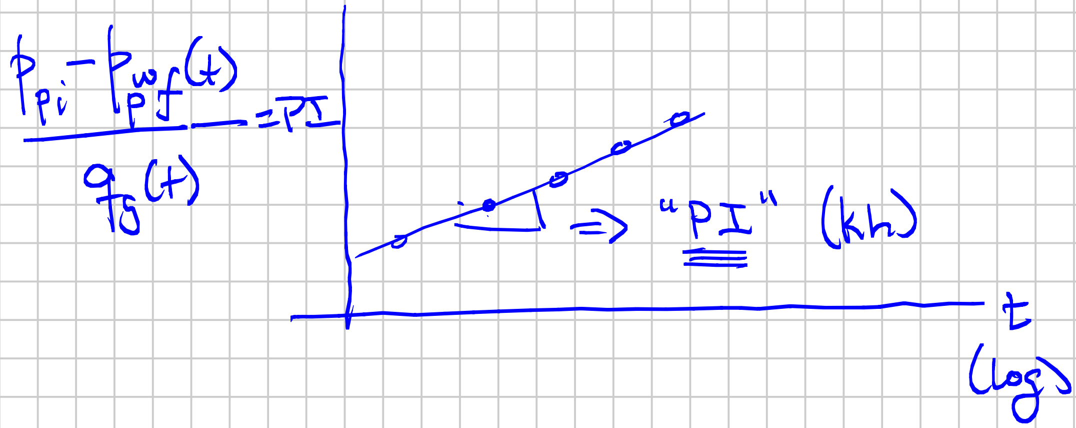
Eq. 2

$t_{pss} = 100$ days



To find "$kh/[T_R(\ln\frac{r_e}{r_w}+s)]$" PI

Run a transient test $q(t)$ & $p_{wf}(t) \Rightarrow$ "PI"(t)



Flow in Porous Media with "High" Velocities ("non-Darcy")
("Turbulent")
("High-Velocity Flow")

$$\boxed{\frac{dp}{dx} = \underbrace{\frac{\overset{F}{\mu}}{\underset{R}{k}}\, v}_{\text{Darcy}} + \underbrace{\underset{R}{\beta}\ \underset{F}{\rho}\ v^2}}$$

Forchheimer

Becomes important for "Reynold's" number $\gtrsim 1$

$$\left\{ Re \equiv \frac{\rho\, v_p\, \bar{d}_g}{\mu} \right\}$$

$\phi = 0.2$

$h = 20\ m$

$q_g = 1000000 = 10^6\ Sm^3/d$

$B_g = 0.01\ m^3/Sm^3 @ 100bar$

$r = 0.5\ m$

$$v_p = \frac{q}{A\phi} = \frac{[10^6(0.01)] \cdot D}{2\pi(0.5)20\ (3600 \cdot 24\ s)(0.2)}$$

$2\pi r h$

e.g. gas $\rho = 100\ \frac{kg}{m^3}$

$\bar{d}_g = 50\ \mu m$

$\mu = 0.02\ mPa \cdot s$

$v_p = 0.01\ m/s$

$$Re = \frac{(100)(0.01)(50 \cdot 10^{-6})}{0.00002}$$

$$Re = 2.5 > 1$$

$$q_g = \frac{(kh)\left[p_{pR} - p_{pwf}\right]}{(T_R)\left[\underbrace{\ln\frac{r_e}{r_w} - \frac{3}{4}}_{p_D} + \underbrace{\left(s + D\,q_g\right)}_{\text{Dimensionless } \Delta p}\right]}$$

Damage
Geometry
⋮

$$S_t = s + \underbrace{D q_g}_{\text{Rate-dependent skin contribution}}$$

$$\boxed{D \propto \beta}$$

$\left[\frac{1}{Sm^3/d} \text{ or } \frac{1}{MMscf/D}\right]$

$$\left(\frac{p_{pR} - p_{pwf}}{q_g}\right) = A + B q_g$$

$$p_{pR} - p_{pwf} = q_g \cdot \overbrace{\frac{T_R}{kh}\left[\ln\frac{r_e}{r_w} - \frac{3}{4} + s\right]}^{A} + q_g^2 \underbrace{\frac{T_R}{kh} \cdot D}_{B}$$

$$p_R^2 - p_{wf}^2$$

$$\boxed{0 = B q_g^2 + A q_g - (p_{pR} - p_{pwf})}$$

How to determine A & B:

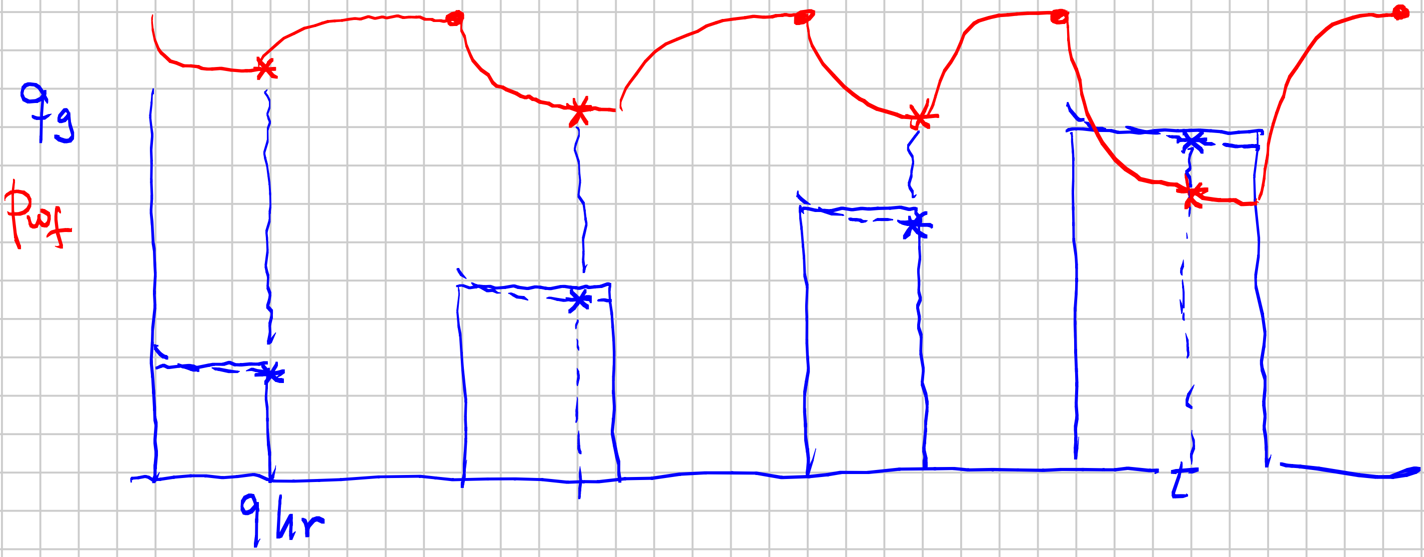
minimum 2 flow rates (q_g, p_{wf}) measurements

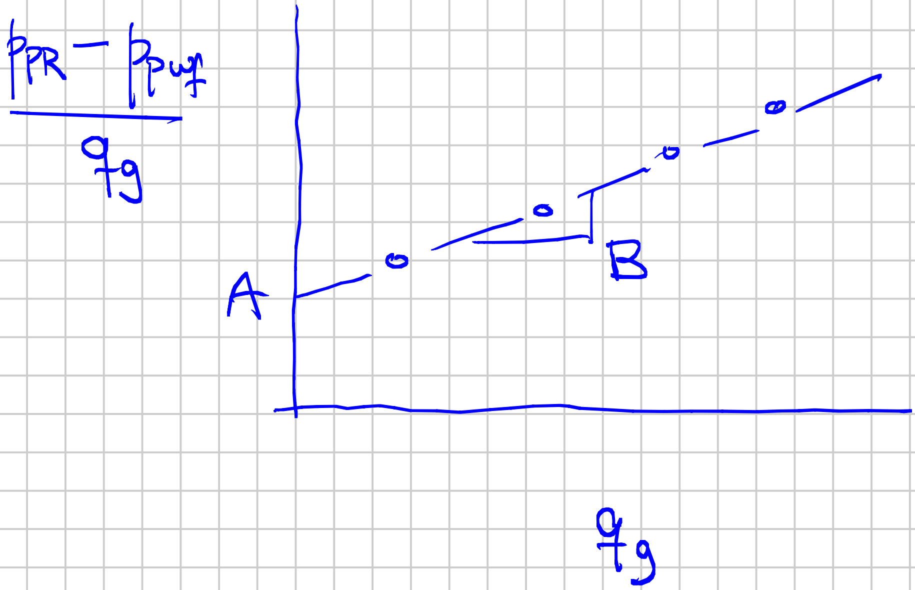
Industry standard is (3 –) 4 different flow tests (i.e. 4 chokes)

⇒ "Multi-Point Testing of Gas Wells"

Isochronal Test

- Each flow period is
  - same duration - e.g. 6 hr
  - Collect the (p_{wf}, q_g) "point" at the same production time
- Should be a shut-in between each flow period ⇒ $\bar{p}_R$ to be reached (same each time)




$\frac{P_{pR} - P_{pwf}}{q_g}$
A
B
q_g

MULTI-POINT WELL TEST FOR GAS WELLS

Note Title 2014-11-06

$$q_g = \frac{kh\,(p_{pR}-p_{pwf})}{T_R\left[\underbrace{\left(\ln\frac{r_e}{r_w}-\frac{3}{4}\right)}_{7-10}+\underbrace{s+Dq_g}_{\text{Total Skin}}\right]}$$

$$\underbrace{Bq_g^2 + Aq_g}_{\text{Unknown}} - (p_{pR}-p_{pwf}) = 0$$

$B\ (D\ ;\ \beta)$: $\boxed{Re = \frac{\rho v d}{\mu} \gtrsim 1 \Rightarrow B}$ $r \sim 1\text{ m}$

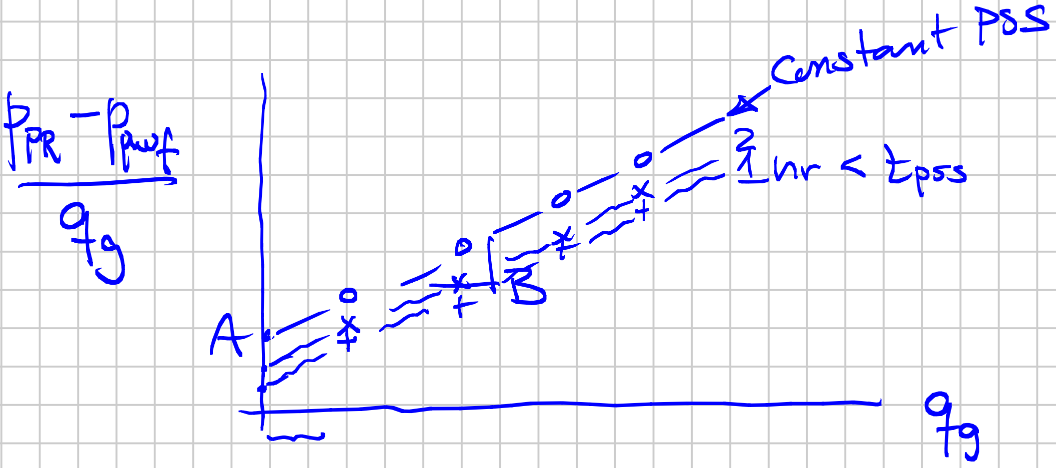
$v \propto \frac{1}{r}$

Radial flow near the wellbore BUT need "high" $q_g = 5\text{-}50$ MMscf/D $\simeq 0.1\text{-}1 \cdot 10^6$ Sm^3/d

$Dq_g \sim 1\text{-}100$

$$v = \frac{q_g \cdot B_g}{A_\perp}$$

$$A_\perp = 2\pi r h$$



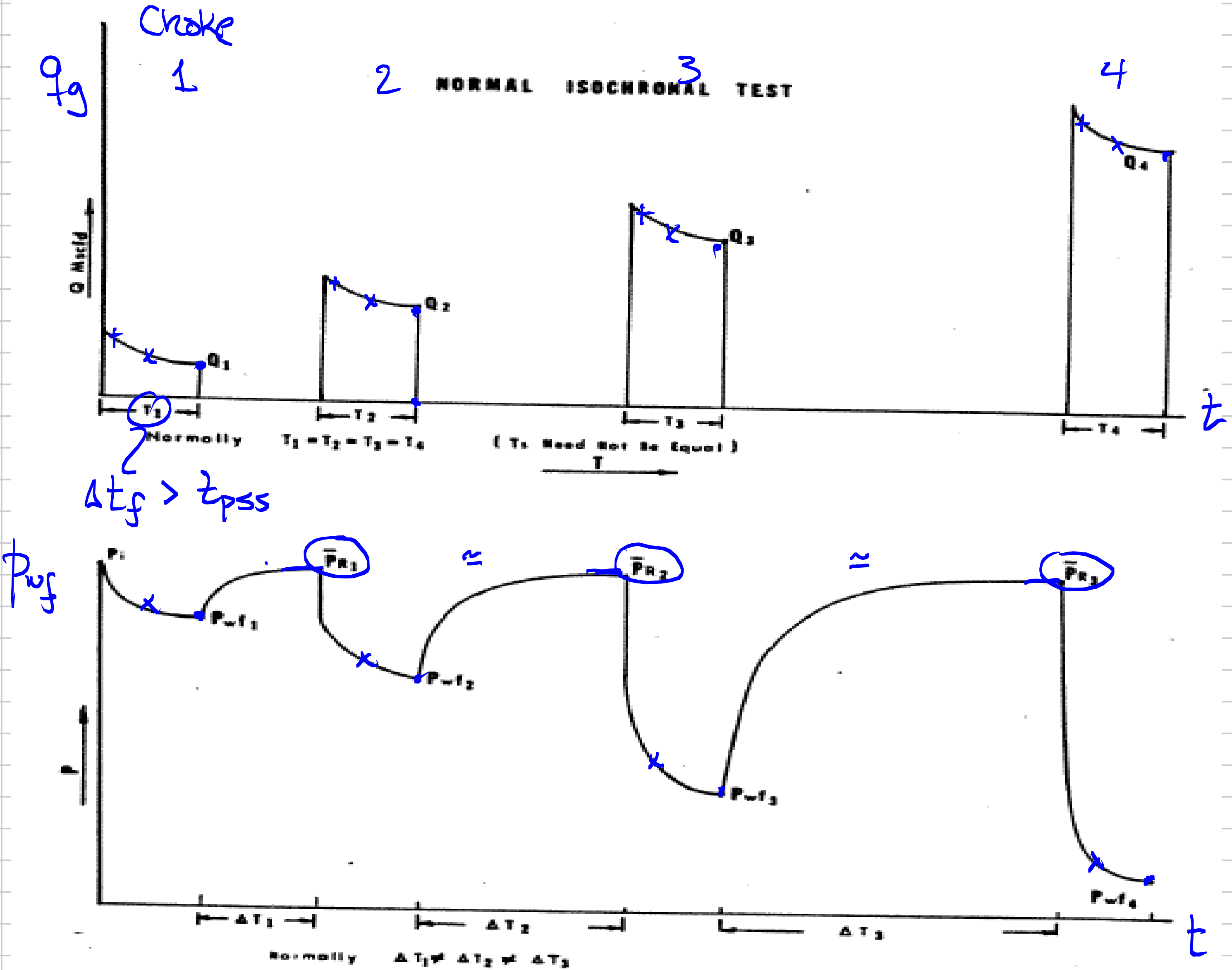


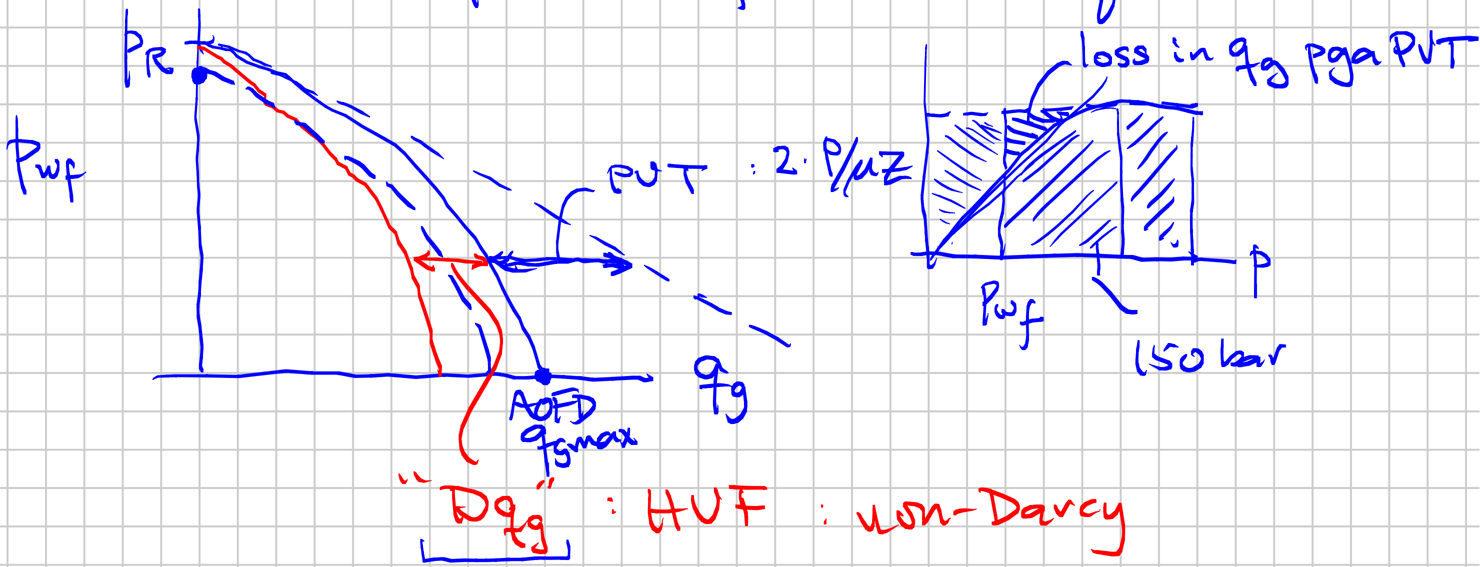
FIG. 3

$$A(t) = \frac{T_R}{kh}\left[\underbrace{p_D(t_D)}_{\frac{1}{2}\left[\ln t_D + 0.809\right]} + s\right] \qquad t < t_{pss}$$

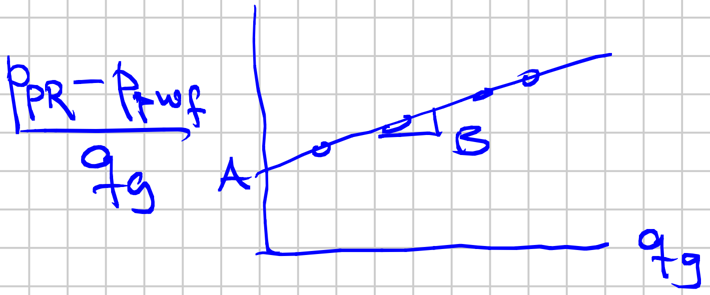
If $Bq_g << Aq_g$: Darcy

Alternative Graphical Representation of IPR

I.



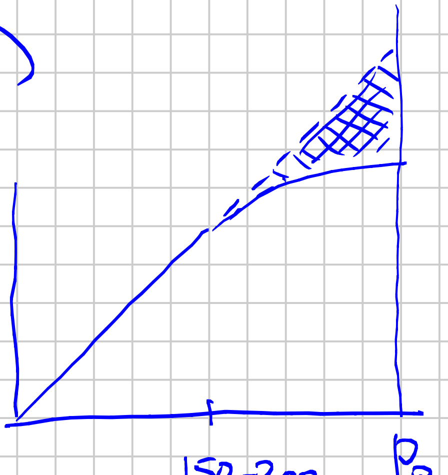
II.



1940s →

III. (Fetkovich +++ before 1990)
(Log-Log)
Backpressure Plot

- p_p : p^2 ; $p_R \lesssim 200$ bar



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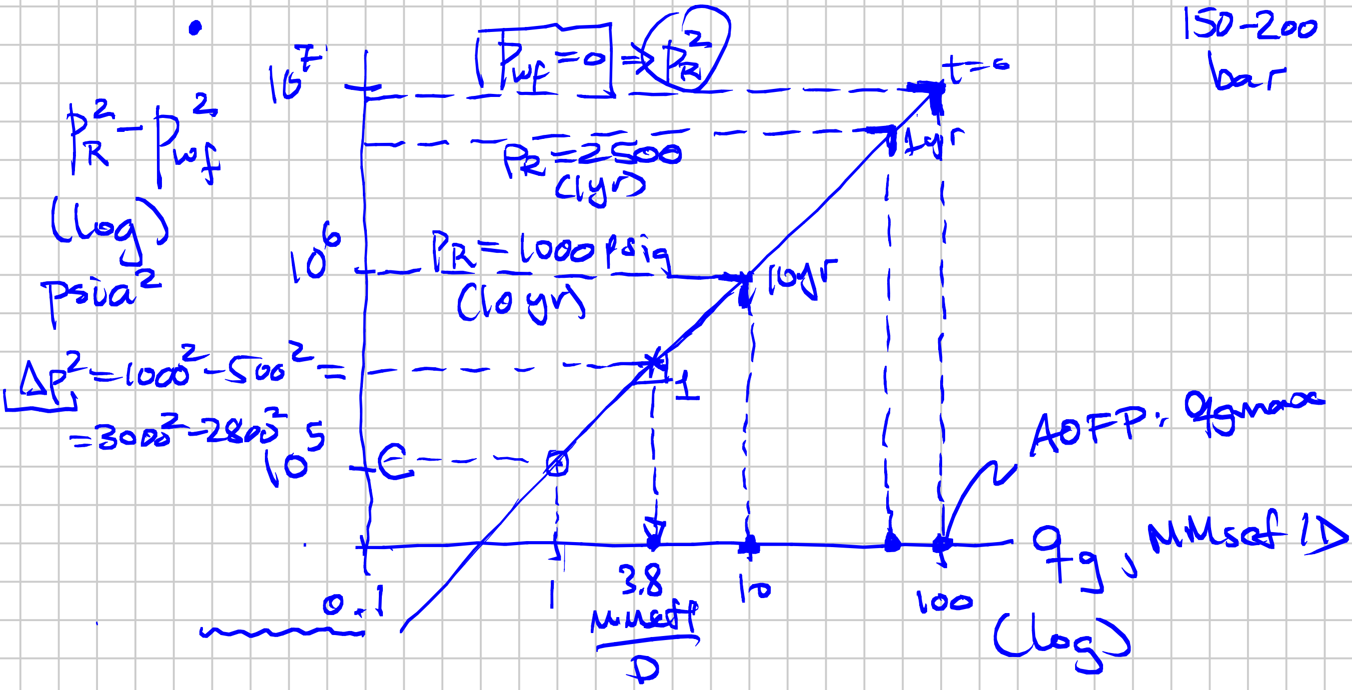


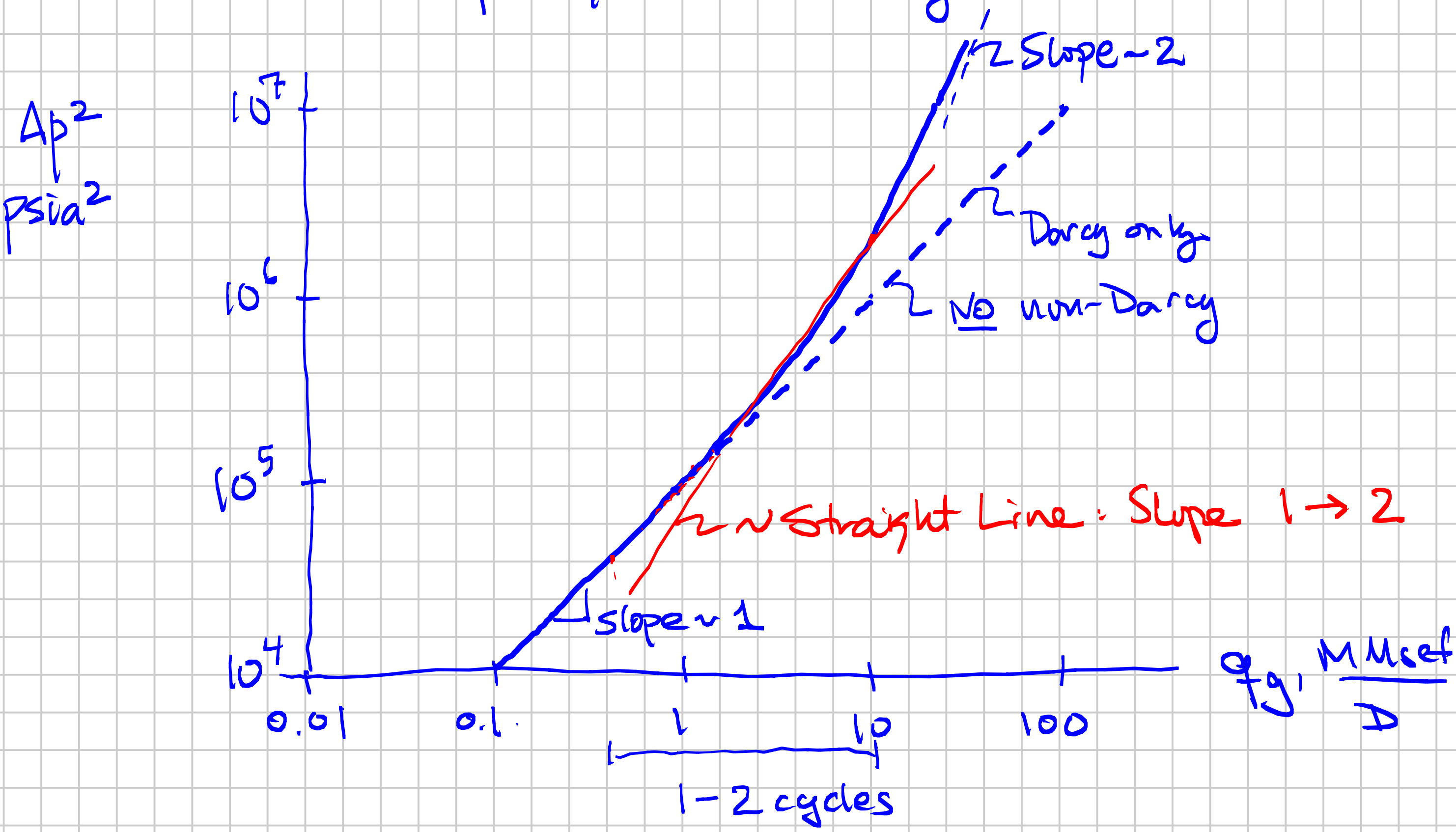
Darcy:
$$q_g = \frac{kh}{\underbrace{T_R\left[\ln\frac{r_e}{r_w}+s\right]}_{\text{Constant}}}\cdot\left(p_R^2-p_{wf}^2\right)$$

slope=1

$$\log q_g = \log C + \log(\Delta p^2)$$

$$\log \Delta p^2 = \log q_g + \log C$$

General Rate Eq. w/ non-Darcy Term



$$\Delta p^2 = p_R^2 - p_{wf}^2 = B q_g^2 + A q_g$$

$$\lim_{q_g \to 0} \to A q_g \qquad \text{Slope} = 1$$

$$\lim_{q_g \to \text{large}} \to B q_g^2 \qquad \text{Slope} = 2$$

Approximate log-log straight line "model"

$$q_{tg} = \underbrace{C_R}_{\text{"Reservoir"}}(p_R^2 - p_{wf}^2)^n$$

"Reservoir" $\sim \dfrac{kh}{(\mu Z)T_R\left[\ln\frac{r_e}{r_w} - \frac{3}{4} + S\right]}$

only =A to this if $n=1$

Slope $= \dfrac{1}{n}$

$0.5 \le n \le 1$

$\left\{\begin{array}{c}\text{Highly non-Darcy} \\ Bq_{tg}^2\,!\end{array}\right\}$ $\left\{\begin{array}{c}\text{Darcy} \\ Aq_{tg}\,!\end{array}\right\}$

if $n=0.5$

$$C_R = \frac{1}{\sqrt{B}}$$

$$D \propto \beta \propto \frac{1}{k}$$

Pipe Flow:

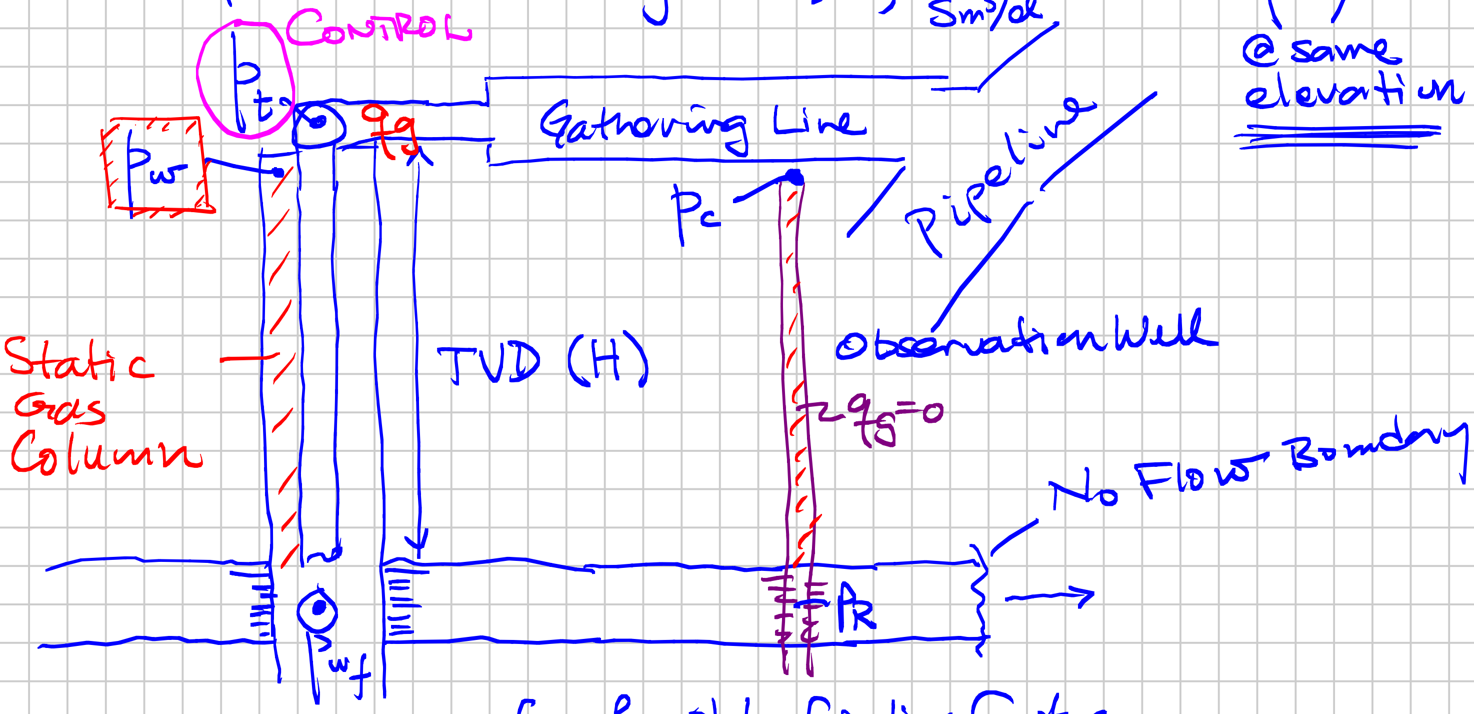
① Tubing

② Pipeline (Gathering Line)

Ignore Gravity (only consider friction)

$$\underset{Sm^3/d}{q_g} = C\left(p_{in}^2 - p_{out}^2\right)^{0.5}$$

@ same elevation



f_R : Reynolds friction factor

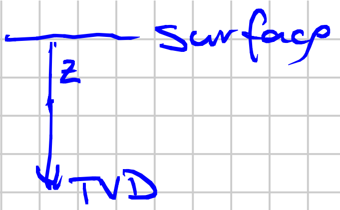
$$C\left(d,\ L,\ \overbrace{\epsilon,\ \mu}^{f_R}\right)$$

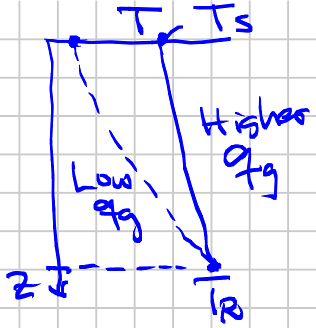
roughness of the pipe

Correcting for gravity to bring p_{wf} and p_R @ TVD depth datum to SURFACE depth datum where p_t (that we control) is measured.

PRESSURE	Datum	Datum	PRESSURE
⇒ p_R	TVD	Surface	p_c
p_{wf}	TVD	Surface	p_w
p_t	Surface	Surface	p_t

$p_{wf} \leftrightarrow p_w$





Static Fluid Column:

$$\frac{dp}{dz} = \text{constant} = \rho_g g$$

$$\rho_g = \frac{pM}{R\bar{T}\bar{Z}}$$

$$= \left(\frac{M}{R\bar{T}\bar{Z}}\right) \cdot p$$

$$\bar{T} \simeq \frac{1}{2}(T_s + T_R)$$

$$Z(p,T) : Z(p_s, T_s) \approx \bar{Z}$$

constant

$$\int_{p_T}^{p_B} \frac{1}{p}\,dp = \underbrace{\left(\frac{Mg}{R\bar{T}\bar{Z}}\right)}\int_0^{H(TVD)} dz$$

ft °R

where S = 0.0375 GH/(T_a Z_a)

$$S \equiv \underbrace{\quad\quad}_{\substack{\text{units} \\ 28.97\ M_{air} \\ R \\ g \\ 1/2}} \frac{\gamma_g H}{\underbrace{\bar{T}\bar{Z}}}$$

$$\ln(p_B/p_T) \simeq \underbrace{\left(\frac{Mg}{R\bar{T}\bar{Z}}\right) H}_{= S/2}$$

$$\frac{p_B}{p_T} \simeq \exp(S/2)$$

$$\frac{p_{wf}}{p_w} = e^{S/2}$$

$$\boxed{\frac{p_{wf}^2}{p_w^2} = e^{S}} \sim \text{constant}$$

$$\boxed{\frac{p_R^2}{p_c^2} = e^{S}}$$

Reservoir Δp
$p_R - p_{wf}$

$$\left(\frac{p_R^2}{e^s}\right) - \left(\frac{p_{wf}^2}{e^s}\right) = \left(\frac{B_R}{e^s}\right) q_{g}^2 + \left(\frac{A_R}{e^s}\right) q_g$$

$$\downarrow \qquad \downarrow \qquad \downarrow \qquad \downarrow$$

$$p_c^2 - p_w^2 = B'_R\, q_g^2 + A'_R\, q_g$$

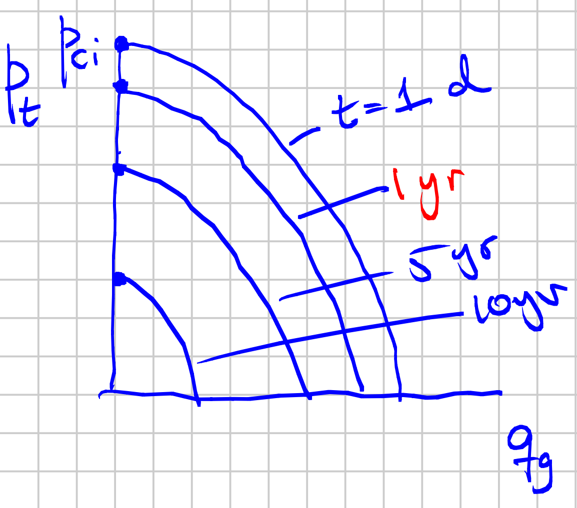
Tubing Δp
$p_{wf} - p_t$

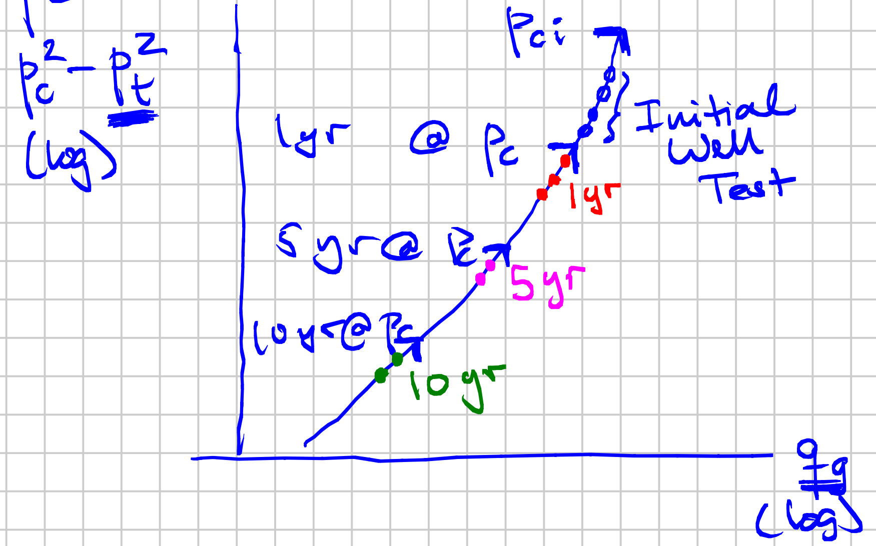
$$p_w^2 - p_t^2 = \frac{1}{C_T^2}\, q_g^2$$

$$\boxed{p_c^2 - p_t^2 = \underbrace{\left(B'_R + \frac{1}{C_T^2}\right)}_{\text{non-Darcy + Friction}} q_g^2 + \underbrace{A'_R\, q_g}_{\text{Darcy}}}$$

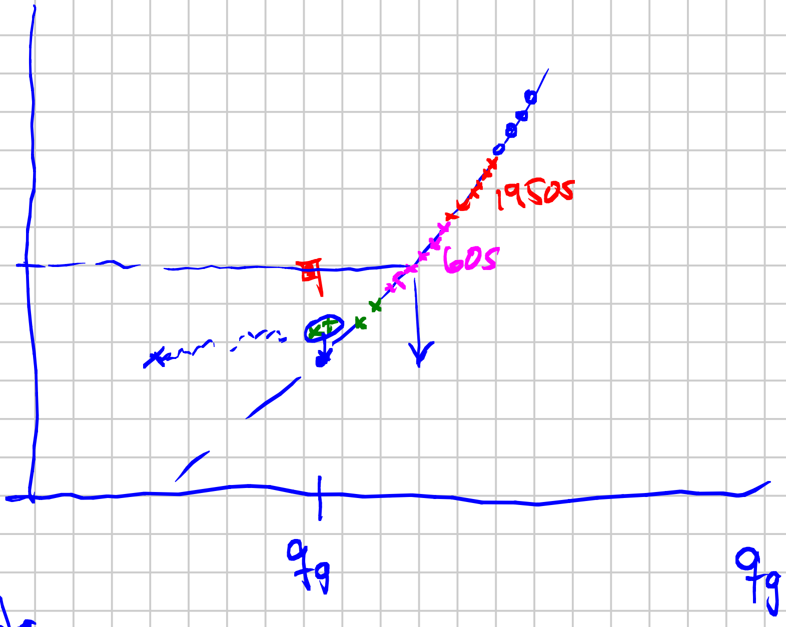
$$\boxed{p_c^2 - p_t^2 = B_{WH}\, q_g^2 + A'_R\, q_g}$$

Wellhead Backpressure Eq. @ a particular time in depletion when p_c exists.





$$\underbrace{p_c^2 - p_t^2}_{R + T}$$



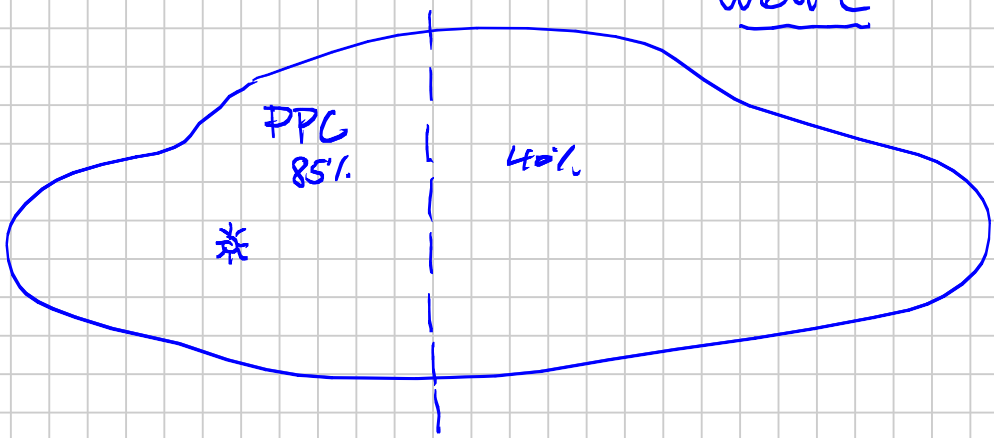
$$P_R\big(t(G_p)\big)$$

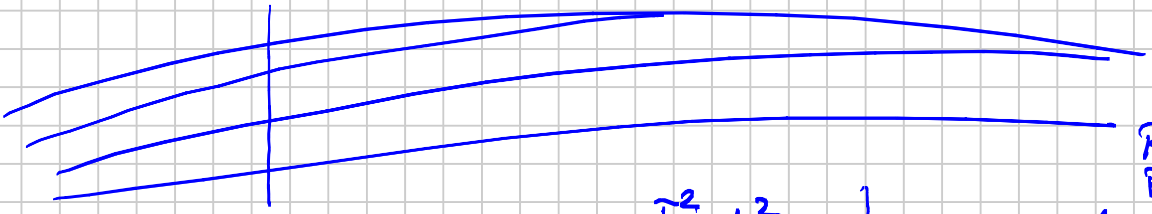
$$\downarrow$$

$$\underline{\underline{p_c}}$$

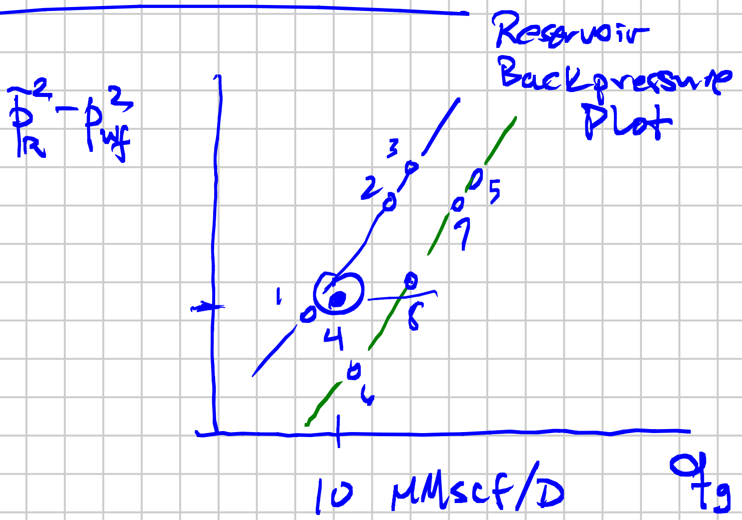
$$G_p = \int_0^t q_g \, dt$$

Well C





Test	q_g	p_{wf}
1		
2		
3		
4		



Max Backpressure: $p_{wf} = \bar{p}_R$

$q = 0$

No BP: $p_{wf} = p_{sc}$

(No Choke)

Gas Material Balance

(p_R) $\bar{p}_R$ = volumetric average pressure

G_p = cumulative gas produced = $\int_0^t q_g(t)\,dt$

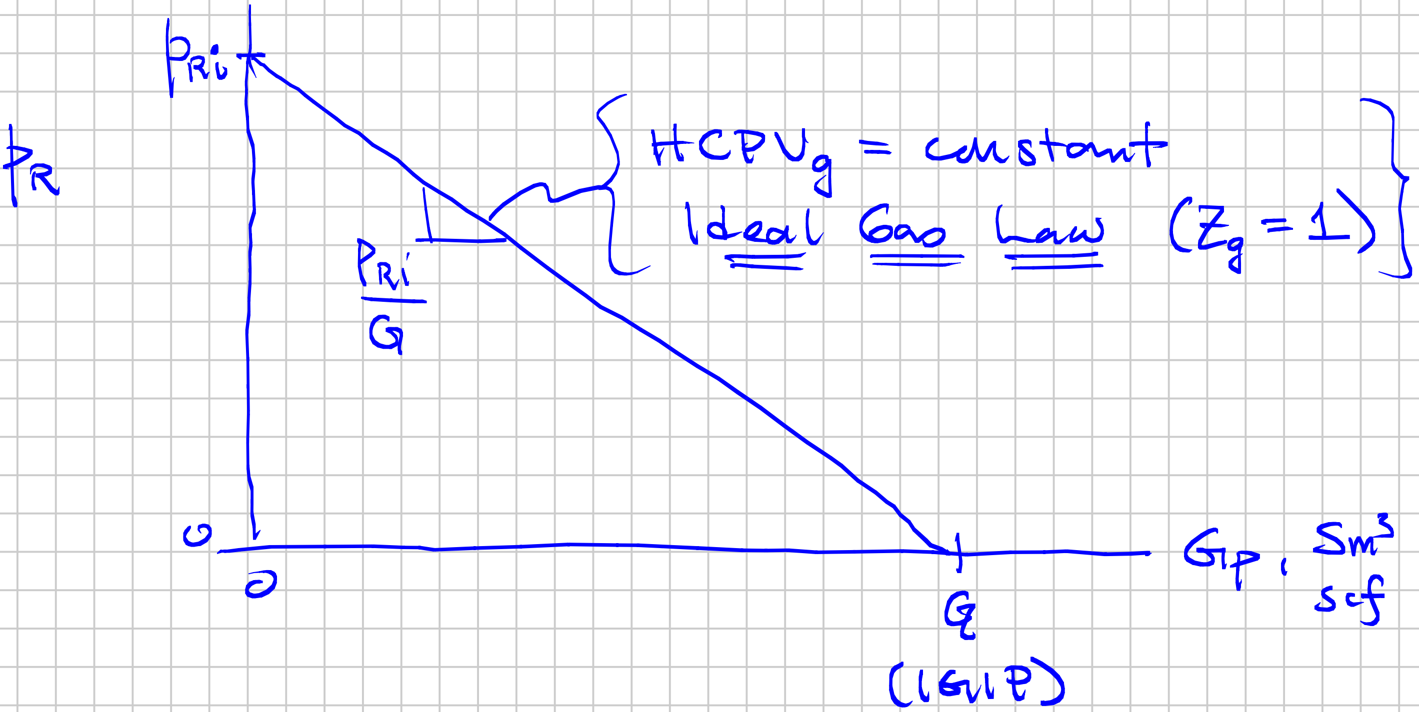
No dependence on how fast/slow $G_p(t)$

$\boxed{p_R(G_p)}$ $\qquad p_R(t) = p_R(\underline{G_p(t)})$

Need this because of the Reservoir Gas Rate Eq.

$$q_g(t) = \frac{kh\left(p_R^2(t) - p_{wf}^2\right)}{T_R(\mu Z)\left[\ln\frac{r_e}{r_w} - \frac{3}{4} + s + Dq_g\right]}$$ ✓

q_g (p_{wf} @ a given time – i.e. @ a given p_R)



$$p_R = p_{Ri} - \left(\frac{p_{Ri}}{G}\right)\cdot G_p$$

$$p_R = p_{Ri}\left(1 - \frac{G_p}{G}\right)$$ $\qquad \frac{G_p}{G} = RF_g$

$$\frac{p_R}{p_{Ri}} = 1 - \frac{G_p}{G}$$ Fraction of GIIP Still in the reservoir

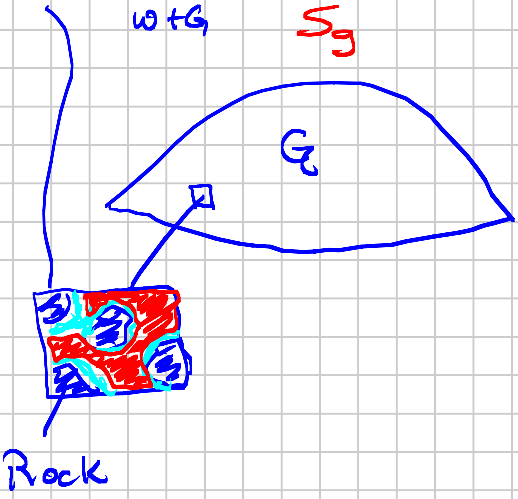
Over-simplified but ~ 1st order correct

$$\frac{dp_R}{dG_p} < 0$$

Assumptions:

① $HCPV_g$ = constant as p_R declines

$$\underbrace{V_b} \cdot \underbrace{\phi}_{w+G} \cdot \underbrace{(1-S_w)}_{S_g}$$



Side View of a Channel sand

If: (a) V_b = constant
(b) V_p = constant ⇒ ϕ = constant $\Big\}$ c_p, c_r = 0
(c) $\left.\begin{matrix} c_w \\ \frac{\Delta V_w}{\Delta p} \end{matrix}\right\} = 0$

② $pV = nRT$ applies: in the reservoir ✗
: at the surface ✓

(I) $pV = nRT\,Z(p)$

Initially $p_R = p_{Ri}$ $\quad \underline{\underline{T_R}}$ $\quad n_{gi}$

Initial Res. Press

"

Initial moles gas in place

$$\boxed{p_{Ri} \, V_{pg} = n_{gi} \, R \, T_R}$$

Constant $HCPV_g$

Later (anytime) : p_R applies

$$n_{gR} = n_{gi} - n_{gp}$$

Cum. produced gas moles

$$\boxed{p_R \, V_{pg} = (n_{gi} - n_{gp}) \, R \, T_R}$$

$$V_{pg} = \frac{n_{gi} \cancel{R} \cancel{T_R}}{p_{Ri}} = \frac{(n_{gi} - n_{gp}) \cancel{R} \cancel{T_R}}{p_R}$$

$$p_R = p_{Ri} \left(\frac{n_{gi} - n_{gp}}{n_{gi}} \right)$$

$$\boxed{p_R = p_{Ri} \left(1 - \frac{n_{gp}}{n_{gi}} \right)}$$

$$\left. \begin{array}{l} 23.68 \ \dfrac{sm^3}{kg\text{-}mole} \\ \\ 379 \ \dfrac{scf}{lb\text{-}mole} \end{array} \right\} \quad \frac{V_g}{n_g} = \frac{R \, T_{sc}}{p_{sc}}$$

Ideal Gas Law

$$\underline{G_p} = \underline{n_{gp}} \cdot \underline{\cancel{\frac{RT_{sc}}{p_{sc}}}}$$

$$G = n_{gi} \cdot \cancel{\frac{RT_{sc}}{p_{sc}}}$$

$$\frac{G_p}{G} = \frac{n_{gp}}{n_{gi}}$$

$$\boxed{p_R = p_{Ri}\left(1 - \frac{G_p}{G}\right)} \quad \Leftarrow$$

(II) $$\frac{V_{pg}}{V_{pgi}} = \alpha(p)$$

$$\alpha_{Ri} = 1$$

$$\alpha_R = \frac{V_{pg}(p_R)}{V_{pg}(p_{Ri})} \quad \longleftarrow$$

Exam Q & A's (also Wed 12.15-14 next week)

Note Title 2014-11-20

① Gas PVT Properties Excel

- Best Work Award

$$q = \frac{kh\,(\overset{\downarrow}{p_{PR}} - p_{pwf})}{T_R\left[\ln\frac{r_e}{r_w} \underset{\uparrow}{-\left(\frac{3}{4}\right)} + s\right]}$$

(1) • Use p_{PR} instead of p_{pe}

(2) • Assume No-Flow O.B. condition

$\left(\frac{dp}{dr}\right)_{re} = 0$ instead of p_e = const

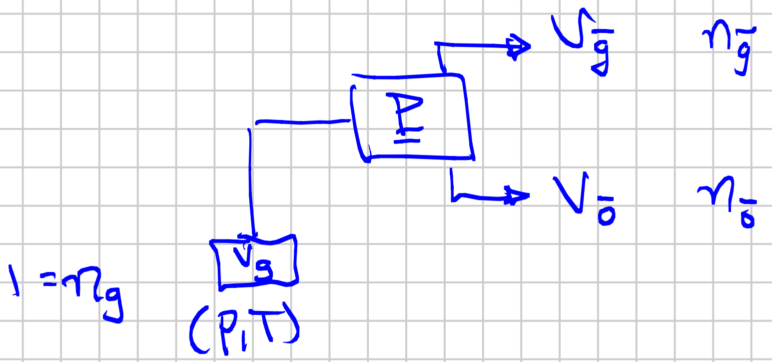
$\ln\frac{r_e}{r_w}$

7-10

		O.B. Condition	
	Driving Pressure	p_e = const Const Pres	$\left(\frac{dp}{dr}\right)_{re} = 0$ No Flow
	p_e	0	$-\frac{1}{2}$
	p_R	?	$-\frac{3}{4}$

Dry Gas FVF $B_{gd} = \frac{V_g(p,T)}{V_{\bar g}}$

$V_{\bar g}$ = surf gas after processing



$n_{\bar g} + n_{\bar o} = n_g$

$f_{\bar g} = \frac{n_{\bar g}}{n_g} = 0.9$

$f_{\bar o} = \frac{n_{\bar o}}{n_g} = 0.1$

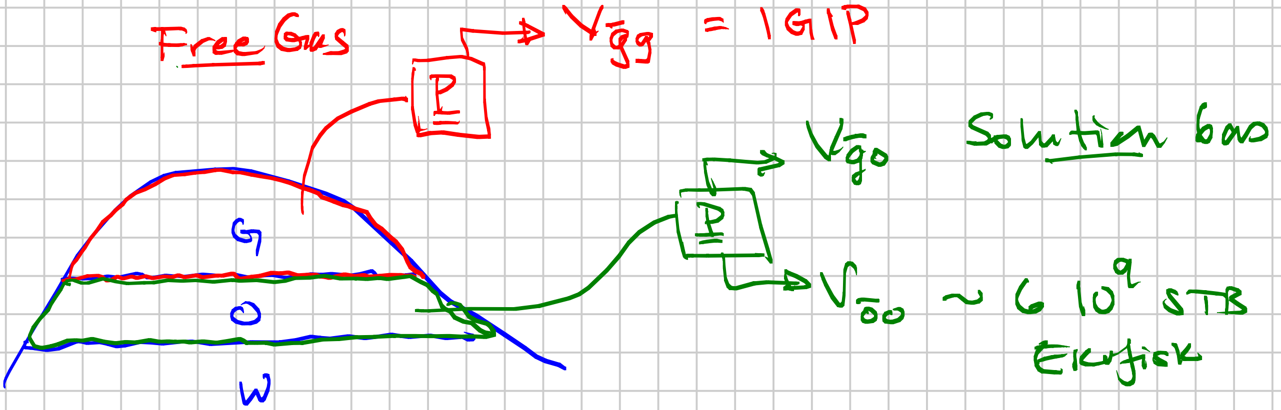
$$\boxed{B_{gd} = \underbrace{\left[\frac{p_{sc}}{T_{sc}} \cdot \frac{T_R Z_g(p,T)}{p}\right]}_{B_{gw}} \cdot \underset{\left(\frac{1}{1-f_{\bar o}}\right)}{\left(\frac{1}{f_{\bar g}}\right)}}$$

$\downarrow$

Find in ALL
Reservoir Eng.
Text books

$f_{\bar o} \sim <1\% \to 20\%$

$\overset{\text{"}\bar g\text{"}}{\downarrow}$
IGIP = Initial Gas in Place = $IGIP_{RG} + IGIP_{RO}$



$$IOIP = \overset{=0\text{ (Ekofisk)}}{IOIP_{RG}} + IOIP_{RO}$$

ST "Condensate"   STO

$$|O|P_{RO} = \frac{HCPV_{RO}}{B_{oi}}$$

$$|O|P_{RG} = |G|P_{RG} \cdot r_{si} = HCPV_{RG} \cdot \left(\frac{r_{si}}{B_{gdi}}\right)$$

$$|G|P_{RG} = \frac{HCPV_{RG}}{B_{gdi}}$$

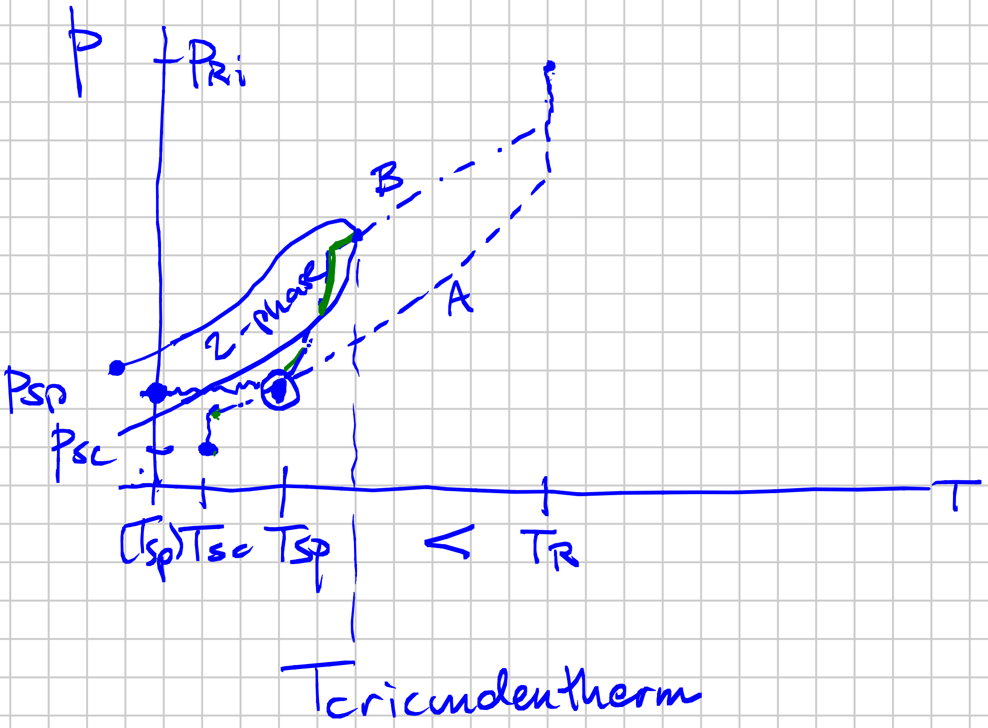
$$|G|P_{RO} = |O|P_{RO} \cdot R_{si} = HCPV_{RO} \cdot \left(\frac{R_{si}}{B_{oi}}\right)$$

HCPV's : Geo Number

B_{oi} r_{si} B_{gdi} R_{si} : PVT

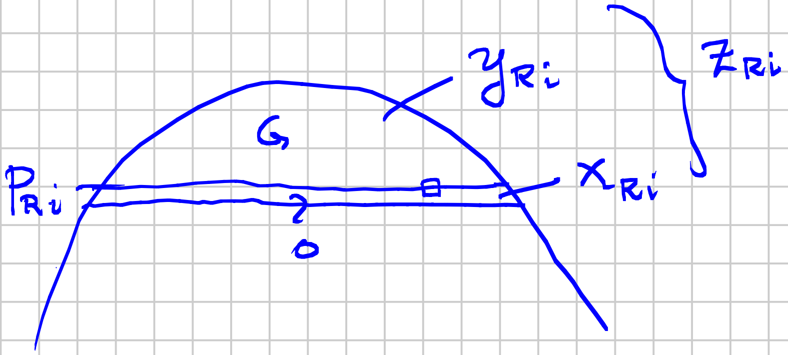
WET vs DRY GAS RESERVOIR FLUID (>95 mol-% C_1)

$\boxed{P} \rightarrow V_{\bar{o}g} = 0$ DRY   Few components, mostly methane



P-T Diagram for a Saturated Gas-Oil Reservoir

for a fixed composition



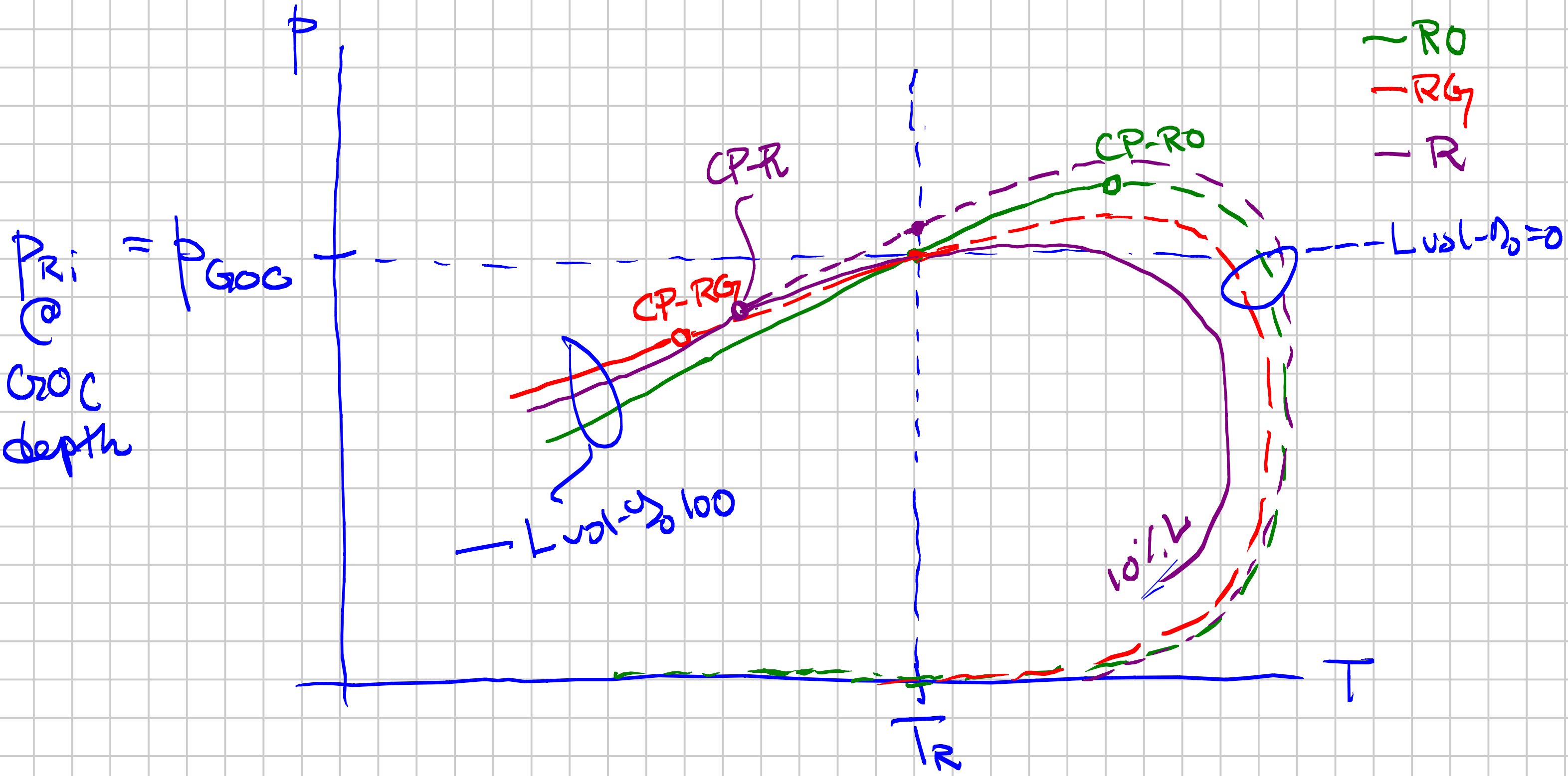
y_{Ri} @ $p_d(T_R) = p_{GOC}$

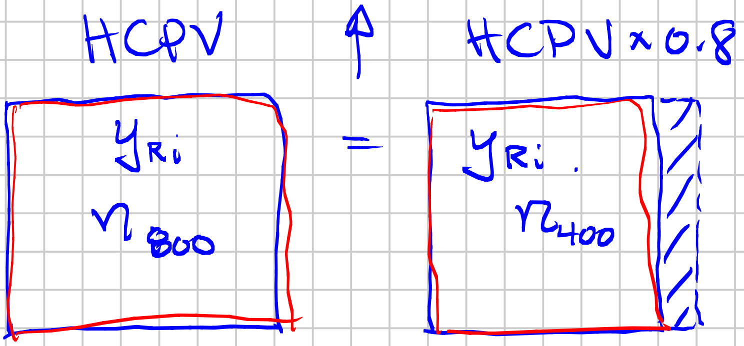
x_{Ri} @ $p_b(T_R) = p_{GOC}$

} Always for saturated Gas-Oil Contact

z_{Ri} @ T_R Two Phase G + O

(90%) (10% vol oil)





$$\boxed{p_R \geq p_d}$$

$$\left(\frac{n_p}{n}\right) = \frac{n_{p\bar{g}}}{n_{\bar{g}}} = \frac{n_{p\bar{o}}}{n_{\bar{o}}}$$

GOR = const

$p_{Ri} = 800$ bara

T_R

Z_{Ri}

$p_R = p_d = 400$ bara

T_R

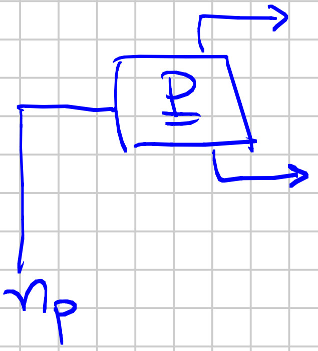
Z_{R400}

$RF = RF_{\bar{g}} = RF_{\bar{o}}$

$$pV = nRTZ_{(p,T)}$$

↓ ✓ ✓ ↑ ✓ ✓ ✓

$$\Delta n = n_{800} - n_{400} = n_p$$



$n_{\bar{g}p} \Rightarrow G_{pd} = 23.68 \cdot n_{\bar{g}p}$

$n_{\bar{o}p} \Rightarrow N_p = n_{\bar{o}p} \cdot \frac{M_{\bar{o}}}{\rho_{\bar{o}}}$

2011

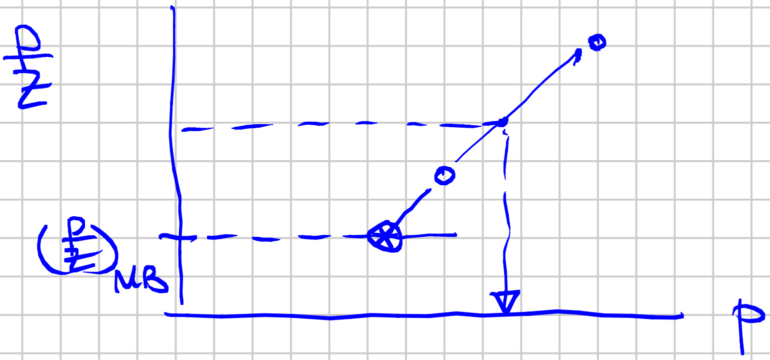
1F : $\frac{G_p}{G}$ ✓ $\Rightarrow$ $\left(\frac{p}{Z}\right)$ ✓ mat. bal. eq.

Know p/Z, find p

$$\frac{p}{Z(p)}$$

Know Z_i @ p_i

Calc Z @ any p (e.g. @ $\frac{1}{2}$ p_i)



Prob. 2 (2011)

ρ_{oi} ?

$$\rho_{ob} = 0.7245 \ \frac{g}{cc} \Rightarrow \frac{m_o}{V_{ob}} \times \frac{V_{ob}}{V_{oi}} = \frac{m_o}{V_{oi}} = \rho_{oi}$$

CCE : $V_{rt} = \frac{V_t}{V_{ob}} = \frac{V_o(p>p_b)}{V_{ob}}$ $\quad p > p_b$

$$\frac{V_{oi}}{V_{ob}} = 0.9843$$

$$\rho_{oi} = \frac{0.7245}{0.9843} =$$

TPG 4145 2014 Q & A EXAM

Note Title 2014-11-26

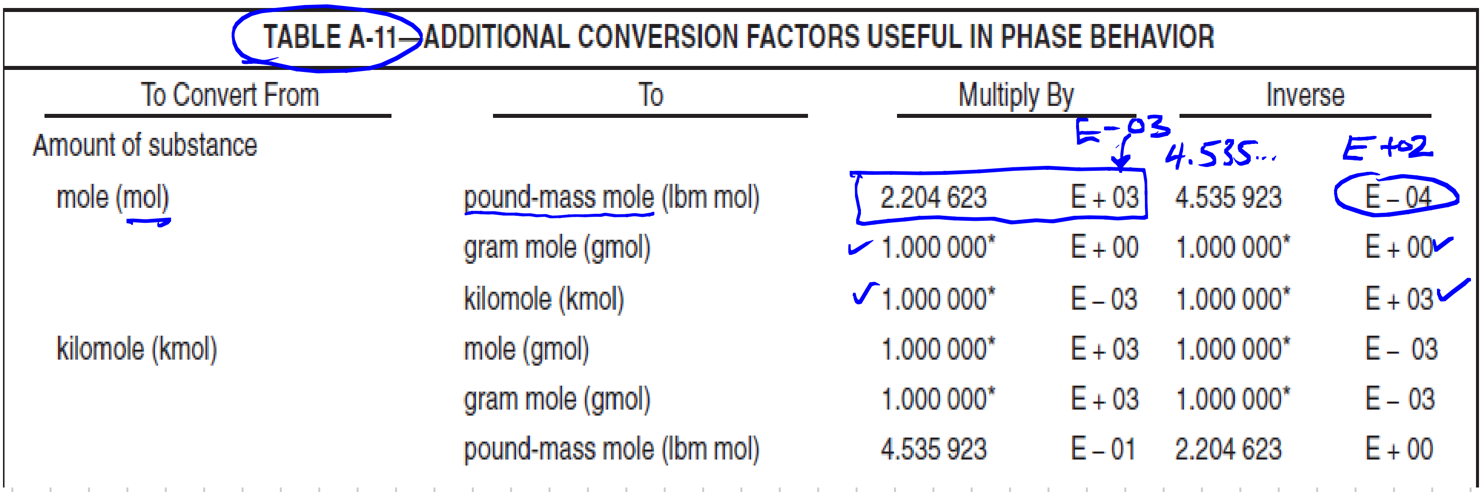


TABLE A-11—ADDITIONAL CONVERSION FACTORS USEFUL IN PHASE BEHAVIOR

To Convert From	To	Multiply By		Inverse	
Amount of substance					
mole (mol)	pound-mass mole (lbm mol)	2.204 623	E + 03 (E−03)	4.535 923 (4.535...)	E − 04 (E+02)
	gram mole (gmol)	✓ 1.000 000*	E + 00	1.000 000*	E + 00 ✓
	kilomole (kmol)	✓ 1.000 000*	E − 03	1.000 000*	E + 03 ✓
kilomole (kmol)	mole (gmol)	1.000 000*	E + 03	1.000 000*	E − 03
	gram mole (gmol)	1.000 000*	E + 03	1.000 000*	E − 03
	pound-mass mole (lbm mol)	4.535 923	E − 01	2.204 623	E + 00

$n = 1$ gmol ⇒ $n =$ lb-mole

$m = 1$ g ⇒ $m =$ lb

2.204 lb/kg

$$2.204\ \frac{lb}{1000\,g}$$

$$m = 1\,\cancel{g} \times \underbrace{2.204\ \frac{lb}{1000\,\cancel{g}}}_{2.204\cdot 10^{-3}} = 2.204\cdot 10^{-3}\ lb$$

gmole lbmole

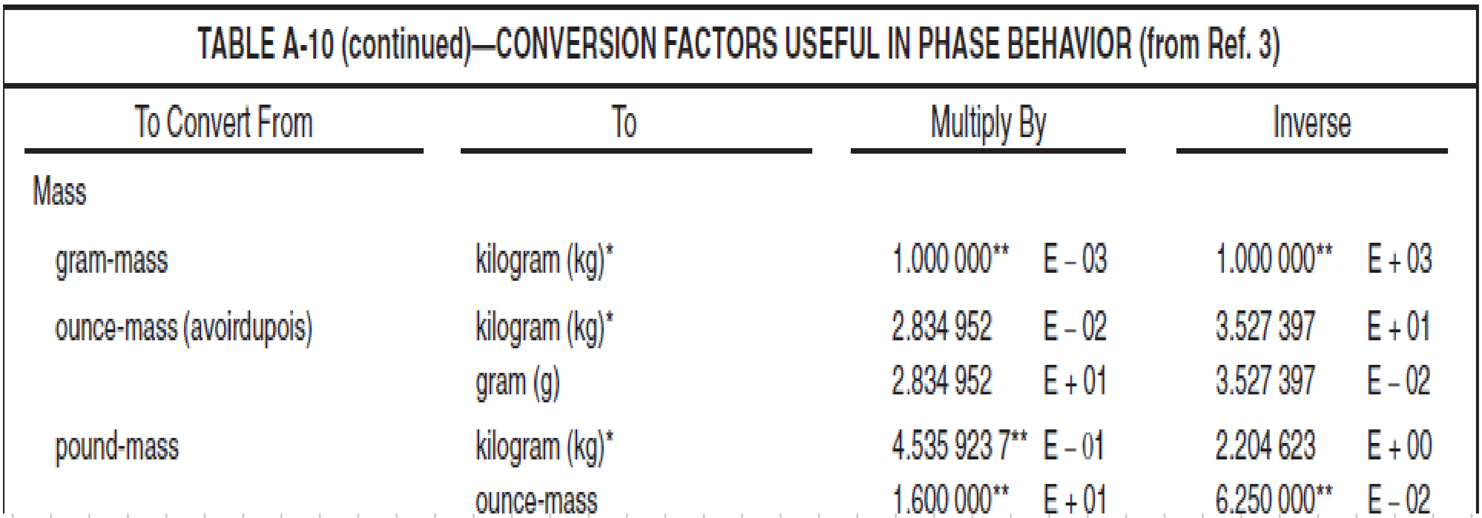
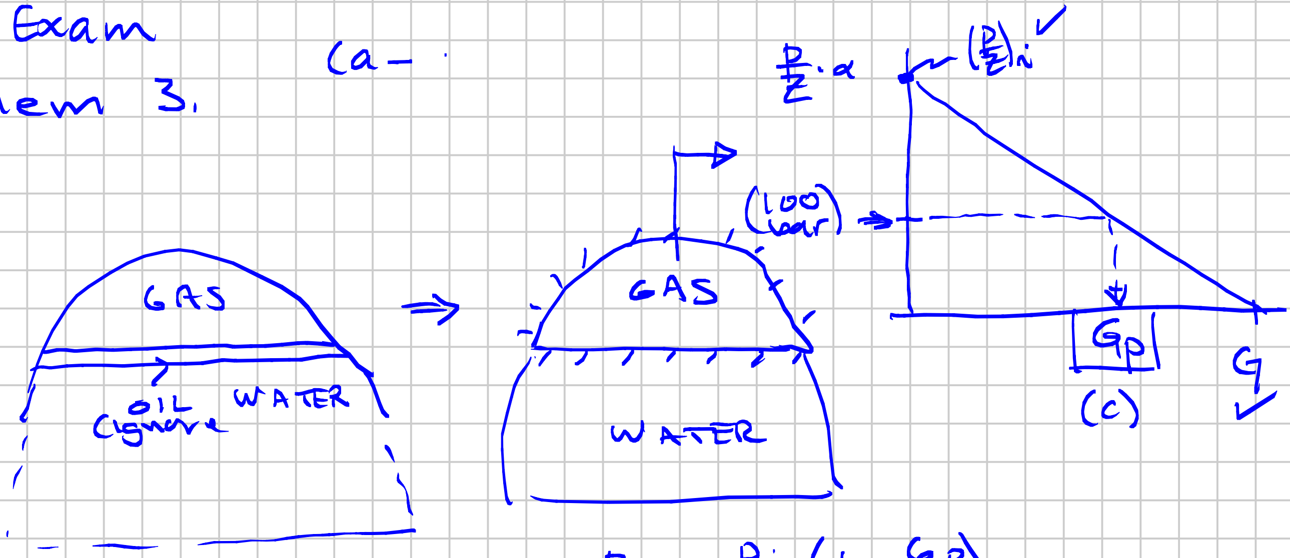


TABLE A-10 (continued)—CONVERSION FACTORS USEFUL IN PHASE BEHAVIOR (from Ref. 3)

To Convert From	To	Multiply By		Inverse	
Mass					
gram-mass	kilogram (kg)*	1.000 000**	E − 03	1.000 000**	E + 03
ounce-mass (avoirdupois)	kilogram (kg)*	2.834 952	E − 02	3.527 397	E + 01
	gram (g)	2.834 952	E + 01	3.527 397	E − 02
pound-mass	kilogram (kg)*	4.535 923 7**	E − 01	2.204 623	E + 00
	ounce-mass	1.600 000**	E + 01	6.250 000**	E − 02

2009 Exam
Problem 3.

(a –



$$[\alpha]\,\frac{p}{z} = \frac{p_i}{z_i}\left(1-\frac{G_p}{G}\right)$$

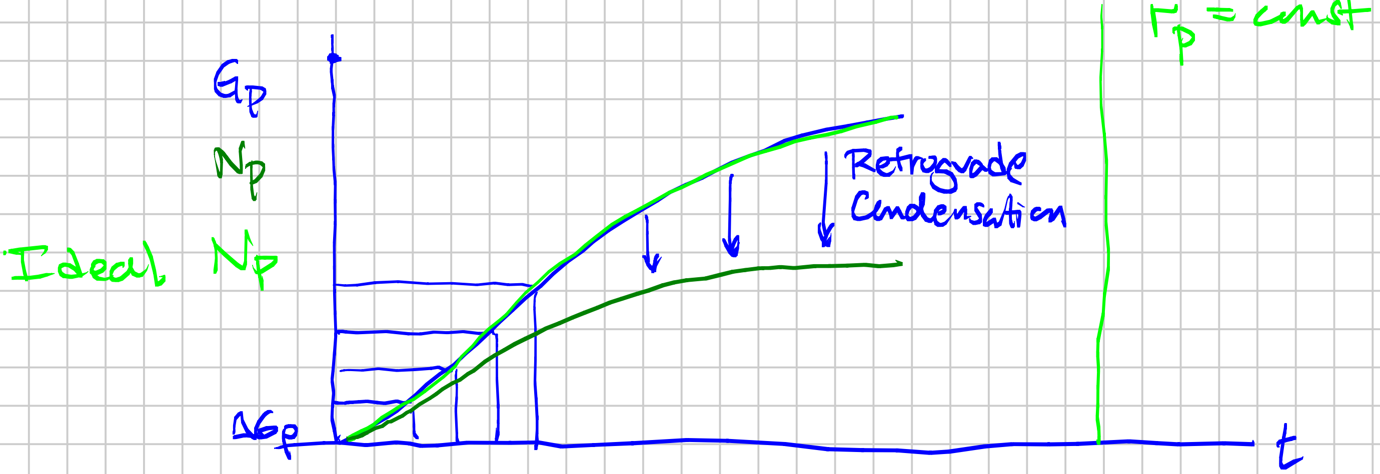
Solve for Gp when p = 100

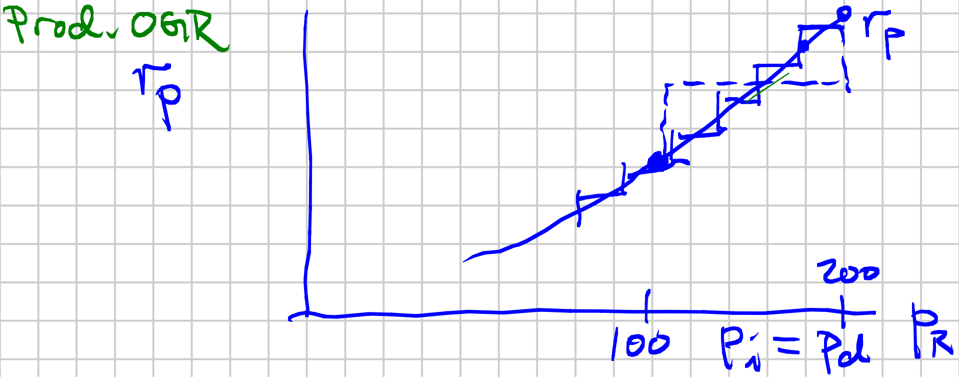
$$c_e = \frac{(c_p + c_w S_{wi}) + M(c_p + c_w) + \{\cancel{c_o \ldots}\}^{0}_{oil}}{1 - S_{wi}}$$

$$\alpha = 1 - c_e(p_i - p_R)$$

$$r_{si} = 2.7\cdot 10^{-5}\ \frac{Sm^3}{Sm^3}$$

$$\underbrace{N_p} = \sum \Delta G_p \cdot \bar{r}_p < [G_p \cdot r_{si}]$$





Composition of the Gas @ p_d : $y_{C_1} = 0.99$ $\underline{y_{C_{10}} = 0.01}$

Table A-1

$$r_{sd} = \frac{V_{\bar o}}{V_{\bar g}} = \frac{y_{C_{10}} \cdot \left(\frac{M_{C_{10}}}{\rho_{C_{10}}}\right)}{(1-y_{C_{10}}) \cdot \left(\frac{R T_{sc}}{p_{sc}}\right) \checkmark} \qquad \frac{Sm^3}{Sm^3}$$

@STC

$\bar o$: C_{10}

$\bar g$: C_1

2013: Problem 1 Q-5:

B_o R_s μ_o B_{gd} r_s μ_g ✓

$p = 75$ bara

[$R_p = 1000$ Sm^3/Sm^3]

Ch. 7

$R_{s_{75}} < R_p < \frac{1}{r_{s75}}$

g + o flowing

$\lambda_g > 0$

$\lambda_o > 0$

$$q_{\bar o} = q_{\bar o o} + q_{\bar o g}$$

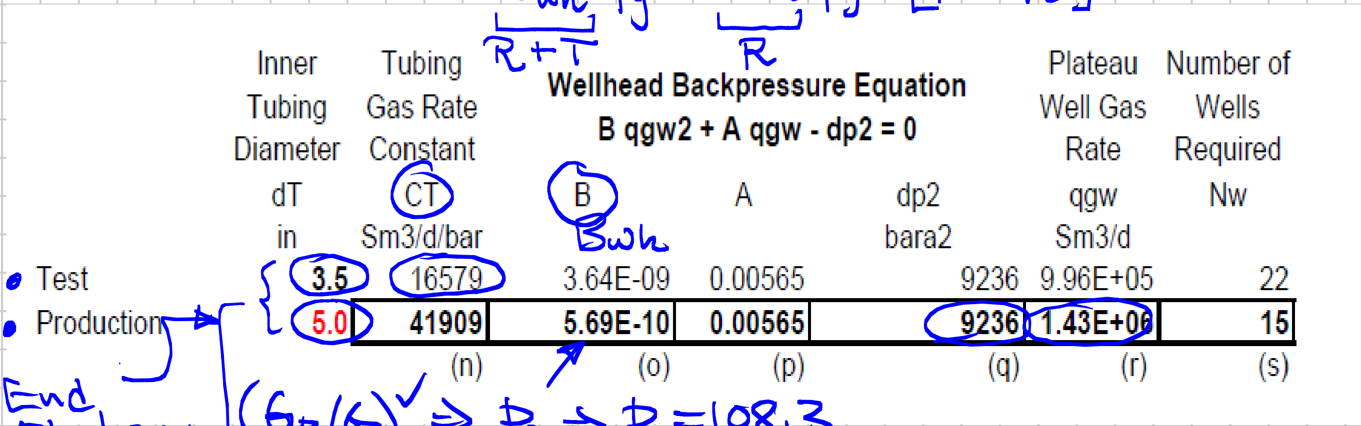
$$\underbrace{1-F_{\bar o o}} = \frac{q_{\bar o g}}{q_{\bar o g} + q_{\bar o o}} \; (?)$$

calculate % of stock tank oil rate that produces from flowing reservoir gas.

Eq. 7.38 : $F_{\bar o o} = \frac{q_{\bar o o}}{q_{\bar o g} + q_{\bar o o}} = \underbrace{\frac{1 - \overset{\checkmark}{R_p}\, \overset{\checkmark}{r_s}}{1 - \underset{\checkmark}{R_s}\, \underset{\checkmark}{r_s}}}$

2008 : Table 1

$$\underbrace{B_{wh}}_{R+T} q_g^2 + \underbrace{A_{wh}}_{R} q_g = \left[p_c^2 - p_t^2\right] : R + T$$



	Inner Tubing Diameter dT in	Tubing Gas Rate Constant CT Sm3/d/bar	Wellhead Backpressure Equation B qgw2 + A qgw - dp2 = 0 B Bwh	 A	 dp2 bara2	Plateau Well Gas Rate qgw Sm3/d	Number of Wells Required Nw
Test	3.5	16579	3.64E-09	0.00565	9236	9.96E+05	22
Production	5.0	41909	5.69E-10	0.00565	9236	1.43E+06	15
		(n)	(o)	(p)	(q)	(r)	(s)

End Plateau (G_p/G)✓ $\Rightarrow p_R \Rightarrow p_c = 108.3$

$$\boxed{B_{wh} = B_R + B_T}$$

Sometimes
$B_R << B_T$
neglect B_R
$B_{wh} \sim B_T$

$$T: \quad q_g = C_T \left(p_w^2 - p_t^2\right)^{0.5}$$

$$q_g^2 = C_T^2 \left(p_w^2 - p_t^2\right)$$

$$\underbrace{\frac{1}{C_T^2}}_{B_T} q_g^2 = \left(p_w^2 - p_t^2\right)$$ = pressure-squared drop in Tubing

Fetkovich paper: C_{Tnow} with d_{Tnow}

$$C_{Tnew} = C_{Tnow} \cdot \left(\frac{d_{Tnew}}{d_{Tnow}}\right)^{2.612}$$

$$= 16579 \cdot \left(\frac{5}{3.5}\right)^{2.612}$$

$$= 41909$$ ✓

$$\underbrace{B = (B_T)_{3.5}}_{\underbrace{B_R = 0}_{\downarrow}} = \frac{1}{C^2_{T3.5}} = \frac{1}{16579^2} = 3.6\cdot10^{-9}$$

$$B_{wh} = (B_T)_5 = \frac{1}{C^2_{T5}} = \frac{1}{\left[C_{T3.5}\cdot\left(\frac{d_5}{d_{3.5}}\right)^{2.7}\right]^2} = \frac{1}{41909^2}$$

$$= 5.61\cdot10^{-10}$$

$q_{gF} = 2\cdot10^6$ Sm³/d

$N_w = ?$

$p_t = 50$ bara

p_c @ $t=0$ $= p_{Ri}/e^{s/2} = 208.3$

p_c @ End Plateau $= 108.3$ by knowns G_p/G

$$B_{wh}\, q_g^2 + A_{wh}\, q_g - (\underbrace{108.3^2 - 50^2}_{9236\ \checkmark}) = 0$$

<u>Solve for q_g</u>

$= 1.43\cdot10^6$ Sm³/d

2002. Problem 2 (D):

$\bar{o}$ $\bar{g}$

D. Assume the reservoir fluids consist of two "components", *surface gas (SG)* and *surface oil (SO)*. If the SG composition in the reservoir oil is 60 mol-%, it's K-value is 1.662, calculate the molar compositions (mol-% SG and mol-% SO) of the GOC reservoir gas and reservoir oil, and the K-value of the surface oil.

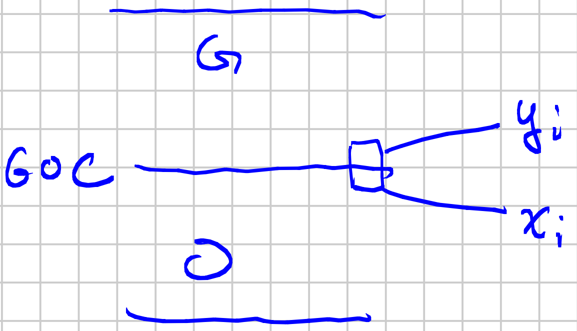
$$\left\{\begin{array}{l} x_{\bar{g}} = 0.6 \\ K_{\bar{g}} = \dfrac{\boxed{y_{\bar{g}}}}{x_{\bar{g}}} = 1.662 \end{array}\right\}$$

$$x_{C_1} = 0.6$$

$$K_{C_1} = \frac{y_{C_1}}{x_{C_1}}$$

$$\Rightarrow y_{\bar{g}} = K_{\bar{g}} \cdot x_{\bar{g}} = 0.6(1.662) = 0.9972$$

$\bar{o} : C_{10}$



$y_{\bar{g}} = 0.9972$ $y_{\bar{o}} = 0.0028$

$y_{C_1} = 0.9972$ $y_{C_{10}} = 0.0028$

$x_{C_1} = 0.6$ $x_{C_{10}} = 0.4$

$x_{\bar{g}} = 0.6$ $x_{\bar{o}} = 0.4$

$$K_{\bar{o}} = K_{C_{10}} = \frac{0.0028}{0.4} = 0.007$$

Gas Rate Eq.

$$q_g = \frac{(\;a\;)\, kh(p_R^2 - p_{wf}^2)}{T_R(\mu Z)\left[\ln\frac{r_e}{r_w} - \frac{3}{4} + s + Dq_g\right]}$$

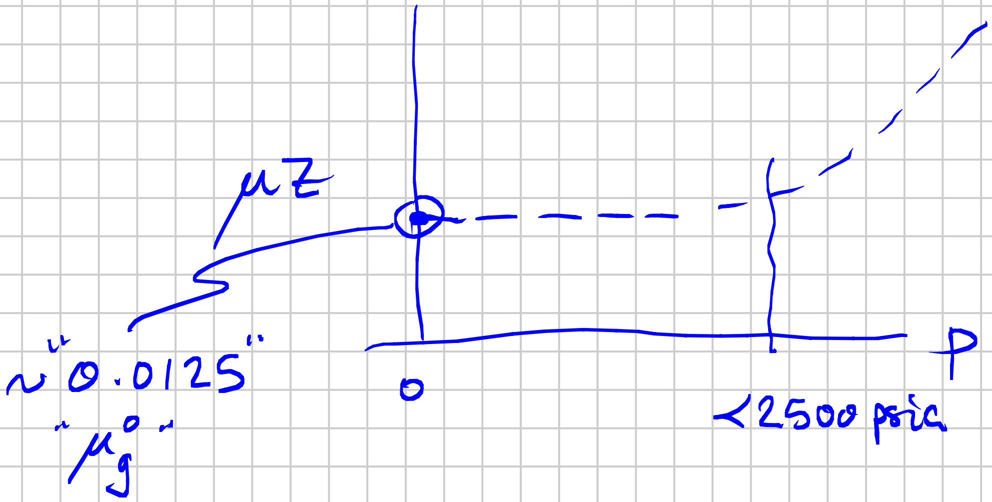
$a = 0.703$ | k(md) h(ft) p(psia) T(°R) q_g(scf/D) μ(cp)

$a = 7.7$ | k(md) h(m) p(bara) T(K) q_g(Sm³/d) μ(cp)

$a = \frac{1}{1424}$ | k (md) h (ft) p (psia) T (°R)

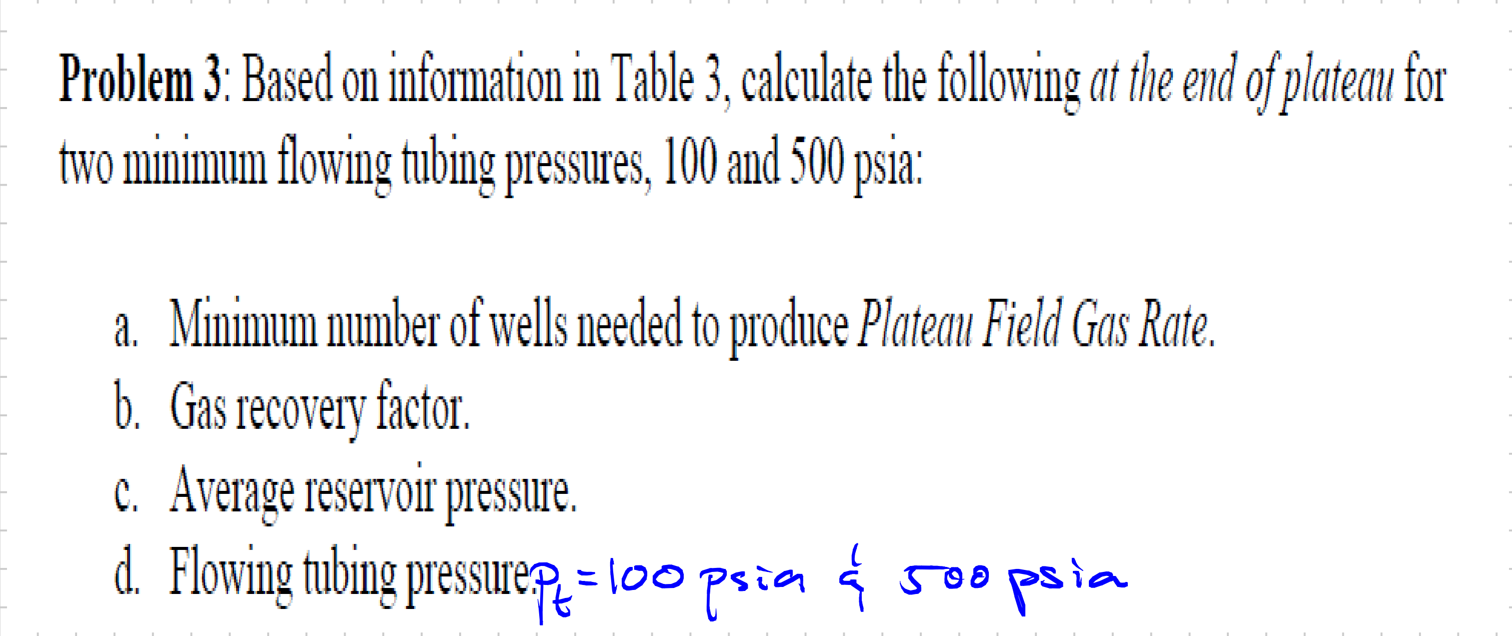
q_g (Mscf/D) μ (cp)

a contains $2\pi\,(T_{sc}/p_{sc})$ & units conversion



Rule of Thumb

2007:



Problem 3: Based on information in Table 3, calculate the following *at the end of plateau* for two minimum flowing tubing pressures, 100 and 500 psia:

a. Minimum number of wells needed to produce *Plateau Field Gas Rate*.
b. Gas recovery factor.
c. Average reservoir pressure.
d. Flowing tubing pressure $p_t = 100$ psia & 500 psia

TABLE 3 – Problem 3 – Dry-Gas Reservoir.

Assume Ideal Gas Law and Straight-Line Gas Material Balance ($M=c_w=c_f=0$)

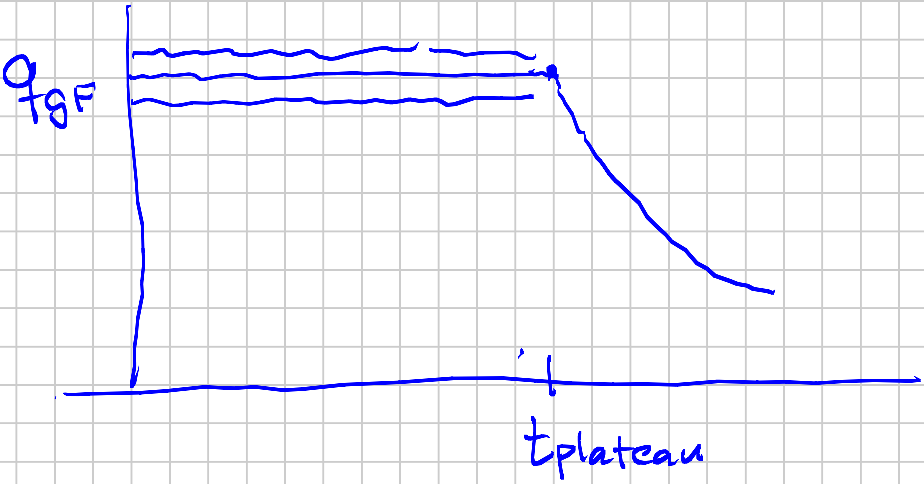
Initial Reservoir Pressure (psia)	1500
Initial Gas in Place (scf)	1E12
Plateau Field Gas Rate (MMscf/D = 10^6 scf/day)	137
Plateau Period (years)	10
Gas Static Column Gravity Term ($p_{reservoir}/p_{surface}$)	1.1
Wellhead Backpressure Deliverability Equation* Constant C	400
Wellhead Backpressure Deliverability Equation* Exponent n	0.8

* $q_g = C(p_c^2-p_t^2)^n$ with p(psia) , q_g(scf/D)

$$RF_g = \frac{G_p}{G}$$

$$G = 10^{12}\ scf$$

$$G_p = q_{gF\,plateau} \cdot t_{plateau} = 137 \cdot 10^6 \frac{scf}{D} \cdot 10\,yr \cdot 365$$



2010

2010

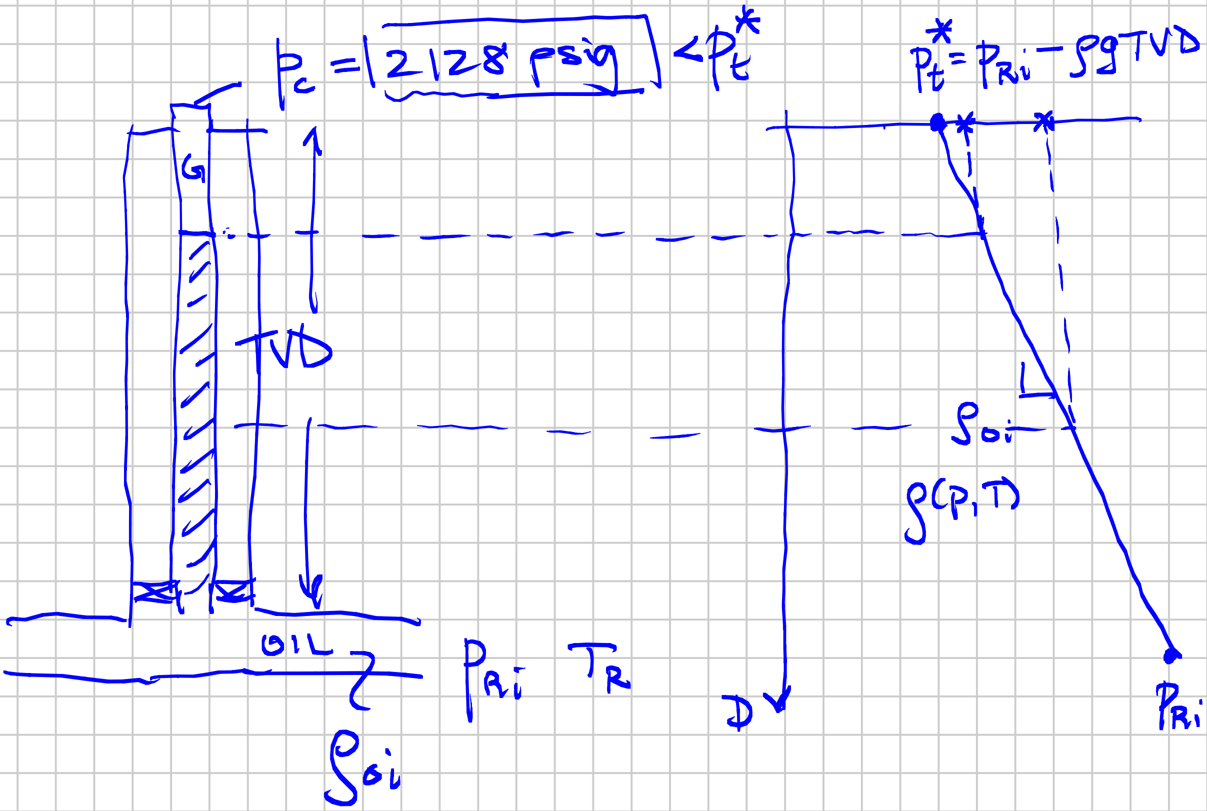
General

An undersaturated oil reservoir is described by the PVT properties and other information given in Appendix D of the Phase Behavior monograph. Additional data are given in Table 1.

En undermettet oljereservoar er beskrevet av PVT egenskaper og annen informasjon gitt i Appendix D av Phase Behavior monografen. Ytterligere data er gitt i tabell 1.

Problem 1: Calculate the following at initial reservoir conditions.

A. Initial surface oil in place (IOIP), N.
B. Initial surface gas in place (IGIP), G.
C. Initial oil formation volume factor, B_{oi}.
D. Hydrocarbon pore volume, HCPV.
E. Initial oil density.
F. Reservoir pressure at top of structure (12 000 ft) and at water-oil contact (13 000 ft).
G. Based on reported shut-in tubing pressure of 2128 psig, estimate whether the tubing is filled with oil or a oil+gas at the time of sampling.



$$\frac{dp_o}{dD} = \rho_o g$$