PVT & $\boxed{\text{Flow}}$

Note Title 8/19/2009

$\boxed{\text{PVT}}$ = Pressure Volume Temperature
Phase Behavior (gas, oil, water)
Phase Equilibria

Phase Properties:
Density ρ
Viscosity μ
Composition

API Gravity

$\gamma_{API} = 10^\circ$ water $\rho = 1000\ \text{kg/m}^3 = 1\ \text{g/cm}^3$

Oils $\gamma_{API} > 10 \xrightarrow{\text{Lighter}} \cdots 100$ $\rho \sim 600\ \text{kg/m}^3$

Specific Gravity (Relative Density)

$$\gamma_L \equiv \frac{\rho_L\left(1\,\text{atm} = 1.0135\,\text{bar} = 14.69\,\text{psia};\ T = 15.56^\circ\text{C} = 60^\circ\text{F}\right)}{\rho_w\left(1\,\text{atm}, 60^\circ\text{F}\right)}$$

$$\text{“}\gamma_{API}\text{”} \equiv \left(\frac{141.5}{\gamma_L}\right) - 131.5$$

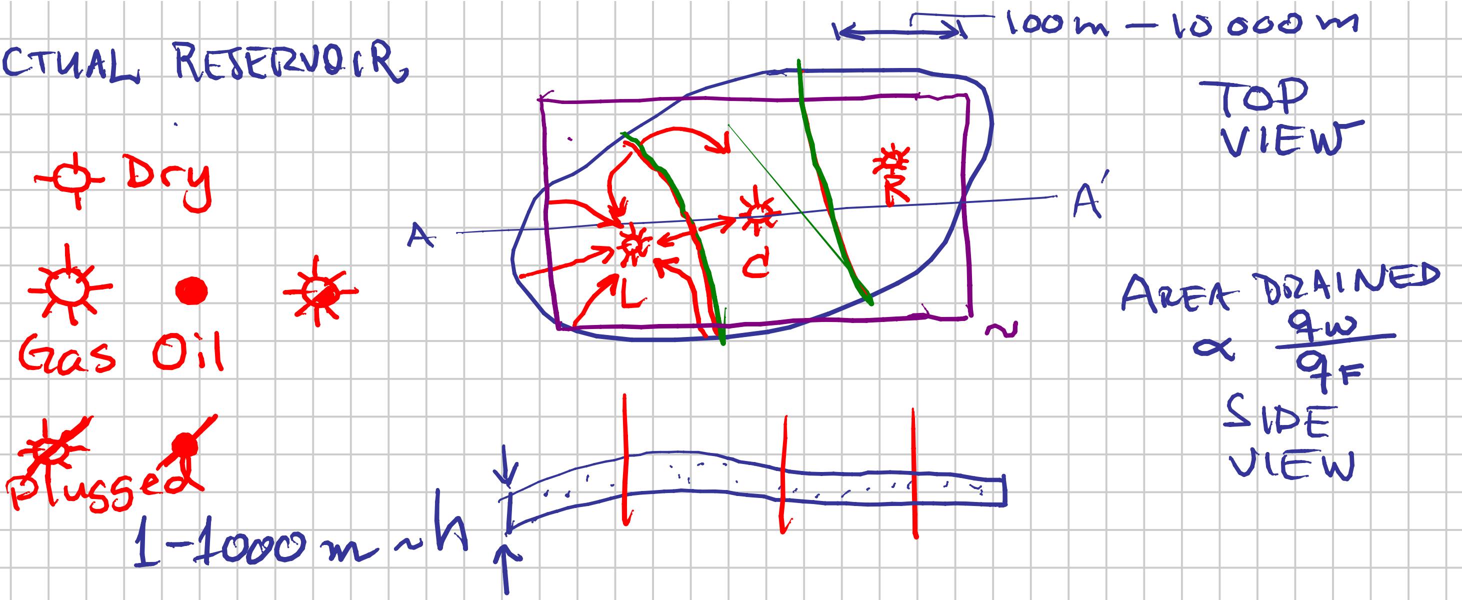
$$\gamma_o = \underline{\underline{0.6}} = \frac{600}{999.14}$$

Permeability Ranges

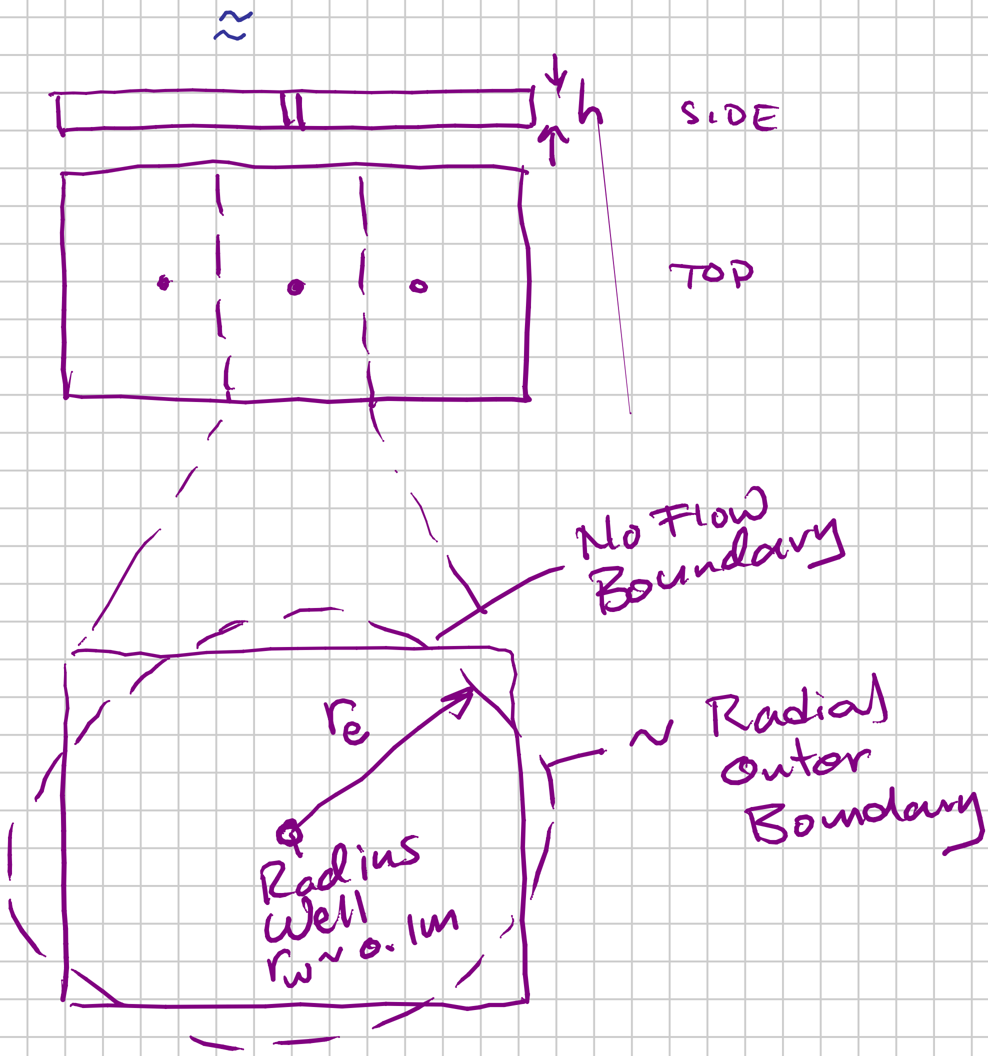
$10^{-4} - 10^{-2}$	md	Shale – Tight Gas
$10^{-1} - 10^{4}$	md	Sandstone / Carbonates
~ $0.1 - 5$	md	Chalk
$10 - 10^{4}$	md	North Sea (most) Sandstones

↑ millidarcy

ACTUAL RESERVOIR



Radial / Cylindrical Flow Geometry



Radial (Areal) Flow Geometry

Flow Equation

Darcy Equation:

$$v = C \cdot \frac{dp}{dx}$$

Material Balance Equation

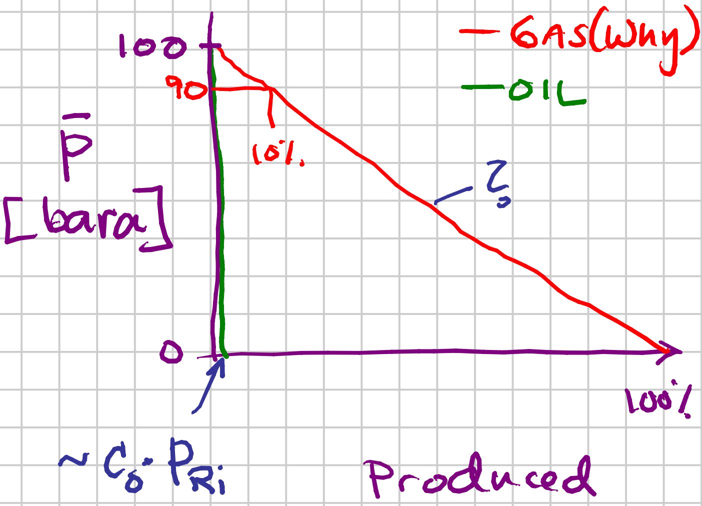
$$\bar{p} = f(\%\,\text{Produced})$$

$\rho(p)$ "PVT" Behavior

$$\underbrace{v}_{\text{Darcy Velocity}} = -\frac{\overset{\text{ROCK}}{k}}{\underset{\text{FLUID}}{\mu}} \cdot \underbrace{\frac{dp}{dx}}_{\text{DRIVING POTENTIAL}}$$

d'Arcy

Not the true traveling velocity!



$c_w \sim 3 \cdot 10^{-6} \frac{vol/vol}{psi}$

$14.50377 \frac{psi}{bar}$

~ 14.5 psi/bar

$c_w \sim 50 \cdot 10^{-6} \frac{1}{bar}$

$c_o \sim 150 \cdot 10^{-6} \frac{1}{bar}$

$$\frac{\Delta V_{max}}{V_i} = c_o (P_{Ri} \to 1)$$

$$= c_o \cdot P_{Ri}$$

$150 \cdot 10^{-6} \frac{1}{bar} \times 100\ bar$

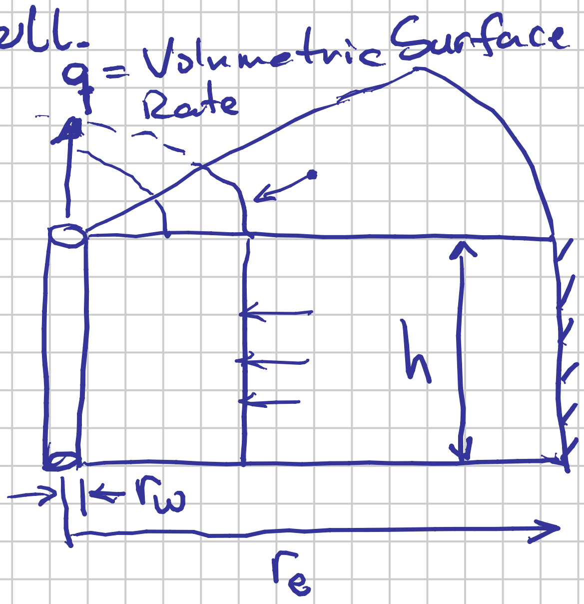
$1.5 \cdot 10^{-4} \cdot 10^{2}$

$1.5 \cdot 10^{-2}$

0.015

1.5% recovery

Darcy Eq. used to develop the "Rate Eq." for a single well.



$$v = -\frac{k}{\mu}\frac{dp}{dr}$$

$$\left\{ \begin{array}{l} v_z = -\dfrac{k}{\mu}\dfrac{d\phi}{dz} \\ \\ \qquad \phi = p + \rho g z \end{array} \right\}$$

high-k
gas/water
injection

Assume: q @ Reservoir ~ q @ Surface (✓ water ✓ stock-tank oil)

$$q = \overset{\text{Darcy}}{\overset{\downarrow}{v}} \cdot \underset{\substack{\uparrow \\ \text{Bulk Area} \\ \perp \text{ to flow}}}{A_\perp}$$

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

Assumption: "Steady State Condition" (SS)

$$\dot{m} \equiv \left(\frac{dm}{dt}\right)_r = \text{constant}$$

$$\dot{m} = q \cdot \rho = \text{const}$$

Liquids (ρ = constant)

$$q\rho = \text{const}$$

$$\rho = \text{const}$$

$$q = \text{const} = v A$$

$$= \frac{k}{\mu}\frac{dp}{dr} \cdot 2\pi r h$$

$$\int_{r_w}^{r_e} \frac{1}{r}\, dr = \underbrace{\frac{2\pi k h}{q\mu}}_{\text{const}} \int_{P_{wf}}^{P_e} dp$$

Solved for $p(r_e) = P_e$

$$\ln \frac{r_e}{r_w} = \frac{2\pi k h}{q\mu}\left(P_e - P_{wf}\right)$$

$$q_o = \frac{2\pi k h \left(P_e - P_{wf}\right)}{\mu_o \cdot \ln r_e/r_w}$$

Same

Average Volumetric Reservoir Pressure

$$\bar{P}_R \text{ or } P_R \equiv \frac{\int_{r_w}^{r_e} p(r)\, r\, dr}{\int_{r_w}^{r_e} r\, dr}$$

$$q_o = \frac{2\pi k h \left(\bar{P}_R - P_{wf}\right)}{\mu_o\left[\ln \frac{r_e}{r_w} - \frac{1}{2}\right]}$$

$$\bar{P}_R \simeq p(r \sim 0.6\, r_e)$$

The more realistic outer boundary condition

$$\left(\frac{dp}{dr}\right)_{r=r_e} = 0 \qquad \text{(No-flow O.B.)}$$

$$\Rightarrow \quad q_o = \frac{2\pi k h \left(\bar{P}_R - P_{wf}\right)}{\mu_o \left[\ln \frac{r_e}{r_w} - \frac{3}{4}\right]}$$

$$\left.\begin{array}{l} r_e \sim 200 - 2000\,\text{m} \\ r_w \sim 0.1\,\text{m} \end{array}\right\} \ln \frac{r_e}{r_w} \simeq 7-10$$

An Oil Rate Equation

$$q_o = \frac{2\pi \boxed{kh} \boxed{\left(\bar{P}_R - P_{wf}\right)}}{\boxed{\mu_o} \left[\ln \frac{0.47 r_e}{r_w}\right]}$$

$$\bar{P}_R \text{ @ } p(r \sim 0.47 r_e)$$

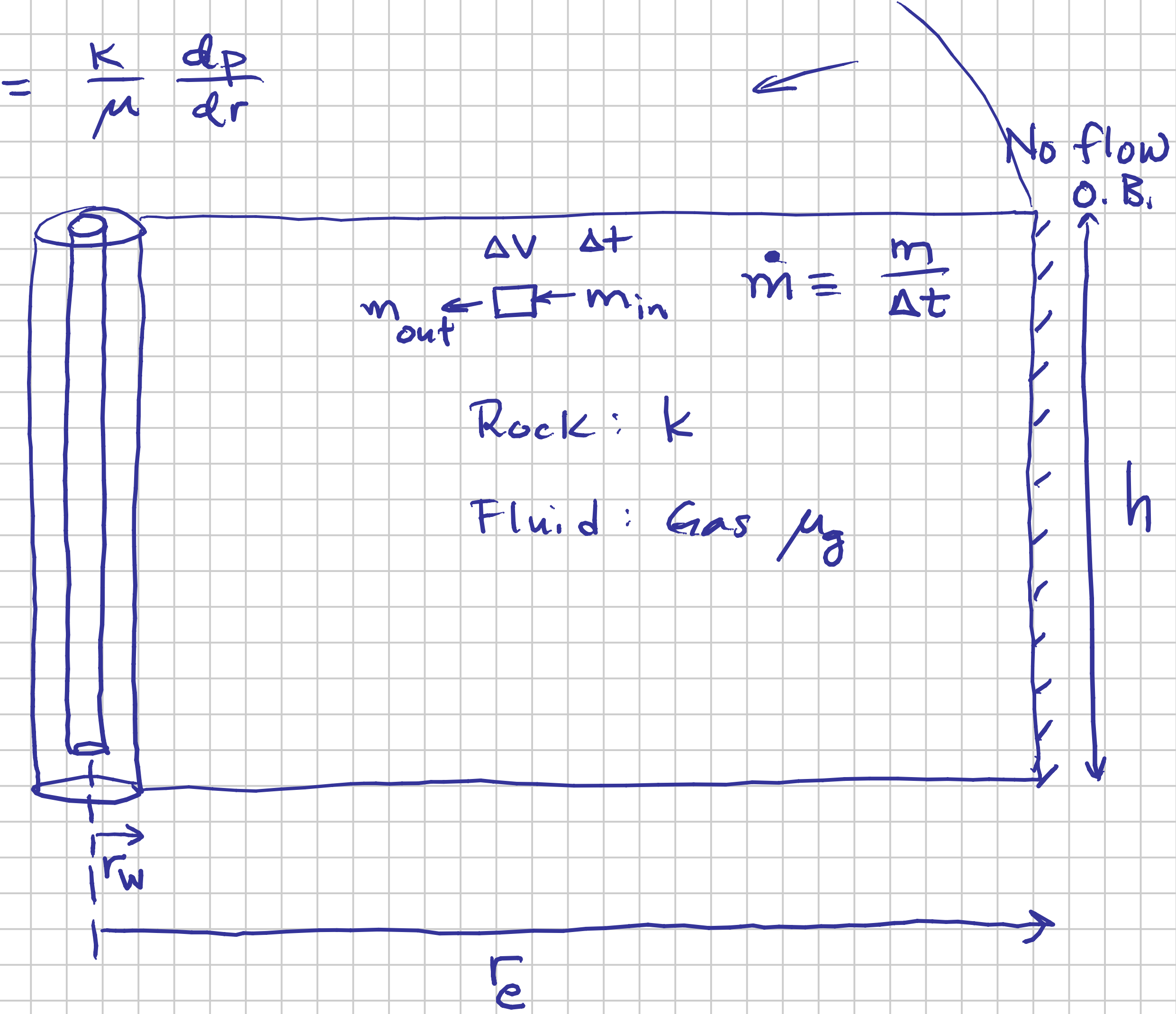
	Variables	Orders of Mag.	Range	Unit
Rock	k	8	10^{-4} – 10^{4}	md
Fluid	μ_o	5	0.1 – 10^{4+}	cp [≡mPa.s]
Geological	h	3	1 – 10^{3}	m
$\boxed{\Delta p}$	$\bar{P}_R$	2	10 – 1000	bara
	P_{wf}	2	1 – 100	bara

GAS RATE EQUATION DEVELOPMENT

Note Title 8/24/2009

DARCY'S LAW

$$v = \frac{k}{\mu}\frac{dp}{dr}$$



Assumption 1 : Ideal Gas

$$\boxed{pV = n\,R\,T}$$

Universal Gas Constant 8.314

Pressure:

volume

Moles (amount)

Absolute T (K, °R)

$T_R = 1.8\, T_K$

$= \frac{9}{5}$

- absolute
- gauge $\equiv$ abs $- (p_a)_{local}$

ambient

has a mass unit associated

8314

p [Pa]

V [m^3]

n [kg]

T [K]

bara barg mol gmol

psia psig

kPa(a)

kPa(g)

kg kg-mol (kmol)

lb lb-mol

$R = 10.7315$

$p\,[\text{psia}]$

$V\,[ft^3]$

$n\,[lb]$

$T\,[°R]$

e.g. 1 mol $C_1 = n_{C_1}$

$\underline{M} \equiv$ molar mass
molecular weight $\equiv \frac{m}{n}$

$$m_{C_1} = n_{C_1} \cdot M_{C_1}$$

$$[g] = 1[gmol] \; 16.04\left[\frac{g}{gmol}\right]$$

$$m_{C_1} = 16 \; g$$

e.g.(2) $n_{C_1} = 1$ lb-mol

$$m_{C_1} = n_{C_1} \cdot M_{C_1}$$

$$1 \text{ lb-mol} \cdot 16.04 \; \frac{lb}{\text{lb-mol}}$$

$$m_{C_1} = 16 \; lb$$

Q's

Ideal Gas Law – ok for "low" pressures ✓

$P_{sc} =$ ~ 1 atm
14.69 psig
1.0135 bara

$$\frac{V_{gsc}}{n} = \frac{R T_{sc}}{P_{sc}}$$

any T (T_{sc})

$$\frac{Sm^3}{\text{kg-mol}} = 8314 \; \frac{(15.56°C + 273.15)}{1.0135 \cdot 10^5}$$

$T_{sc} =$ 15.56 °C
60 °F

$$\boxed{\frac{Sm^3}{\text{kg-mol}} = 23.68 \ \frac{Sm^3}{\text{kg-mol}}}$$

- Gas Rate Eq.

$$v = \frac{k}{\mu}\frac{dp}{dr}$$

$pV = nRT$ (Assumption 1)

Assumption 2:

"Steady State" (SS) Flow Condition

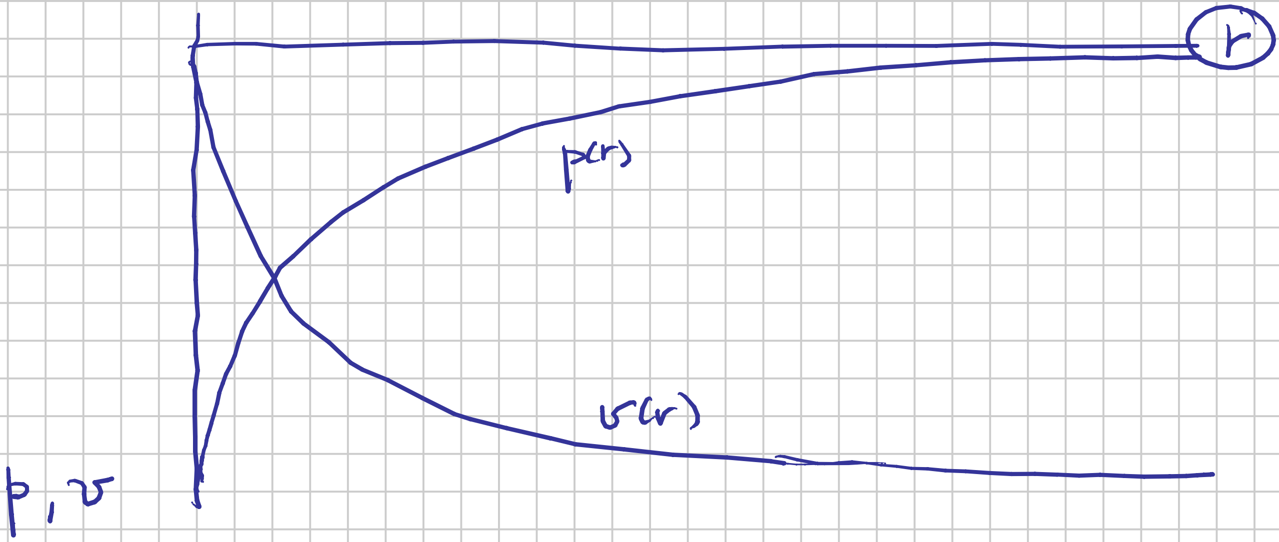
$\dot{m}(r) = \text{constant}$

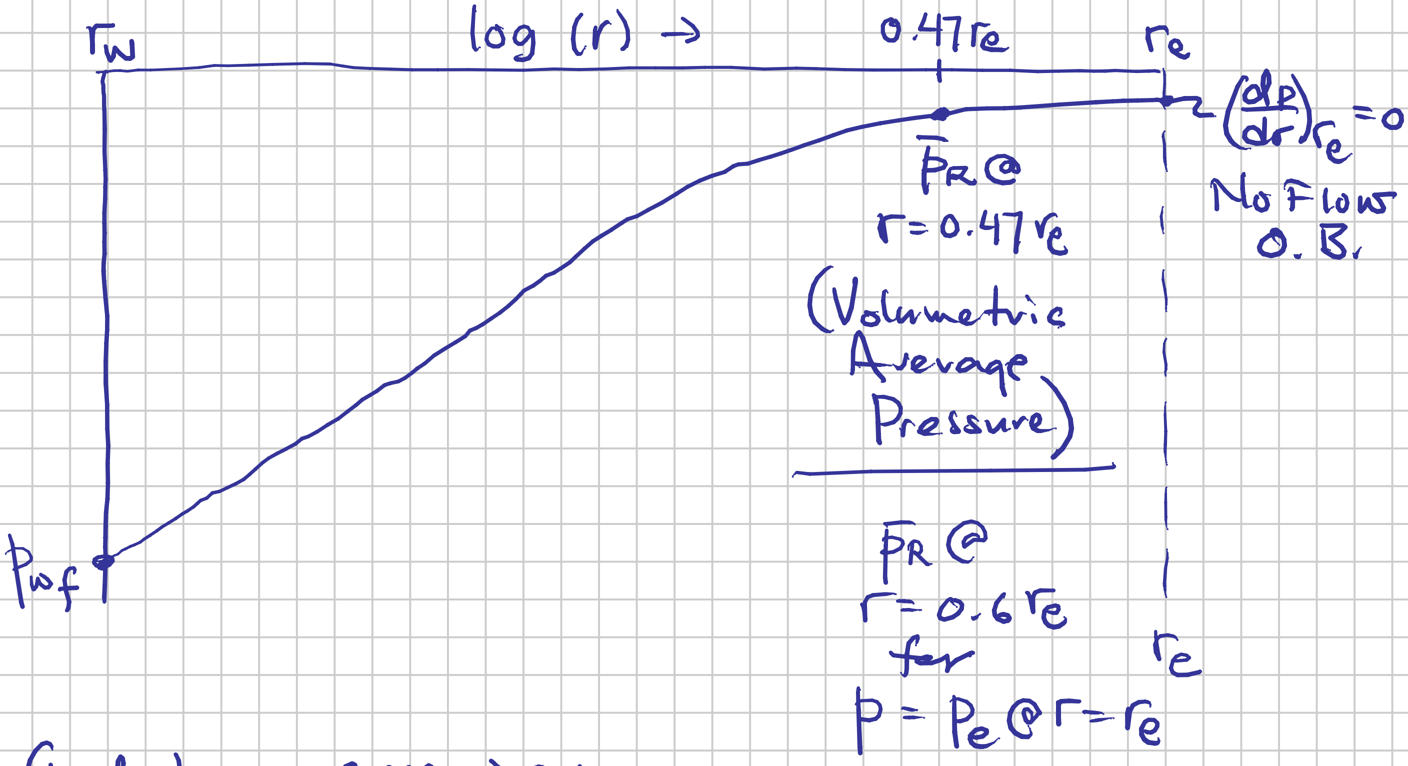
Liquid:

$$q_w = \frac{2\pi kh(\bar{P}_R - P_{wf})}{\mu_w \cdot \ln r_e/r_w}$$

1. $p(r) \propto \ln(r)$
2. $v(r) \propto \frac{1}{r}$

$\Rightarrow$ Most of the "action" happens in the 1st 10 m away from r_w





Good home excercise:

Plot in Excel $p(r)$ and $v(r)$

psia ft/s

Field Units

for Liquid flow:

$q_o = 1000$ bbl/D

$k = 10$ md

$\mu_o = 1$ cp

$h = 10$ ft

$p_R = 1000$ psia

r_e for $A = 160$ acres

$r_w = 0.1$ m

$\dot{m} =$ constant : Known

Use instead (Known) : q_g = surface gas volumetric rate

$$\boxed{q_g = \dot{m}_g \cdot \frac{1}{\rho_{gsc}}}$$

$$\frac{Sm^3}{d} \qquad \frac{kg}{d} \cdot \frac{Sm^3}{kg}$$

$$\dot{m}_g = q_{\bar{g}} \rho_{\bar{g}}$$

Reservoir Flow (Darcy)

$$q_R = v A_\perp \qquad \frac{m^3}{d}$$

$$\dot{m} = \underset{\uparrow}{q_R} \cdot \rho_g$$

Reservoir Conditions

$$\rho_g \equiv \frac{m_g}{V_g} = \left(\frac{n_g M_g}{V_g}\right)$$

Ideal Gas Law

$$\rho_g = \frac{p M_g}{R T}$$

At S.C. $\quad \rho_{gsc} = \dfrac{p_{sc} M_g}{R T_{sc}}$

Subscripts:

$\bar{g} = gsc$

$\bar{o} = osc$ (STO)

$V_{\bar{g}}$

$V_{\bar{o}}$

$$q_{\bar{g}} \rho_{\bar{g}} = \dot{m}_g = \underset{\checkmark}{v} A \rho_g$$

$$= \left(\frac{k}{\mu_g} \cdot \frac{dp}{dr}\right)(2\pi h r)\Big($$

$$q_{\bar{g}} = 2\pi k h \cdot \left(\frac{\rho_g}{\rho_{\bar{g}}}\right) \frac{1}{\mu_g} r \frac{dp}{dr}$$

$$; \left(\frac{\rho_g}{\rho_{\bar{g}}}\right) = \frac{\dfrac{p \cancel{M}}{\cancel{R} T_R}}{\dfrac{p_{sc} \cancel{M}}{\cancel{R} T_{sc}}}$$

$$= \left(\frac{T_{sc}}{T_R p_{sc}}\right) p$$

$$q_{\bar{g}} \int_{r_w}^{r_e} \frac{1}{r}\,dr = 2\pi k h \left(\frac{T_{sc}}{T_R P_{sc}}\right) \int_{P_{wf}}^{P_e} \frac{P}{\mu_g}\,dp$$

Assume : $\mu_g \simeq$ const

$$q_{\bar{g}} \ln\frac{r_e}{r_w} = \frac{2\pi k h \left(\frac{T_{sc}}{T_R P_{sc}}\right)}{\mu_g} \frac{1}{2}\left(P_e^2 - P_{wf}^2\right)$$

$$q_{\bar{g}} = \frac{\pi k h \left(P_e^2 - P_{wf}^2\right)}{\left(\frac{T_R P_{sc}}{T_{sc}}\right) \mu_g \left[\ln\frac{r_e}{r_w}\right]}$$

No-Flow O.B. $\bar{P}_R$ @ 0.47 r_e

$$\boxed{q_g = \frac{\pi k h \left(\bar{P}_R^2 - P_{wf}^2\right)}{\left(\frac{T_R P_{sc}}{T_{sc}}\right) \mu_g \left[\ln\frac{r_e}{r_w} - \frac{3}{4}\right]}}$$

↓ Pure SI

$$\boxed{q_g = C\left(P_R^2 - P_{wf}^2\right)}$$

↑

Constant

C : Rock (k)
Fluid (μ_g, T_{sc}, P_{sc}, T_R)

Geometry (r_e, r_w, h, π)

Darcy Eq: (cgs)   Darcy : 1000 md = 1 D

$$v\left[\frac{cm}{s}\right] = \frac{k\,[D]}{\mu\,[cp]} \cdot \frac{\Delta p\,[atm]}{\Delta r\,[cm]} \qquad \frac{[\cancel{F}]}{[L]}$$

$$\frac{L}{t}$$

centipoise $\equiv$ mPa·s $[\cancel{F} \cdot t \quad]$

Dimensional analysis of $k\,[L^2]$

$$1\ \text{Darcy} \ \textcircled{$\cong$} \ 1\ \mu m^2 = 10^{-12}\ m^2$$

SPE

$\equiv$

$$v\left[\frac{m}{s}\right] = \frac{k\,[m^2]\quad \Delta p\,[Pa]}{\mu\,[Pa \cdot s]\quad \Delta r\,[m]}$$

Pure SI

Time: days   86400 s/d

$$q_g\left[\frac{Sm^3}{d}\right] = \underset{\text{number}}{\boxed{}}\;\frac{k[md]\; h[m]\;\left\{p_R^2 - p_{wf}^2\;\;[bara^2]\right\}}{\mu_g[cp]\;\; T_R[K]\;\;\left[\ln(r_e/r_w) - 3/4\right]}$$

UNITS / SIMPLEST GAS MATERIAL BALANCE / GAS RATE FORECAST

Gas Rate Eq. (Pure SI Units) $\left\{\begin{array}{l}\text{Ideal Gas Law}\\ \text{Darcy's Law } (\mu_g = \text{const})\\ \text{Steady State Flow}\end{array}\right.$

$$\underset{\left[\frac{Sm^3}{s}\right]}{q_g} = \frac{\pi\, k[m^2]\, h[m]\, (p_R^2 - p_{wf}^2)\, [\cancel{Pa^2}]}{\left(\frac{p_{sc}[\cancel{Pa}]}{T_{sc}[\cancel{K}]}\right) T_R[\cancel{K}]\, \mu_g[\cancel{Pa\cdot s}] \cdot \ln r_e/r_w} \qquad \frac{m^3}{s}$$

$$\underset{\left[\frac{Sm^3}{d}\right]}{q_g} = (\quad)\, \frac{\{k[md]\}\, h[m]\, \Delta p^2\, [bar^2]}{T_R[K]\, \mu_g[cp] \cdot \underset{[ft/ft]}{\ln r_e/r_w}}$$

$$\underbrace{\pi\left(\frac{T_{sc}}{p_{sc}}\right)} \cdot \{s \to d\} \cdot \{md \to m^2\} \cdot \{bar \to Pa\} \cdot \{cp \to Pas\}$$

$$= \left\{\pi\, \frac{(273.15+15.56)}{1.0135 \cdot 10^5}\right\} \left\{k[\cancel{md}] \cdot \underbrace{\frac{1\cancel{D}}{10^3\cancel{md}}}_{=1} \cdot \underbrace{\frac{10^{-12}\, m^2}{1\cancel{D}}}_{=1}\right\}$$

$$\frac{\cdot \left\{\Delta p^2[bar^2] \cdot \underbrace{\frac{10^{10}\, Pa^2}{bar^2}}_{=1}\right\}}{\left\{\mu_g[cp] \cdot \frac{1\, mPa\cdot s}{1\, cp} \cdot \frac{1\, Pa\cdot s}{10^3\, mPa\cdot s}\right\}}$$

$$q_g\left[\frac{m^3}{s}\right] = \left\{\overset{9{,}00\cdot10^{-3}}{\pi\,\frac{(273.15+15.56)}{1.0135\cdot10^{5}}}\right\}\left\{10^{-15}\right\}\left\{10^{10}\right\}\left\{10^{3}\right\}$$

$$\cdot\ \frac{k[md]\,h[m]\,\Delta p^2[bar^2]}{T_R[K]\,\mu_g[cp]\ \ln r_e/r_w}$$

$$\underbrace{= 9\cdot10^{-5}\ \frac{k[md]\,h[m]\,\Delta p^2[bar^2]}{T_R[K]\,\mu_g[cp]\ \ln r_e/r_w}}_{\downarrow\ \frac{m^3}{\cancel{s}}\cdot\frac{60\cancel{s}}{\cancel{min}}\cdot\frac{60\cancel{min}}{\cancel{hr}}\cdot\frac{24\cancel{hr}}{d}}$$

$$= 9\cdot10^{-5}\times3600\times24$$

$$\boxed{q_g\left[\frac{Sm^3}{d}\right] = 7.7\cdot\frac{k[md]\,h[m]\,\overset{f(t)}{\Delta p^2}[bar^2]}{T_R[K]\,\mu_g[cp]\ \ln r_e/r_w}}$$

~~Realistic~~ Economic Gas Rates

$P_g \sim \overset{\$}{USD}\ 3/Mscf$ (20090826)

Monthly operations in domestic USA : \$1000/mo

$$q_{g_{min}} = \frac{\cancel{\$}1000}{30d}\cdot\frac{Mscf}{\cancel{\$}3} \sim 10\ Mscf/D$$

$$35.31\ \frac{scf}{Sm^3} \qquad \frac{ft^3}{m^3}$$

$$1\ Mscf = 10^3\ scf$$

$$q_{g_{min}} \sim 10\cdot\frac{\cancel{Mscf}}{D}\cdot\frac{10^3\cancel{scf}}{1\cancel{Mscf}}\cdot\frac{Sm^3}{35.31\cancel{scf}} = 283\ \frac{Sm^3}{d}$$

M = 1000

~~MM = 2000~~ ~~Roman times~~

MM = 1000 · 1000 = 10^6

Field Units for Gas Volumes

scf = standard ft^3 at T_{sc}, p_{sc}

Mscf = 10^3 scf

MMscf (MMCF) = 10^6 scf

Used for well gas rates
10 → 150 000 Mscf/D
150 MMscf/D

bcf (Bcf) = 10^9 scf

Tcf = 10^{12} scf

Used to define GAS Reserves, GAS IN PLACE
(Recovered Gas)

1 Tcf : Giant USA Gas field
Marginal Norwegian Gas Field

~5-10 Tcf : Frigg, Sleipner, Ormen Lange

40^+ Tcf : Troll Gas Field

~900 Tcf : World's largest conventional Gas Field (North Field, QATAR)

Simplest
GAS MATERIAL BALANCE

- Ideal Gas Law
- Gas-filled Pore Volume

(HC) (PV)

HCPV = constant

$$\boxed{p_R = p_{Ri}(1 - RF)}$$

Nature Controls

Surface Gas Recovery Factor

$$= \frac{\text{Cum. Gas Produced}}{\text{Initial Gas In Place}} = \frac{G_p}{G}$$

$$G_p = \int_0^t \boxed{\underline{q_g}(t)}\, dt \qquad q_g = C(p_R^2 - p_{wf}^2) \qquad \frac{Sm^3}{Sm^3}$$

Nature Controls — We control

$$G \;\; \begin{matrix}[IGIP]\\ [OGIP] \\ [GIIP]\end{matrix} = \underbrace{\underbrace{V_{bulk} \cdot \bar{\phi}}_{PV} \cdot \underbrace{(1 - \bar{S}_w)}_{HC\ \text{"gas"}}}_{HCPV} \qquad m^3$$

IN the Reservoir

V_{pHC}

$V_{pg} \rightarrow G$?

Gas-PVT e-note

$$p_{sc}V_{sc} = nRT_{sc}$$

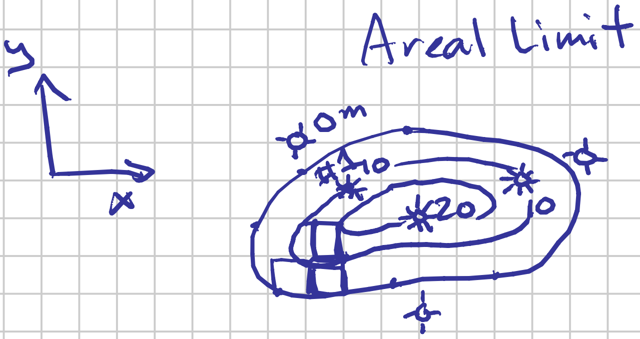
$$p_{Ri}V_{gi} = nRT_R$$

$$\frac{G}{V_{pg}} = \frac{V_{sc}}{V_{gi}} = \frac{\dfrac{\cancel{nR}T_{sc}}{p_{sc}}}{\dfrac{\cancel{nR}T_R}{p_{Ri}}}$$

↑
HCPV

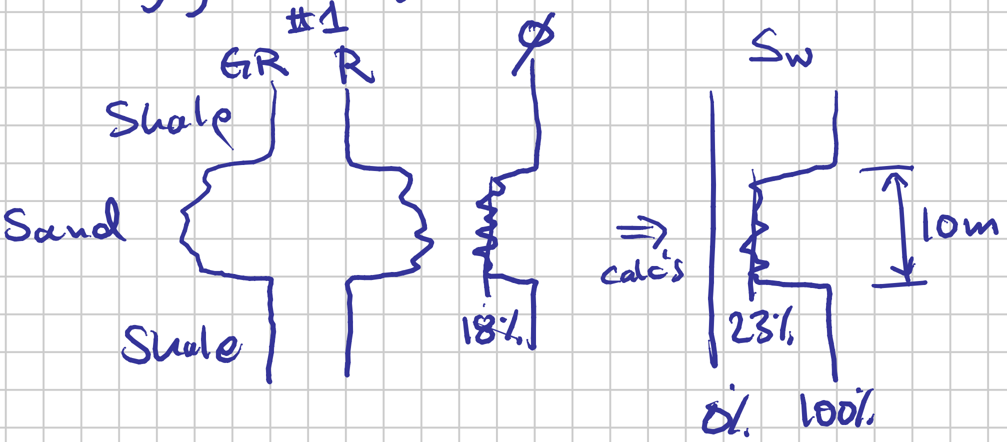
$$\boxed{G = \underbrace{V_{gi}}_{HCPV} \cdot \underbrace{\frac{T_{sc}}{T_R} \cdot \frac{P_{Ri}}{P_{sc}}}_{50-250}}$$

$\left\{\begin{array}{l}\text{Geologic +} \\ \text{Well Log Data}\end{array}\right\}$



Top View

$$V_b = \iint h_g(x,y)\;dx\,dy = \sum A_{box} \cdot \bar{h}_{box}$$

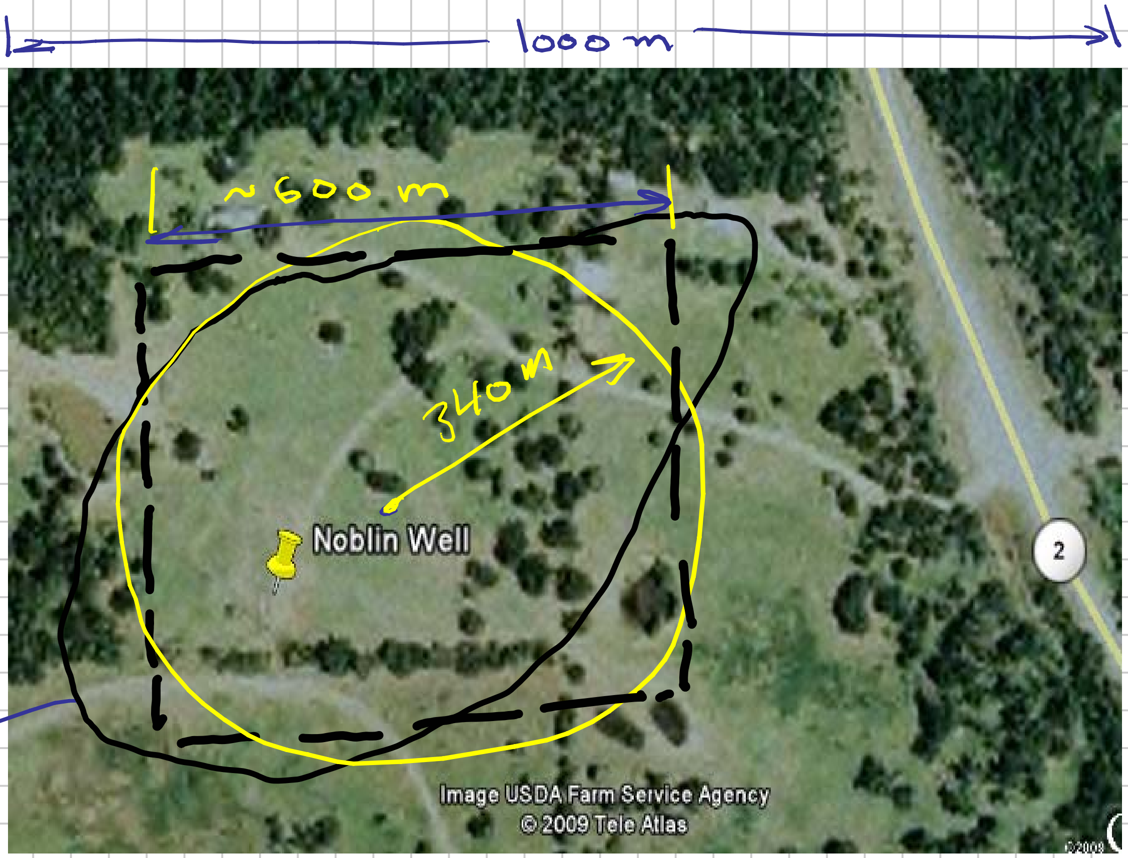


$\bar{\phi} \sim 18\%$

$\bar{S_w} \sim 23\%$

$$T_C = (T_F - 32)/1.8$$

$$T_R = T_F + 459.67$$



Atoka formation

h ~ 10 m

Areal Extent

$A \sim 600 \times 600\ m$

$h \sim 10\ m$

$\bar{\phi} \sim 0.14$

$\bar{S}_w \sim 0.35$

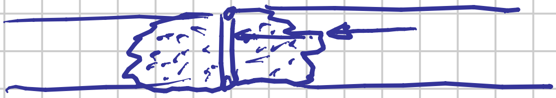
$P_{Ri} \sim 350$ psia

$T_R \sim 115\ °F$

Depth ~ 1000 m

$\pi r_e^2 = A$

Well was fractured



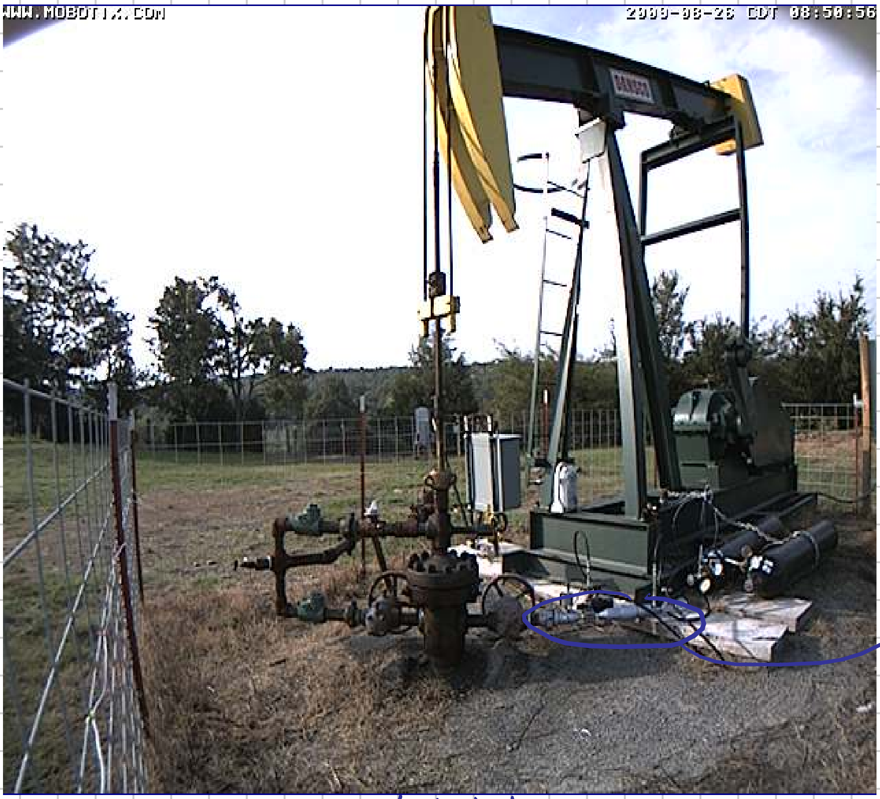
$r_{wa} = r_w \cdot \{1 \to 10^{3+}\}$

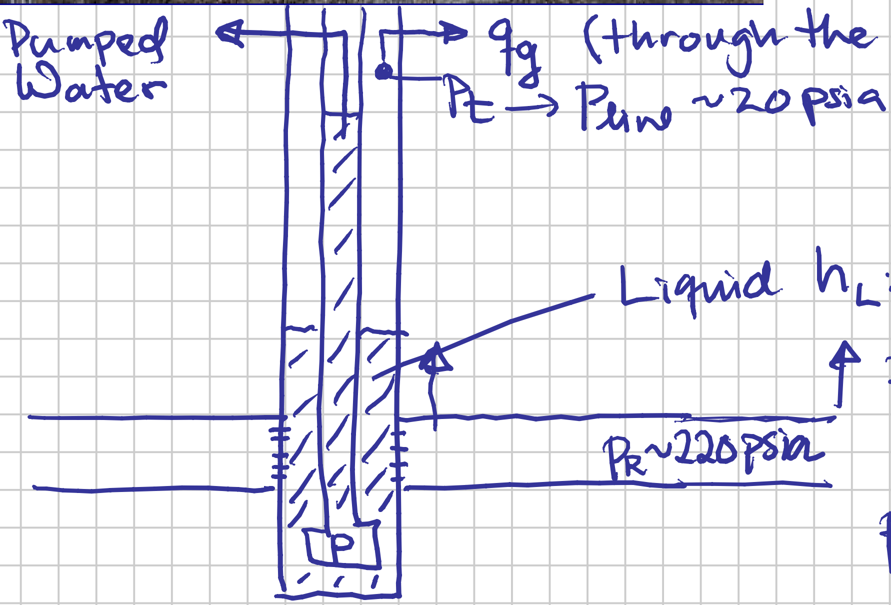
Problem Definition:

① Estimate G

② Estimate C_g in $q_g = C_g (P_R^2 - P_{wf}^2)$

③ Combine the Rate & Mat. Bal. Eqs. to forecast production rate $q_g(t)$ for a fixed P_{wf} = given.





250 Mcf/D

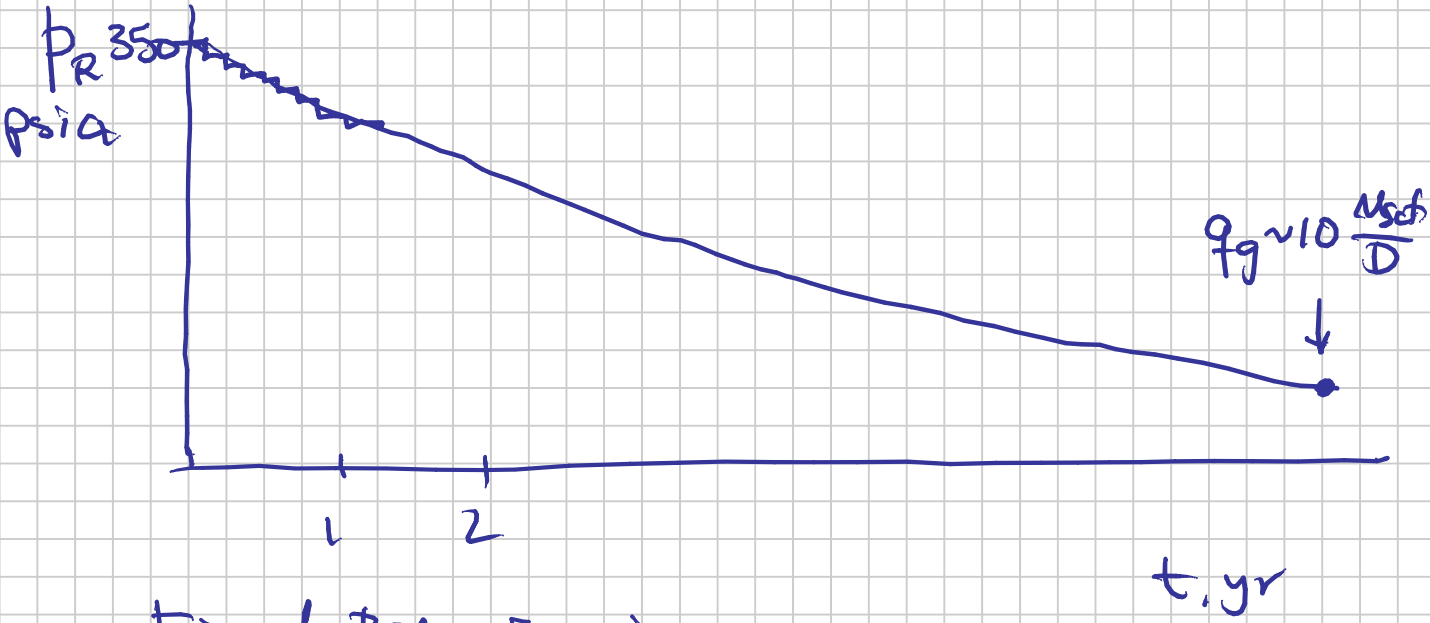
15

$$p_{wf} = \underset{=}{p_t} + \underbrace{\rho_w g h_L}$$

$$p_{wf} \sim p_t$$

$$G(\text{bcf}: 10^9\,\text{scf}) = G(\cancel{\text{Sm}^3}) \cdot 35.31 \frac{\cancel{\text{scf}}}{\cancel{\text{Sm}^3}} \cdot \frac{\text{bcf}}{10^9\,\cancel{\text{scf}}}$$

Time Step: 1 month



Fixed p_{wf} = 50 psia

$\Delta t_1 = 1$ mo

$P_{R1} = P_{Ri}$

$q_{g1} = C_g \cdot (350^2 - 50^2)$

$(\Delta G_p)_1 = 30.4 \text{ days} \times q_{g1}$

$$RF_1 = \left(\frac{G_p}{G}\right)_1 = \frac{\sum_{i=1}^{N} (\Delta G_p)_i}{G}$$

$\downarrow$

$\bar{P}_{R2}$ Δt_2

$\hookrightarrow q_{g2} \cdot \Delta t_2 = \Delta G_{p2} \Rightarrow G_{p2} \xRightarrow{M.B.} P_{R3}$

$$q_g\left[\frac{Sm^3}{d}\right] = \underset{\uparrow}{10}\,\left(P_R^2 - P_{wf}^2\right)\,[\text{bara}^2]$$

$$\text{Unit}: \frac{Sm^3/d}{\text{bara}^2}$$

$$\underset{\sim\sim\sim}{q_g\left[\frac{Mscf}{D}\right]} = \underset{\uparrow}{C}\,\left(\underset{\sim}{p_R^2} - \underset{\sim}{p_{wf}^2}\right)\,\underset{\sim}{[\text{psia}^2]}$$

- Value
- Unit

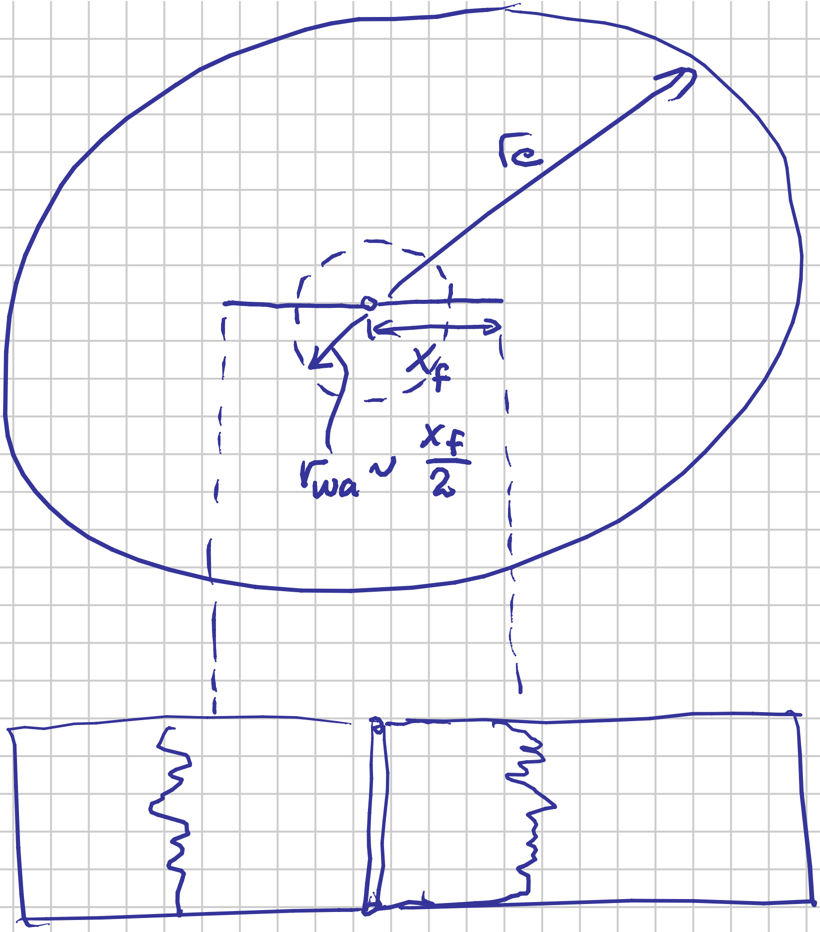
$$q_g\left[\frac{Sm^3}{d}\right] = 10\,\underbrace{\left\{\left(\underset{\uparrow}{P_R[\text{psia}]}^2 - \underset{\uparrow}{P_{wf}[\text{psia}]}^2\right)\right\}\underbrace{\left(\frac{\text{bara}}{14.5\ \text{psia}}\right)^2}}_{\text{bara}^2}$$

$$\boxed{10\cdot\frac{1}{\underset{=}{14.5^2}}\left(P_R[\text{psia}]^2 - P_{wf}[\text{psia}]^2\right)}\left[\frac{\cancel{Sm^3}}{d}\right]\cdot\frac{35.31\ \cancel{scf}}{\cancel{Sm^3}}\cdot\frac{Mscf}{10^3\ \cancel{scf}}$$

$$C = 10\,\frac{1}{14.5^2}\cdot\frac{35.31}{10^3} = 1.68\cdot 10^{-3}$$

$$\boxed{q_g\left[\frac{Mscf}{D}\right] = 1.68\cdot 10^{-3}\cdot\left(P_R^2 - P_{wf}^2\right)}$$

where P in psia



$$q_g = 7.7 \cdot \frac{kh(\Delta p^2)}{\mu T_R \cdot \ln\left(\frac{r_e}{r_{wa}}\right)}$$

$$r_{wa} \sim \frac{x_f}{2} \text{ or } \frac{x_f}{e}$$

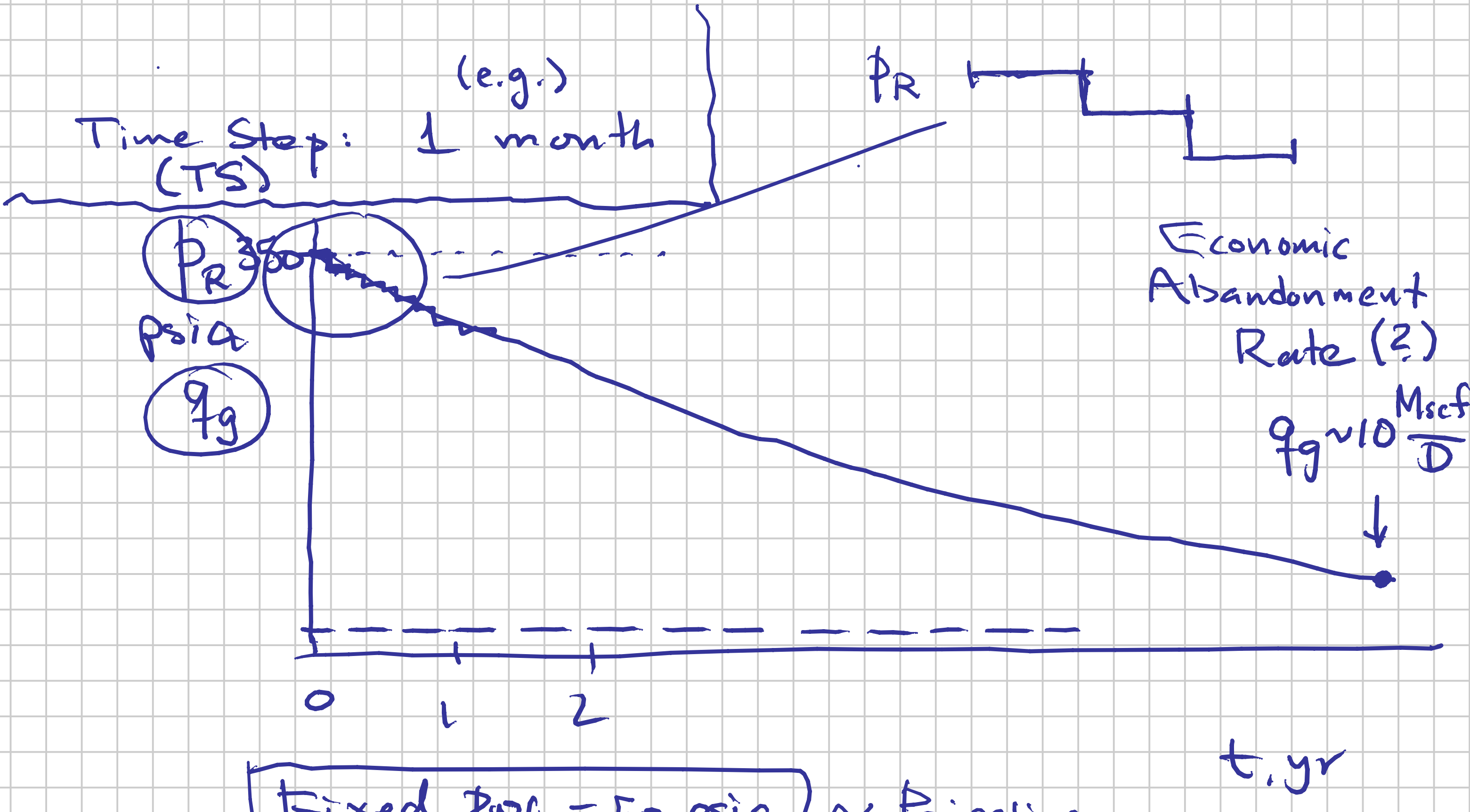
Noblin

$r_{wa} = 10$ m

Stimulation

Fracturing

Time Step: (e.g.) 1 month
(TS)



$\boxed{\text{Fixed } p_{wf} = 50 \text{ psia}}$ ~ $P_{pipeline}$

(TS) $\Delta t_1 = 1$ mo

$P_{R1} = P_{Ri}$

$q_{g1} = C_g \cdot (350^2 - 50^2)$

Assume CONSTANT during TS

$(\Delta G_p)_1 = 30.4 \text{ days} \times q_{g1}$

$$RF = \left(\frac{G_p}{G}\right) = \frac{\sum_{i=1}^{N} (\Delta G_p)_i}{G}$$

During a time step (TS)

$P_R = $ const

$q_g = $ const

- End of TS:

$\Delta G_p = q_g \cdot \Delta t$

Total $G_p = \sum \Delta G_p$ Cumulative

Material Balance

New: $\overline{P}_R = P_{Ri}\left(1 - \frac{G_p}{G}\right)$

⇒ Used as $\overline{P}_R$ for the NEXT TS

1) We've done the Excel Sheet Solution

2) ~~We go drink~~ beer ~~(water)~~

$P_{Ri} = 350$ psig

$P_{wf} = 25$ psia

$C = 4.02$ scf/D/psia^2

$G = 2.49 \cdot 10^8$ scf

$\Delta t = 3$ mo

TS 1: 0 → 3 mo

$P_R = P_{Ri} = 350$ psia

$q_{g_1} = 4.02\left(350^2 - 25^2\right) = 489 \cdot 10^3$ scf/D

$\Delta G_{p1} = 489 \cdot 10^3 \left(3 \text{ mo} \times \frac{365}{12} \frac{D}{mo}\right) = 4.47 \cdot 10^7$ scf

$G_{p_1} = \Delta G_{p1} = 4.47 \cdot 10^7$ scf

$G_{p1}/G = \frac{4.47 \cdot 10^7}{\boxed{2.49 \cdot 10^8}} = 0.179$ ✓ (17.9% RF)

$P_R = 350(1 - 0.179)$ psia

$= 287$ psia ✓ $= 19.8$ bara

$\underline{\text{TS } 2}$: $p_R = 287$ psig

$$q_{g2} = 4.02\left(287^2 - 25^2\right)$$

$$= \underline{3.29} \cdot 10^5 \text{ scf/D} \checkmark$$

$$\Delta G_{p2} = \underline{3.29} \cdot 10^5 \cdot 3 \text{ mo} \frac{365}{12} \text{ scf}$$

$$= 3.00 \cdot 10^7 \text{ scf}$$

$$G_{p2} = \overset{4.47\cdot 10^7}{\Delta G_{p1}} + \overset{3.00\cdot 10^7}{\Delta G_{p2}} = 7.47 \cdot 10^7 \text{ scf}$$

$$\frac{G_{p2}}{G} = RF = 0.300 \checkmark$$

GAS PVT PROPERTIES

- Self-study & help
  Gas-PVT e-note

- Problem 1 now on ItsLearning
  Due: Friday midnight Sept. 11

GAS PVT: "Real" Gas Behavior

$$pV = nRT \cdot \underbrace{\left\{\begin{matrix}\text{Correction}\\ \text{Term}\end{matrix}\right\}}_{Z}$$

Equation of State
"Gas"

Magnitude:

$$\boxed{0.7 \rightarrow 2^{+}}$$

Significant

What does the $\underline{\underline{Z}}$ depend on?

$$- \boxed{\underbrace{p, T}, \text{ gas composition}}$$

mass, molar amounts of compounds

non-HCs
0 → xx mol-%

$$\left\{\begin{matrix} CO_2 \\ N_2 \\ \underline{H_2S} \end{matrix}\right\}$$

$$\left\{\begin{matrix} C_1 \\ C_2 \\ C_3 \\ i\text{-}C_4 \\ n\text{-}C_4 \end{matrix}\right\}$$

methane

Light HCs

$i-C_5$

$n-C_5$

C_{6s}

C_7

$$\left.\begin{matrix} C_8 \\ \vdots \\ \vdots \end{matrix}\right\} \; 0 \rightarrow 10\text{-}15 \text{ mol\%}$$

In the late 1800s van der Waals

"Theory of Corresponding States"

$$\left(\frac{V}{n}\right) = f(P, T, \text{composition})$$

$\boxed{\left(\frac{PV}{nRT}\right)}$ behaved in the same way as a function of $\left(\frac{P}{P_{ref}}, \frac{T}{T_{ref}}\right)$

$P_r = \frac{P}{P_c}$ Reduced Pressure

$T_r = \frac{T}{T_c}$ Reduced Temperature

$$\left\{\begin{matrix} P_{ref} = P_c \\ T_{ref} = T_c \end{matrix}\right\} \text{ of a component}$$

P_c

T_c

C_1 vs N_2

C_2 vs CO_2

@ same (P_r, T_r) same $\left(\frac{PV}{nRT}\right)$

$(5, 2)$ 1.1

1930s → 1940s

y_i = molar composition of a gas

Measurements for different gases

y_i of A — of B — . . . — Z

p_r T_r | p T V | p T V | p T V

(pV/nRT) (pV/nRT)

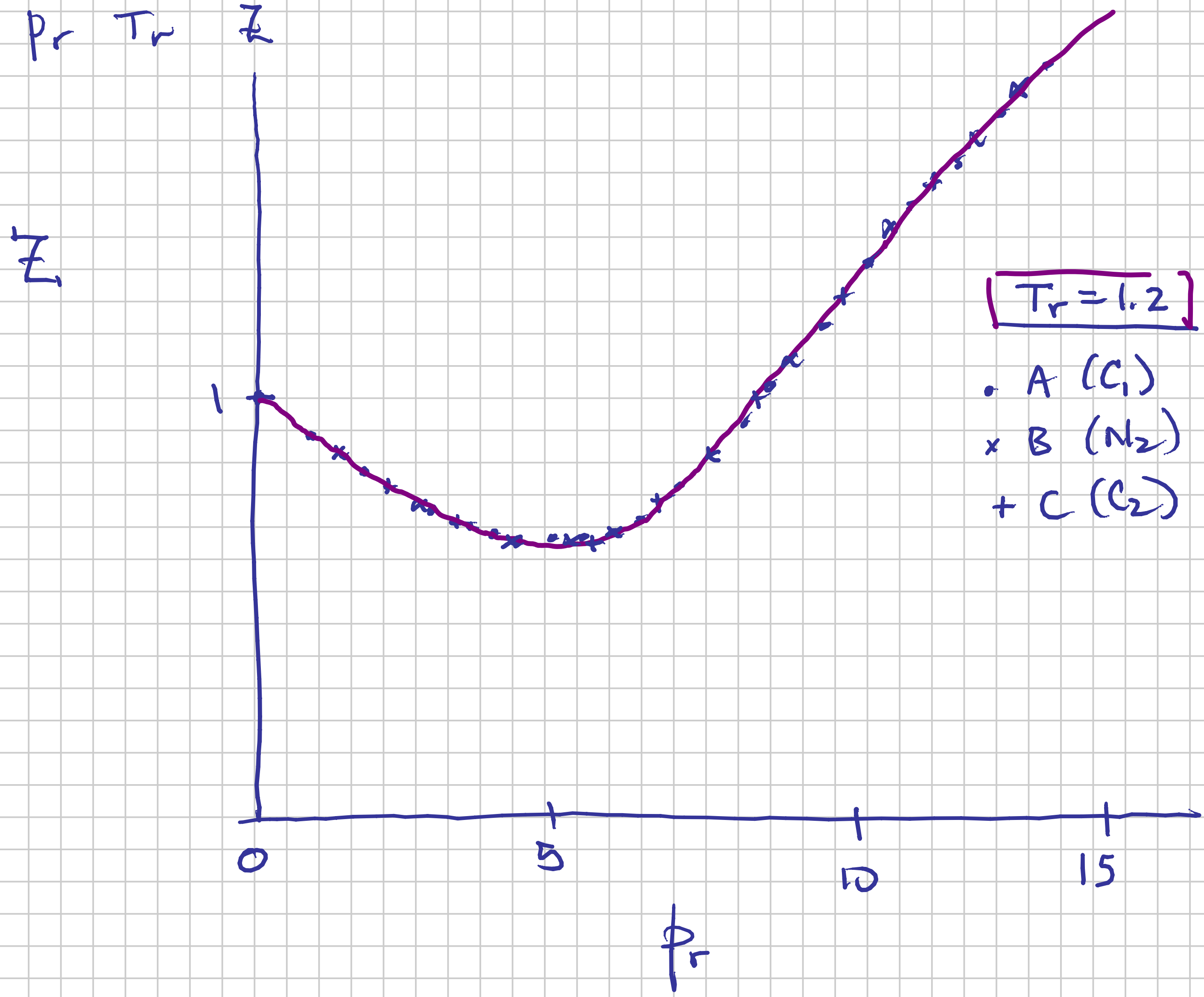
U. Michigan

Donald Katz & Marshall B. Standing
"Muz"

$$Z \equiv \left(\frac{pV}{nRT}\right)$$

Ⓐ — B — . . . . — Z

p_r T_r Z



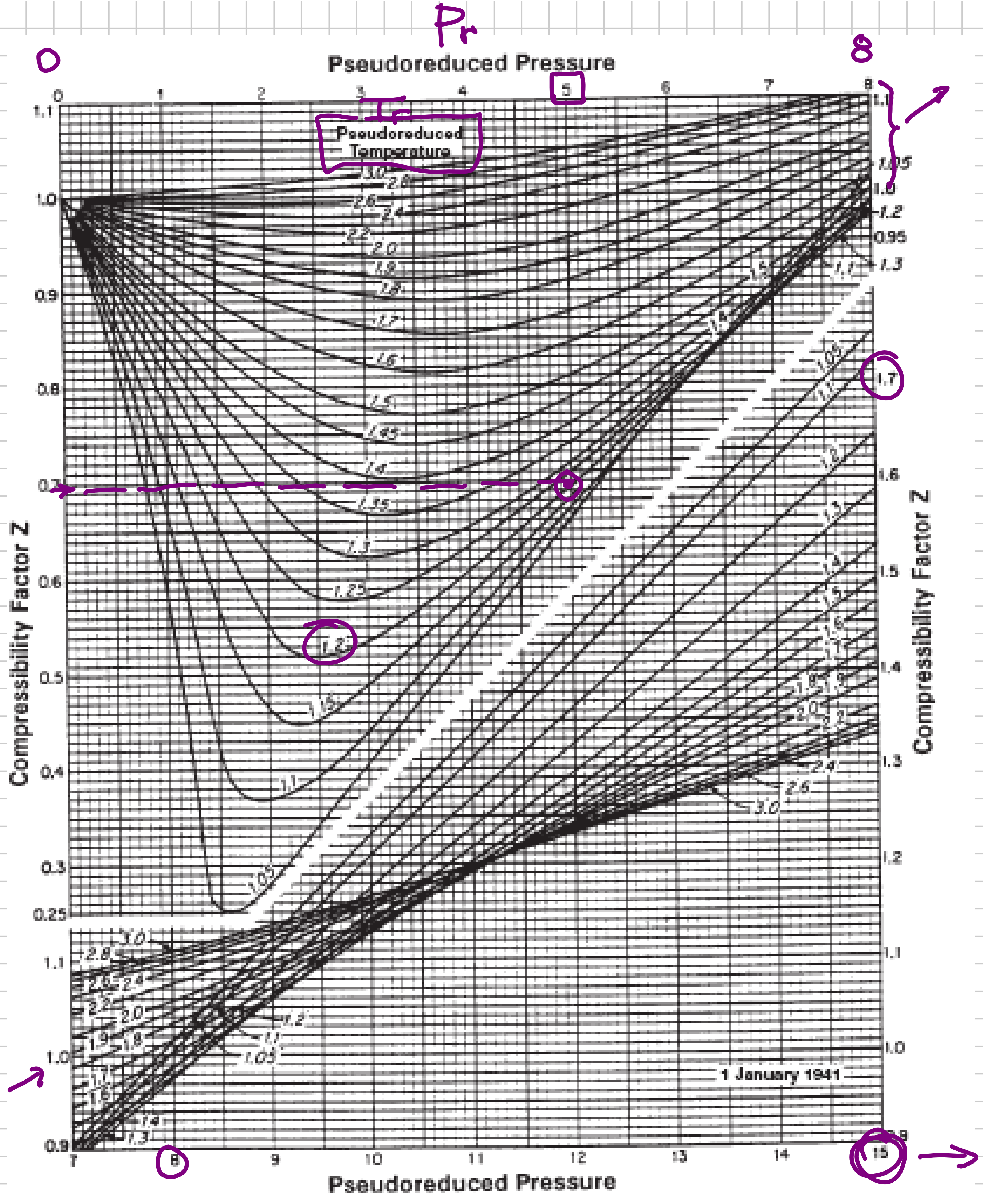
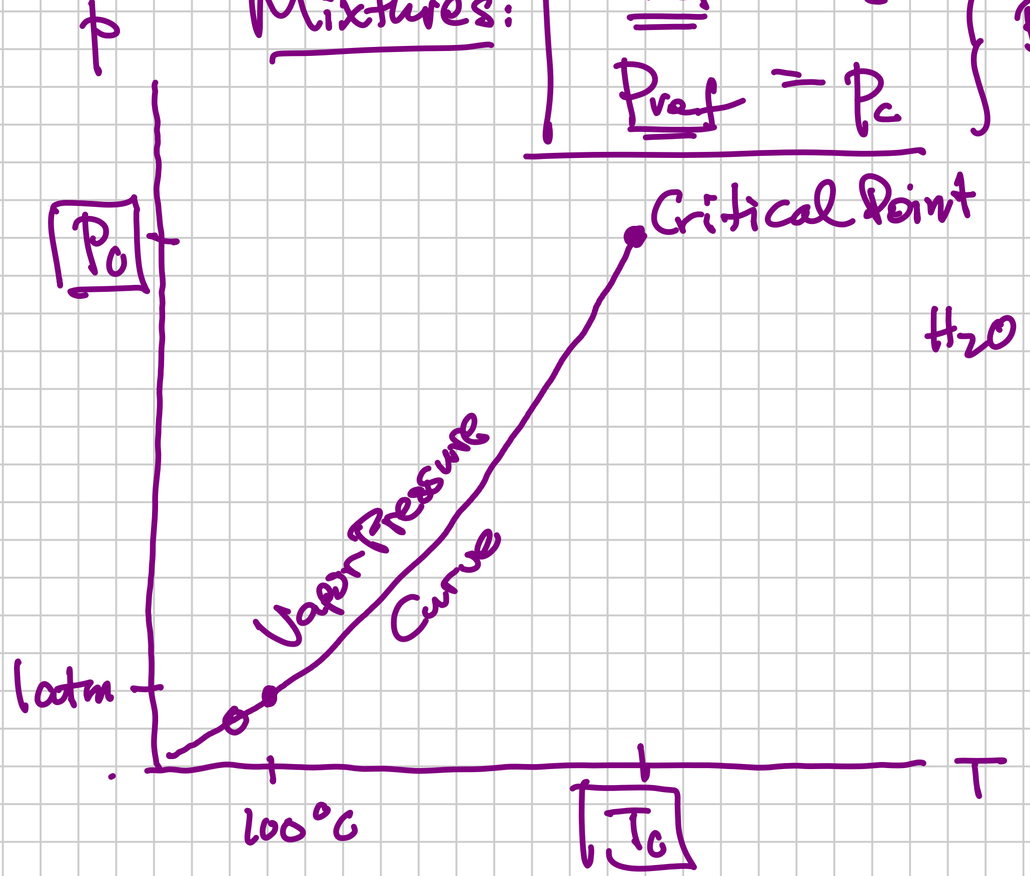


Fig. 3.6—Standing-Katz[4] Z-factor chart.

$$pV = nRT \cdot Z(T_r, p_r)$$

<u>Trick</u>: Find the right reference T_{ref}, P_{ref} for a given gas

$$\underline{\text{Mixtures:}}\quad \left.\boxed{\begin{array}{l} \underline{\underline{T_{ref}}} = T_c \\ \underline{\underline{P_{ref}}} = P_c \end{array}}\right\}\ \text{Pure Compound}$$



Mixtures: Standing-Katz $Z(T_r, P_r)$ $\underline{\text{Chart}}$ $\uparrow$ Special Best-fit Equation

Hall & Yarborough

1st Order Estimate of T_{ref} P_{ref}:

$$T_{ref} \equiv \text{“}T_{pc}\text{”} = \sum_{i=1}^{N} y_i T_{ci}$$

pseudo critical

$$p_{ref} \equiv \text{“}p_{pc}\text{”} = \sum_{i=1}^{N} y_i p_{ci} \quad ✓$$

Gases with $\underline{\text{little}}$ (< 1 mol%) C_{7+} & non-HC

Clean, light HC gas

$Z(T_{pc}, P_{pc}) \Rightarrow$ Very Accurate ±1%

* (Gases w/ > x mol-% C_{7+} and/or non-HCs)

Accuracy of $Z(T_{pr}, p_{pr})$ $\boxed{\pm 2\text{–}4\%}$

Close to experimental accuracy for commercial labs.

* Modification of the T_{pc}, p_{pc}

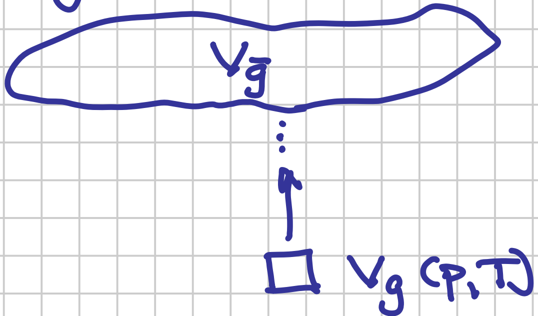
Gas : Known y_i

Can est. w/in ± 1-3% $Z(p,T)$

$$pV = nRT \cdot Z$$

Applications of Real Gas Law (Z-factor) in Petroleum Engineering

- Conversions from Reservoir gas volume to Surface (SALES) gas volume.



$$B_g \equiv \frac{V_g(p,T)}{V_g(p_{sc},T_{sc})}$$

Gas Formation Volume Factor

$$\frac{1}{50} \rightarrow \frac{1}{250}$$

Rule-of-Thumb
Ball Park

Inverse Gas FVF $b_g \equiv \frac{1}{B_g}$

$50 \rightarrow 250$

$$B_g = \frac{\left(\frac{\cancel{n}RT}{p} \cdot Z\right)}{\left(\frac{\cancel{n}RT_{sc}}{p_{sc}}\right)}$$

$\underline{\underline{Z_{sc} \simeq 1}}$

$$\boxed{B_g = \frac{p_{sc}}{T_{sc}} \cdot \frac{T\,ⓩ}{p}}$$

Geo ± HCPV $\rightarrow \underbrace{\boxed{G} \times 0.75 \updownarrow}$

$\boxed{G \times 0.5}$ 10 year

$$G = \frac{HCPV}{B_{gi}} \propto HCPV \cdot \frac{1}{\boxed{Z_i}}$$

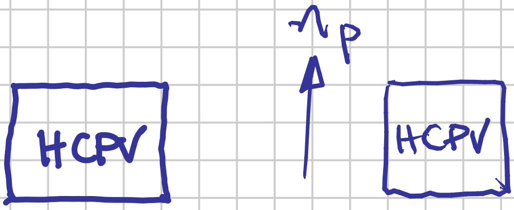
$$G \propto \frac{1}{Z}$$

- Gas Material Balance

$$p_R(G_p) \Rightarrow RF_{ult}$$

$$p_R = p_{Ri}(1 - RF)$$

Ideal Gas Law
assumption
HCPV = const.



V_g = constant = HCPV (assumption)

$$P_{Ri}, T_R : \left\{ n_i = \frac{P_{Ri} \cdot HCPV}{R\, T_R\, Z_{Ri}} \right\}$$ | Initially

Later after removing n_p moles

$$\left\{ (n_i - n_p) = \frac{p_R \cdot HCPV}{R\, T_R \cdot Z_R} \right\}$$ | Currently

$$\left(\frac{G_p}{G}\right) \equiv \underline{\underline{RF}} = \left(\frac{n_p \cdot \cancel{23.68}}{n_i \cdot \cancel{23.68}}\right)$$

"22.4"

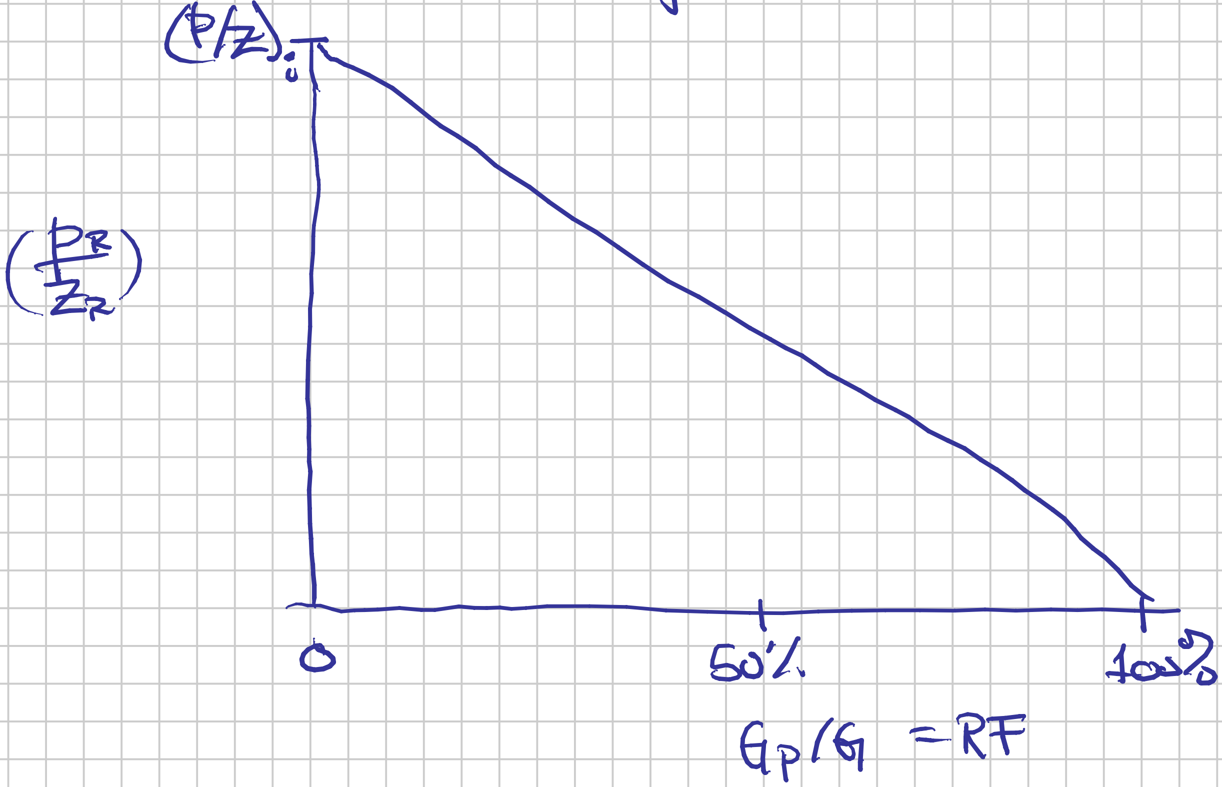
$23.68 \frac{Sm^3}{kg\text{-}mole}$

$$\frac{n_i - n_p}{n_i} = \frac{\dfrac{P_R \cdot \cancel{HCPV}}{\cancel{RT_R} Z_R}}{\dfrac{P_{Ri} \cdot \cancel{HCPV}}{\cancel{RT_R} Z_{Ri}}}$$

$$1 - \left(\frac{n_p}{n_i}\right) = \frac{p_R / Z_R}{P_{Ri} / Z_{Ri}}$$

$$\boxed{\frac{P_R}{Z_R} = \frac{P_{Ri}}{Z_{Ri}} \left(1 - \frac{G_p}{G}\right)}$$

Straight-Line Gas Material Balance



Kristin: $P_{Ri} \sim 900$ bara

@ $P_R \sim 450$ bara

} Ideal Gas Law (Marit) RF = 50%

$P_{ri} \sim 20 \Rightarrow Z_i \sim 2$

$P_r(@450) \sim 10 \Rightarrow 1.2$

} RF = ?

$$\boxed{RF_g = 1 - \frac{(P/Z)_R}{(P/Z)_{Ri}}} = 1 - \frac{(450/1.2)}{(900/2)} = 0.2$$

Z-factor important

- Gas Rate Eq. (Monday)

GENERAL GAS RATE EQUATIONS

⊙ Pseudopressure

- Forcheimmer : deviation from Darcy
- Tubing Flow
- (R+T) "Wellhead" Deliverability

$\left.\begin{array}{l}\text{Forcheimmer}\\ \left.\begin{array}{l}\text{Tubing Flow}\\ \text{(R+T) "Wellhead" Deliverability}\end{array}\right\} *\end{array}\right\}$ e-note Gas-Rate

(*) Fetkovich reference in e-note

Pseudopressure Function

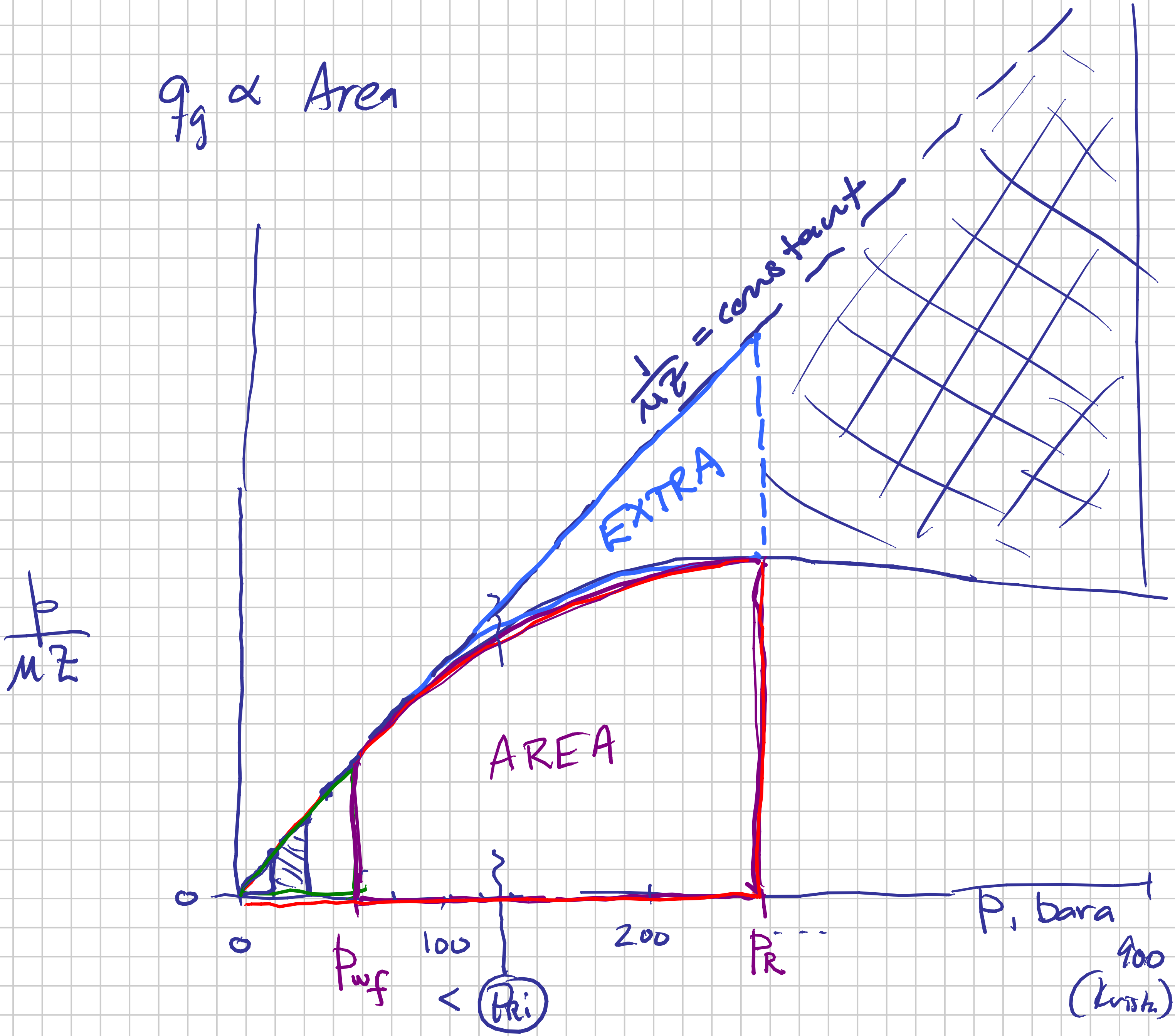
$$q_g = \frac{(15.4)\,kh}{T_R \cdot \ln \frac{0.472\, r_e}{r_w}} \cdot \underbrace{\boxed{\int_{p_{wf}}^{p_R} \frac{p}{\mu_g Z}}}_{(7.7)(2)\ \boxed{\frac{1}{2}\underbrace{\left(\frac{1}{\mu_g Z}\right)}_{\substack{\text{Ideal Gas}\\ \frac{1}{\mu_g}}}\left(p_R^2 - p_{wf}^2\right)}}$$

Al-Hussainy, Ramey, Crawford

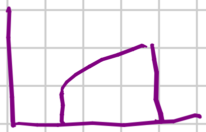
$$\underset{\uparrow}{m(p)} \equiv \underline{\underline{2}} \cdot \int_{\underset{=0}{p_{ref}}}^{p} \frac{p}{\mu Z}\, dp$$

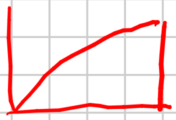
"Pseudopressure"

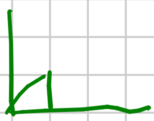
$q_g \propto$ Area



$$\int_{P_{wf}}^{P_R} = \int_{\underset{0}{P_{ref}}}^{P_R} - \int_{\underset{0}{P_{ref}}}^{P_{wf}}$$



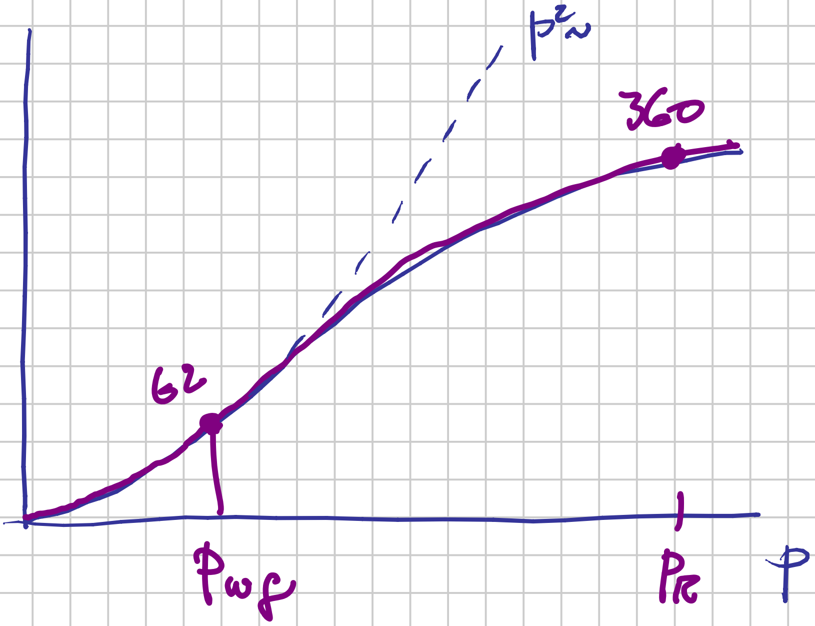




$\equiv m(p)$

p, bara	$(P/\mu Z)$	ΔArea	$\Sigma\Delta$Area
0			0
10		$\frac{1}{2}(\ )(10)$	⋮
20		$\frac{1}{2}(\ )(10)$	|

$$p_p \;\; \cancel{m(p)} \equiv 2\int_0^{p} \frac{p}{\mu Z}\,dp$$



Invariant w/ time

1980 – 1990's ?

$\cancel{m(p)}$

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

$$\boxed{q_g = \frac{7.7\; kh\,(p_{pR} - p_{pwf})}{T_R \cdot \ln \frac{0.47 r_e}{r_w}}}$$

All gas fluid non-idealities are "handled"

Flow non-ideality

Forcheimmer Equation

– Generalization of Darcy

$$\boxed{\frac{dp}{dx} = -\frac{\mu}{k} v - \rho \beta v^2}$$

Flowing Fluid Density

Rock

⇓

Radia/Cylindrical
No-Flow O.B.
Real Gas Laws
(good at math)

$R(p) \rightarrow S(p_{sc}, T_{sc})$

Muskat

"f"

$$Re_{(v)} = \frac{\rho v D}{\mu}$$

$$\boxed{q_g = \frac{7.7 \cdot kh(p_{pR} - p_{pwf})}{T_R\left[\underbrace{\ln\frac{0.47 r_e}{r_w}}_{8\ (10)} + D \cdot q_g\right]}}$$

non-Darcy "Skin"
Rate-dependent

$D \propto \beta$

Can solve this explicitly for q_g

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

$$B = D \cdot \frac{T_R}{7.7\,kh}$$

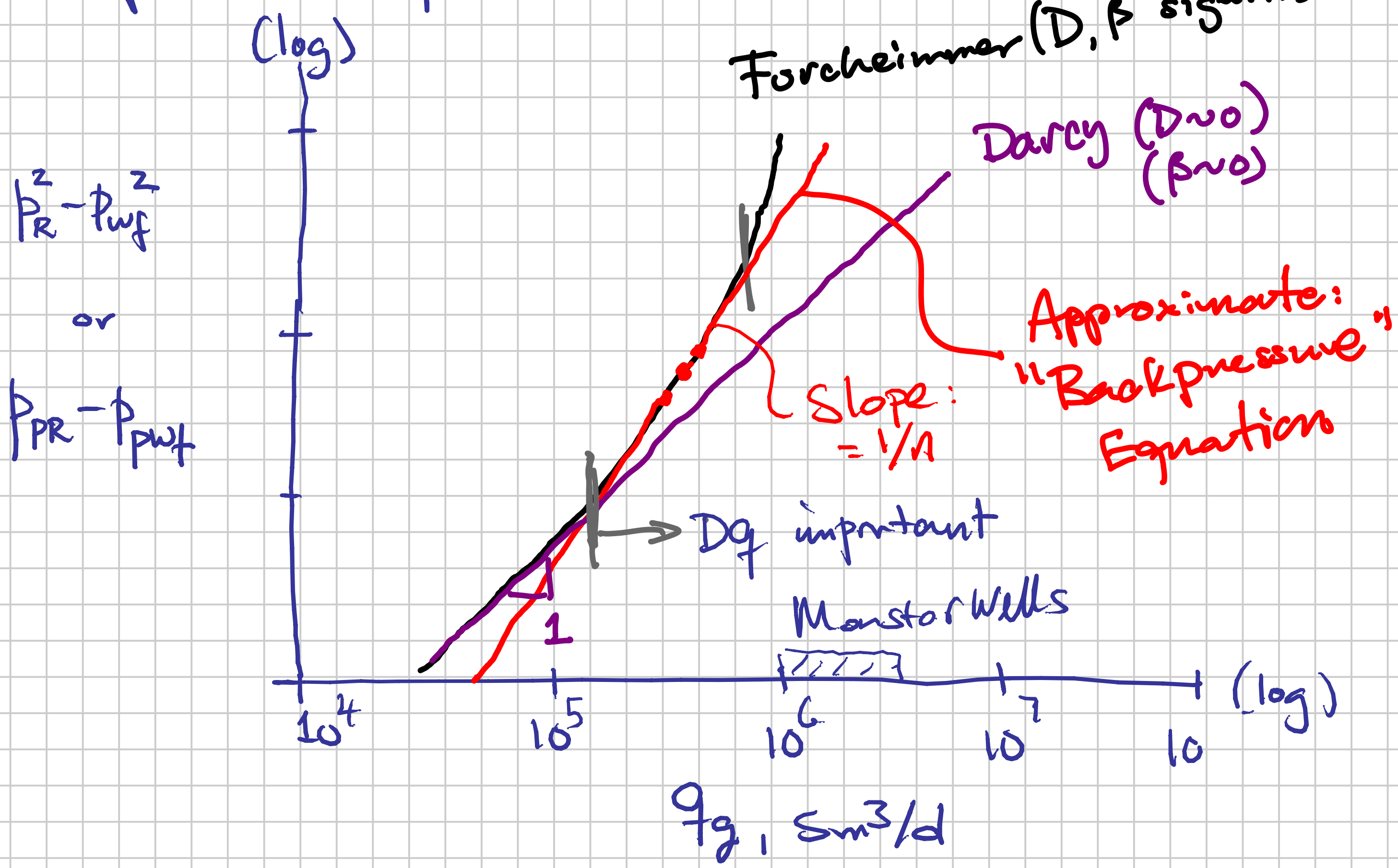
$$A = \left(\ln \frac{0.47 r_e}{r_w}\right) \frac{T_R}{7.7\,kh}$$

Dq_g becomes important ($\gtrsim 1$)

- Usually for high-k wells

	k	
< 10 md	10 – 1000	> 1000 md
ignore $Dq \ll 10$	could get important	likely important

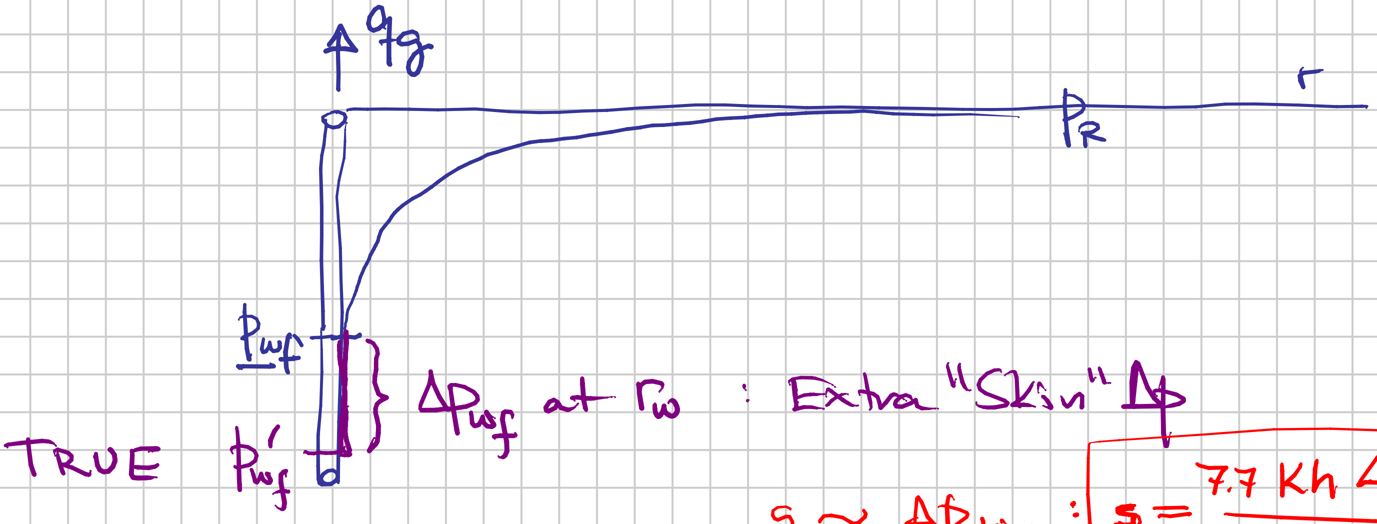
Graphical Representation:



$$\boxed{q_g = C(p_{pR} - p_{pwf})^n}$$

~ "Curved" Forcheimmer Eq.

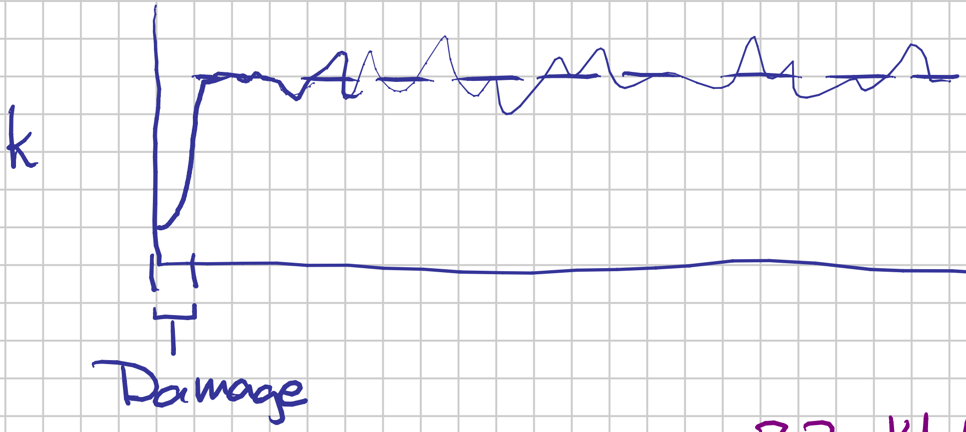
Steady State SKIN Concept



Δp_{wf} at r_w : Extra "Skin" Δp

$s \sim \Delta p_{skin}$: $\boxed{s = \frac{7.7\,kh\,\Delta p_{skin}}{T_R}}$

Dimensionless!



$$q_g = \frac{7.7\ kh\left(p_{PR} - \overset{\text{Actual}\ \downarrow}{p_{wf}}\right)}{T_R\left[\ln\left(\frac{0.47 r_e}{r_w}\right) + \underset{\uparrow\ \text{Damage SKIN}}{s}\right]}$$

Ideal Gas Law to solve Problem 1

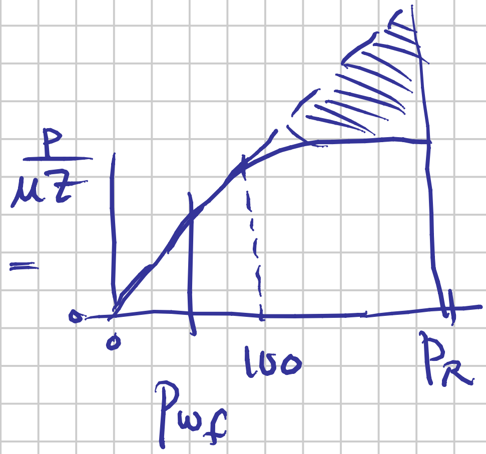
$$B_g = \frac{V_{gR}}{V_{\bar{g}}} = \frac{p_{sc}}{T_{sc}} \cdot \frac{T_R}{p_R}$$

$$q_g(t)$$
↑
yr

Recap Monday:

- Pseudopressure $p_p = 2 \cdot \int_0^p \frac{p}{\mu Z} dp$ $\quad (= m(p))$
  - $p_R \gtrsim 100$ bar
  - $p_R \lesssim 100$ bar

$$p_p \sim \frac{1}{(\mu Z)_R} (p^2)$$



- Forcheimmer Eq.

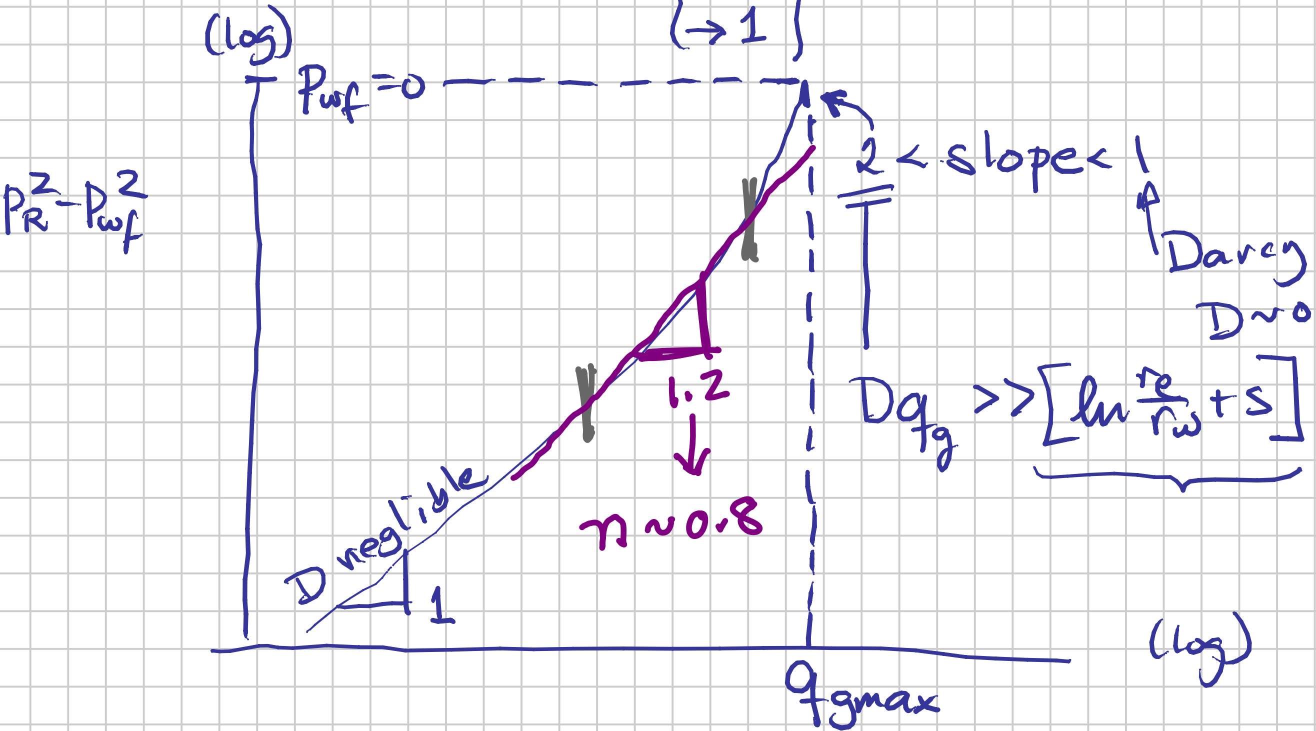
$$B q_g^2 + A q_g - (p_R^2 - p_{wf}^2) = 0$$

$$q_g = \frac{7.7 \cdot kh \, (p_R^2 - p_{wf}^2)}{T_R (\mu_g Z)_R \left[\ln \frac{r_e}{r_w} + D q_g + \underset{\uparrow}{S} \right]}$$

$$A = \frac{T_R(\mu_g Z)_R}{7.7\,kh} \cdot \left[\ln\frac{r_e}{r_w} + s\right]$$

$$B = \frac{T_R(\mu_g Z)_i}{7.7\,kh} \cdot D$$

Dq_g usually important only if q_g is "high"
(>0.1 → 1) 10^6 Sm^3/d



q_g

$q_{g\max}$ (AOFP)

Absolute Open Flow Potential

$p_{wf} \to 0$

Straight-Line Approx:

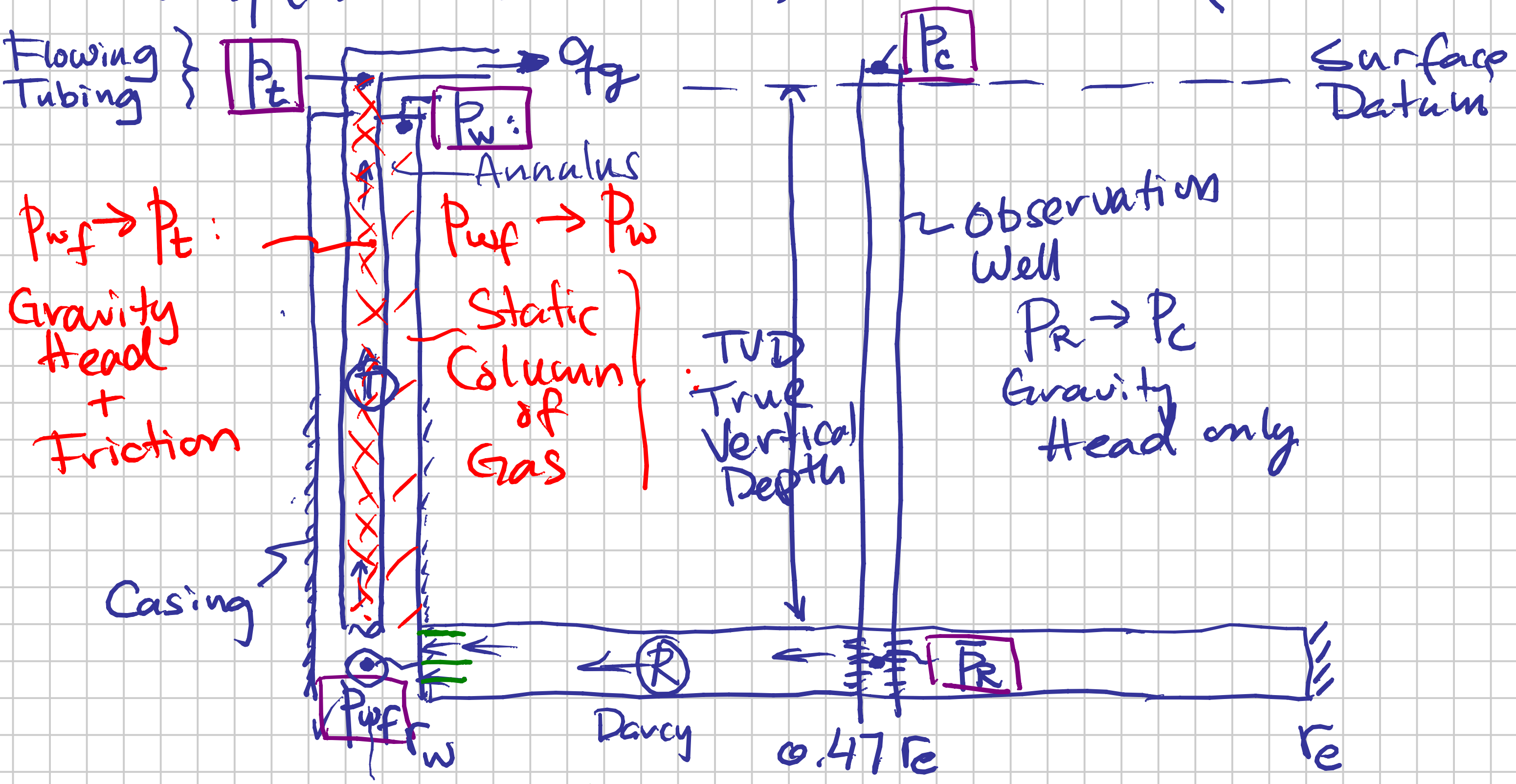
$$q_g = C\left(p_R^2 - p_{wf}^2\right)^n$$

$$n = 1/\text{slope}$$

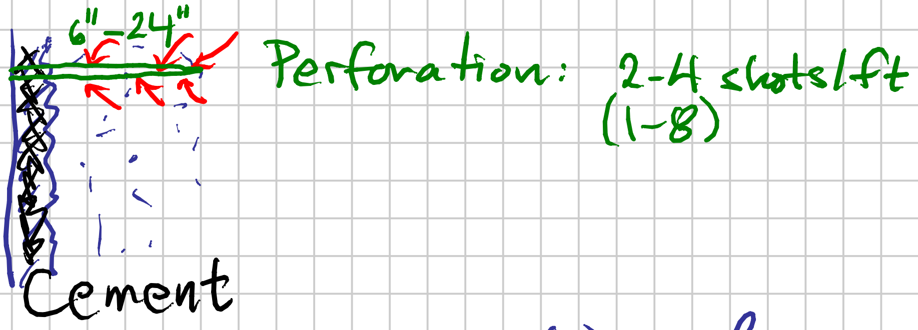
Ⓡ RESERVOIR GAS RATE EQS.

- Darcy or Forcheimmer

Ⓣ TUBING (VERTICAL PIPEFLOW) GAS RATE EQ



$P_w - P_t$ =
Only Friction ΔP



Quiz:

$P_c \rightarrow P_t$: R Δp (Darcy)
T Δp (friction)

$P_c \rightarrow P_w$: R Δp

$P_w \rightarrow P_t$: T Δp (friction)

$p(r) \propto \ln r$

$\bar{P}_R$ @ $r = 0.47 r_e$

All at surface datum

Water Gravity Head

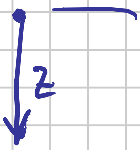
$$P_R = P_{surface} \boxed{+ \rho_w g \cdot TVD}$$ Intuitive

$\uparrow$

$$\left.\boxed{\frac{dp}{dz} = \rho g}\right\} \uparrow \rho = const(P,T)$$

Gas: $\rho_g = \frac{M}{RT} \cdot \left(\frac{p}{Z}\right)$

$$\Rightarrow \quad \frac{dp}{dz} = \left(\frac{M}{RT}\right) \cdot \frac{p}{Z} g$$



$$\int_{P_{surf}\ P_c}^{P_R\ P_{Reservoir}} \frac{Z}{p} dp = \frac{gM}{RT} \int_0^{TVD} dz$$

Assume $\bar{Z}$ is used, and $\bar{T}$

$$\begin{array}{l} P_{wf} \\ \\ P_w \end{array} \quad \int_{P_c}^{P_R} \frac{1}{p} dp = \frac{gM \cdot TVD}{R\bar{T}\bar{Z}}$$

$$\ln P_R - \ln P_c = \frac{gMTVD}{R\bar{T}\bar{Z}}$$

$$\ln \frac{P_R}{P_c} =$$

$$\frac{P_{wf}}{P_w} \cong \underbrace{\frac{P_R}{P_c}} = \exp\left\{\frac{gMTVD}{R\bar{T}\bar{Z}}\right\}$$

Annulus ↓ Producer

Observation Well

"Static Gas ≡ Column Constant"

$$\boxed{S = 2\,\frac{g M \,TVD}{R \bar{T} \bar{Z}}}$$

$$\exp(S) = \left(\frac{P_{wf}}{P_w}\right)^2 = \exp\left\{2 \cdot \frac{g M \,TVD}{R \bar{T} \bar{Z}}\right\}$$

$$\left(\frac{P_{wf}}{P_w}\right) = \exp\left(S/2\right)$$

$$\frac{P_{@R}}{P_{@s}} = \text{const} = \underbrace{\exp\left(\frac{S}{2}\right)}_{\underline{\underline{\sim 1.1-1.4}}}$$

$$\frac{p^2_{@R}}{p^2_{@s}} = \text{const} = \exp(S)$$

Example:

$TVD = 1000\,m$

$M = 20$ kg/kgmole

$\bar{T} = 40°C + 273 = 313\ K$

$\bar{Z} \simeq 1$

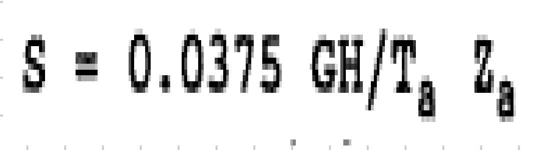
$g = 9.8\ m/s^2$

$p\ [Pa]$

$$S = 2\,\frac{(9.8)(20)(1000)}{(8314)(313)(1)} = 0.15$$

$$\exp(S/2) = 1.078$$

Fetkovich paper:


$S = 0.0375\ GH/T_a\ Z_a$

$G = \gamma_g = \dfrac{M_g}{M_{air}}$

$H = TVD\ [ft]$

$T_a = \bar{T}\ [°R]$

$Z_a = \bar{Z}$

$H = 3280\ ft$

$T_a = 313 \times 1.8 = 563\ °R$

$Z_a = 1$

$\gamma_g = G = \dfrac{20}{28.97} = 0.69$

$S = 0.15$ ✓

* * *

Gas Pipeflow (with <u>No</u> elevation difference in pressures)

- <u>Friction</u> is the only source of Δp
- <u>Turbulent gas flow</u> is almost always the case.

$$(\dot{m}_g)\quad(\dot{n}_g)\quad \boxed{q_g = C\cdot(P_{in}^2 - P_{out}^2)^{0.5}}$$

- f
- total flow length L
- Diameter

@ same elevation!

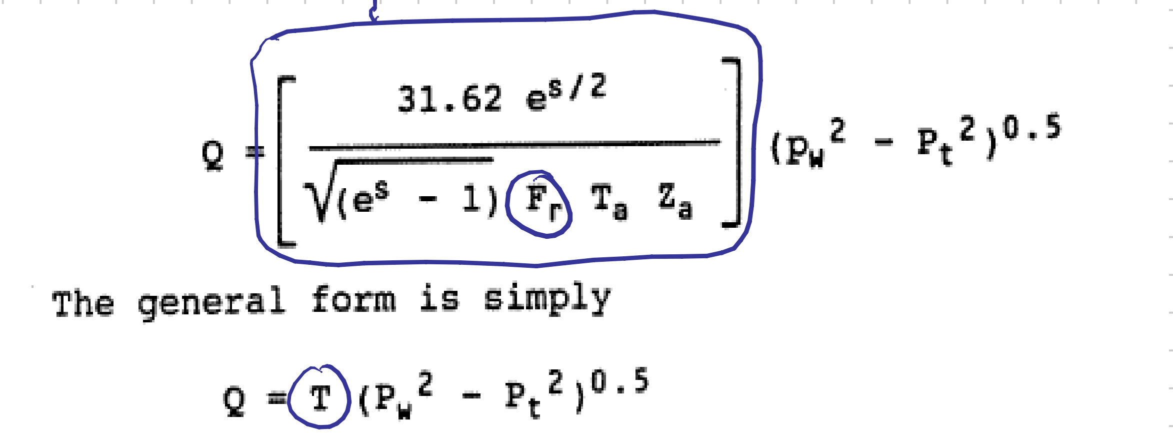
C ~ constant throughout the life of the pipe.

Example: Tubing:

C_t

$$\left.\begin{aligned} P_{in} &= P_w \\ P_{out} &= P_t \end{aligned}\right\} \text{@ same datum}$$

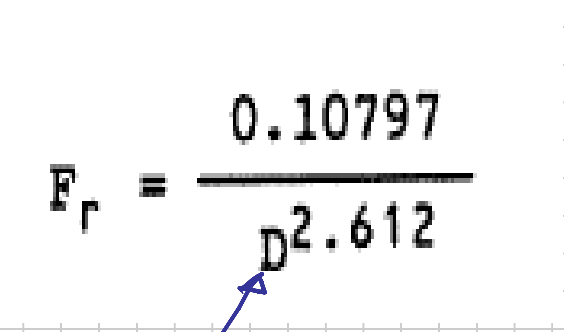
$$\boxed{q_g = \boxed{C_t}\left(P_w^2 - P_t^2\right)^{0.5}}$$



$$Q = \boxed{\left[\frac{31.62\, e^{s/2}}{\sqrt{(e^s - 1)\,\boxed{F_r}\; T_a\; Z_a}}\right]}\left(P_w^2 - P_t^2\right)^{0.5}$$

The general form is simply

$$Q = \boxed{T}\left(P_w^2 - P_t^2\right)^{0.5}$$



$$F_r = \frac{0.10797}{D^{2.612}}$$

Pipe diameter

Flow length enters: S (TVD = flow length)

Combining the ΔP_R and ΔP_T we can develop the relationship between

q_g and p_t

$\uparrow$

We control this @ surface

$B' = B \cdot e^{-s}$

$B = \frac{T_R (\mu Z)_R}{7.7\, kh} \cdot D$

$$R: \frac{p_R^2}{e^s} - \frac{p_{wf}^2}{e^s} = \frac{B}{e^s} q_g^2 + \frac{A}{e^s} q_g$$

Forcheimmer

$$R: p_c^2 - p_w^2 = B' q_g^2 + A' q_g$$

$$T: p_w^2 - p_t^2 = \frac{1}{C_t^2} q_g^2$$

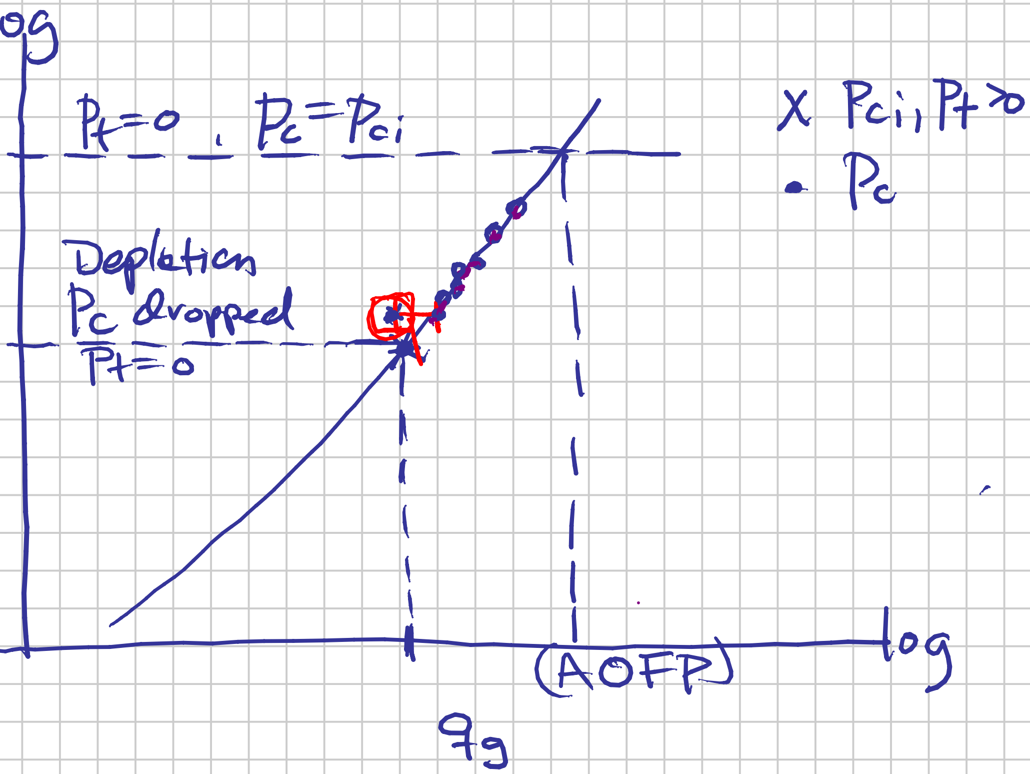
$$\underbrace{p_c^2 - p_t^2}_{} = \underbrace{\left(\overset{\uparrow}{B'} + \frac{1}{\overset{\uparrow}{C_t^2}}\right)}_{} q_g^2 + A' q_g$$

Wellhead (R+T) Rate Eq.

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

$\downarrow$

$$\underbrace{p_c^2 - p_t^2}_{}$$



Periodic P_c

Continuous or Periodic P_t

GENERALIZED GAS MATERIAL BALANCE

Note Title 9/14/2009

Ref. e-notes : Gas – Material - Balance

Key Reference (4 in e-note) : Fetkovich, Reese, Whitson

"POT AQUIFER (++)"

– Swi
– c_f
– NNP

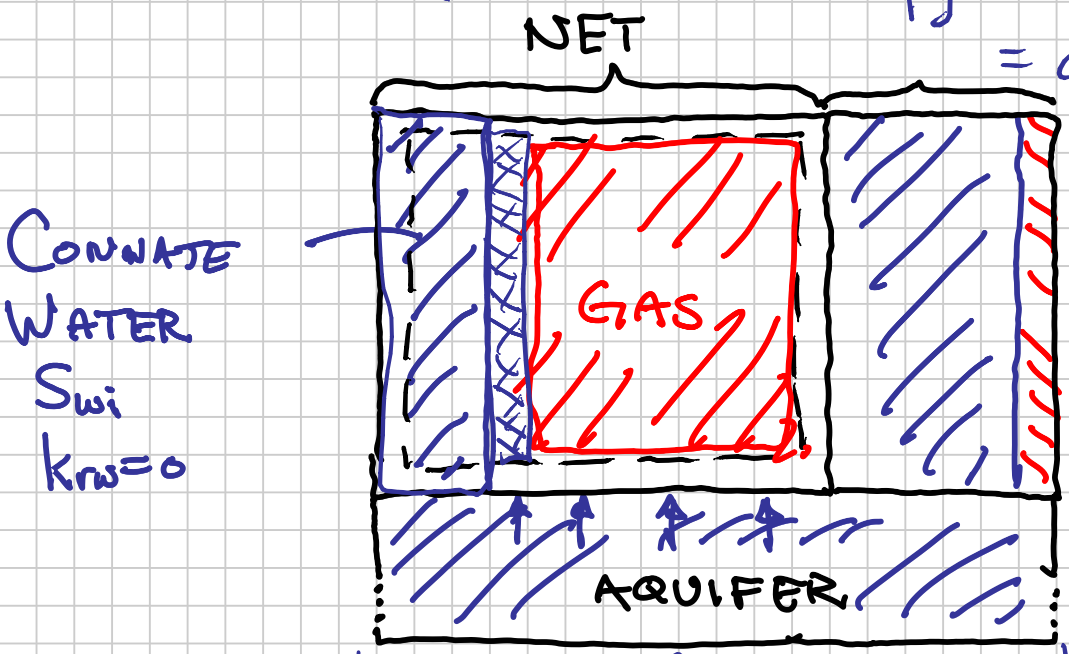
– Aquifer

$$\boxed{\frac{p_R}{Z_R}\boxed{\left[1-\bar{c}_e\left(p_{Ri}-p_R\right)\right]} = \frac{p_i}{Z_i}\left(1-\frac{G_p}{G}\right)}$$

$$\Rightarrow \boxed{\frac{p_R}{Z_R} = \frac{p_i}{Z_i}\left(1-\frac{G_p}{G}\right)}$$

Straight-Line Gas M.B.

- Real Gas Law
- $\dfrac{G}{n_{gi}} = \dfrac{G_p}{n_{gp}} = \dfrac{Sm^3}{kg\text{-}mole} = 23.68$
- ASSUMPTION : $V_{pg} = HCPV$
  $= \text{constant}$



NON-NET
- Low k
- High Sw
- Shale &/or Dirty rock
- $\lambda_w > 0 = k_w/\mu_w$

$\lambda \equiv k/\mu$

• Allow PV changes $\underbrace{p_R \downarrow \quad V_p \downarrow}$

c_f : Rock, Formation Compressibility

• Water expands:
– Connate Swi

- Non-net Volume, V_{NNP}
- AQUIFER, V_{AQ}
  - Same geological reservoir, below the "HC(g)" part of the R
  - Contains water

⇒ HCPV, V_{pg} ↓ as $\bar{P}_R$ ↓

in HCPV: & everywhere else

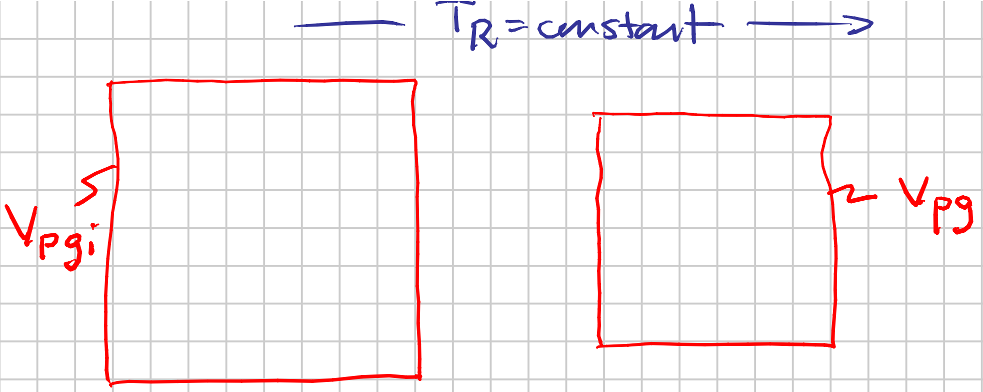
$$\underbrace{\left[1-\bar{c}_e(\bar{P}_{Ri}-\bar{P}_R)\right]}$$

Effective Cumulative Compressibility term

- Amount of Encroachable Water
  - S_{wi}
  - V_{NNP}
  - V_{AQ}

Acting

- c_w
- c_f : Acting V_{pg} & V_{wTotal}



Initial Conditions

Current Conditions

p_R	p_{Ri}	p_R
Amount Gas Remaining	n_i G	$n_i - n_p$ $G - G_p$

HCPV $\left\{ V_{pgi} \quad - \quad V_{pg} \right\}$

Water Encroachment 0

Pore Volume Change

$$\left\{\begin{matrix}(\Delta V_w)_{total} \\ + \\ (\Delta V_p)_{Net}\end{matrix}\right\}$$

Connate NNP AQ

Entire Net PV

Connate Water: constant = $c_w = -\frac{1}{V_w}\frac{dV_w}{dp}$

$$\Delta V_w = \underbrace{V_{PR} \cdot S_{wi}}_{\substack{\text{Initial} \\ \text{Connate} \\ \text{Water} \\ \text{Volume} \\ V_{wi}}} \cdot c_w \cdot \Delta p \qquad \simeq -\frac{1}{V_w}\frac{\Delta V_w}{\underset{\substack{\uparrow \\ (p_{Ri} - p_R)}}{\Delta p}}$$

"R" Net Reservoir

Non-Net Pay : V_{pNNP}

$(S_w)_{NNP} = 1$

$$\Delta V_w = V_{pNNP} \cdot (C_w + C_f)\,\Delta p$$

AQUIFER : V_{AQ}

$(S_w)_{AQ} = 1$

$$\Delta V_w = V_{AQ}\,(C_w + C_f)\,\Delta p$$

Net Reservoir PV

$$\Delta V_{PR} = V_{PR} \cdot C_f\,\Delta p$$

$$V_{pgi} - V_{pg} = \left(\sum \Delta V_w \right) + \Delta V_{PR}$$

$$V_{pg} = V_{pgi} - \left\{ V_{pRi}\, C_w S_{wi} + \left(V_{NNP} + V_{AQ}\right)(C_w + C_f) + V_{pRi}\, C_f \right\} \Delta p$$

$$= V_{pgi} - V_{pRi}\left\{ (C_w S_{wi} + C_f) + \frac{V_{NNP} + V_{AQ}}{V_{pRi}} (C_w + C_f) \right\} \Delta p$$

Introduce $M \equiv \dfrac{V_{NNP} + V_{AQ}}{V_{pRi}}$

$$C_e \equiv \frac{(C_w S_{wi} + C_f) + M(C_w + C_f)}{1 - S_{wi}}$$

$$V_{pg} = \underbrace{V_{pgi}}_{= V_{pRi}(1 - S_{wi})} - V_{pR}(1 - S_{wi}) \cdot C_e\,\Delta p$$

$$\underline{V_{pg}} = \underbrace{\left[V_{pRi}(1 - S_{wi}) \right]}_{V_{pgi}} \left[1 - C_e\,\Delta p \right] = \frac{(n_i - n_p) R T_R Z_R}{p_R}$$

$$V_{pgi} = \frac{n_i R T_R Z_i}{P_i}$$

$$\frac{n_i \cancel{R T_R} Z_i}{P_i}\left[1 - c_e(P_{Ri} - P_R)\right] = \frac{(n_i - n_p)\cancel{R T_R} Z_R}{P_R}$$

$$\boxed{\frac{P_R}{Z_R}\left[1 - c_e(P_{Ri} - P_R)\right] = \frac{P_i}{Z_i}\underbrace{\left(1 - \frac{G_p}{G}\right)}_{= \left(1 - \frac{n_p}{n_i}\right)}}$$

$$c_e \equiv \frac{c_w S_{wi} + c_f + M(c_w + c_f)}{1 - S_{wi}}$$

$$M \equiv \frac{V_{WNP} + V_{AQ}}{V_{pRi}}$$

0.1 – 5
(smallish aquifers)

Pot Aquifer model valid:

$M \lesssim 5$ moderate $k > 100$ md

→ $M \sim 10$ $k >$ x,000 md ("Darcy" perm)

General "Pot Aquifer (++)" Gas Material Balance

$$\frac{p_R}{z_R}\left[1-\underbrace{\bar{c}_e\left(p_{Ri}-p_R\right)}_{>0.0x}\right] = \left(\frac{p_{Ri}}{z_{Ri}}\right)\left(1-\frac{G_p}{G}\right)$$

$$\bar{c}_e \equiv \frac{c_w S_{wi} + c_f + \overset{\downarrow}{M}\left(c_w + c_f\right)}{\left(1-S_{wi}\right)}$$

$$M \equiv \frac{V_{AQ} + V_{NNP}}{V_{PR}}$$

~ Fundamental Assumption:

All fluids and rock "feel and react completely" to pressure drop in the gas reservoir ($HCPV_i$) "immediately" (~ days, weeks, month)

$$\left(\frac{k_w}{\phi \mu_w \underset{\overset{\uparrow}{c_w}}{c_t} x^2}\right)$$

- Valid k high
- and/or the distance is "short"/ reasonable

$\Rightarrow \downarrow HCPV(p_R \downarrow)$

$\Rightarrow \frac{G_p}{G} = \underset{\sim}{50\%} \Rightarrow (n_i - n_p)$ remaining moles $= n_{gR}$

Natural Pressure Maintenance

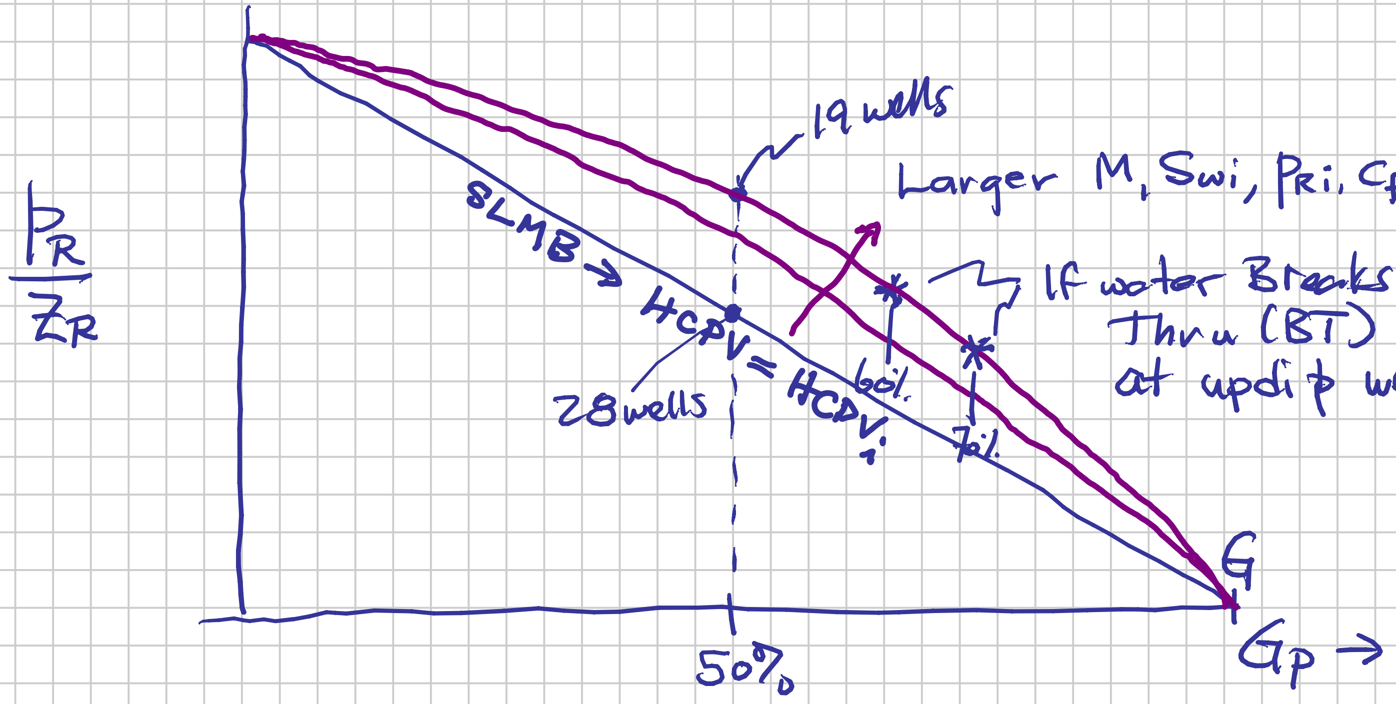
$$\uparrow\left(\frac{P_R}{Z_R}\right) = \frac{\overset{\checkmark}{n}_{gR}\,\overset{\checkmark}{R}\,\overset{\checkmark}{T}_R}{V_{gR}}$$

$$>$$

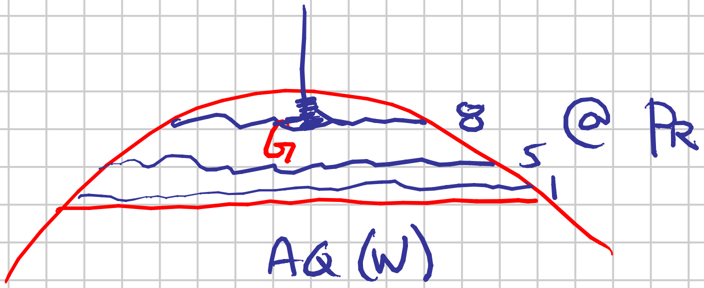
$$\left(\frac{P_R}{Z_R}\right)_{SLMB} = \frac{n_{gR}\,R\,T_R}{V_{gRi}}$$

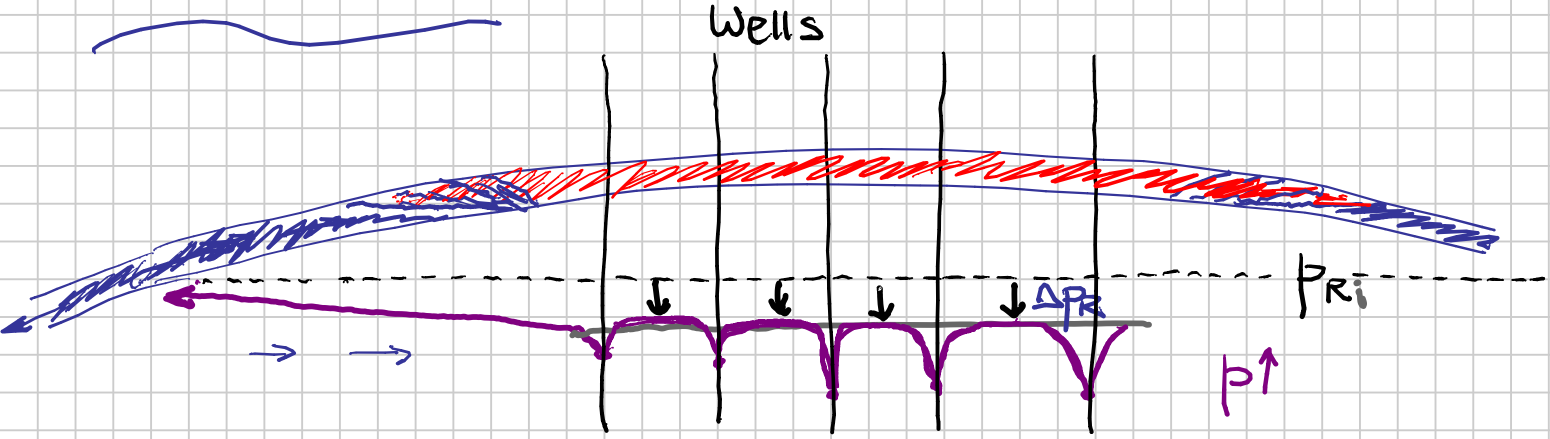
$$\Rightarrow P_R > (P_R)_{SLMB}$$

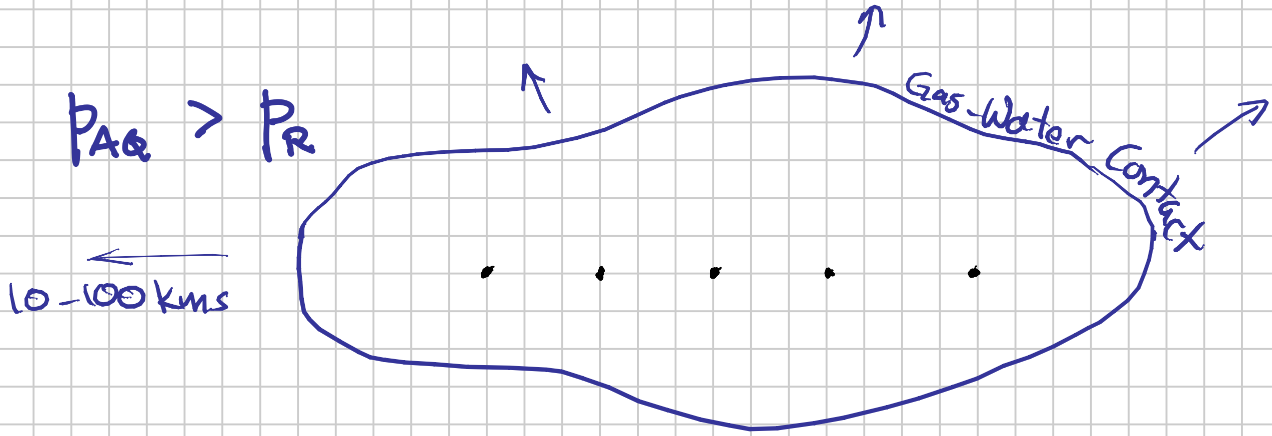
$$\underset{\uparrow}{q_g} = C\,(\underset{\overset{\nearrow}{\text{Good}}}{P_R^2} - \underset{\overset{\uparrow}{\text{Fixed}}}{P_{wf}^2})$$



Significant water production in a gas well means "it's over ~~baby~~"
death





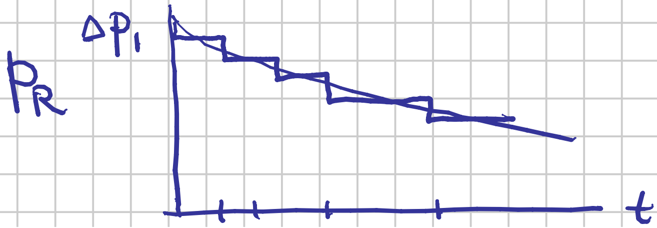


$P_{AQ} > P_R$

Large V_{AQ} (x, y) away from R and/or low-moderate $k_{AQ} \sim 10-100$ md

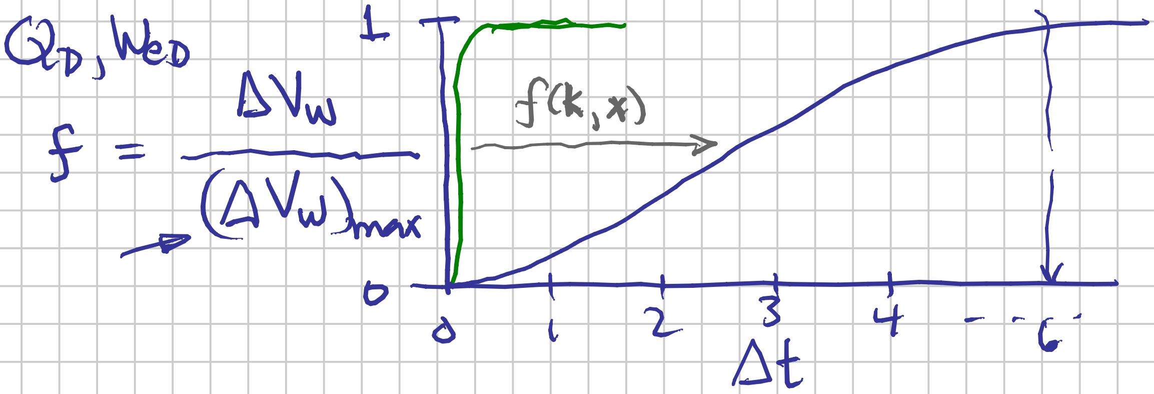
$\Rightarrow$ Δt required for all of the $(\Delta V_w)_{AQ}$ for a give ΔP_R might be years or decades.

$$(V_w)_{AQ}(t) = \sum (\Delta V_w)_{AQ}(t)$$



Pot Aquifer Model

$$f = \frac{\Delta V_w}{(\Delta V_w)_{max}}$$



Superposition Methods to calculate

$$W_e \equiv (V_w)_{\text{encroachment into the R}}(t) = \sum \Delta W_e(\Delta t)$$

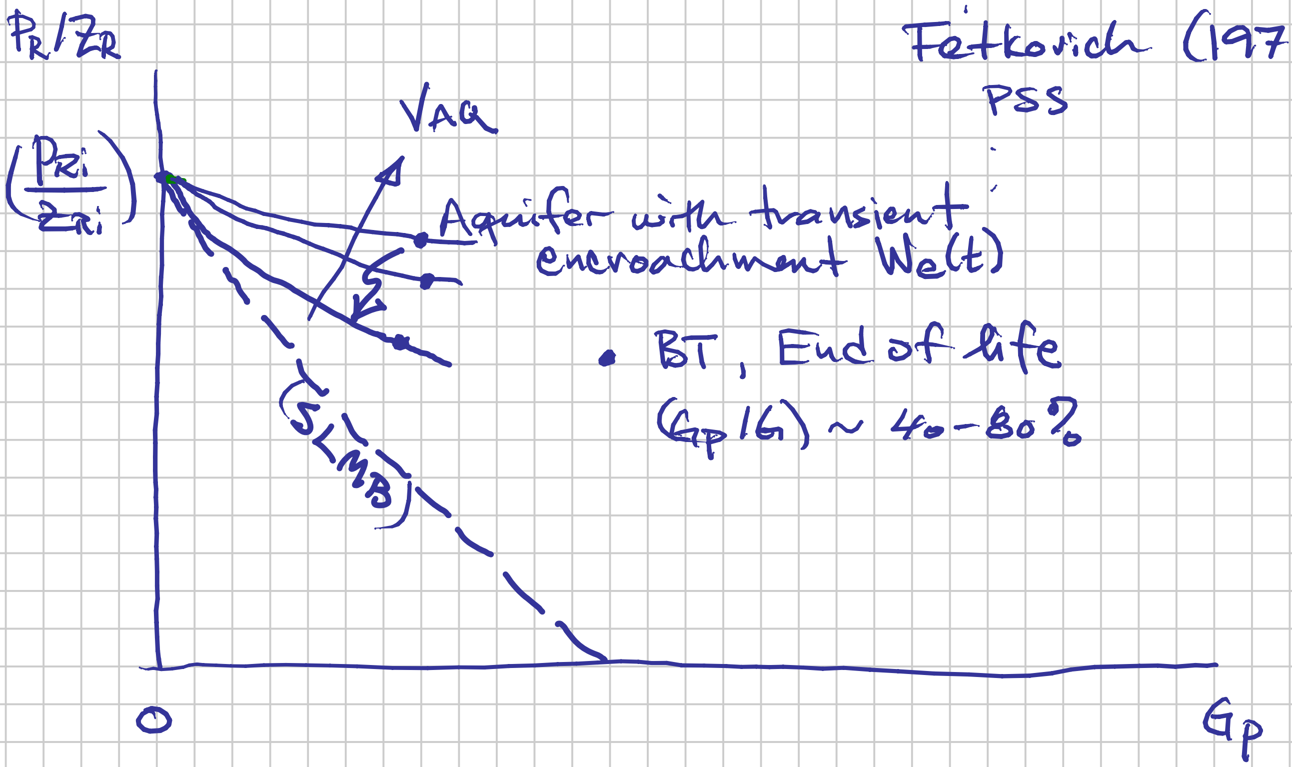
Van Everdingen-Hurst

Tracy

⋮

Fetkovich (1972)

PSS



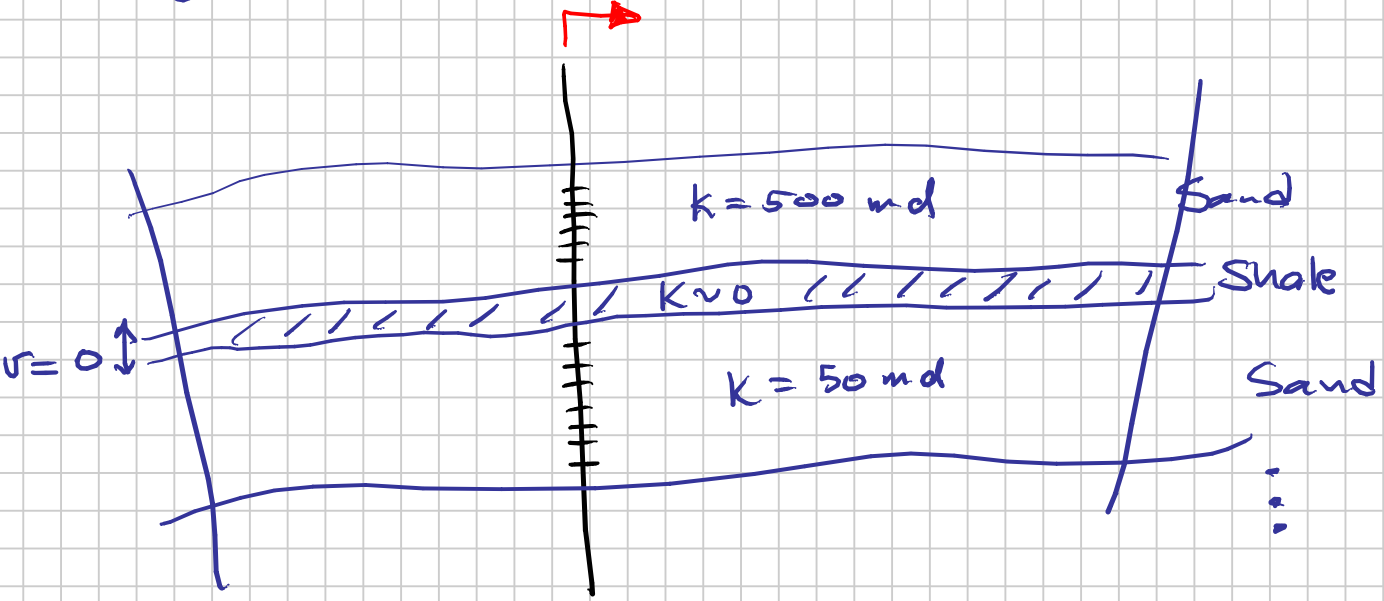
Aquifer with transient encroachment We(t)

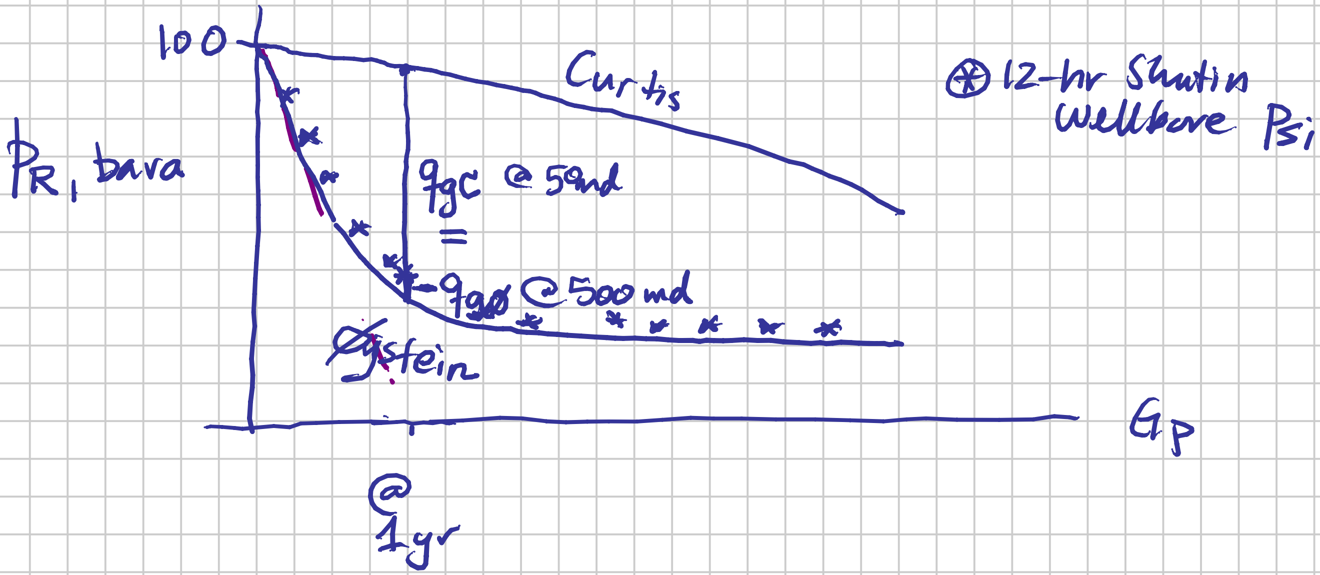
- BT, End of life $(G_p/G) \sim 40-80\%$

Fetkovich : $k \lesssim 1$ md : No real effect of Aquifer (any size) on P_R

⇒ S.L.M.B

LAYERED NO-CROSSFLOW (LNX)



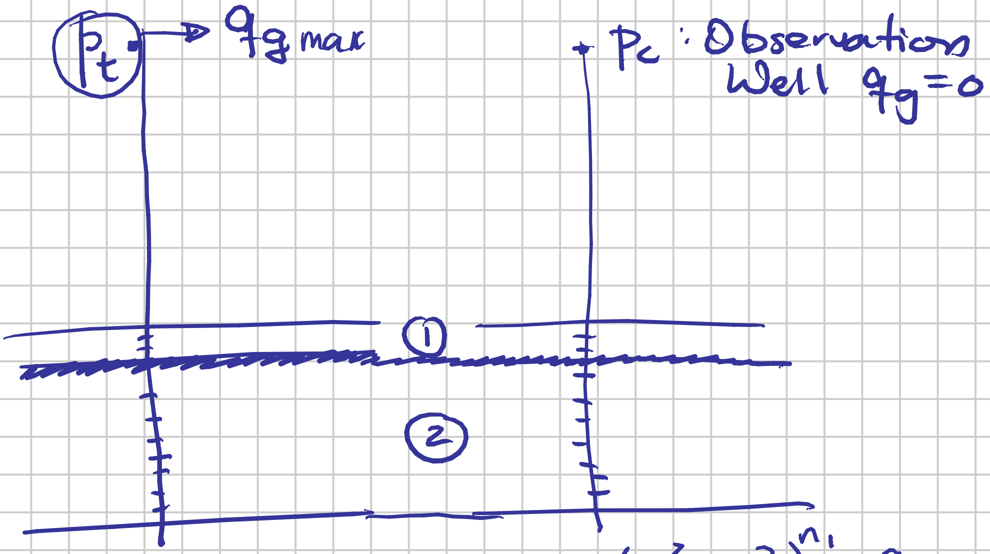


Two-Layer Example

Layer 1: Reservoir Unit 1	Layer 2: Reservoir Unit 2
$p_{ci} = 100$ bar	100 bara
$C = 100$ Sm³/d/bar²	10 Sm³/d/bar²
$G = 10^7$ Sm³	10^8 Sm³
$n = 0.9$	1

Each Layer (Reservoir Unit) $\boxed{q_g = C(p_c^2 - p_t^2)^n} \sim Bq_g^2 + Aq_g = (p_c^2 - p_t^2)$

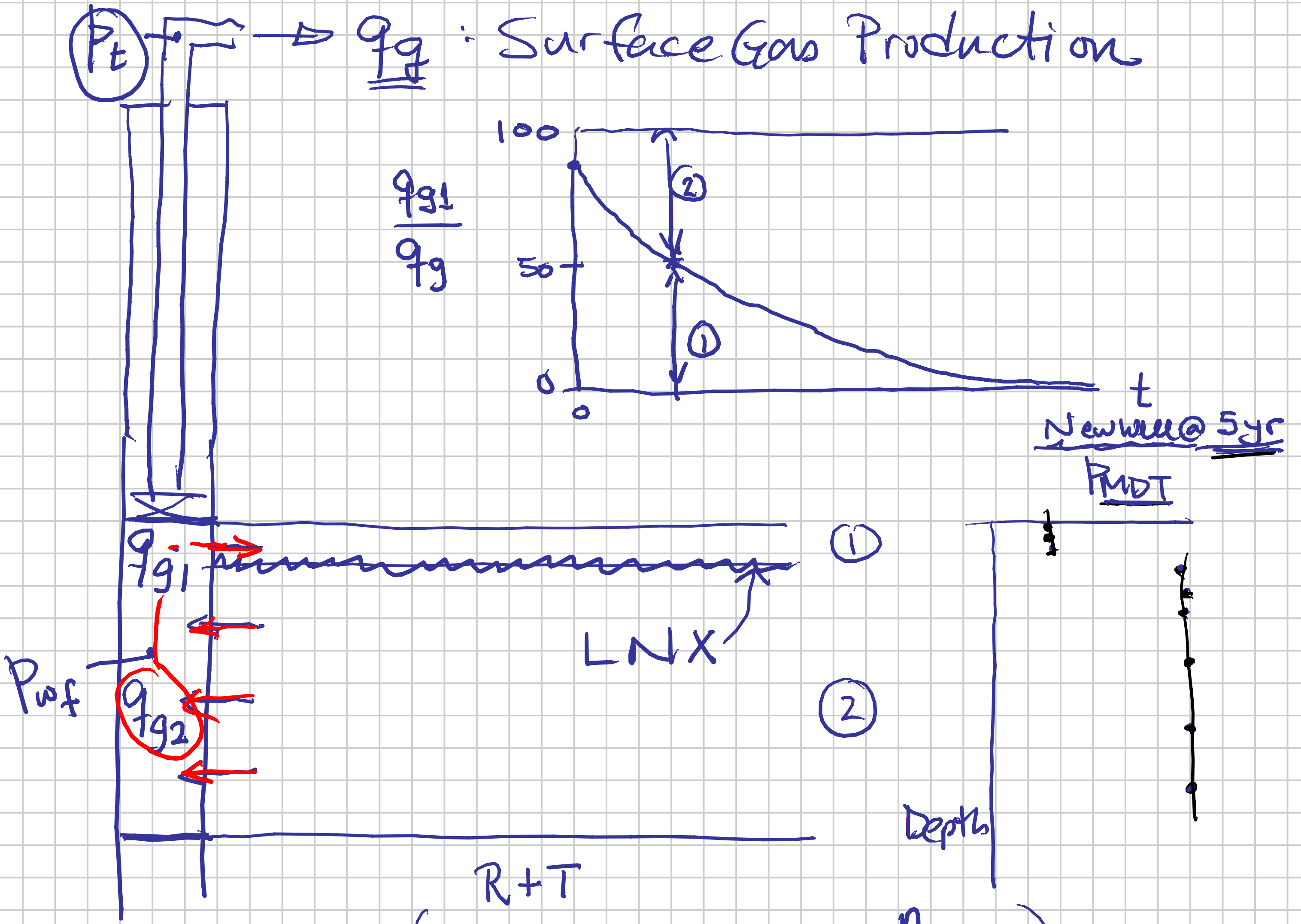
$p_{pipeline} = \boxed{p_t} \rightarrow q_{g\,max}$



During SI: $q_{g1} = C_1(\underset{\overset{\uparrow}{p_{wf}}}{p_{s1}^2} - p_{c1}^2)^{n_1} = q_{g2} = \underset{\overset{\Downarrow}{p_{SI}}}{C_2(p_{c2}^2 - p_{s1}^2)^{n_2}}$

$\underline{\underline{k}}m^3 = (km)^3 \neq 1000\ m^3$

$Mscf = 1000\ scf = 1000\ ft^3$



R+T

$$\begin{cases} q_{g1} = C_1(P_{c1}^2 - P_t^2)^{n_1} \\ \qquad\qquad\qquad\quad \Updownarrow \\ q_{g2} = C_2(P_{c2}^2 - P_t^2)^{n_2} \end{cases}$$

Also ~ work during a shut-in

(Darcy) R: $q_{g\ell} = C_{R\ell}(P_{R\ell}^2 - P_{wf}^2)$; $P_{R\ell} > P_{wf}$ layer produces in to wellbore

$$\uparrow$$

$$\frac{(kh)_\ell}{\left[\ln\frac{r_e}{r_w} + s_\ell\right]}$$

$$-q_{g\ell} = C_{R\ell}\left(P_{wf}^2 - P_{R\ell}^2\right) \quad ; \quad P_{wf} > P_{R\ell}$$

wellbore injects into layer

Conservation: $-q_{g1} = q_{g2}$

Solve: P_{wf} satisfies

$$C_{R1}\left(P_w^2 - P_{c1}^2\right) = C_{R2}\left(P_{c2}^2 - P_w^2\right)$$

↑ ↑

equivalent @ surface

Solve for P_w ⇒

$$C_{R1}P_w^2 + C_{R2}P_w^2 = C_{R2}P_{c2}^2 + C_{R1}P_{c1}^2$$

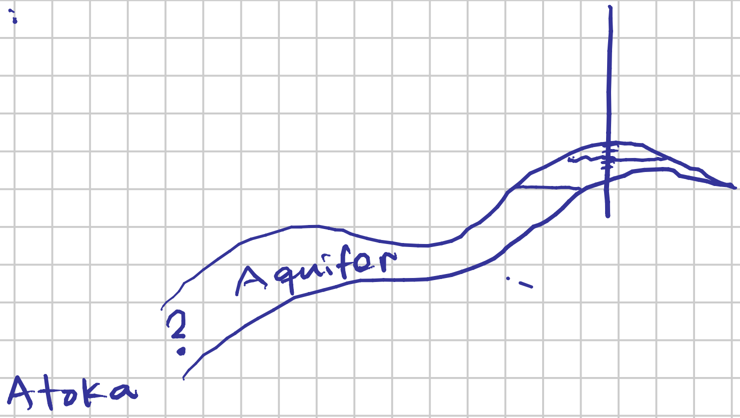
Shutin Pressure @ Surface : $P_w^2 \simeq \dfrac{\underline{\underline{C_{R2}}}\,P_{c2}^2 + \underline{\underline{C_{R1}}}\,P_{c1}^2}{C_{R2} + C_{R1}}$

Averaging based on weight factors C_{R1} and C_{R2}

Water Influx

Problem 1 (Noblin) well:

$$M = \left(\frac{V_{AQ}}{V_{PR}}\right)$$



Concern if $\underset{\parallel}{(W_e)} \sim \frac{1}{2} V_{PR}$

max $\underline{\underline{V_{w\,influx}}}$

$$W_{e\,max} = \underset{\overset{\uparrow}{?}}{V_{AQ}} \times (c_w + c_f) \times (P_{Ri}) = \frac{1}{2} V_{PR}$$

"Problem" $M = \frac{V_{AQ}}{V_{PR}} = \frac{0.5}{(c_w + c_f)(P_{Ri})}$

c_w ? $\simeq 3 \cdot 10^{-6}$ 1/psi (Chart 54)

c_f $\simeq 4 \cdot 10^{-6}$ 1/psi

$$M = \frac{0.5}{(3+4)(10^{-6})(435)}$$

$$= \frac{0.5}{3000\ 10^{-6}} = \frac{5\ 10^{-1}}{3 \cdot 10^{-3}} = 1.5 \cdot 10^{2}$$

$$= 150$$

$\frac{640\text{ acres}}{1 \times 1\text{ mile}}$

$A_{gR} \sim 40$ acres $\Rightarrow$ $A_q \sim 4000$ acres

$\left.\begin{array}{l} 3 \times 3 \text{ miles} \\ 5 \times 5 \text{ km} \end{array}\right\}$ Plausible

COMPONENTS, MIXTURES, PROPERTIES & EQUILIBRIUM

Note Title 9/23/2009

COMPONENTS:

GASeous

non-Hydrocarbons (non-HC)

CO_2 N_2 H_2S … H_2O (salts)

Hydrocarbons —— GROUPS: HC

C_1

C_2

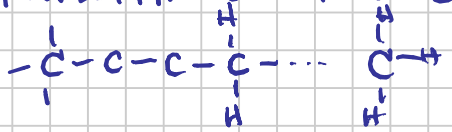
Grilling! { C_3, i-C_4 n-C_4 }

LIQUID: i-C_5 n-C_5, C_6, C_7 … C_{20} … C_{45} … C_{100} …

SOLID

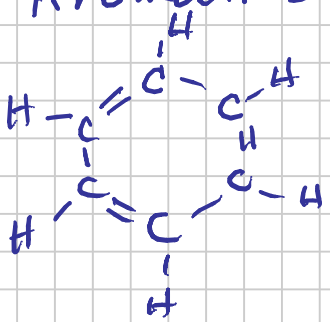
- Wax "P" {n>20}
- Asphaltene
- Hydrates

{ Paraffin (n-Alkane) }



Naphthene (Cycloalkanes) — Google it

Aromatics



Benzene Rings

n Carbon atoms:

$$M_n\left[\frac{kg}{kg\text{-}mole}\right] = 14\cdot n + h$$

P: $h = +2$ e.g. C_1 $M = 14\cdot1+2 = 16$

N: $h = 0$

A: $h = -6$

Quantifying Amounts of Components i

- Molar $\boxed{n_i}$ Mole Fractions $\frac{n_i}{n}$: $\left\{ \begin{array}{ll} z_i = n_i/n & \text{mixture} \\ y_i = n_{iv}/n_v & \text{vapor} \\ x_i = n_{iL}/n_L & \text{liquid} \end{array} \right.$

Total Moles

  - Not usually measured.

- Mass m_i (Weight) Mass Fractions $\frac{m_i}{m} \equiv \underset{\uparrow}{w_i}$ (x_{mi})

  - Can be measured.

$m_i \to n_i$: Use M_i (molar mass) $\equiv \frac{m_i}{n_i}$

$$n_i = m_i / M_i \quad \text{or} \quad m_i = n_i M_i$$

(Volumetric) V_i

- Ideal Gas Volumes V_{iv} $= y_i = \frac{V_{iv}}{V_v} = \frac{\cancel{23.68}\, n_{iv}}{\cancel{23.68}\, n_v}$

  (same as mole fraction)

- Ideal Liquid Volumes at s.c. 1 atm, 15.56 °C

$$[m^3] \quad V_{iL} = \frac{m_i}{\rho_{iL}} \quad \begin{array}{l} [kg] \\ [kg/m^3] \end{array}$$

@ s.c.

Volume Fraction $x_{vi} \equiv \frac{V_{iL}}{V_L}$

HC Liquids at ~ Standard Condition

("Stock-Tank" or Sellable Oil)

$$V_L \cong \sum_{i=C_6}^{C_{50+}} V_{iL} = \sum \frac{m_i}{\rho_{iL}}$$

1 L of gasoline + 1 L of diesel

= 2 L mix

Non-ideal mixing of liquids:

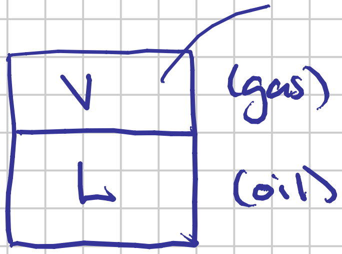
1 L Water + 1 Liter Tronder Sprit

≠ 2 L mix

= 1.9x L mix

Examples:

Gas Chromatography : mole fractions (gas) $y_{C_1} = 0.9$, $y_{C_{10}} = 0.1$



$n_V = 8$ lb-mole

$n_L = 2$ lb-moles

$n_{C_1} = 8$ lb-mole ✓

$n_{C_{10}} = 2$ lb-mole ✓

$n = 10$ lb-moles

Q: How many (mass) moles of C_1, C_{10}

- overall $[\text{lb-}\cancel{\text{moles}}]$ $\left[\frac{\text{lb-mole}}{\text{lb-}\cancel{\text{mole}}}\right]$

- in vapor $(n_{C_1})_V = 8 \cdot 0.9 = 7.2$ lb-moles

$(n_{C_{10}})_V = 0.8$ lb-moles $= 8 - 7.2$

- in liquid $\quad (n_{C_1})_L = n_{C_1} - (n_{C_1})_V$

$= 8 - 7.2 = 0.8$ lb-moles

$(n_{C_{10}})_L = n_{C_{10}} - (n_{C_{10}})_V$

$= 2 - 0.8 = 1.2$ lb-moles

$(n)_L = 2$ lb-moles ✓

$0.8 + 1.2$

$$x_{C_1} = \frac{(n_{C_1})_L}{n_L} = \frac{0.8}{2} = 0.4$$

Sum of x_i always 1 : $\quad x_{C_{10}} = 1 - x_{C_1} = 0.6$

At home: Calc. m_i $\quad$ } Vapor

x_{mi} or w_i $\quad$ } Liquid

$$m \rightarrow \textcircled{M} \leftarrow n$$

└ App. A : non-HCs, HCs $C_1 \cdots C_{10}$ (n-Alkanes)

C_6 and heavier "component mixtures with a single carbon number SCN"

"C_7" {n-Alkane C_7 isomers + benzene}

$$\underbrace{100 \qquad \begin{matrix} A \\ N \end{matrix} \downarrow \begin{matrix} M_{C_6H_6} \\ 78 \end{matrix}}_{84}$$

$14.7 + 2$

$$\begin{array}{r} {}^{2} \\ 14 \\ 7 \\ \hline 98 \\ 2 \end{array}$$

Ch. 5: Average SCN M's $C_6 \cdots C_{45}$

Katz & Firoozabadi

Liquid Specific Gravity $\gamma_i \equiv \dfrac{\rho_{iL}(1\text{atm}, 15.56°C)}{\rho_w(\text{ —"— })}$

$$\gamma_i \downarrow$$

$$m_i \rightarrow V_{iL}$$

"P+N+A"

$$(\gamma_{C7})_{\underline{\underline{KF}}} = 0.727 \quad \uparrow \quad A\ (N)$$

$$(\gamma_{C7})_P = 0.683$$

Properties of Components $\longrightarrow$ Equilibrium

Phase Behavior

Gas
Liquid

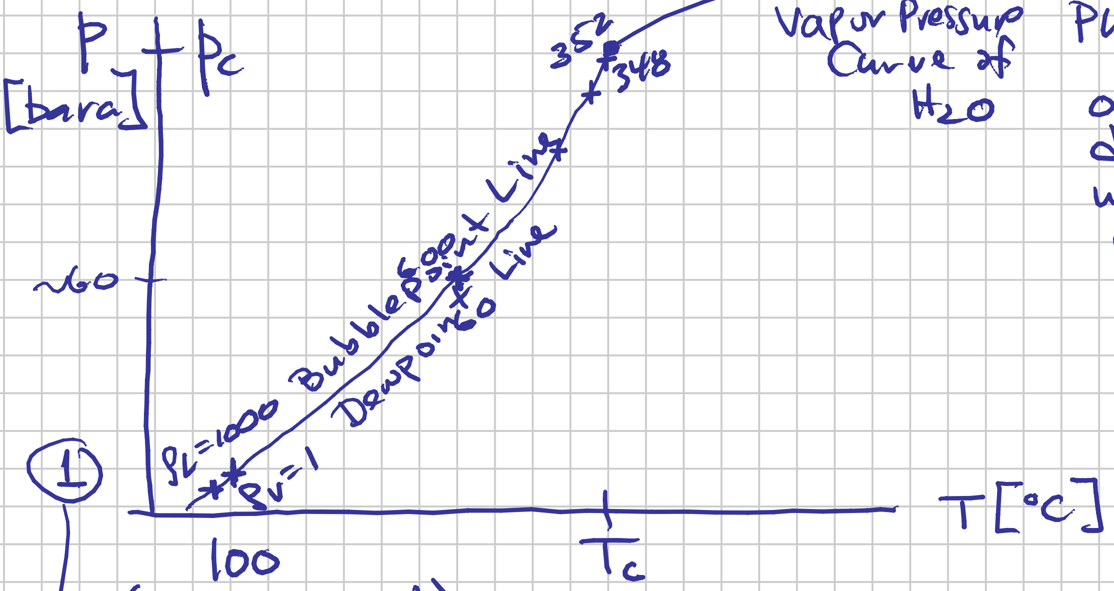
- State (gas / liquid / g+l)
  (saturated / undersaturated)
- Component partitioning
- Amounts (molar, mass, volumetric)
- Properties (M, ρ, … μ)

Chemical Equilibrium (Thermodynamics)

Single Component : H_2O

Critical Point: $\rho_L = \rho_v$, $\mu_L = \mu_v$ …

Vapor Pressure Curve of H_2O



(Bubblepoint)
Vapor Pressure of H2O at 100°C

Phase Diagram — orientation diagram on which phases exist, where (p, T)

+ Two phases
L, ∈ V
↓
∈ L, V
0.5 L 0.5 V
0.9 L 0.1 V
kg

$$1 \text{ L water} = 10^{-3} \text{ m}^3$$

$$(\rho_w)_L \sim 10^3 \text{ kg/m}^3$$

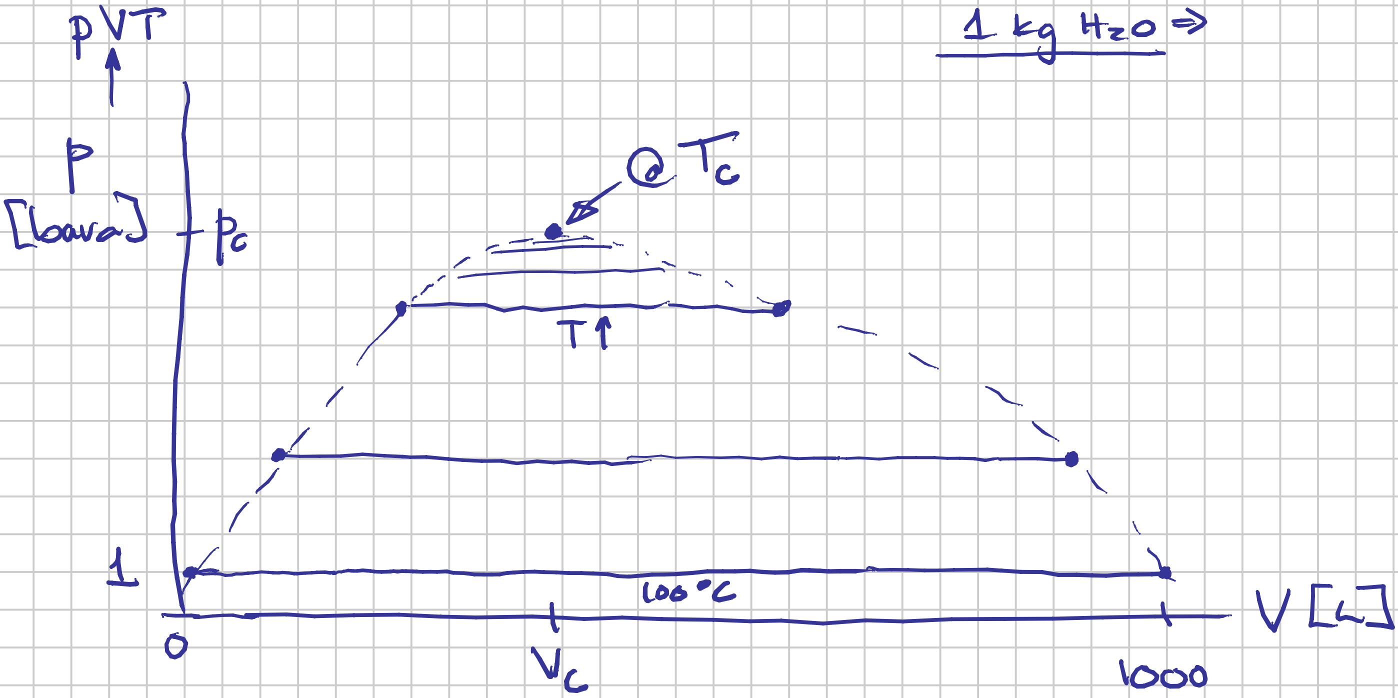
$$m_w = 1 \text{ kg}$$

$$n_w = 1 \text{ kg} / 18 \text{ kg/kg-mol} = 0.55 \text{ kg-mol}$$

$$\rho_g \sim \frac{pM}{RTZ}$$

$$(\rho_w)_v \sim 1 \text{ kg/m}^3$$

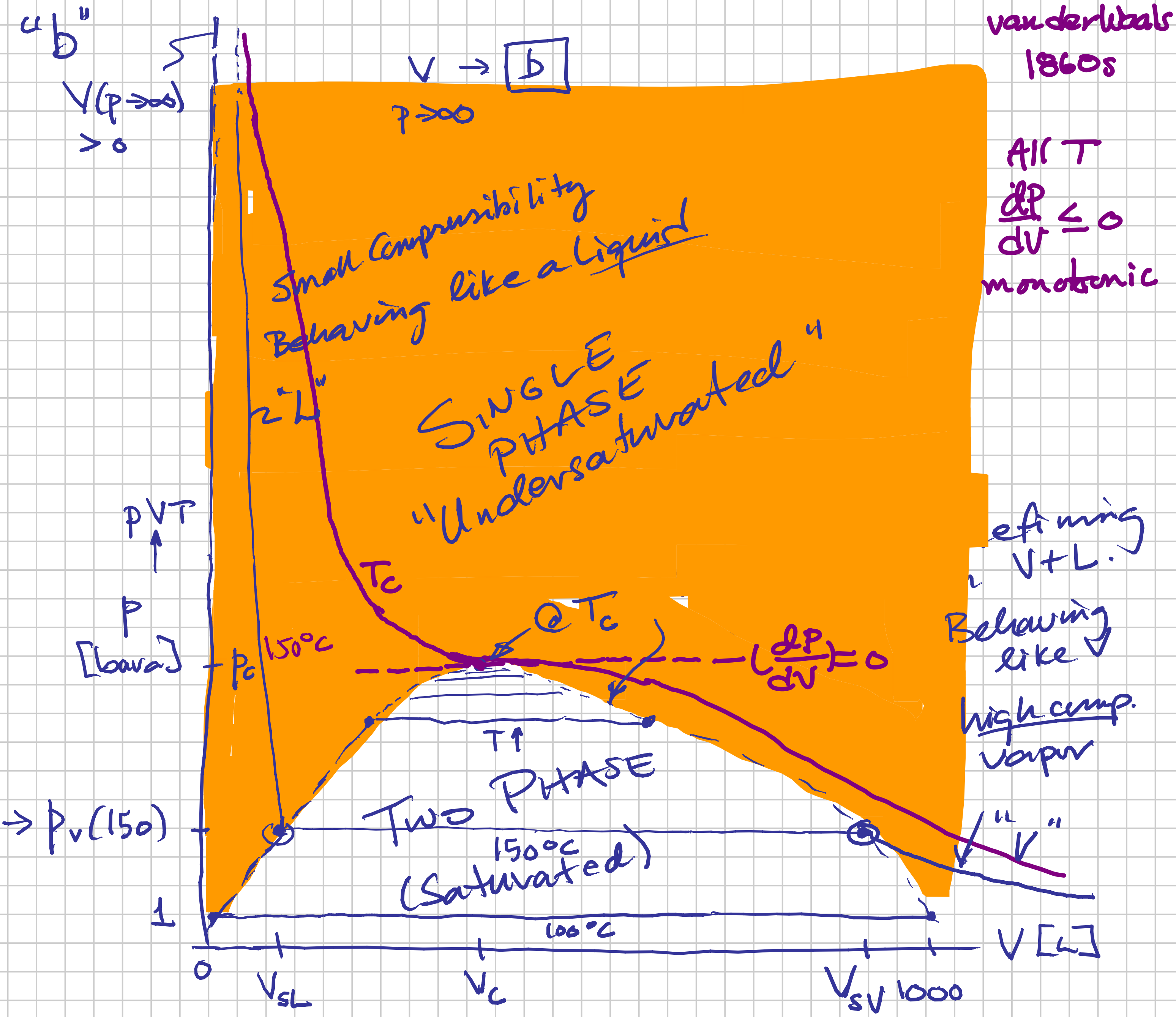
$1\ \text{kg}\ H_2O \Rightarrow$



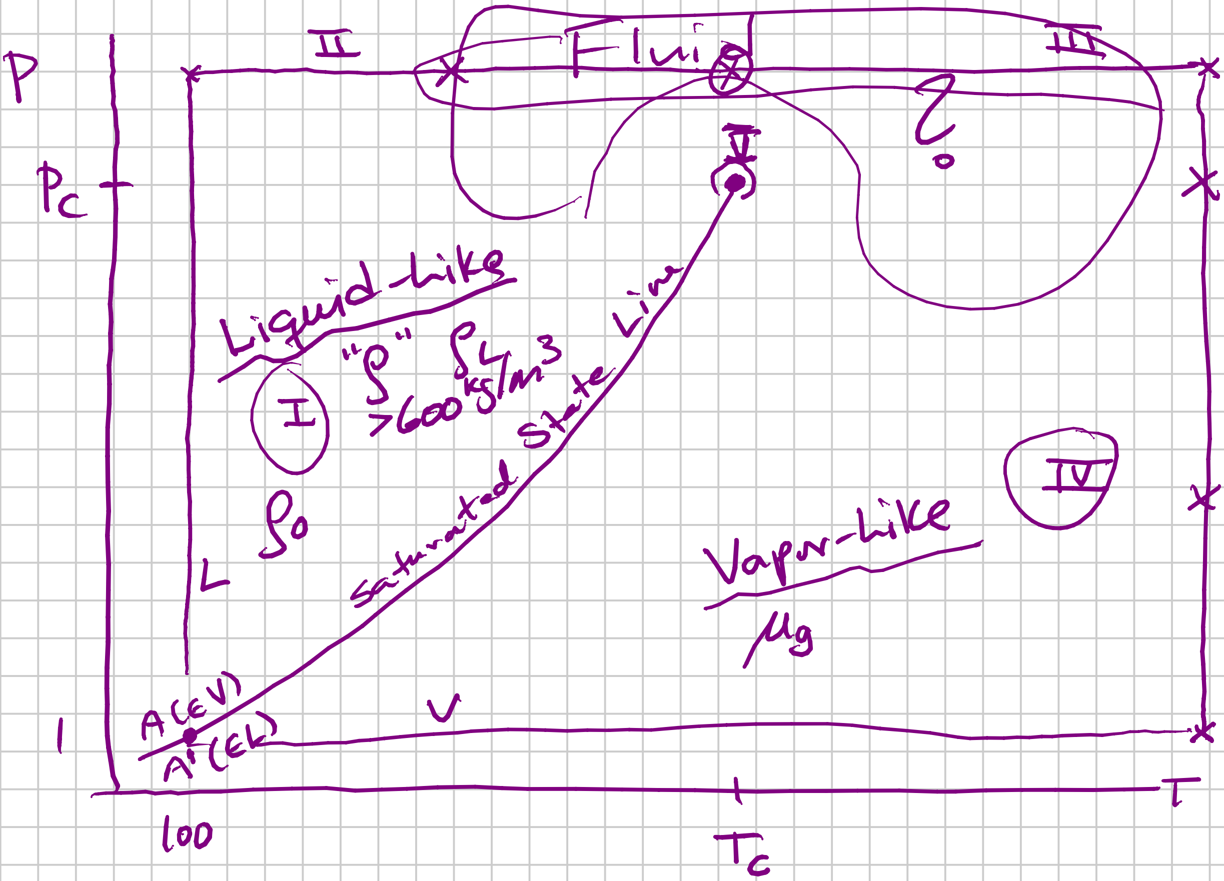
$$\rho = \frac{m}{V} = \frac{1\,\text{kg}}{V}$$

$$V_c = 0.0572\ \frac{m^3}{\text{kg-mol}}$$

$$\rho_c = \frac{M\left[\text{kg}/\cancel{\text{kg-mol}}\right]}{V_c\left[\frac{m^3}{\cancel{\text{kg-mol}}}\right]}\ \frac{\text{kg}}{m^3} = \frac{18}{0.0572} = 315\ \frac{\text{kg}}{m^3}$$



"Saturated" A phase is saturated w.r.t. (with respect to) another phase (component)



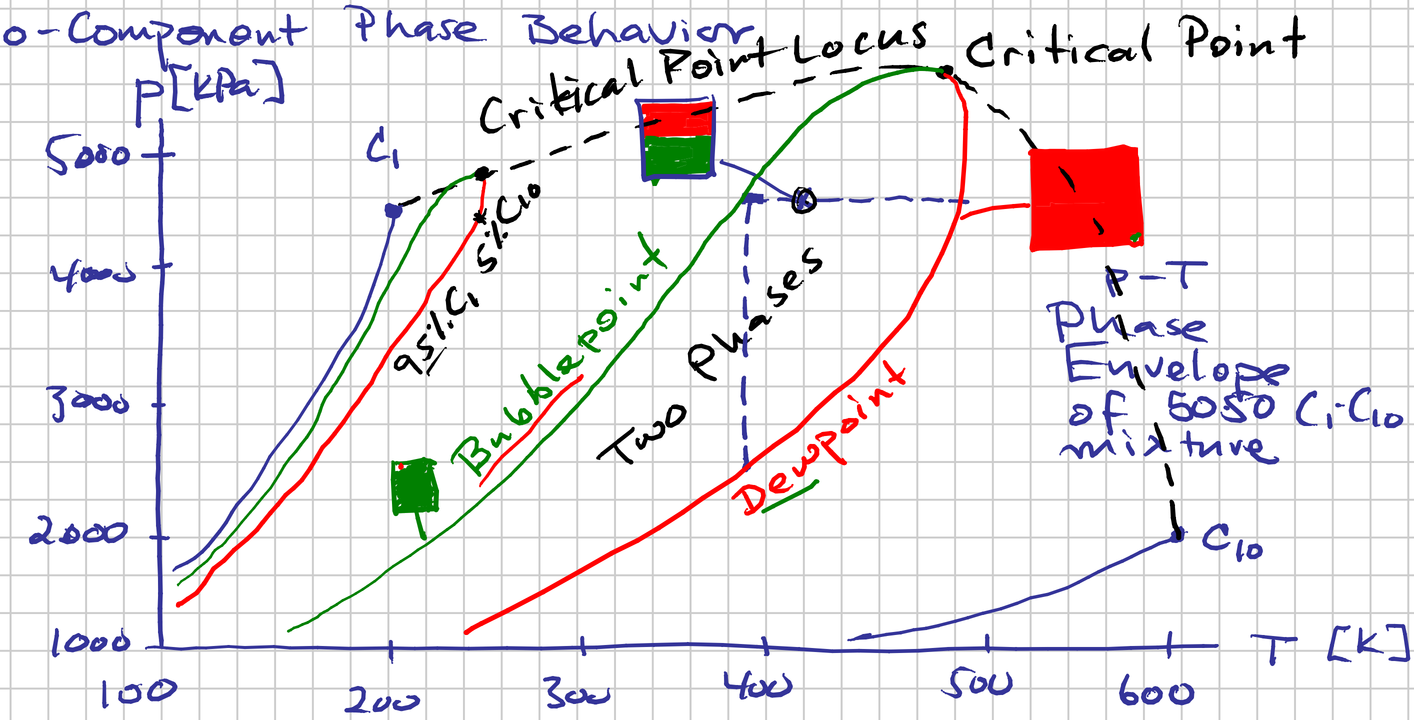
	L	V
I	most	2
II	most	5
III	?	most
IV	1	most
V	?	?

✓

A : L

A' : V

Two-Component Phase Behavior



$C_1 - C_{10}$

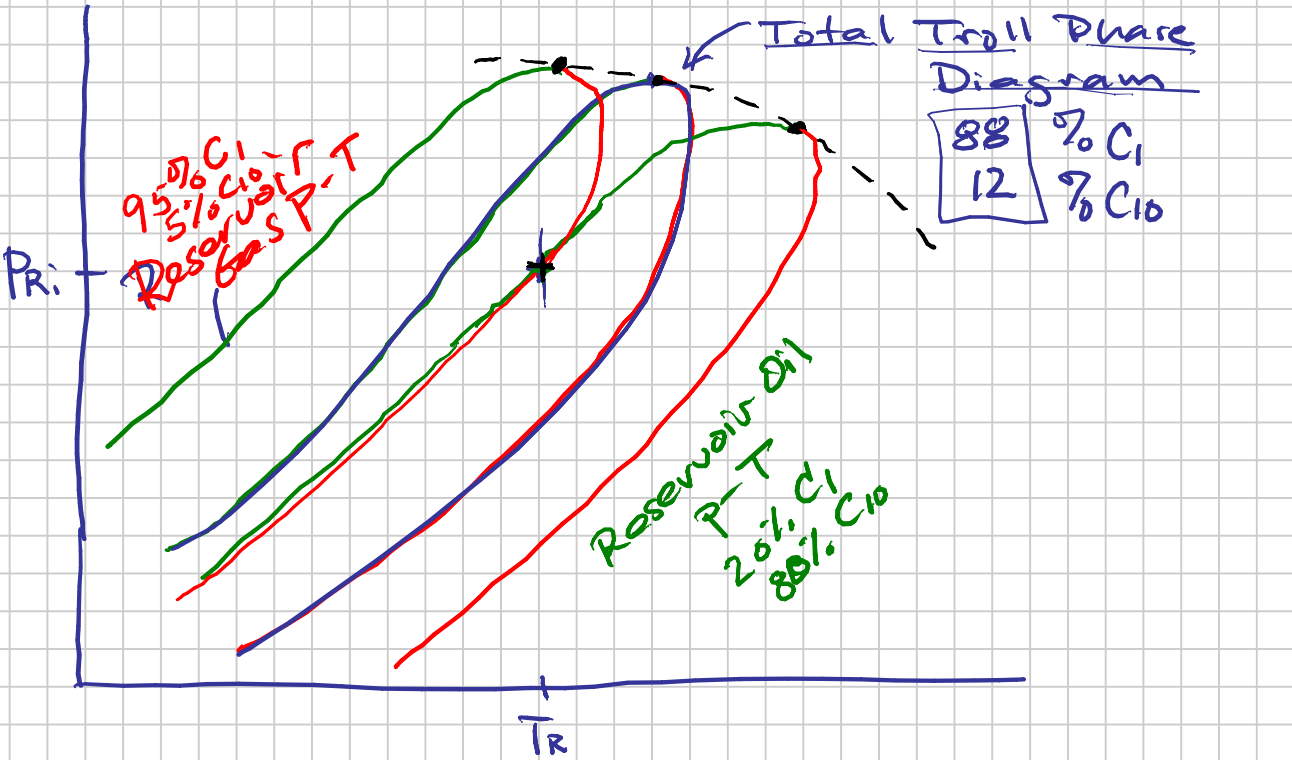
Example : 50-50 molar

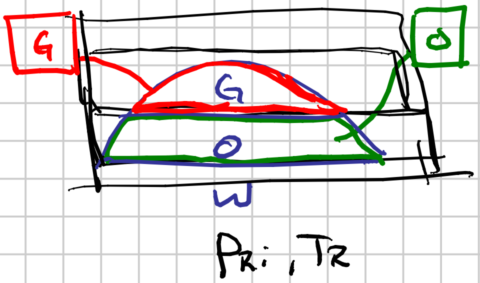
p-T phase envelope defines the range of p & T w/ two phases.

p-T depends on f(molar composition)

C.P.(z_i) z_i

$p-T : f(z_i)$





* Saturated Gas at (p, T)
is at its dewpoint $p_d(T) = p$

* Saturated Oil at (p, T)
is at its bubblepoint $p_b(T) = p$

$(z_i)_{\text{Troll Field}}$?

Reservoir bbl

$\underline{\text{IOIP}} \sim 4 \cdot 10^9 \text{ STB} \sim 4.8 \, 10^9 \, \boxed{\text{RB}} = V_{oR} = 2.7 \cdot 10^{10} \, \underline{\underline{ft^3}}$

$\underline{\text{IGIP}} = 45 \text{ Tcf} = 45 \cdot 10^{12} \text{ scf} \Rightarrow V_{gR} = \dfrac{\text{IGIP}}{150} = 3 \cdot 10^{11} \, \underline{\underline{ft^3}}$

$p_R \sim 150 \text{ bara} \Rightarrow \dfrac{150 \text{ scf}}{R \, ft^3}$ "Expansion Factor"

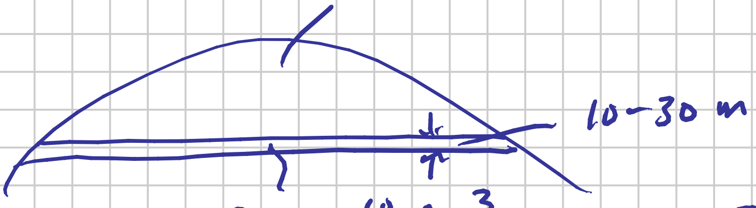
$$\frac{4.5 \cdot 10^{13}}{1.5 \cdot 10^2} = 3 \cdot 10^{11}$$

$5.6146 \; \dfrac{ft^3}{bbl}$

$$\begin{array}{r} {}^{4} \\ 4.8 \\ 5.6 \\ \hline 288 \\ 240 \\ \hline 26.88 \end{array}$$

$35.31 \frac{ft^3}{m^3}$

$30 \cdot 10^{10}\ ft^3 = \underline{\underline{0.9 \cdot 10^{10}\ m^3}}$



$2.7 \cdot 10^{10}\ ft^3 = 0.08 \cdot 10^{10}\ \underline{\underline{m^3}}$

ctw

$$\boxed{\rho_{gR}} = \frac{m_{gR}}{V_{gR}} \Rightarrow m_{gR} = \rho_{gR} \cdot V_{gR} =$$

$$150 \cdot 0.9 \cdot 10^{10} = 135 \cdot 10^{10}\ kg$$

$$\boxed{\rho_{oR}} = \frac{m_{oR}}{V_{oR}} \Rightarrow m_{oR} = \rho_{oR} \cdot V_{oR} =$$

$$850 \cdot 0.08 \cdot 10^{10} = 68 \cdot 10^{10}\ kg$$

$$\rho_{gR} = \frac{pM}{ZRT} \sim 150\ kg/m^3$$

✓

$$\rho_{oR} = 850\ kg/m^3$$

$$M = \frac{m}{n}$$

$$n_{gR} = m_{gR} / M_{gR} = \frac{135 \cdot 10^{10}\ kg}{22.3} = 6 \cdot 10^{10}\ kgmole$$

$$n_{oR} = m_{oR} / M_{oR} = \frac{68 \cdot 10^{10}\ kg}{115} = 0.6 \cdot 10^{10}\ kgmole$$

$$M_{gR} = \overset{y_{c1}}{0.95}(\overset{M_{c1}}{16}) + \overset{y_{c10}}{0.05}(\overset{M_{c10}}{142}) = \underline{22.3}\ kg/kg\text{-mole}$$

$$M_{oR} = 0.2(16) + 0.8(142) = \underline{115}$$

$$\underline{\underline{n_{c1}}} = n_{gR} \cdot y_{c1} + n_{oR} \cdot x_{c1}$$

$$6 \cdot 10^{10}(0.95) + 0.6 \cdot 10^{10}(0.2)$$

$$= 5.82 \cdot 10^{10}\ kg\text{-moles}$$

$$\underline{\underline{n}} = n_{gR} + n_{oR} = 6.6 \cdot 10^{10}\ kg\text{-mole}$$

$$z_{C_1} = \frac{n_{C_1}}{n} = \frac{5.82\cdot 10^{10}}{6.6\cdot 10^{10}} = 0.88$$

$$z_{C_{10}} = 1 - z_{C_1} = 0.12$$

12 mol% "stock-tank oil"

⇓

If brought to single phase w/ increasing pressure, you

$$\left.\begin{array}{l}\text{might get a } p_b\\ \text{or might get a } p_d\end{array}\right\}?$$

"Near critical fluid"

12 – 15 mol% "C_{7+}"

STO

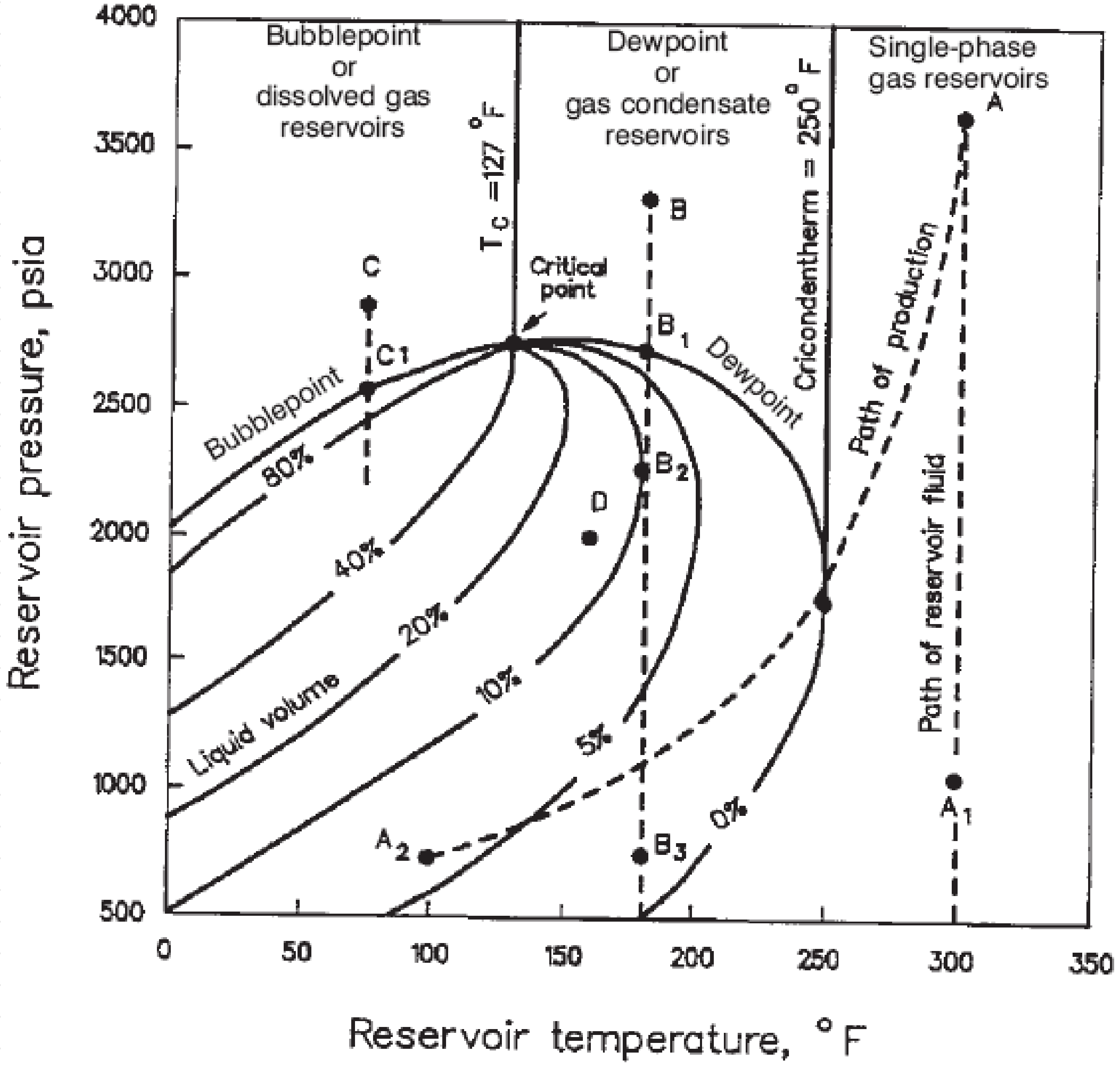
C_{10}

$\boxed{z_{C_{7+}}} < 12$ mol% – 15%

$\Rightarrow p_d(T_R)$

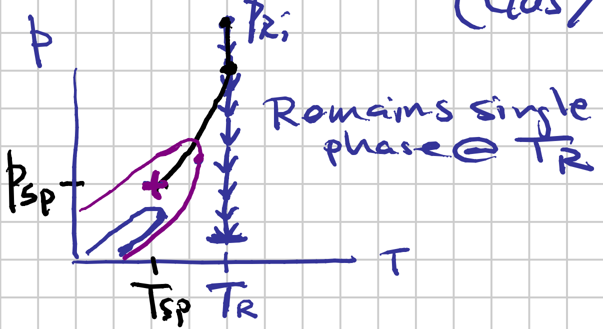
$>$ 12 mol% – 15%

$\Rightarrow p_b(T_R)$

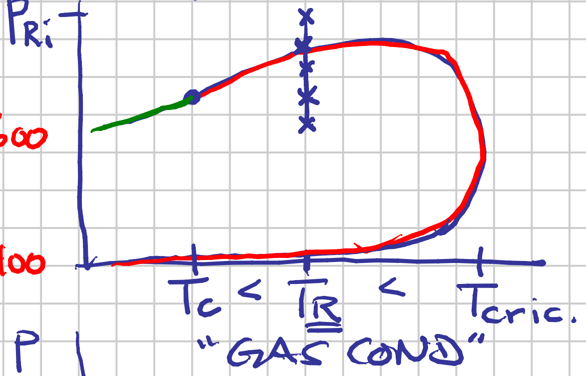

4000
3500
3000
2500
2000
1500
1000
500
Reservoir pressure, psia
0
50
100
150
200
250
300
350
Reservoir temperature, °F
Bubblepoint or dissolved gas reservoirs
Dewpoint or gas condensate reservoirs
Single-phase gas reservoirs
T_C =127 °F
Cricondentherm = 250 °F
Critical point
Bubblepoint
Dewpoint
Liquid volume
80%
40%
20%
10%
5%
0%
A
A1
A2
B
B1
B2
B3
C
C1
D
Path of production
Path of reservoir fluid

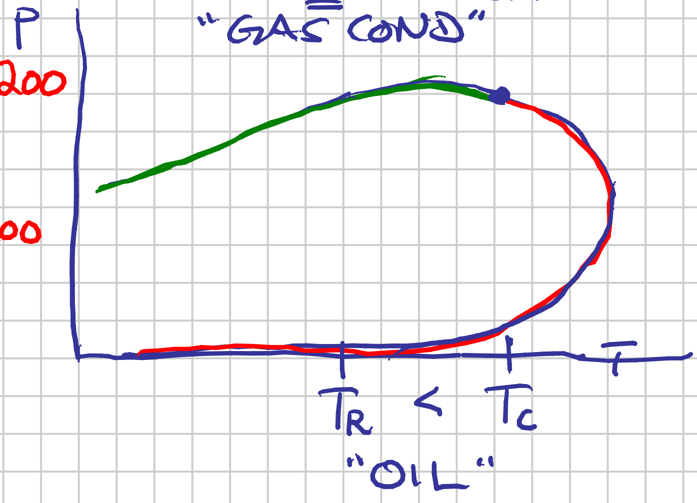
p-T Phase Diagram Used to Define Reservoir Fluid "Type" (Gas/Oil)

RESERVOIR FLUID TYPES	C_7 mol-%	GOR $\frac{Sm^3}{Sm^3}$
— DRY GAS ↑@surface	<0.5	∞
— WET GAS ↑@Surface	0.5-1	50-20,000
"GAS CONDENSATE"	1-12	20000-600
~ NEAR-CRITICAL FLUID ~ G / O	12-15	600-400
VOLATILE OIL $T_R \rightarrow T_c$ ~high C_1 content	15-25	400-200
BLACK OIL $T_R \longrightarrow T_c$ lower C_1 content	25-90	<200
HEAVY OIL	>90	
(DEAD OIL)	~100	



Cricondentherm = T_{max} PT



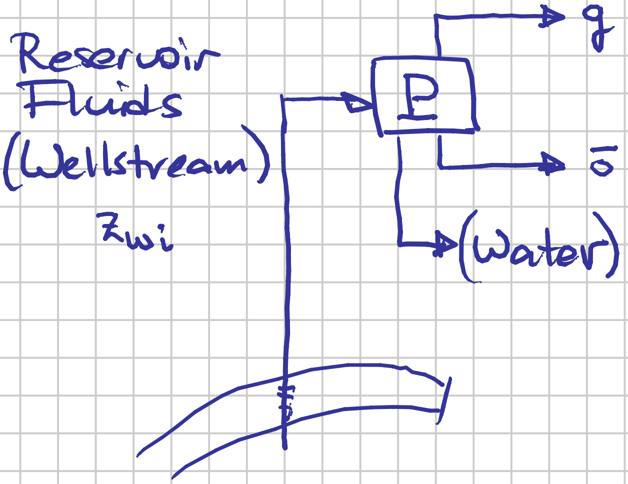


SURFACE PROCESSING, GOR-COMPOSITION (..."FLASH" CALCS)

Note Title 10/5/2009

↑ Ch. 4 (4.3): Wed

SURFACE PROCESSING $\boxed{P}$



Surface Gas (SG)

Surface Oil (SO) : Stock Tank Oil (STO)

~@ Standard Conditions

1 atm

60 °F (15.56 °C)

$\boxed{P}$

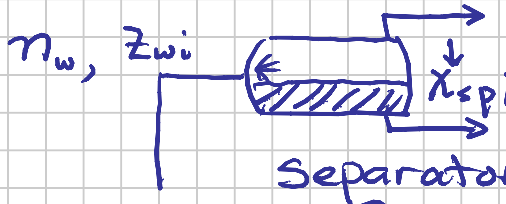
Simplest

y_{spi} {V_{spg} ... amounts}

Sep Gas = SG

x_{spi} {V_{spo} ... amounts}

Sep. Oil = SO (STO)



Separator @ {T_{sc}, P_{sc}}

Single Separator

$V_{\bar{g}}$ = SG volume

$V_{\bar{o}}$ = SO volume

$GOR \equiv \frac{V_{\bar{g}}}{V_{\bar{o}}}$ SPE (R)

$OGR \equiv \frac{V_{\bar{o}}}{V_{\bar{g}}}$ (r)

Assume (True) Gas & Oil Leaving the separator are in thermodynamic equilibrium

f(p,T)

⇒ Inefficient process

$$\left\{ \begin{array}{l} V_{\bar{g}} \times (\$/Mscf) \\ V_{\bar{o}} \times (\$/STB) \end{array} \right\} = \text{Revenue}$$

Efficiency is mainly related to "moving" $\{C_3 - C_6\}$ components to the SO ($\bar{o}$)

$$\left(\frac{\text{Value}}{\text{mole}}\right)_{\bar{o}} \sim 3\text{-}5 \left(\frac{\text{Value}}{\text{mole}}\right)_{\bar{g}}$$

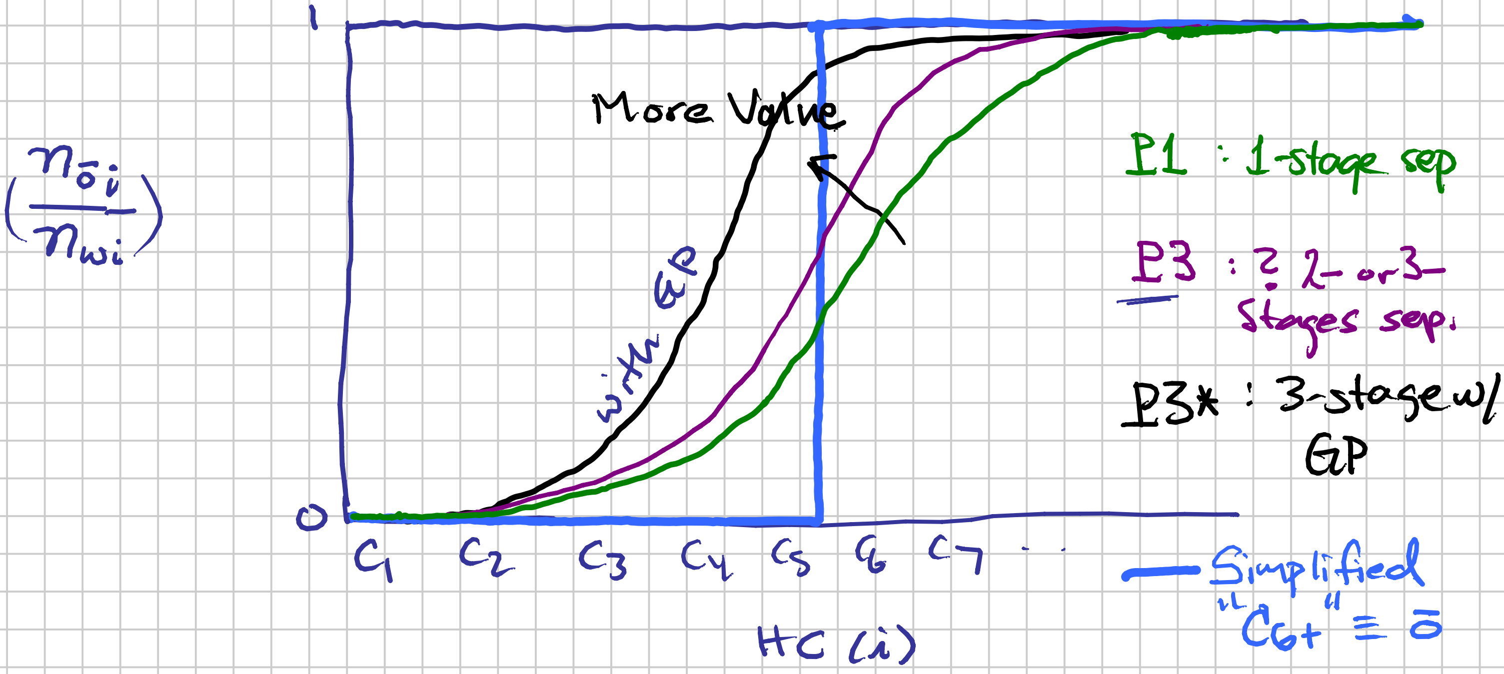
SG : 6000 scf ~ SO : 1 bbl

same "energy"

\$3/Mscf \$70/bbl

$$\text{Value } \bar{o} = 1 \text{ bbl} \times 70 \frac{\$}{\text{bbl}} = \underline{70}$$

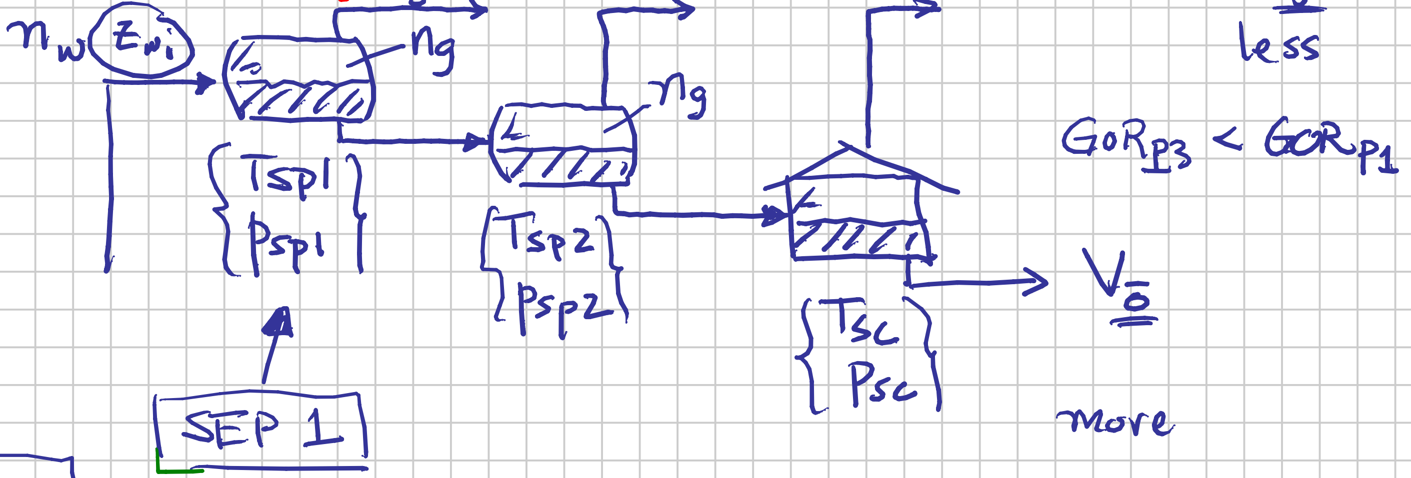
$$\text{Value } \bar{g} = 6 \text{ Mscf} \times 3 \frac{\$}{\text{Mscf}} = 18$$



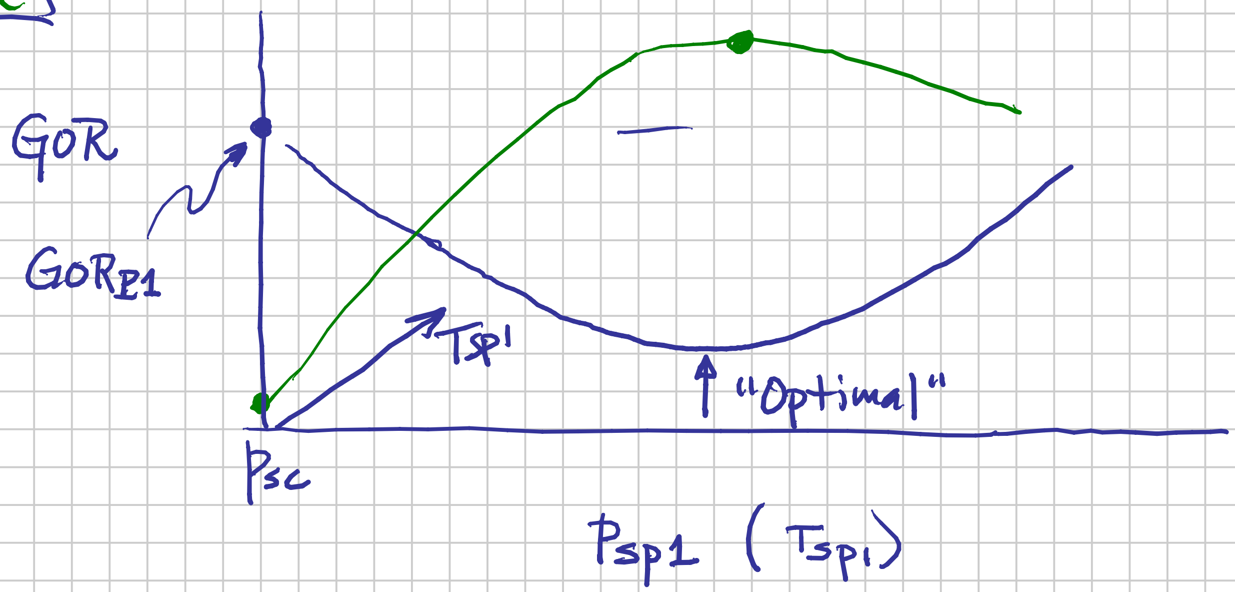
* Partitioning of components i $\{C_3 \ldots C_6\}$ in vapor phase & liquid phase $= f(P, T)$.

* Amount of phases at each stage

$\left\{ V_{\bar{g}1} [Sm^3/d] \right\} + V_{\bar{g}2} [Sm^3/d] + V_{\bar{g}3} [Sm^3/d] = V_{\bar{g}} \}$

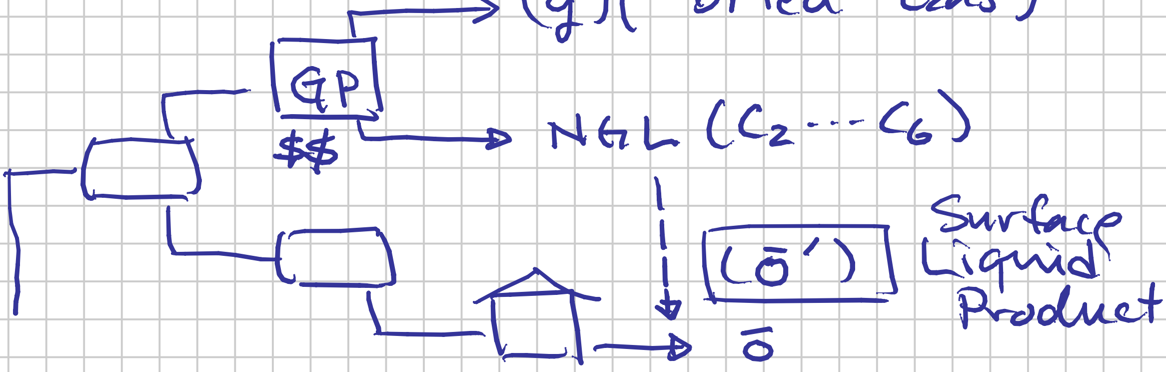


Value



Gas Processing of Separator Gases

(Gas Plant)



$$GOR_{P*} = \frac{V_{\bar{g}'}}{V_{\bar{o}'}} \quad \downarrow \quad \text{Value} \uparrow$$

Simplified Surface Process : C_{5-} : SG ($\bar{g}$)

C_{6+} : SO ($\bar{o}$)

$$GOR = \frac{V_{\bar{g}}}{V_{\bar{o}}} = \frac{\left(\frac{n_{\bar{g}}}{n_{\bar{o}}}\right) 23.68 \left[Sm^3/kg\text{-}mole\right]}{(M_{\bar{o}}/\rho_{\bar{o}})}$$

$$\frac{n_{\bar{g}} = (z_w)_{C5-} \cdot \cancel{n}}{n_{\bar{o}} = (z_w)_{C6+} \cdot \cancel{n}}$$

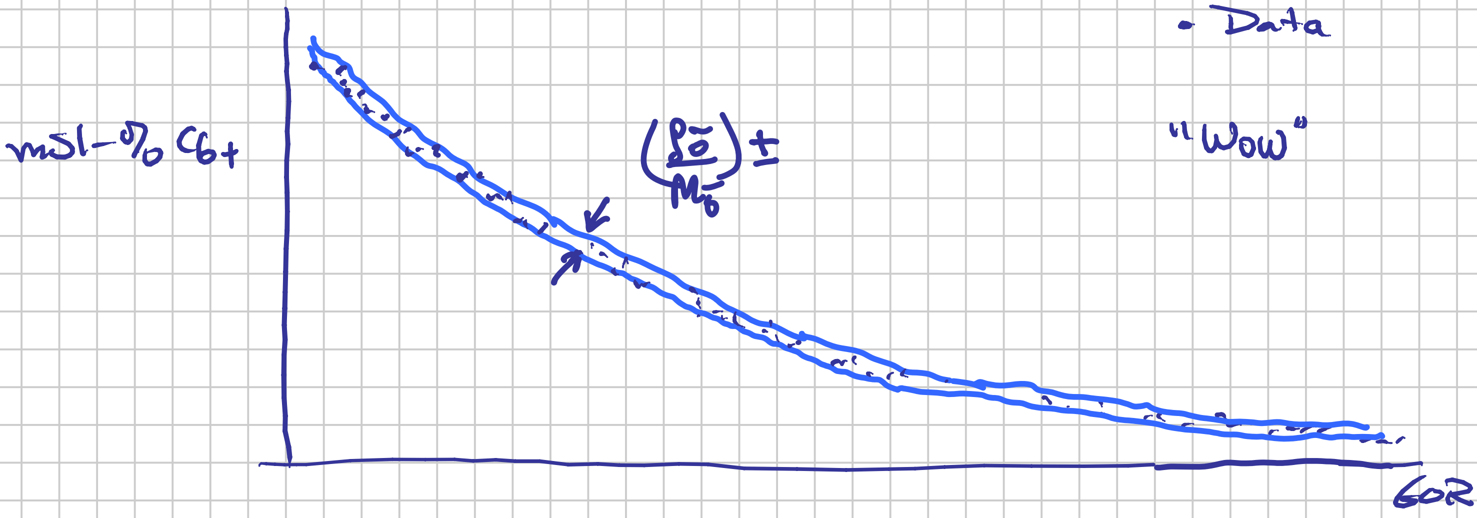
$$GOR\left[Sm^3/Sm^3\right] = \frac{(z_w)_{C5-}}{(z_w)_{C6+}} \cdot 23.68(\rho_{\bar{o}}/M_{\bar{o}})$$

$$\boxed{\underset{GOR}{GOR} = \underbrace{\frac{(1-(z_w)_{C6+})}{(z_w)_{C6+}}}_{C6+} \left\{ 23.68\left(\frac{\rho_{\bar{o}}}{M_{\bar{o}}}\right)\right\}}$$

$\rho_o \left[kg/m^3\right]$

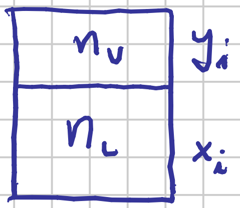
$23.68 \frac{\rho_{\bar{o}}}{M_{\bar{o}}}$ ~ constant all fields

C_{6+} wt-% vs GOR


mol-% C6+
(ρ̃o/M̃o) ±
• Data
"Wow"
GOR

FLASH / TWO-PHASE EQUILIBRIUM / RACHFORD-RICE CALC

Note Title 10/7/2009



n = total moles

$z_i n$ = total moles of i

Known

(p, T)

$\updownarrow$ z_i Overall molar composition

n

Calculating

- Phase ($\overset{V}{\text{gas}}$ and $\overset{L}{\text{oil}}$) amounts
- Component partitioning

  i.e. phase molar compositions y_i and x_i

* Material Balances

* Known thermodynamic "partitioning" quantity

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

K-value

Equilibrium Ratio

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

Complicated:

Charts

Tables

Simple models

Rigorous EOS model

Molar Component M.B.

	# Eqs
$n \overset{\checkmark}{z_i} = n_v y_i + n_L x_i$ (1)	N
$\overset{\checkmark}{n} = n_v + n_L$ (2)	1

$$\Rightarrow \quad K_i = \frac{y_i}{x_i} \qquad (3)$$

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

$\#$ Unknowns: $2N+2$

Eqs. 2 & 3

$\Downarrow$

$\#$ Unknowns $N+1$

1949 Muskat & McDowell (footnote)

195x Rachford & Rice (short paper)

$$1 - 1 = 0$$

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

$$\boxed{\sum (y_i - x_i) = 0} \quad \checkmark$$

$$n = n_v + n_L$$

$$1 = \frac{n_v}{n} + \frac{n_L}{n}$$

$$F_v = \frac{n_v}{n} \qquad \Rightarrow \qquad \frac{n_L}{n} = 1 - F_v$$

$$\frac{n z_i}{n} = \frac{n_v y_i}{n} + \frac{n_L x_i}{n}$$

$$z_i = \frac{n_v}{n} y_i + \frac{n_L}{n} x_i$$

$$\boxed{z_i = F_V y_i + (1-F_V) x_i} \leftarrow$$

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

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

$$= \underset{\uparrow}{\boxed{\sum (K_i - 1) x_i = 0}} \leftarrow$$

$$z_i = F_V \cdot K_i x_i + (1-F_V) x_i$$

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

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

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

Solve for x_i

$$\checkmark \quad x_i = \frac{\overset{\checkmark}{z_i}}{1 + \underset{\uparrow}{F_V^*}(\underset{\checkmark}{K_i} - 1)} \qquad y_i = K_i x_i$$

N unknowns

x_i

y_i

$$h = \sum y_i - x_i = 0 = \sum (K_i - 1) x_i$$

$$h = \sum_{i=1}^{N} \frac{z_i (K_i - 1)}{1 + F_V (K_i - 1)}$$

Rachford & Rice

Muskat & McDowell

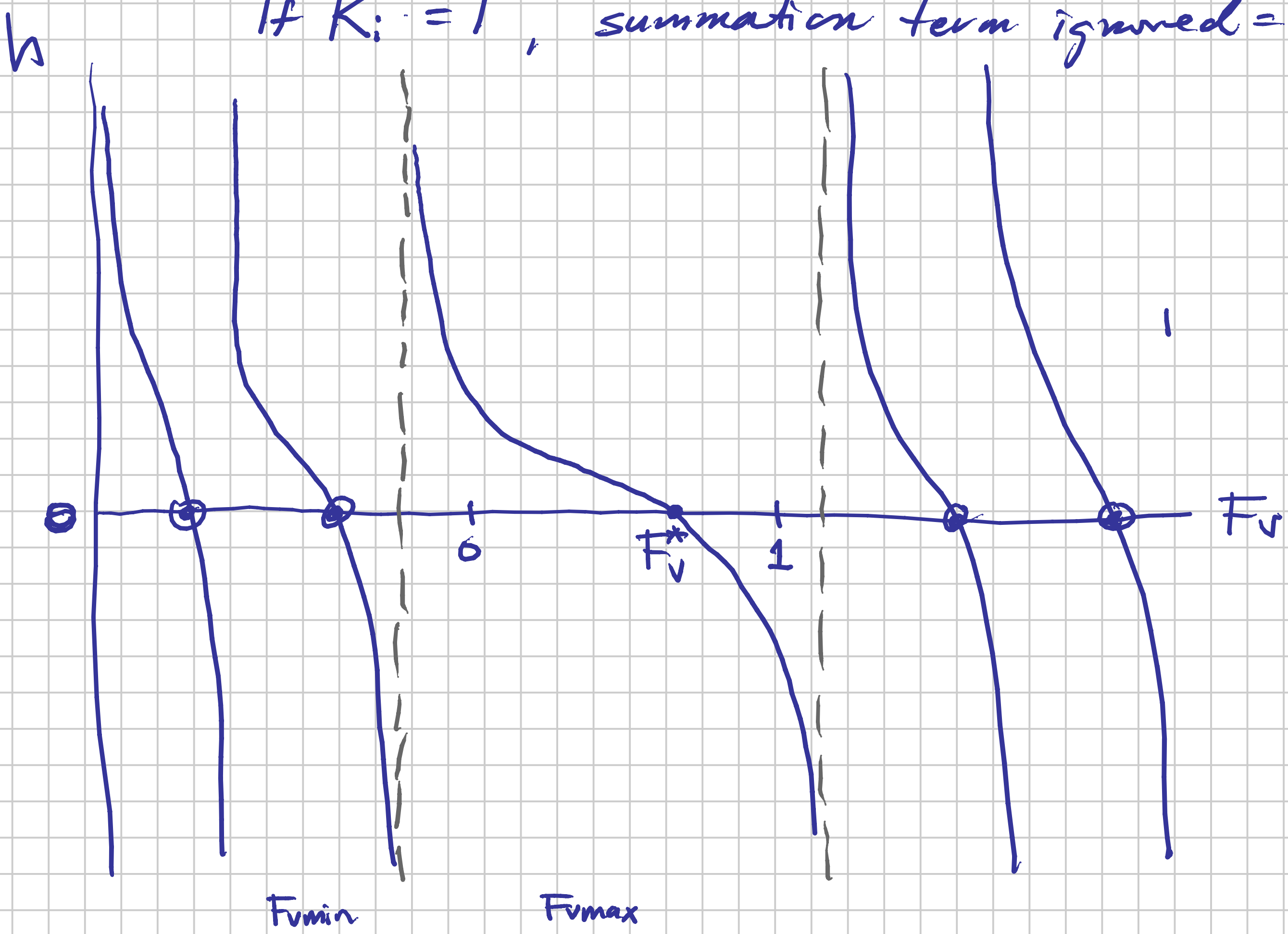
$$c_i \equiv \frac{1}{K_i - 1}$$

Given

i	z_i	K_i	c_i

$$h(F_V) = \sum_{i=1}^{N} \frac{z_i}{c_i + \underset{\uparrow}{F_V}} = 0$$

If $K_i = 1$, summation term ignored $= 0$



- h is monotonic

✓ • N-1 solutions :

✓ • − Only one that results in all ✓ $y_i > 0$ ✓ $x_i > 0$

$\underline{\underline{F_V^*}}$ lies between $F_{Vmin} = \dfrac{1}{1 - K_{max}}$

and $F_{Vmax} = \dfrac{1}{1 - K_{min}}$

✓ • $F_{Vmin} < 0 < 1 < F_{Vmax}$

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

Estimate $K_i(p, T, \underset{\uparrow}{z})$

Overall composition

Light Components $i \in N_2, C_1$

$>1 \to 10^4$ $\quad K_i > 1$ $\quad\uparrow$ i Prefers to be in the V phase

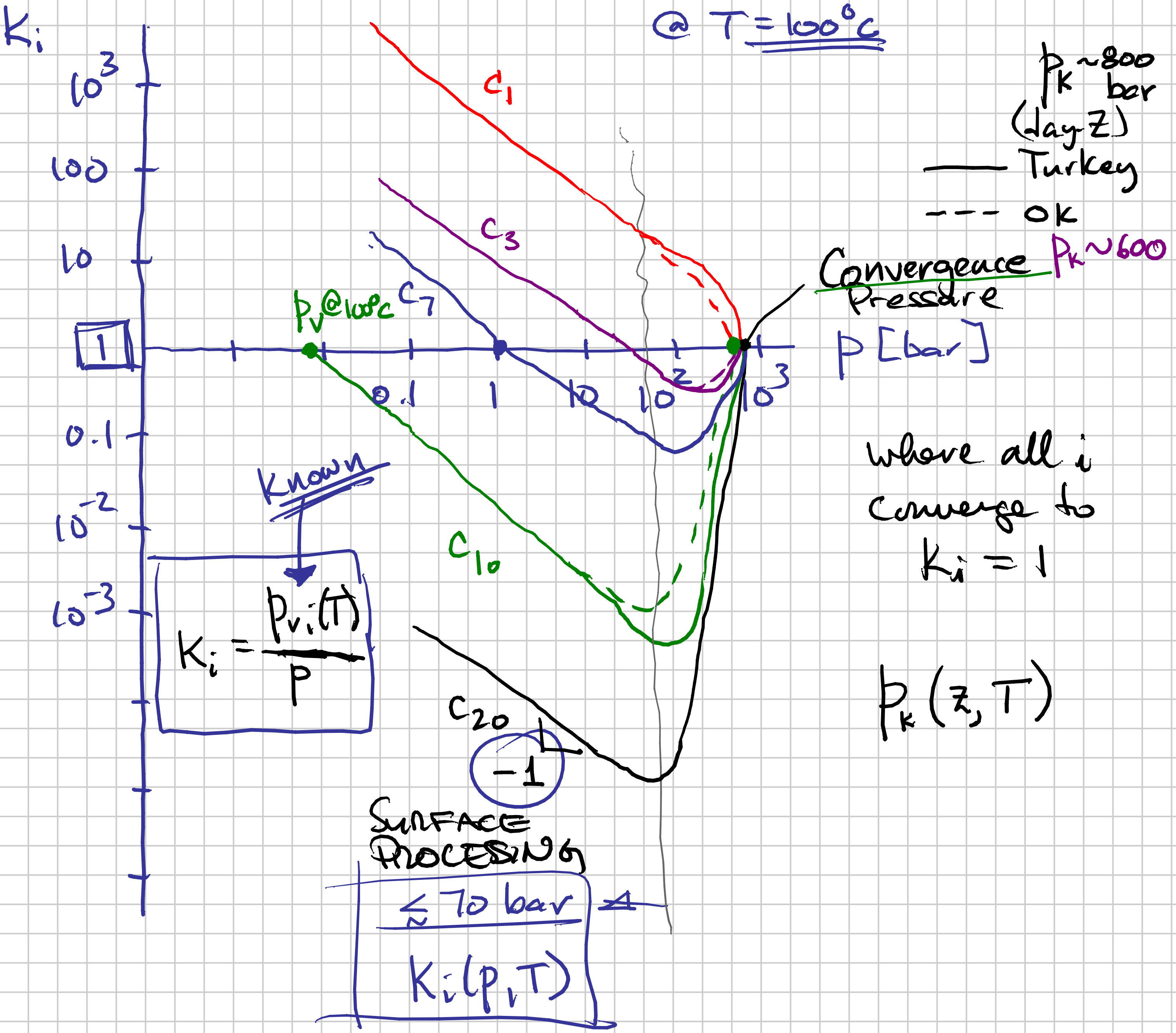
Intermediate Components CO_2 H_2S C_2 C_3

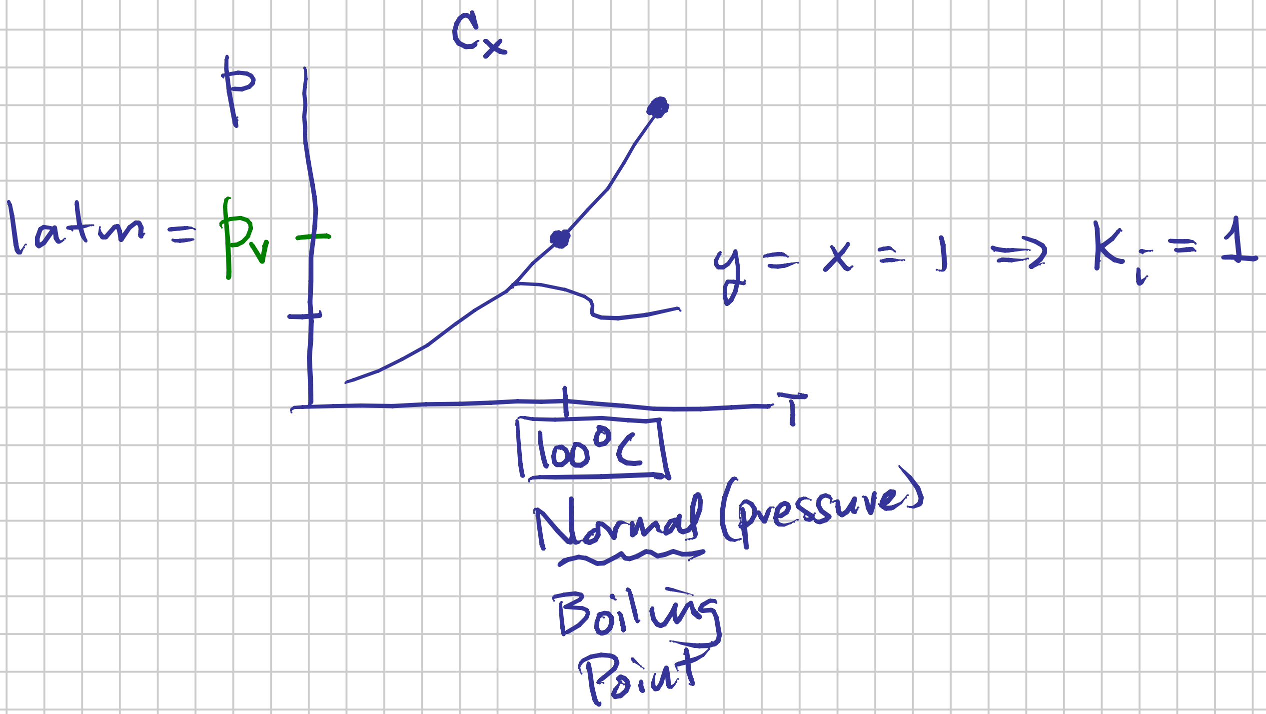
$K_i > 1$

$K_i < 1$ $\quad$ No strong Preference

Heavier Components $C_4 \cdots C_5 \cdots$

$<1 \to 10^{-xx}$ (heaviest ~100 bar-ish) $\quad K_i < 1$ $\quad i$ Prefers to be in the L phase





$y = x = 1 \Rightarrow K_i = 1$

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

$$K_i = \left(\frac{\overset{\checkmark}{p_{ci}}}{p_K}\right)^{\boxed{A_1}-1} \frac{\exp\left[5.37\boxed{A_1}(1+\overset{\checkmark}{\omega_i})\left(1-\overset{\checkmark}{T_{ri}^{-1}}\right)\right]}{\underset{\checkmark}{p_{ri}}},$$

$\uparrow T$

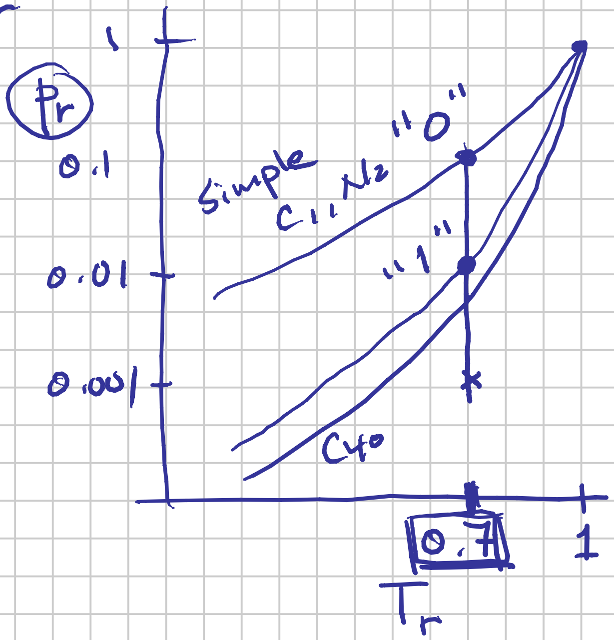
Pitzer

ω_i = Acentric Factor

p_{ci}

$$T_{ri} = \frac{T(K)}{T_{ci}(K)}$$

p_K : end of the nose



$$A_1(p) = 1 - \left(\frac{p}{p_K}\right)^{A_2}$$ "Nose Shape"

$A_2 \sim 0.8$

$A_1 = 0$ at $p = p_K$
$A_1 = 1$ at $p = 1$ atm

$\omega = 0$ $\qquad \frac{p_v}{p_c}(0.7T_c) = 0.1$

$\omega = 1$ $\qquad = 0.01$

$$\boxed{\omega = -1 - \log \frac{p_v(0.7T_c)}{p_c}}$$

Problem 15

Problem. Table B-18 gives the composition of a three-component system of methane, propane, and normal pentane. Use the modified Wilson[13] *K*-value equation (Eq. 3.159) with a convergence pressure of 2,000 psia to estimate *K* values at 500 psia and 160°F. Make a flash calculation using the Muskat-McDowell[14] (or Rachford-Rice[15]) algorithm given by Eqs. 4.36 through 4.40.

TABLE B-21—FINAL FLASH-CALCULATION RESULTS (PROBLEM 15)

	z_i	K_i	c_i	$z_i/(F_V+c_i)$	$z_i/(F_V+c_i)^2$	x_i	y_i
C_1	0.20	9.208	0.122	0.331	0.548	0.0403	0.3713
C_3	0.32	1.439	2.278	0.116	0.042	0.2641	0.3800
n-C_5	0.48	0.358	−1.556	−0.447	0.416	0.6956	0.2487
Total	1.00			7.07×10^{-17}	1.00590	1.0000	1.0000

$h(F_V)=7.07\times10^{-17}$ and $h'(F_V)=-1.00590$.

$$h = \sum \left\{ \frac{z_i}{c_i + F_v} \right\}$$

$K_i = 1$, term $= 0$

FLASH CALCULATION

Known : z_i , p, T

Get : - Number of phases (1 or 2)
- Amounts of each phase (F_v) $0 \le F_v \le 1$
- Component distribution between phases
  → y_i , x_i

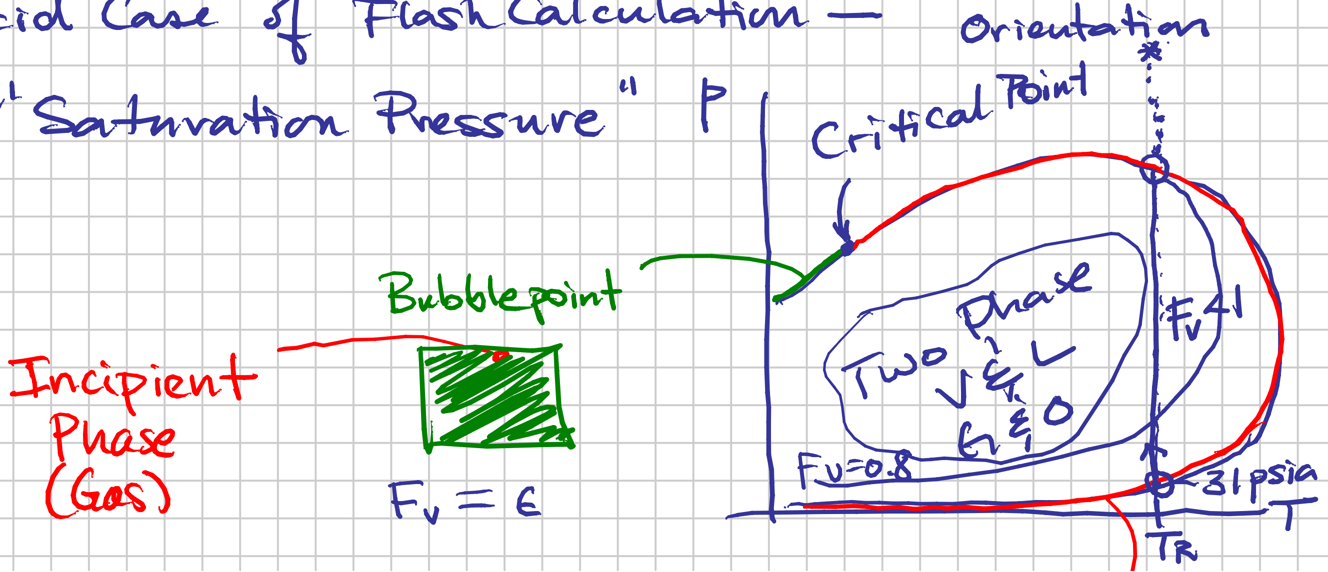
How : - $K_i(p, T, z) \equiv y_i / x_i$

↑ Overall Composition ~ "Convergence Pressure" for simplified K_i equation by Wilson (modified)

- Rachford-Rice (Muskat-McDowell) method

Special Case of Flash Calculation —

"Saturation Pressure"



① Set T

② Finding p where $F_v = 0 \;(\epsilon)$

$= 1 \;(1-\epsilon)$

↑

1 or 2 Solutions

Abu Qir, Egypt

T = 245 °F

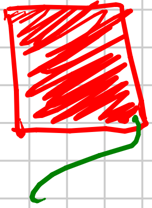
	P [psia]	F_v
	100	0.97...
	10	1.086
	50	0.986
p_{dL}	30	1.002

Lower DP

	P	F_v
	4000	0.9555
	4500	0.9599
	6000	0.9969
	6381	1.0167
p_{du}	6081	1.000

Upper DP

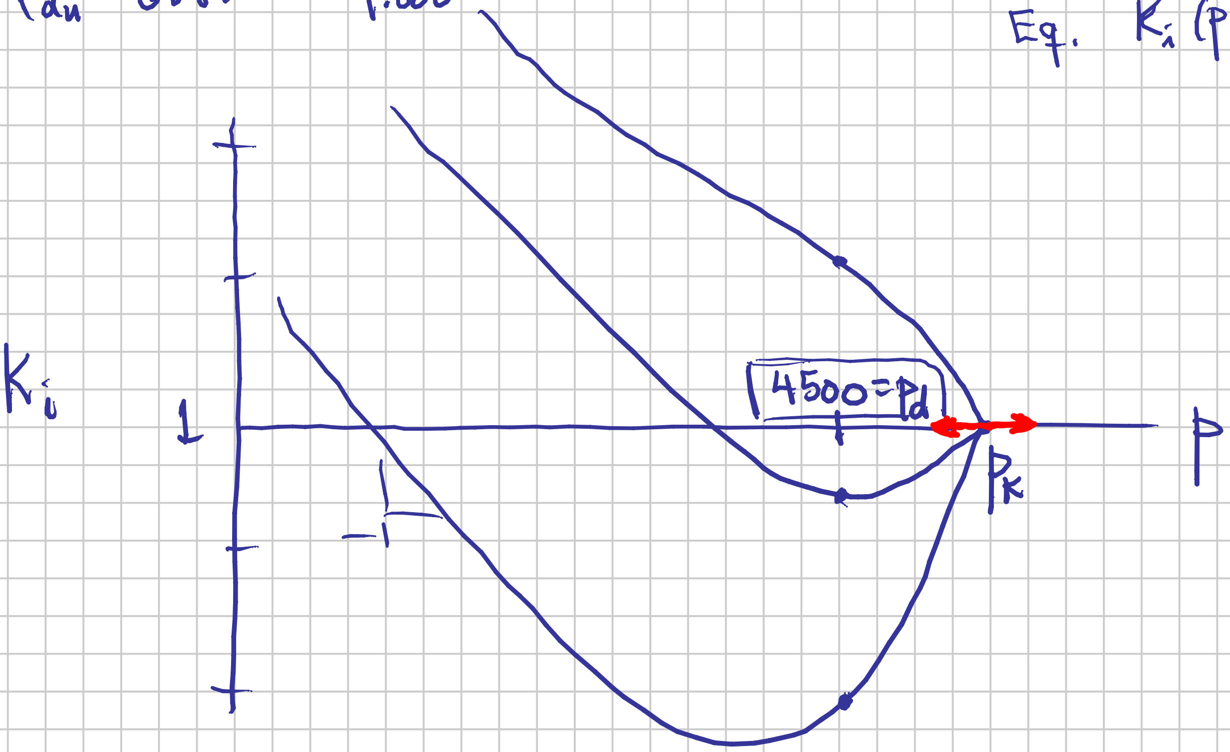
Dewpoints



Incipient Phase (0;1)

$F_v = 1-\epsilon$

Eq. $K_i(p, T, p_K)$



More efficient Solution to Saturation Pressure

Lower Dewpoint:

① $F_v = 1$

$$\frac{dF_v}{dp} < 0$$

$\sum z_i = 1 \Rightarrow \sum y_i = 1$

$(y_i = z_i)$

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

$x_i = z_i / K_i$

$$\boxed{\sum x_i = 1}$$

$$\sum \frac{z_i}{K_i} = 1$$

Eq. to solve

$$\boxed{h_{DP}} = 1 - \sum_i \frac{\overset{\checkmark}{z_i}}{K_i(\underset{\checkmark}{T}, \underset{\checkmark}{p_K}, \underset{\uparrow}{p_d})} = 0$$

Find

Dewpoint Calculation (LDP & UDP)

* * *

Bubblepoint: $F_v = 0$

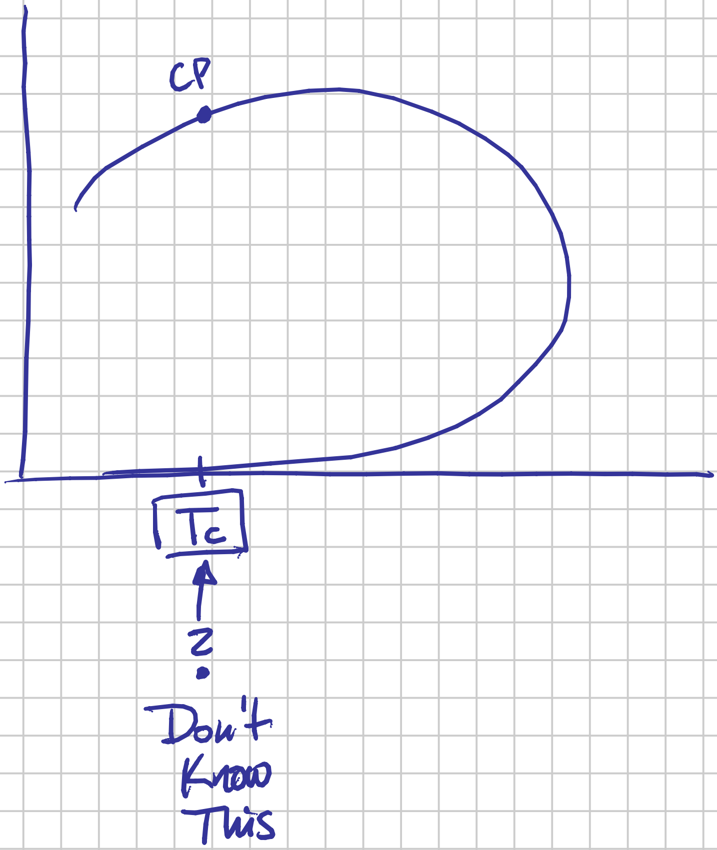
$x_i = z_i$

$y_i = K_i x_i = K_i z_i$

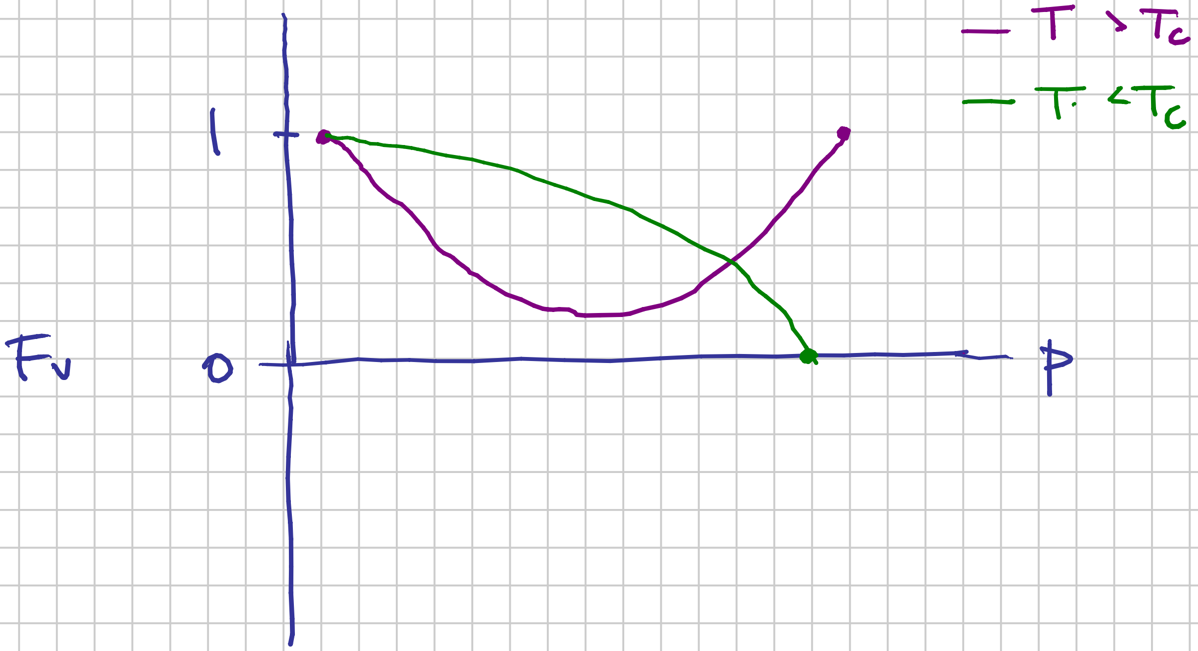
Eq. $\sum y_i = 1 = \sum K_i z_i$

$$h_{BP} = 1 - \sum y_i = 1 - \sum_i z_i K_i(T, p_K, \underset{\uparrow}{p_b}) = 0$$

Solve for



Upper Sat. Pressure, you don't know if BP or (U)DP?



RR Solution: Want either $F_v = 1$ $\quad F_v(p) = 1$

$F_v = 0 \quad F_v(p) = 0$

A solution $\quad g(p) = 0 = F_v(p) \times [1 - F_v(p)]$

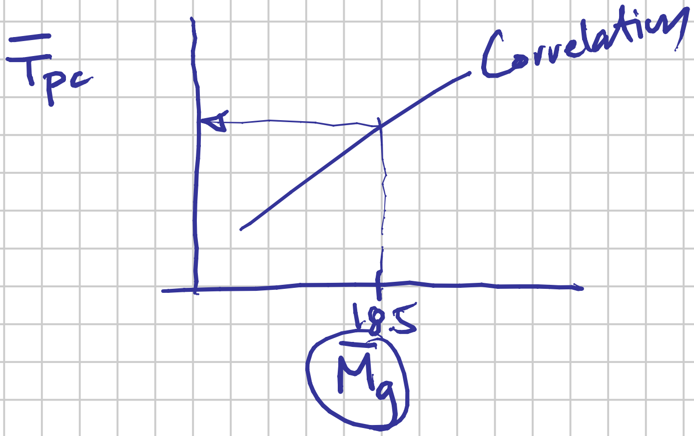
$$g = h_{DP} \cdot h_{BP} \overset{?}{=} 0$$

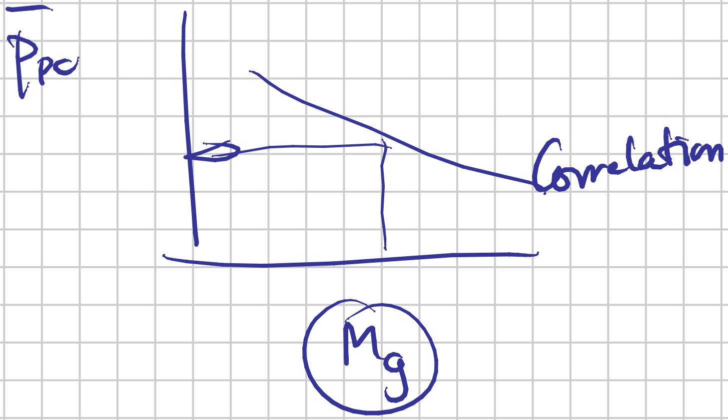
after solved for p_s

Ask, was it $h_{DP} = 0$ or $h_{BP} = 0$

⇒ Easy, simple, accurate to measure M_g ($\underline{\underline{\gamma_g = \frac{M_g}{M_{air}}}}$)

More diffcult, costly etc to get y_i





$$\bar{T}_{pc} = \sum y_i T_{ci}$$

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

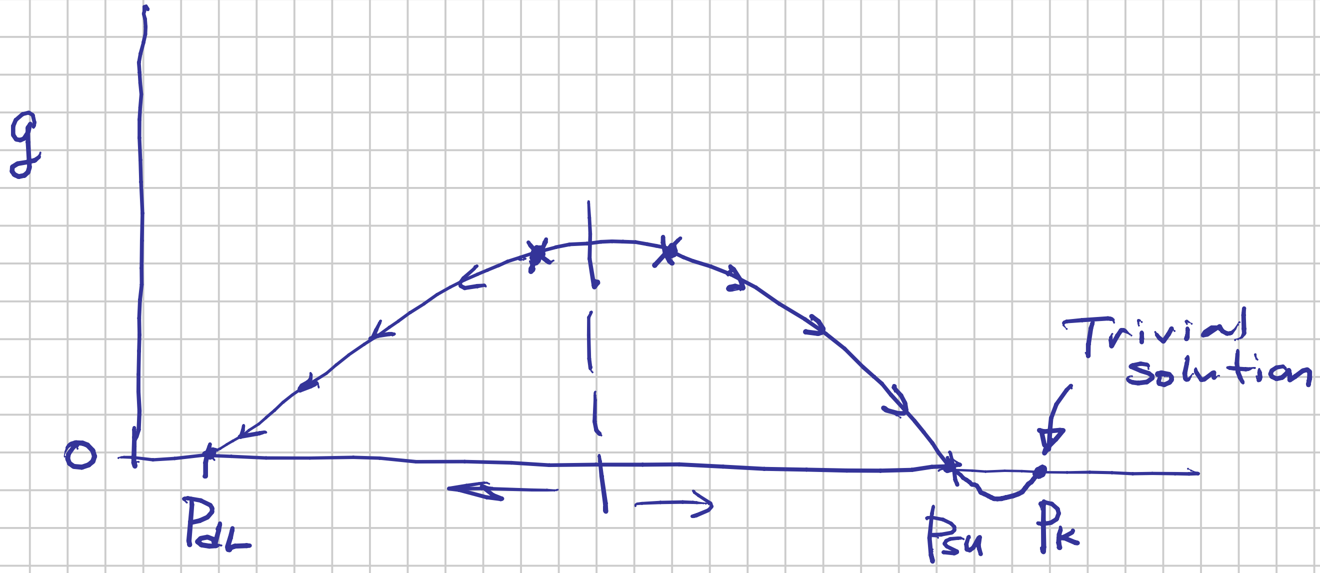
$$M_g = \sum y_i M_i$$

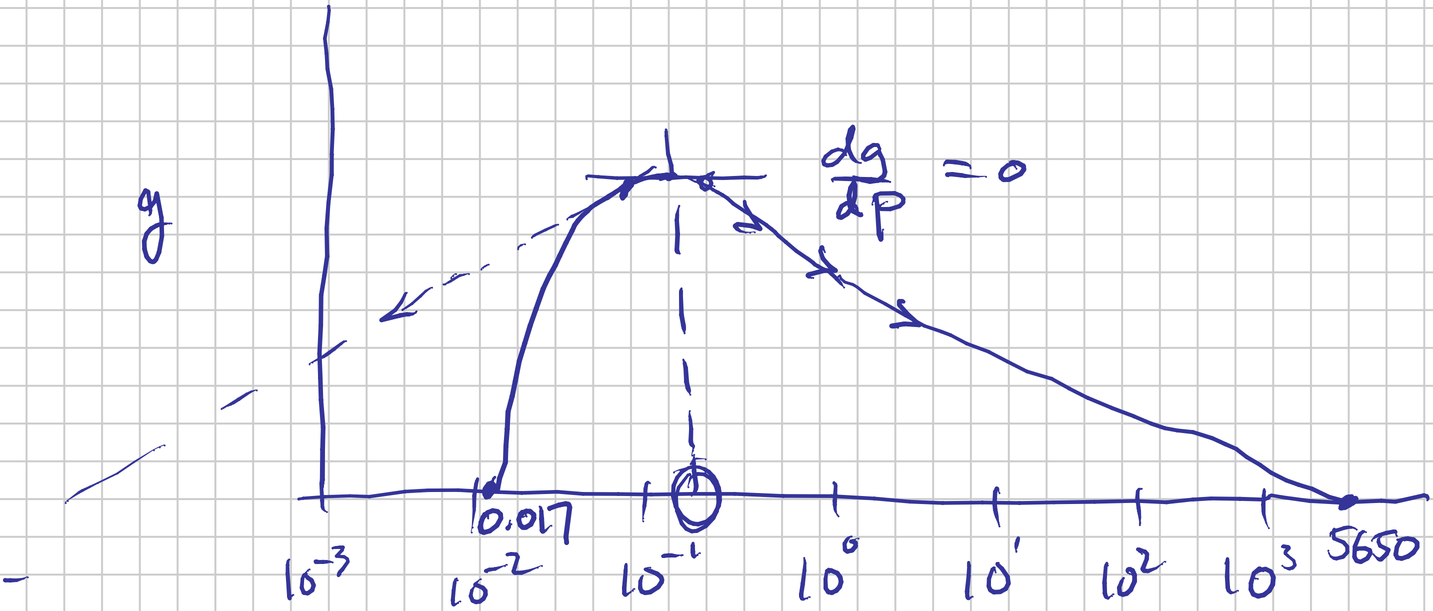
↑ Directly

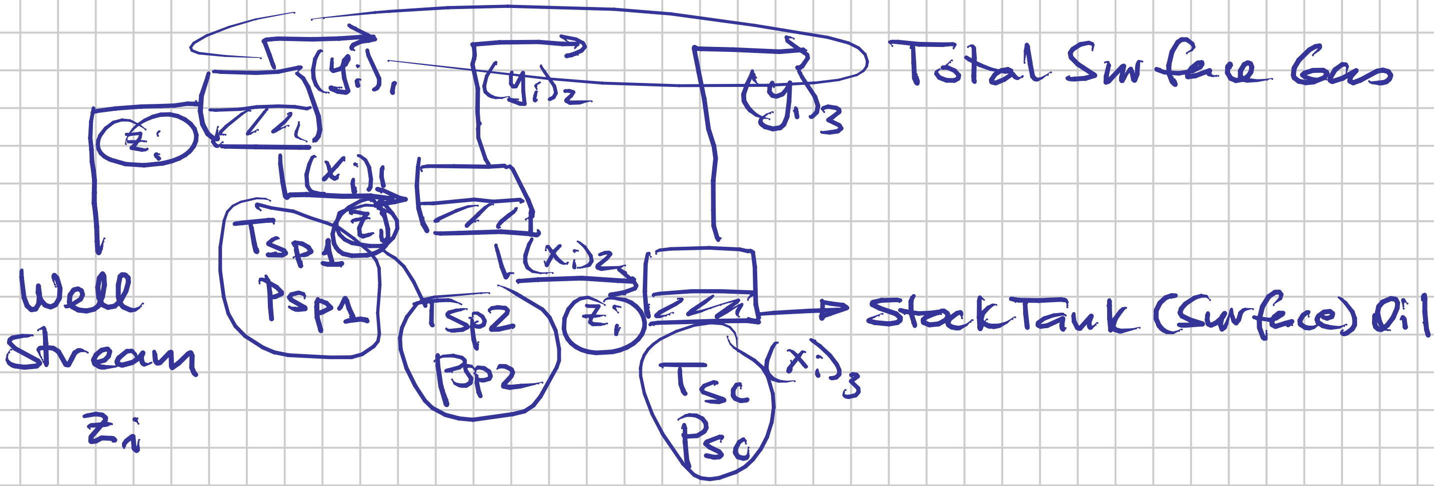
$$T_{ci} \overset{\propto}{\sim} M_i$$

$$P_{ci} \overset{\propto}{\sim} M_i$$

for i in gases


g
0
Trivial solution
P_dL
P_su
P_K

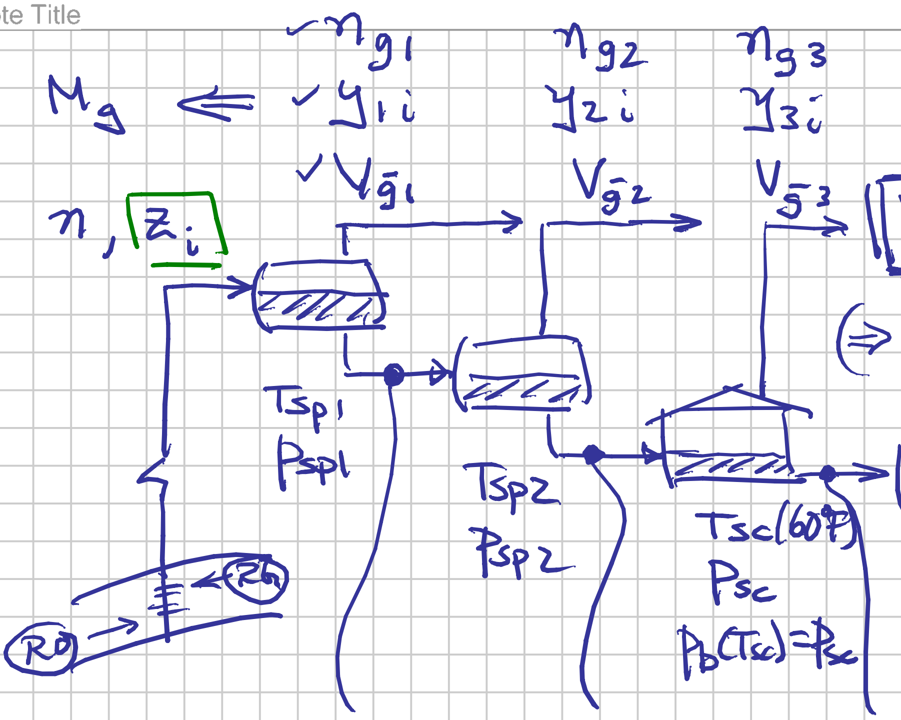

g
dg/dp = 0
0.017
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
5650


Total Surface Gas
$(y_i)_1$
$(y_i)_2$
$(y_i)_3$
z_i
$(x_i)_1$
z_i
T_{sp1}
P_{sp1}
T_{sp2}
P_{sp2}
$(x_i)_2$
z_i
Stock Tank (Surface) Oil
T_{sc}
P_{sc}
$(x_i)_3$
Well Stream
z_i

MULTISTAGE SEPARATOR PROCESS

$$\boxed{\bar{\gamma}_g = \frac{M_{\bar{g}}}{M_{air}} \ (\underline{air=1})}$$

Surface Gas



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

($\Rightarrow$ NGLs) Further processing of $V_{\bar{g}1}$

$\boxed{V_{\bar{o}}}$ Surface Oil

$n_{\bar{o}}$

n_{o1}	n_{o2}	$n_{o3} = \boxed{n_{\bar{o}}}$
x_{1i}	x_{2i}	$\boxed{x_{3i}}$
V_{o1}	V_{o2}	$V_{o3} = V_{\bar{o}}$
$(V_{\bar{o}1})$	$(V_{\bar{o}2})$	

$\boxed{\rho_{\bar{o}}} \Rightarrow$ API Gravity

Direct Measurement

$$\gamma_{\bar{o}} \equiv \frac{\rho_{\bar{o}}}{\rho_w}$$

Specific Gravity (water = 1)

Average Surface Gas $\bar{\gamma}_g$

$$\bar{\gamma}_g = \frac{\bar{M}_g}{M_{air}} = \frac{\bar{\rho}_g}{\rho_{air}}$$

$$\gamma_{API} \equiv \frac{141.5}{\gamma_{\bar{o}}} - 131.5$$

$$\bar{M}_g = \frac{m_{g1} + m_{g2} + m_{g3}}{n_{g1} + n_{g2} + n_{g3}}$$

$$= \frac{n_{g1}M_{g1} + n_{g2}M_{g2} + n_{g3}M_{g3}}{n_{g1} + n_{g2} + n_{g3}}$$

<u>N.S.</u> 30 → 45 °API "Oils"

45 → 75 °API "Gas Condensate"

Stage k:

$$M_{gk} = \sum_i \underset{\uparrow}{y_{ki}} M_i$$

$$n_g \rightarrow V_{\bar{g}}$$

$$V_{\bar{g}k} = n_{gk} \cdot \left(\underbrace{\frac{RT_{sc}}{p_{sc}}}_{} \right)$$

23.68 Sm^3/kg-mol

379 scf/lb-mol

$$\boxed{n_o \rightarrow V_{\bar{o}}}$$ (apparent surface oil volume)

Ideal Volume Mixing

$$V_{\bar{o}} = \sum_i V_{\bar{o}i} = n_o \sum_i (\overset{\downarrow}{x_i}\, \overset{\downarrow}{M_i}) / \overset{\downarrow}{\underset{\uparrow}{\rho_{\bar{o}i}}}$$

Surface (s.c.) liquid density of i
App. A & Ch. 5

ρ_{sc}

<u>Problem 17</u>

Gas-Oil Ratio (GOR) $= \dfrac{V_{\bar{g}}}{V_{\bar{o}}} = R$

Oil-Gas Ratio (OGR) $= \dfrac{V_{\bar{o}}}{V_{\bar{g}}} = r$

Simplifications of the Multi-Stage Process

① Surface Gas ~ C_{4-} (C_ℓ)
e.g.
Surface Oil ~ C_{5+} (C_h)

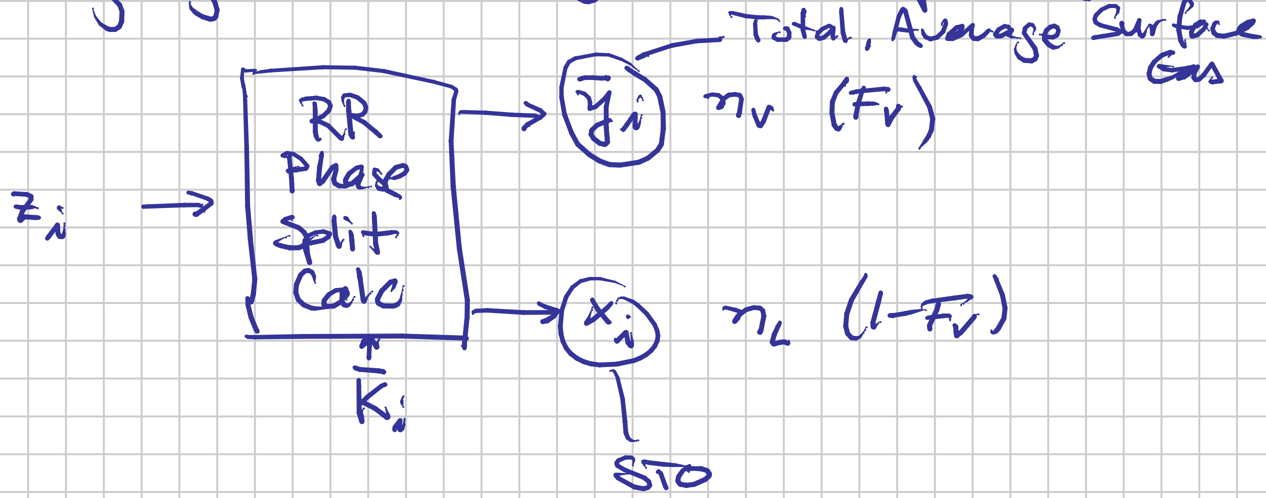
$$GOR = \frac{(1-z_{5+})}{z_{5+}} \cdot \frac{(RT_{sc}/P_{sc})}{(M_{5+}/\rho_{5+})}$$

~±10% actual

- Semi-quantitative (almost accurate)
- Consistent definition
  - "Better to be consistently wrong (a bit) than to be inconsistently right"

② Pseudo K-values $(\bar{K}_i)$

"Averaging the actual surface process"



$$\bar{K}_i = \frac{\bar{y}_i}{x_i}$$

$$\bar{y}_i = \frac{(n z_i) - (n_{\bar{o}} x_i)}{n - n_{\bar{o}}}$$

Let $n=1$ into the Process

$$\bar{y}_i = \frac{z_i - n_{\bar{o}} x_i}{1-n_{\bar{o}}}$$

$$\bar{K}_i = \frac{\bar{y}_i}{x_i} = \frac{z_i/x_i - n_{\bar{o}}}{1-n_{\bar{o}}}$$

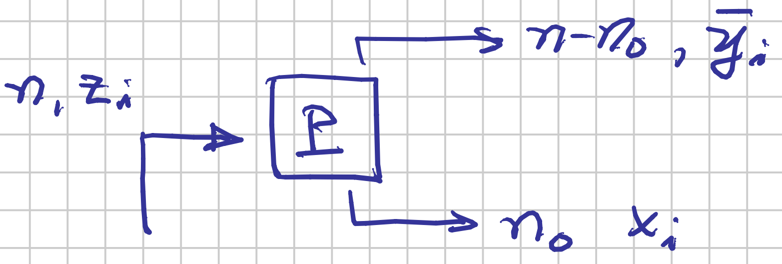
$$\uparrow$$

Actual Process for one z_i

$$z_i \downarrow x_i, n_{\bar{o}}$$

Use for a wide range of incoming process streams (z_i) — i.e. as the streams become "lighter" (higher GORs)

③ Liquid Recovery Factors $R_{\bar{o}i}$ (Surface Oil)

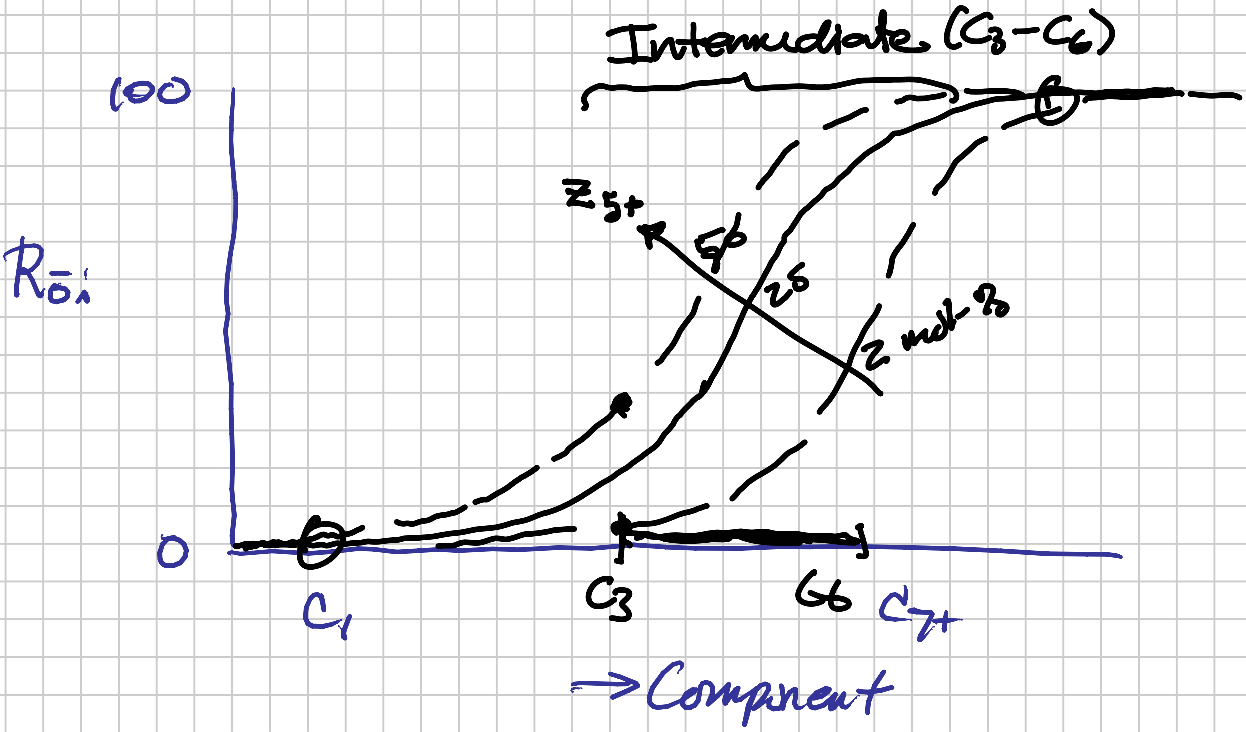


$$R_{oi} \equiv \frac{(n_o x_i)}{\underset{\substack{\uparrow \\ n=1}}{(n z_i)}} = n_o(x_i/z_i) \qquad 0 \to 1$$

"Gas Plant Tables"

R_{oi} (z_{5+})

	Given Project Produced z_{5+}		R_{oi}
2009	$\boxed{28}$	mol-% (z_i)	Full Process → R_{oi}
2015	20	(z_n)	—"—
	12		—"—
	8		—"—
	4		—"—



Ekofisk

$P_{sp1} = 1000$ psia   100 bara

$T_{sp1} = 150$ °F

$P_{sp2} = 265$ psig

$T_{sp2} = 80$ °F

$P_{sc} = 14.7$ psia

$T_{sc} = 60$ °F

Ekofisk-Like $C_1 - C_3 - C_{12}$

60 - 20 - 20

BLACK-OIL PVT

Note Title 10/28/2009

Ch. 7

Reality : $\{N_2 \ CO_2 \ H_2S\}$ $\{C_1 \ C_2 \ C_3 \cdots C_7 \cdots C_{40} \cdots \text{Monsters}\}$

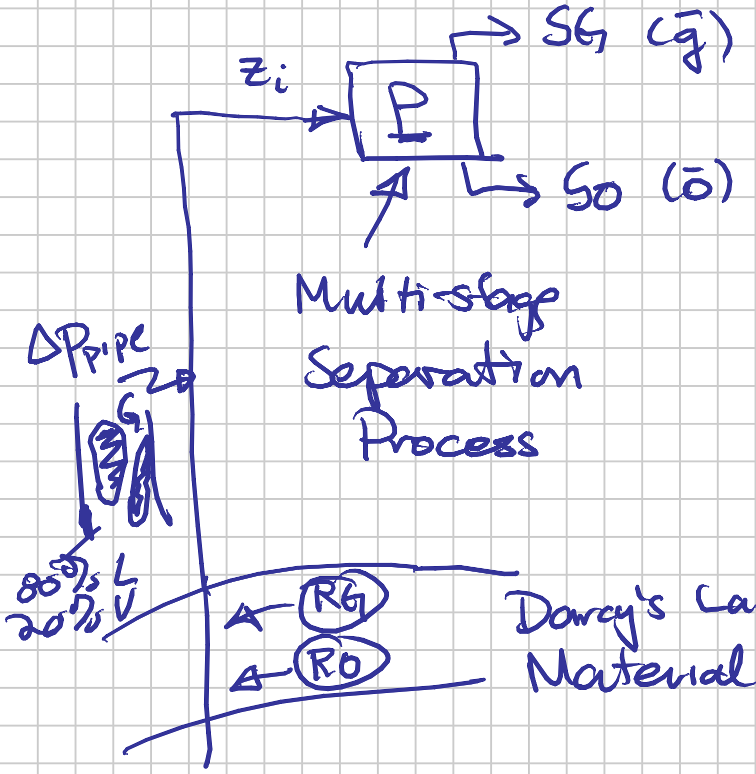
10 s 100s 1000s components

$\{z_i \quad K_i\}$

$K_i(p, T, z)$

BO PVT: Two "pseudo" components

- Surface Gas "light" component
- Surface Oil "heavy" component



Darcy's Law
Material Balance

$\left\{ \begin{array}{l} \text{Gas Phase} \\ \text{Oil Phase} \end{array} \right\}$

$\rho_g \ \rho_o$ $= f(p, T, z)$
$\mu_g \ \mu_o$
Amounts of the phases

$$K_i = \left(\frac{p_{ci}}{p_K}\right)^{A_1-1} \frac{\exp\left[5.37\, A_1\, (1 + \omega_i)\left(1 - T_{ri}^{-1}\right)\right]}{p_{ri}},$$

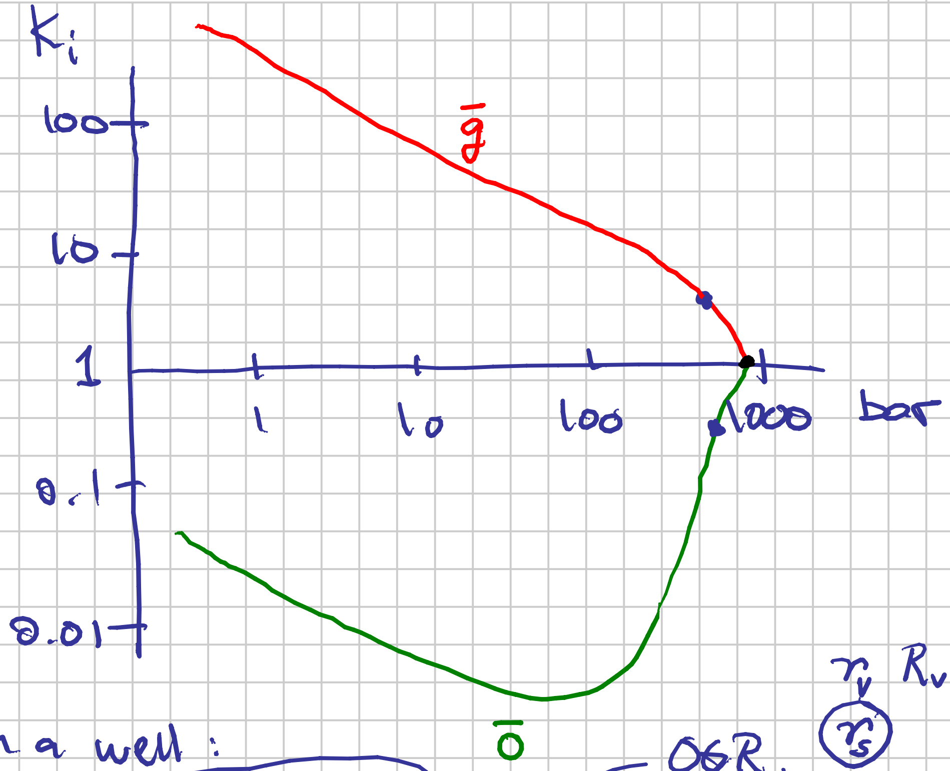
$i \in \{\bar{g}, \bar{o}\}$

$p_{c\bar{g}}$ $p_{c\bar{o}}$

$T_{c\bar{g}}$ $T_{c\bar{o}}$

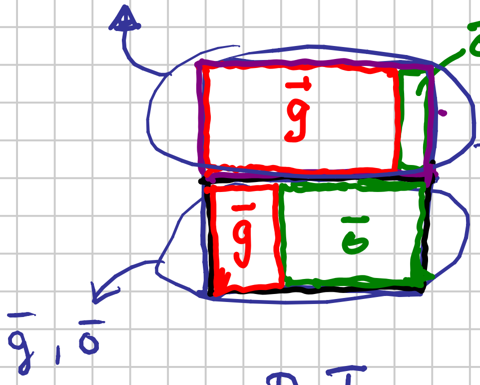
$\omega_{\bar{g}}$ $\omega_{\bar{o}}$

p_K



$\bar{g}, \bar{o}$ Mixture from a well:

$\boxed{GOR = 500\ Sm^3/Sm^3}$



gas phase (GOR)

oil phase (GOR)

"R_s"
Solution
Gas-Oil
Ratio

OGR
Solution
Oil-Gas
Ratio

r_v R_v $\boxed{r_s}$

$$K_{\bar{g}} = \frac{0.8}{0.2} = 4$$

$$K_{\bar{o}} = \frac{0.2}{0.8} = 0.25$$

p_R, T_R

Bo PVT Formulation:

We don't quantify composition z_i, y_i, x_i using mole fractions.

Instead we use component "surface" volume"

ratios.

z_{wi} = total molar composition e.g. of a wellstream

$$R_p = GOR = 500 \frac{Sm^3(\bar{g})}{Sm^3(\bar{o})} = \frac{V_{\bar{g}}}{V_{\bar{o}}}$$

Known: $$\frac{V_{\bar{g}}}{V_{\bar{o}}} = \frac{m_{\bar{g}}/\rho_{\bar{g}}}{m_{\bar{o}}/\rho_{\bar{o}}} = \frac{n_{\bar{g}} M_{\bar{g}}/\rho_{\bar{g}}}{n_{\bar{o}} M_{\bar{o}}/\rho_{\bar{o}}} = GOR$$

			Ekofisk
BO PVT :	$\rho_{\bar{o}}$ =	constant	850 kg/m^3
	$\rho_{\bar{g}}$ =	constant	0.85 kg/m^3
	$M_{\bar{o}}$ =	— " —	200 kg/kg-mol
	$M_{\bar{g}}$ =	— " —	23 kg/kg-mol

$$\frac{n_{\bar{g}}}{n_{\bar{o}}} = GOR \cdot \frac{M_{\bar{o}}}{M_{\bar{g}}} \frac{\rho_{\bar{g}}}{\rho_{\bar{o}}}$$

$$10 \cdot \frac{1}{1000}$$

$$\sim 0.01\, GOR$$

$$n_{\bar{g}} = 0.01(GOR)\, n_{\bar{o}}$$

$$z_{\bar{g}} = \frac{n_{\bar{g}}}{n_{\bar{g}} + n_{\bar{o}}} = \frac{0.01\, GOR\, \cancel{n_{\bar{o}}}}{0.01\, GOR\, \cancel{n_{\bar{o}}} + \cancel{n_{\bar{o}}}}$$

$$= \frac{0.01\, GOR}{0.01\, GOR + 1}$$

$$\boxed{Z_{\bar{g}} \cong \left(1 + 100\ OGR\right)^{-1}}$$

$$\left[\frac{1}{100}\left(\frac{1}{Z_{\bar{g}}} - 1\right)\right] \qquad 100/GOR$$

$$GOR = \left[\frac{(1/Z_{\bar{g}}) - 1}{100}\right]^{-1}$$

$$GOR = 500\ Sm^3/Sm^3$$

$$Z_{\bar{g}} = \frac{1}{1 + \frac{100}{500}} = \frac{1}{1.2} = 0.8$$

$$Z_{\bar{o}} = 1 - Z_{\bar{g}} = 0.2$$

$$GOR = 300\ Sm^3/Sm^3$$

orig. Ekofisk Oil

$$Z_{\bar{g}} = \frac{1}{1 + 0.33} = \frac{1}{1.33} = 0.67$$

Ormen Lange $10000\ Sm^3/Sm^3$

$$Z_{\bar{g}} = \frac{1}{1 + \frac{100}{10 \cdot 10^3}} \sim 0.99$$ ✓

1% of moles produced OL is "surface oil"

$$\left(\frac{70 \cdot 10^6\ Sm^3}{\frac{48 \cdot 10^3\ \cancel{STB}}{6.28\ \cancel{STB}/Sm^3}}\right) = \text{Ormen Lange Sales Product Ratio}$$

$$\frac{70 \cdot 10^6}{7 \cdot 10^6} = 10\,000\ Sm^3/Sm^3 \Rightarrow$$

$$\boxed{GOR \cong \left[\frac{(1/z_{\bar{g}})-1}{100}\right]^{-1}}$$

$RG: \; y_{\bar{g}} = 0.8$

$$\Rightarrow \sim GOR = \frac{1}{r_s} = \left[\frac{1.2-1}{100}\right]^{-1} = \left(\frac{0.2}{100}\right)^{-1}$$

$$= \underline{\underline{500 \; Sm^3/Sm^3}}$$

$RO: \; x_{\bar{g}} = 0.2$

$$GOR = \left[\frac{5-1}{100}\right]^{-1} = \left(\frac{1}{25}\right)^{-1} = 25 \, \frac{Sm^3}{Sm^3}$$

Summary: GORs (or OGR) used to define "composition" in the BO PVT formulation.

$R_p \sim z_{wi}$ total wellstream

$R_s \sim x_i$ oil phase

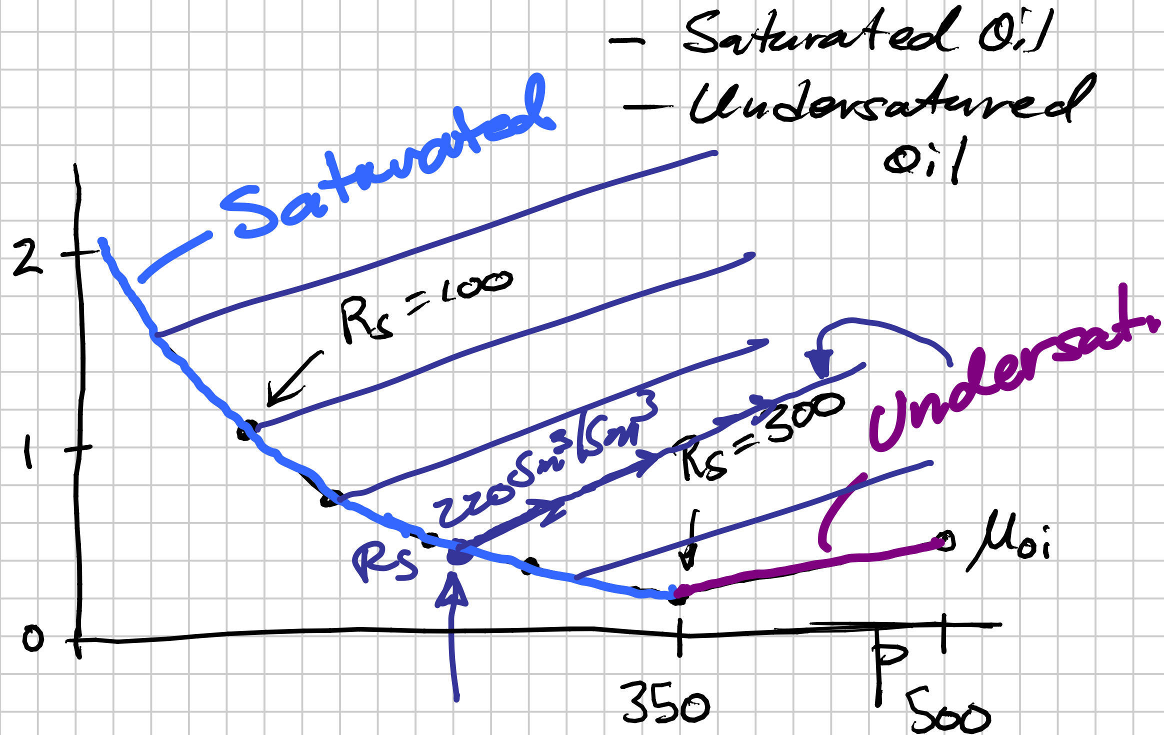
$r_s \sim y_i$ gas phase

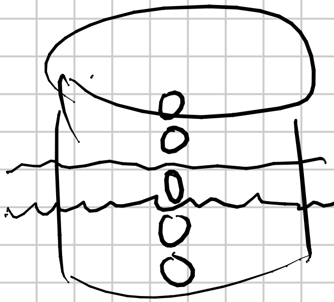
How do we get $\boxed{\rho's}$ $\mu's$?

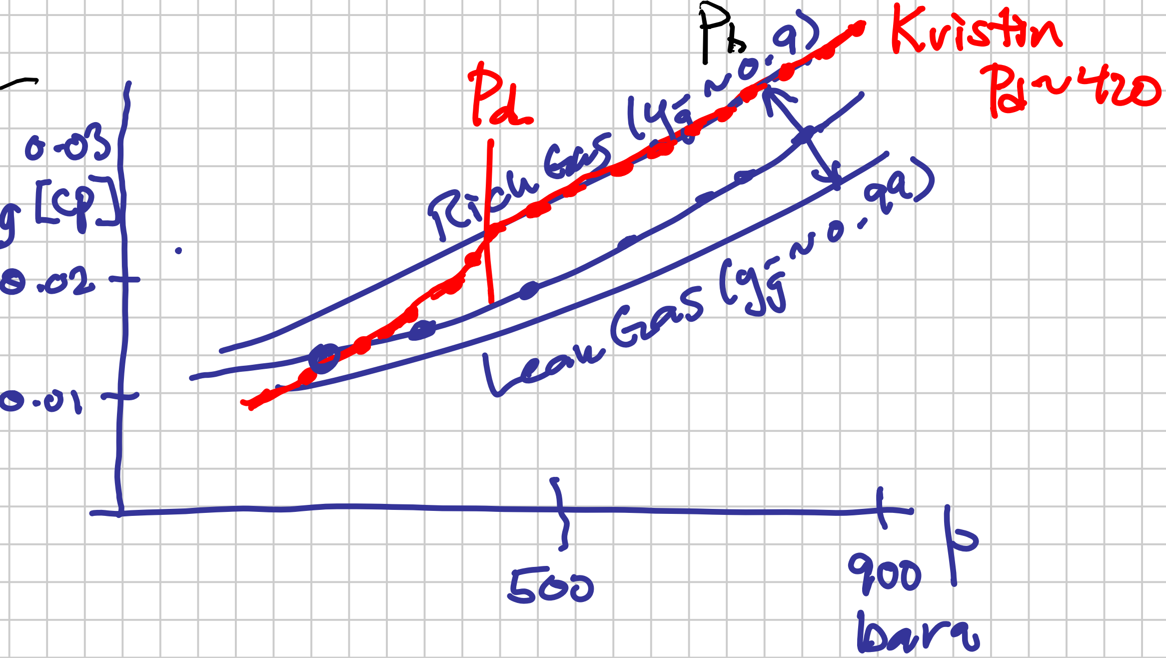
$\uparrow$

$\boxed{\underline{\underline{\text{Tables}}}}$ $f(p,T)$

- Gas μ_g $\sum^{s}_{u}$
- Oil μ_o


— Saturated Oil
— Undersatured Oil
Saturated
μ_o [cp]
2
1
0
$R_s = 100$
$220 Sm^3/Sm^3$
$R_s = 300$
R_s
Undersat.
μ_{oi}
P
350
500
P_b




Kristin
Pd ~ 420
Pd
Rich Gas (γ_g ~ 0.9)
Lean Gas (γ_g ~ 0.99)
0.03
μ_g [cp]
0.02
0.01
500
900
p
bara

685 moles of H_2S

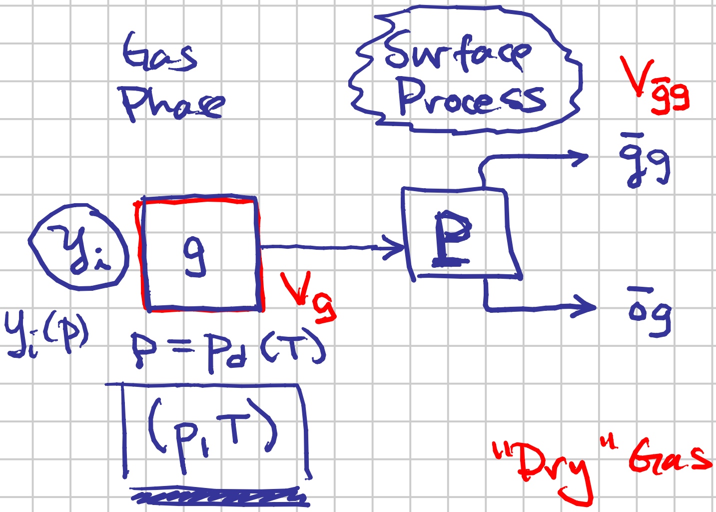
= 685 moles of H

+ 685 moles of H

+ 685 moles of S

Black-Oil PVT — Formation Volume Factors (FVF) "B"

Review: Solution Surface Volume Ratios to define the composition of a phase



$\Rightarrow y_i \, , \; i \in \{\bar g, \bar o\}$

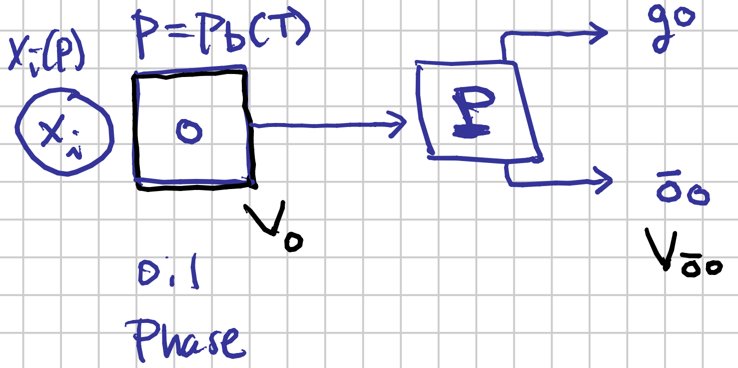
Solution Oil-Gas Ratio (of Gas Phase)

$$r_s = \frac{V_{\bar o g}}{V_{\bar g g}} = r_v = R_v$$

$$* \quad B_{gd} = \frac{V_g(p,T)}{V_{\bar g g}(p_{sc},T_{sc})}$$

Reservoir Simulation

"Dry" Gas FVF



Solution Gas-Oil Ratio (of an Oil Phase)

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

$\Rightarrow x_i \, , \; i \in \{\bar g, \bar o\}$

$$B_o = \frac{V_o(p,T)}{V_{\bar o o}(p_{sc},T_{sc})}$$

$$\text{e.g. } \{z_i, y_i, x_i\}_{i=\bar g} = \frac{GOR}{GOR + \left(\frac{M_{\bar g}}{\rho_{\bar g}}\right)\left(\frac{\rho_{\bar o}}{M_{\bar o}}\right)}$$

⇒ Gas phase is in equilibrium with the oil phase at (p,T)

$$\frac{M_{\bar o}}{M_{\bar g}} \underset{\uparrow}{\sim} 10 \qquad \frac{\rho_{\bar o}}{\rho_{\bar g}} \underset{\uparrow}{\sim} 10^3$$

$$x_{\bar g} = \frac{R_s(\underline{p})}{R_s(\underline{p}) + \boxed{\left\{\left(\frac{M_{\bar g}}{\rho_{\bar g}}\right)\left(\frac{\rho_{\bar o}}{M_{\bar o}}\right)\right\}}(\underline{p})}$$

$\uparrow$

Independent of $\underline{p}$

R_s dependent on $\underline{p}$

FVF (B) = volumetric ratio of a phase volume at (p,T) to the resulting surface volume of "same-phase" product after surface processing

B_g = volume ratio of gas phase at (p,T) to the surface gas (component) volume after processing

B_o = volume ratio of oil phase at (p,T) to the surface oil (component) volume after processing.

$b \equiv \frac{1}{B}$: b is more linear w.r.t. p than B (especially for gas)

b_o : "oil shrinkage" factor

b_g : "gas expansion" factor

* Gas FVF:

$$\underline{\text{Traditional}}\ B_g = \frac{p_{sc}}{T_{sc}} \cdot \frac{\overset{\text{absolute units}}{T}\, Z_g}{p} = B_{gw} = \frac{V_g}{V_{gw}}$$

Assumption is that <u>all</u> of the gas phase becomes surface gas product.

i.e. $V_{\bar{o}g} = 0 \Rightarrow r_s = 0$

Gas Material Balance (MBAL) – ?

Sometimes this B_g is still used even when $r_s > 0$, but production surface products $\bar{g}g$ and $\bar{o}g$ are "combined" into a *fictitious* "surface gas equivalent".

"wet gas"

$23.68\ \mathrm{Sm^3/kg\text{-}mol}$

$$V_{\bar{g}w} = V_{\bar{g}g} + \underbrace{V_{\bar{o}g}\cdot\left(\frac{\rho_{\bar{o}}}{M_{\bar{o}}}\right)}_{n_{\bar{o}g}}\cdot\frac{R\,T_{sc}}{p_{sc}}$$

$$B_{gw} = \frac{V_g}{V_{\bar{g}w}} = \underbrace{\frac{p_{sc}}{T_{sc}}\cdot\frac{TZ}{p}}$$

$$B_{gd} = \frac{V_g}{V_{\bar{g}g}} = B_{gw}\cdot\frac{1}{y_{\bar{g}}}$$

Note: $\dfrac{V_{\bar{g}g}}{V_{\bar{g}w}} = y_{\bar{g}} = f(r_s, p)$

$$\underbrace{\boxed{G_p} = \int_0^t q_{\bar{g}g} \qquad \boxed{N_p} = \int_0^t q_{\bar{o}g} \Rightarrow G_{pw}\,? \qquad \boxed{p_R}}_{\text{Est. } \underline{\underline{G}}\ \text{(IGIP)},\ N}$$

± 5-10%

$\underline{p}$ $\underline{B_{gw}}$? $\underline{B_{gd}}$?

Forecast equilibrium phase composition changes with pressure $y_i(p)$ and $x_i(p)$ @ T_R to forecast BO PVT pressure dependency.

$$\begin{tikzcd}
 & y_i(p) \arrow[r] & \boxed{P} \arrow[r, Rightarrow] & r_s(p) \\
 & & & B_{gd}(p) \\
\begin{Bmatrix} z_i^0 \\ K_i(p) \end{Bmatrix} \arrow[uur] \arrow[dr] & & & R_s(p) \\
 & x_i(p) \arrow[r] & \boxed{P} \arrow[r, Rightarrow] & B_o(p)
\end{tikzcd}$$

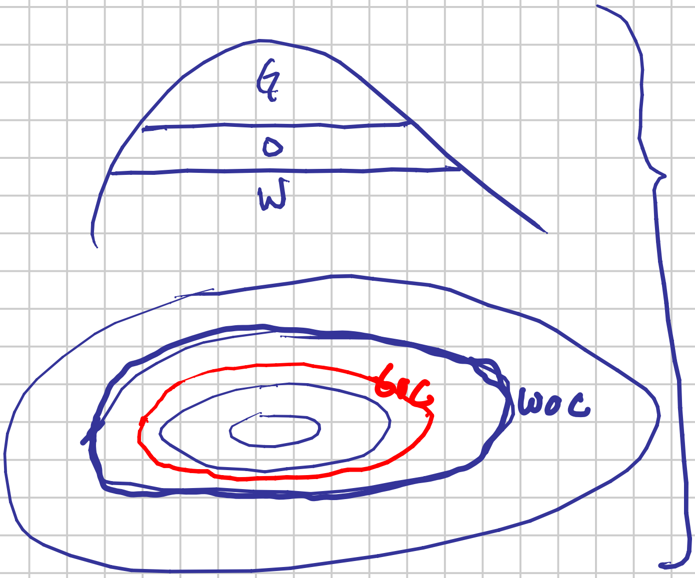
Wed. discuss how $(z_i)_R$ changes with p, and revisit $K_i(p) \Rightarrow y_i(p)$ $x_i(p)$

Application of BO PVT:

① Calculating Initial (Surface Product) Oil & Gas In Place

G – IGIP (OGIP,

N – IOIP (OOIP, STOIP



$$\Rightarrow \quad \begin{array}{lcc} V_{bg}\cdot\bar{\phi}_g\cdot\bar{S}_g & & \\ HCPV_g \rightarrow & G_g & N_g \\ & + & + \\ HCPV_o \rightarrow & \underline{\underline{G_o}} & \underline{\underline{N_o}} \\ & G & N \\ V_{bo}\,\bar{\phi}_o\,\bar{S}_o & & \end{array}$$

$$N_g = \frac{HCPV_g}{(B_{oi})_{Geologist}}$$

$$\boxed{G_g = \frac{HCPV_g}{B_{gdi}}}$$

@ P_{Ri}, T_R

$$N_g = G_g\cdot r_{si} = \frac{HCPV_g}{(B_{gdi}/r_{si})}$$

@ prod. start

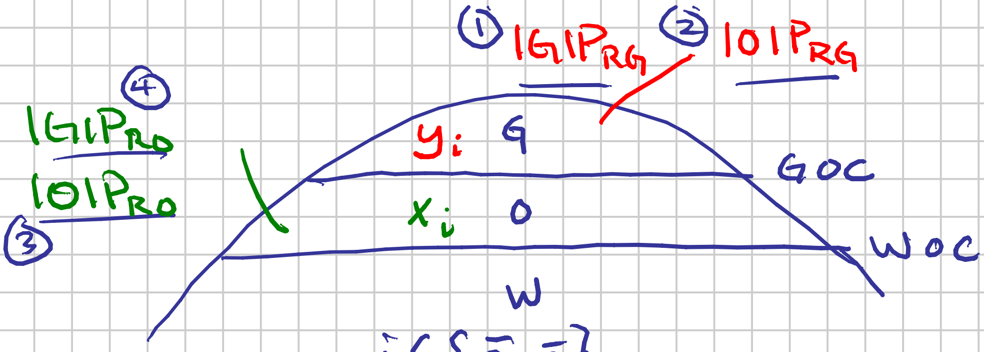
$$\boxed{G_o = N_o\cdot R_{si}} \qquad \boxed{N_o = \frac{HCPV_o}{B_{oi}}}$$

$$(B_{o's})_{geologist} = \frac{B_{gdi}}{r_{si}}$$

$$> 3 \rightarrow 30 \ \frac{m^3}{Sm^3}$$

Example Application of Bo PVT –

Calculating IOIP, IGIP



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

New Discovery

Geologist
Gas Reservoir
"Oil FVF"
"B_{oGeo}" = B_{gd}/r_s.

✓ $HCPV_{RG} = 10^9\ m^3$

✓ $HCPV_{RO} = 10^9\ m^3$

} Gelogical Estimates

GAS CAP: $B_{gd} = \dfrac{V_g}{V_{\bar{g}g}}$ $\quad r_s = \dfrac{V_{\bar{o}g}}{V_{\bar{g}g}}$

$\sim 0.004\ \dfrac{m^3}{Sm^3}$ $\quad$ 100 STB/MMscf

OIL ZONE: $B_o = \dfrac{V_o}{V_{\bar{o}o}}$ $\quad R_s = \dfrac{V_{\bar{g}o}}{V_{\bar{o}o}}$

$$\underbrace{1.7\ m^3/Sm^3 \qquad 300\ Sm^3/Sm^3}_{\text{Dependent on Surface Process}}$$

- GOR_{RG+RO}
- z_i
  mol-% $\bar{o}(C_{7+}) > 15 \Rightarrow P_b$
  $< 15 \Rightarrow P_d$
- p-T
  - RG
  - RO
  - (RG+RO)

$T_{sp1} = 150\ °F$ $\quad P_{sp1} = 1000$ psia

$T_{sp2} = 80\ °F$ $\quad P_{sp2} = 265$ psia

$T_{sp3} = T_{sc} = 60°F$ $\quad P_{sp3} = P_{sc} = 14.7$ psia

$$r_s = 100 \, \frac{STB}{10^6 \, scf} \cdot \frac{35.31 \, scf}{Sm^3} \cdot \frac{Sm^3}{6.28 \, STB}$$

$$= 560 \; Sm^3 / 10^6 \, Sm^3$$

① $\boxed{IGIP_{RG}}$

P_{Ri}, T_R @ "B_{gdi}" $= \frac{V_g}{V_{\bar{g}g}} = \frac{HCPV_{RG}}{IGIP_{RG}} \Rightarrow IGIP_{RG} = \underline{\underline{\qquad Sm^3}}$

—"— $\quad r_{si} = \frac{V_{\bar{o}g}}{V_{\bar{g}g}} = \frac{IOIP_{RG}}{IGIP_{RG}} \Rightarrow IOIP_{RG} = \underline{\underline{\qquad Sm^3}}$

③ $\boxed{IOIP_{RO}}$

$B_{gd} = \frac{V_g}{V_{\bar{g}g}}$ $\quad r_s = \frac{V_{\bar{o}g}}{V_{\bar{g}g}}$

$\sim 0.004 \, \frac{m^3}{Sm^3}$ $\quad 100$ STB/MMscf

$B_o = \frac{V_o}{V_{\bar{o}o}}$ $\quad R_s = \frac{V_{\bar{g}o}}{V_{\bar{o}o}}$

$1.7 \; m^3/Sm^3$ $\quad 300 \; Sm^3/Sm^3$

$$IGIP_{RG} = \frac{\overset{HCPV_{RG}}{10^9 \, \cancel{m^3}}}{\underset{B_{gdi}}{0.004} \, \frac{\cancel{m^3}}{Sm^3}} = 250 \cdot 10^9 = \underline{\underline{2.5 \cdot 10^{11} \; Sm^3}}$$

$\downarrow$

$8.8 \cdot 10^9$ Mscf

(7 Tcf)

$\times 4$ USD/Mscf ~ 36 bUSD

$$IOIP_{RG} = IGIP_{RG} \cdot r_{si}$$

$$= 2.5 \cdot 10^{11} \, Sm^3 \times 560 \cdot 10^{-6} \, \frac{Sm^3}{Sm^3}$$

$$= \underline{\underline{1.40 \cdot 10^8 \; Sm^3}} = 0.879 \cdot 10^9 \; STB$$

$\times 70$ USD/STB ~ 60 bUSD

$IOIP_{RO}$

$IGIP_{RO}$

$\downarrow$

$IGIP$

$IOIP$

$1.2 \cdot 10^9$ NOK

$\underline{0.2 \cdot 10^9 \text{ USD}}$

$70 \cdot$ USD/STB

$\underline{2.85 \cdot 10^6 \text{ STB}}$

6.28 STB/Sm^3

$= 4.54 \cdot 10^5$

$= 0.0045 \; 10^8$ Sm^3

$$\underline{IOIP_{RO}} = \frac{(HCPV_{RO})}{B_{oi}} = \frac{10^9}{1.7} = 0.588 \cdot 10^9 \text{ Sm}^3$$

$$= 3.69 \cdot 10^9 \text{ STB}$$

$$IGIP_{\underline{RO}} = IOIP_{RO} \cdot R_{si} = \frac{10^9}{1.7} \cdot 300 = 1.765 \cdot 10^{11} \text{ Sm}^3$$

$$= 1.765 \cdot 10^{11} (35.31) \cdot 10^{-12}$$

$$= 6.23 \quad \text{Tcf}$$

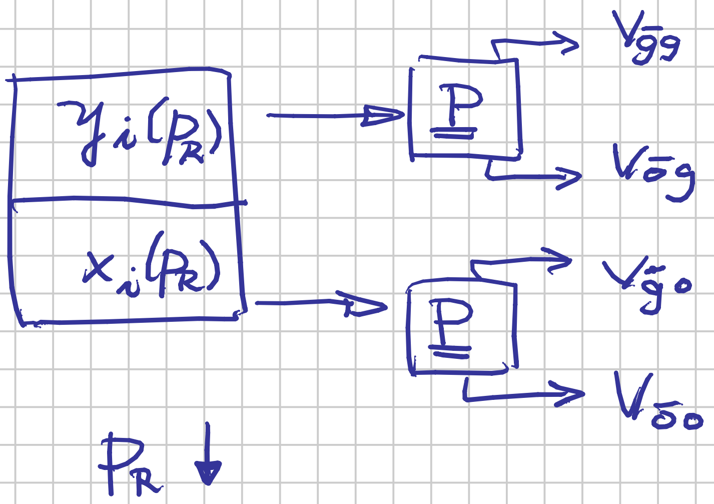
$$= 6.23 \cdot 10^9 \quad \text{Mscf}$$

How the four BO PVT properties vary with pressure?

$$B_{gd} = B_{gw} / y_{\bar{g}}$$

$$B_{gw_i} = \frac{p_{sc}}{T_{sc}} \cdot \frac{Z_{Ri} \, T_R}{p_{Ri}}$$

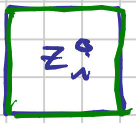
$$y_{\bar{g}} = \left[1 + \underbrace{\left(\frac{\rho_{\bar{o}}}{\rho_{\bar{g}}}\right)\left(\frac{M_{\bar{g}}}{M_{\bar{o}}}\right)}_{\sim 100} r_{si} \right]^{-1}$$



<u>One way</u> to estimate $y_i(p)$ and $x_i(p)$ is to do a {simple constant composition} series of flash calculation.

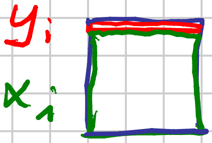
$$RR \begin{cases} z_i^{\circ} = \text{Initial Reservoir Composition} \\ K_i(p, T_R) = \text{modified Wilson eq.} \end{cases}$$

$$\Rightarrow \underline{\underline{y_i}}(p_R, T_R) \ \& \ \underline{\underline{x_i}}(p_R, T_R)$$



$\rightarrow \lambda_o = \frac{k_{ro}}{\mu_o} = 1$

P_{Ri}

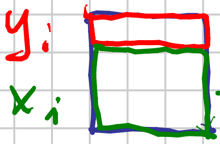


$\rightarrow \lambda_g = 0$

$\rightarrow \lambda_o = 0.9$

$P_R < P_{sat}$

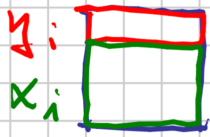
$\bar{z}_{iR}$ becoming "lighter" $\{C_1 \cdots C_4\}\uparrow$ $\{C_{5+}\}\downarrow$



$\rightarrow \lambda_g = 0.1$

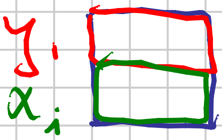
$\rightarrow \lambda_o = 0.5$

$\bar{z}_{iR}$ becoming "heavier" $\{C_1 \cdots C_4\}\downarrow$ $\{C_{5+}\}\uparrow$



$\rightarrow \lambda_g = 0.2$

$\rightarrow \lambda_o = 0.2$



$\rightarrow \lambda_g = 1$

$\rightarrow \lambda_o = 0.05$

$\boxed{z_{iR}\,(P_R)}$ dominated by $k_r(S)$ ↕

$$\text{RR Calc. } \underbrace{z_{Ri}(P_R)\; K_i(p_{R'}, \overset{\text{"}P_K\text{"}}{\downarrow} z)}$$

$$\updownarrow \underbrace{z_{Ri}(P_R),\; K_i(P_R)}$$

$$\Downarrow \quad \text{"}F_g\text{"}(P_R, z_R)$$

You can show (though no-one really has) that $y_i(p)$ and $x_i(p)$ do NOT depend much on $(\lambda_g/\lambda_o)(P_R) \rightarrow GOR(P_R)$.

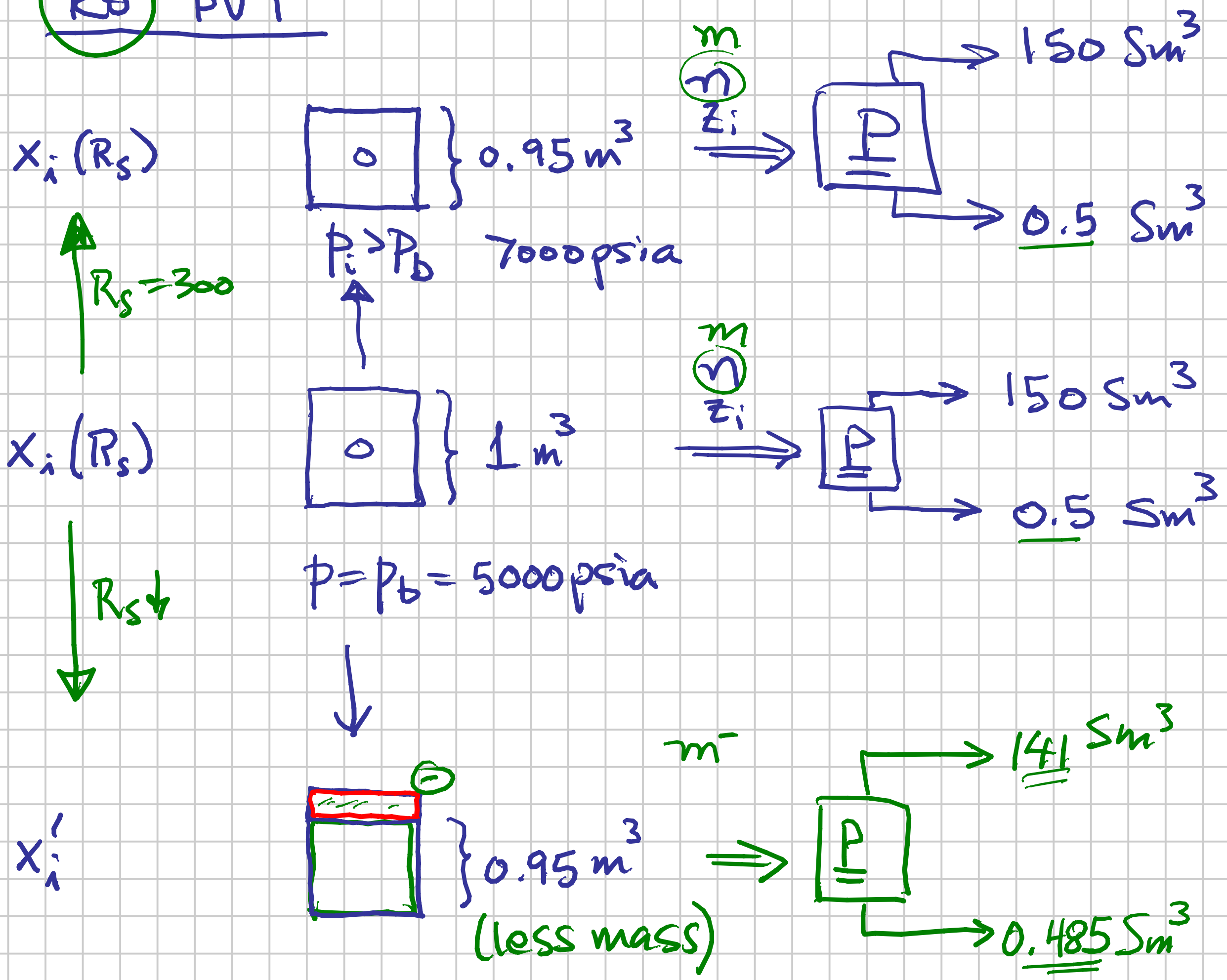
↓ Any depletion process

True

⋮

How do the BO PVT properties vary with p?

Ro PVT



$R_s = 300 \frac{Sm^3}{Sm^3}$

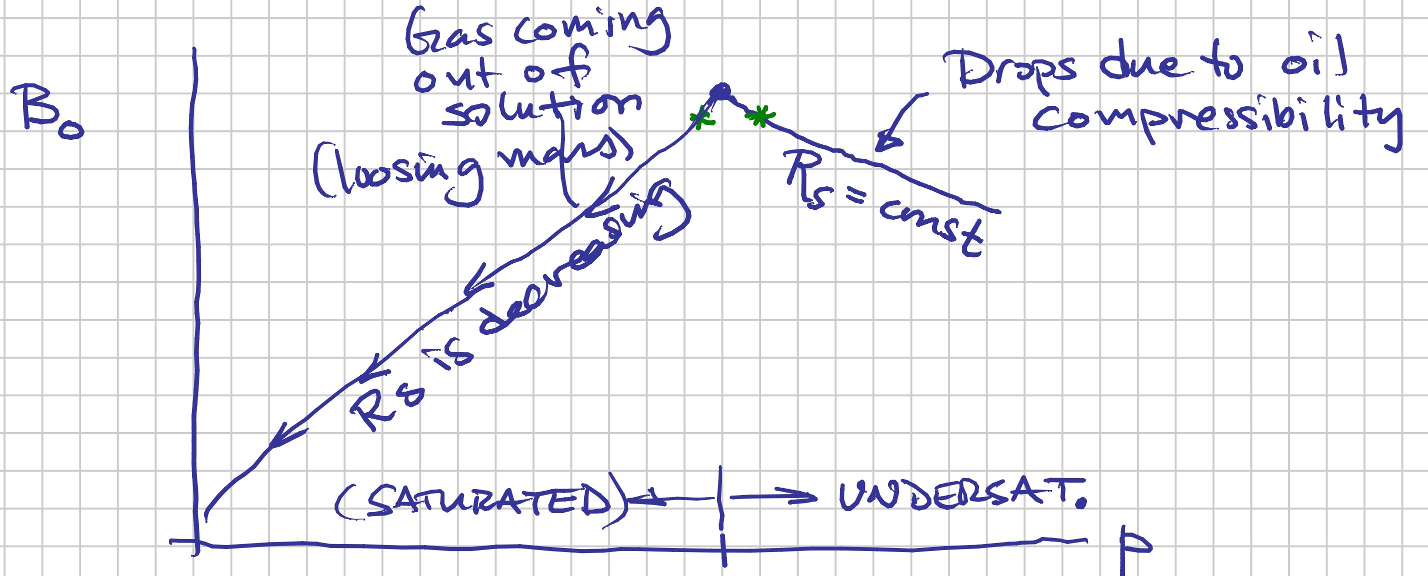
$B_o = \frac{0.95}{0.5} = 1.9 \frac{m^3}{Sm^3}$

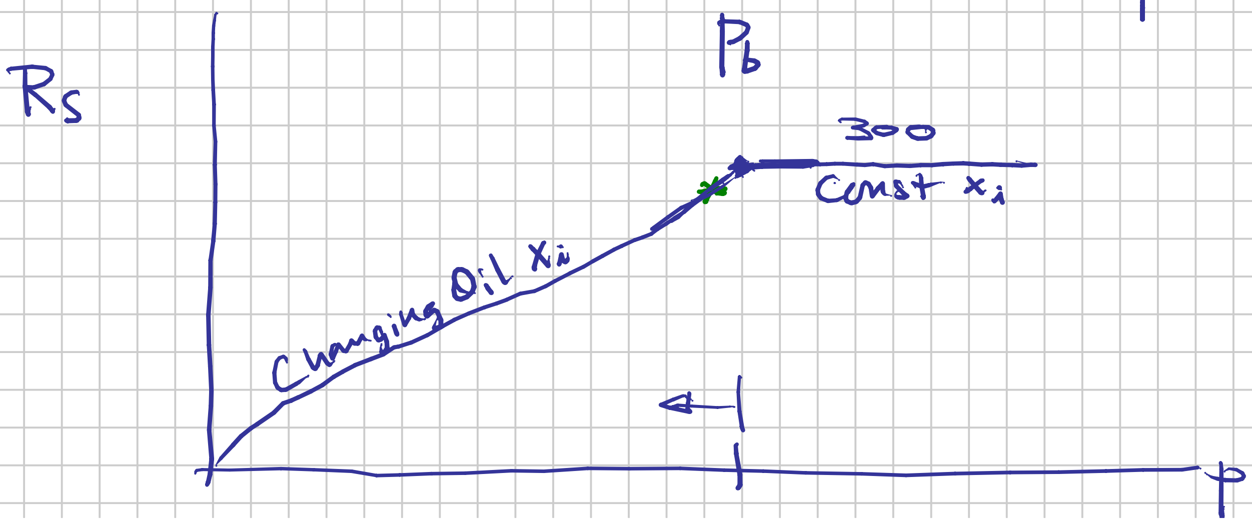
$R_s = 300 \frac{Sm^3}{Sm^3}$

$B_{ob} = 2 \frac{m^3}{Sm^3}$

$R_s = 290 \frac{Sm^3}{Sm^3}$

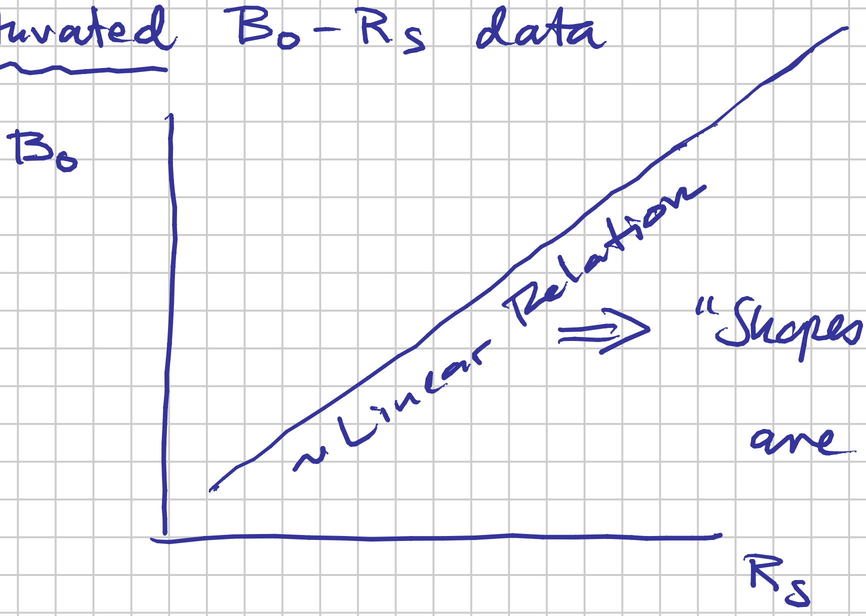
$B_o = \frac{0.95}{0.485} = 1.96$





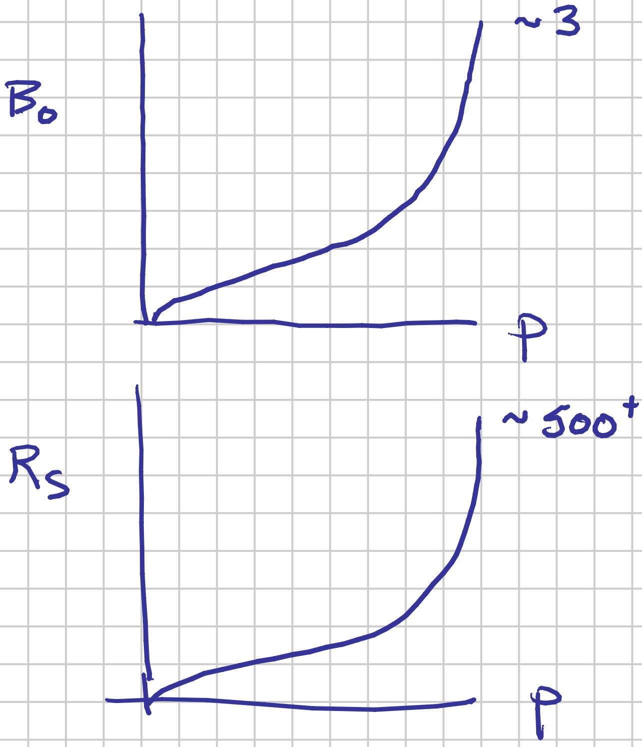
p_b

Saturated B_o-R_s data

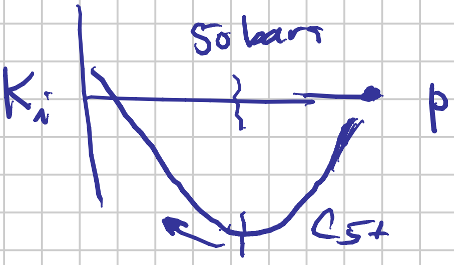


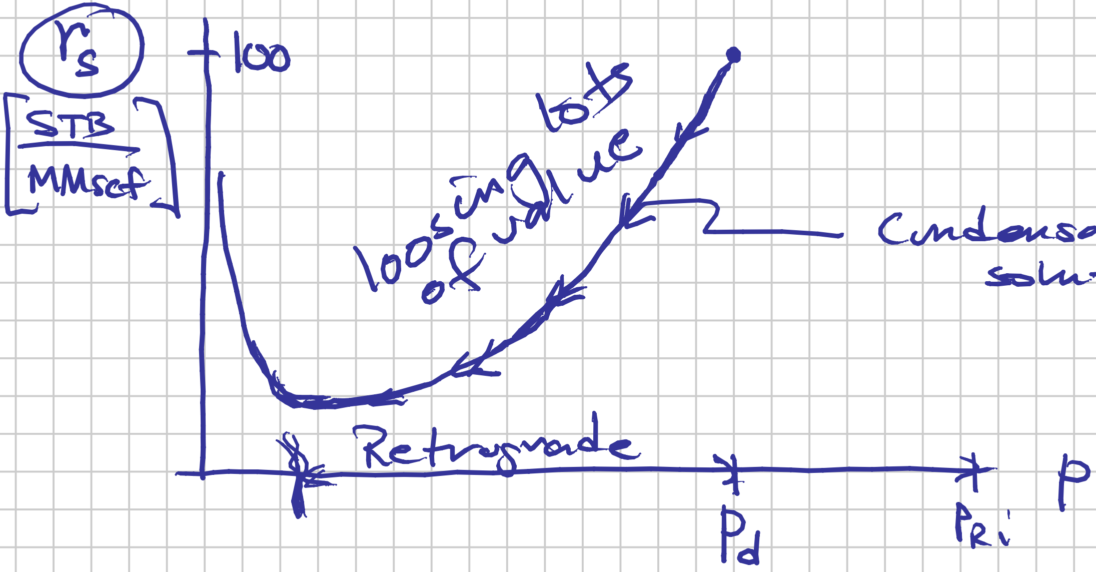
⇒ "Shapes" of $B_o(p)$ and $R_s(p)$ are the same

Smørbukk South:

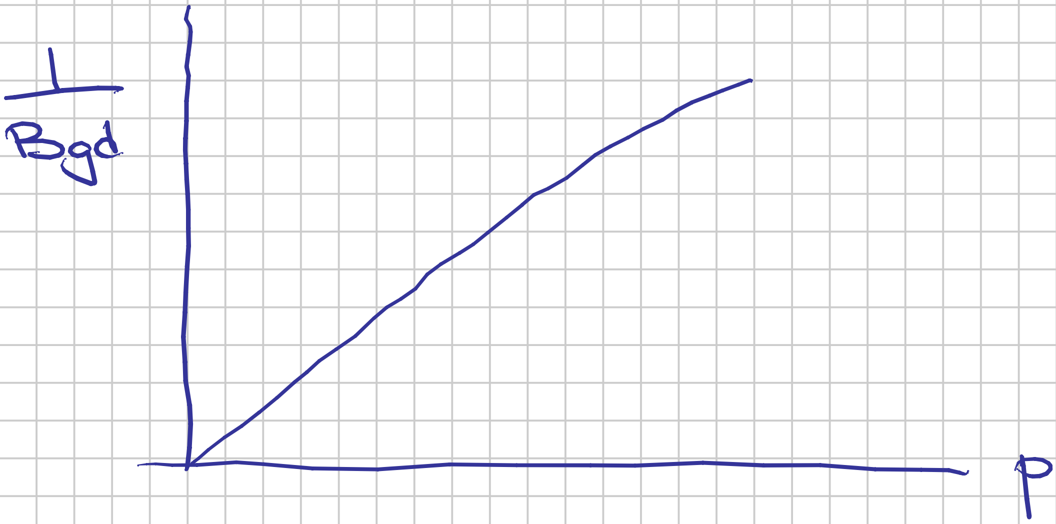


RG BO PVT





Condensate held in solution in the gas



Note Title 11/16/2009

① Study and follow the solution of Prob. 13.

② Study App. D – Oil PVT Lab tests.

Last "lecture" Nov. 25 Problem solution
to Prob. 13 + App. D data

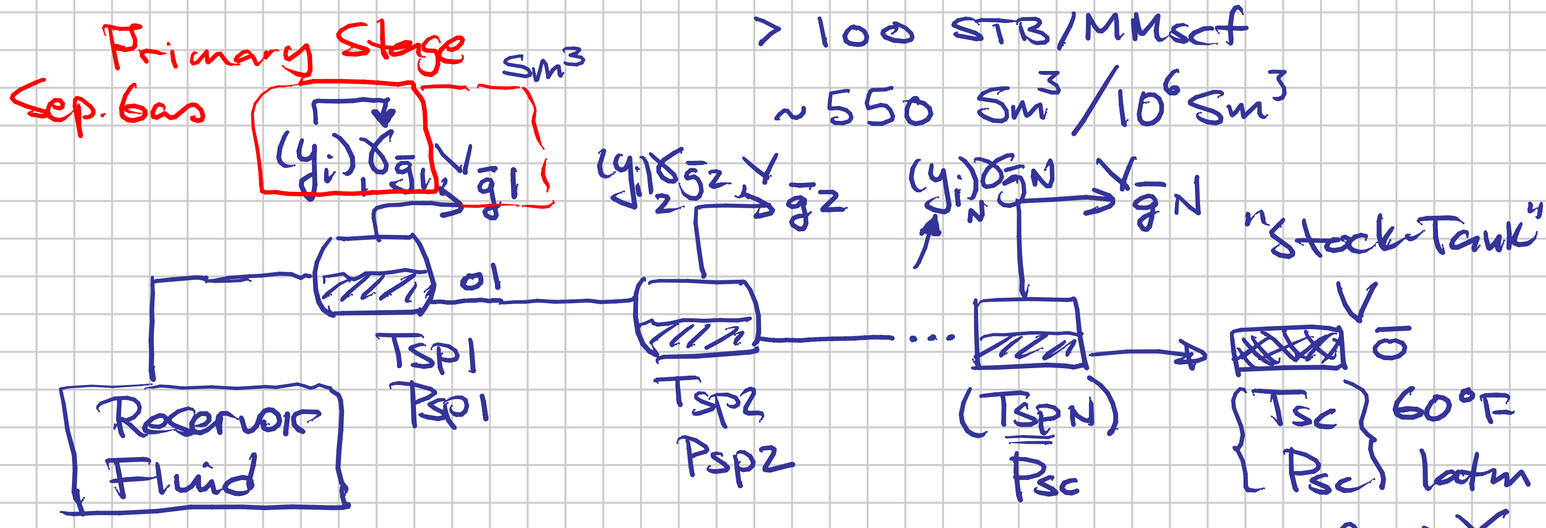
Remaining : Ch. 6 – PVT Lab Tests

① Muti-Stage Separator Test $\boxed{\underline{P}}$

- Oils
- 'Richer' Gas Condensates
  - CGR (OGR) – Initial Solution OGR r_{si}

> 100 STB/MMscf

$\sim 550\ Sm^3/10^6 Sm^3$



$\Rightarrow V_R$ @ Psat, Vsat (Vob, Vgd)

$\rho_{\bar{o}} \rightarrow \gamma_o$

$$\gamma_{\bar{g}} = \frac{M_g}{M_{air}} = \frac{\sum y_i M_i}{M_{air}}$$

$$\frac{141.5}{\gamma_o} - 131.5 = \boxed{\gamma_{API}}$$

<u>SPE</u> $T_{sc} = 60°F$

i = non-HC, $C_1 - C_5$, $\{C_6\ C_7\ C_8\}$
$\{C_{6+} \Uparrow\}$

Stage $\underline{\underline{N}}$

GOR each Stage:

$$GOR_k = \frac{V_{\bar{g}k}}{V_{\bar{o}}} \quad ; \quad \left\{ \overset{\downarrow}{GOR_{sp,k}} = \frac{V_{\bar{g}k}}{\underset{\uparrow}{V_{ok}}} \right\}$$

@ $T_{sp\,k}$
$P_{sp\,k}$

$$\text{Total GOR} = \frac{\sum V_{\bar{g}k}}{V_{\bar{o}}}$$

$$\text{Solution GOR} = \sum GOR_k$$

Oil: R_s scf/STB or Sm^3/Sm^3

G.C.: $1/r_s$ STB/scf ; STB/MMscf ; STB/Mscf ;
Sm^3/Sm^3 ; $Sm^3/10^6 Sm^3$

b_{ob} = Shrinkage Factor

OILS: $$\frac{V_{ob}}{V_{\bar{o}}} = B_{ob} = \text{Bubblepoint Oil FVF} = \frac{1}{\text{Shrinkage}}$$

"dry surface gas" ($\bar{g}$)

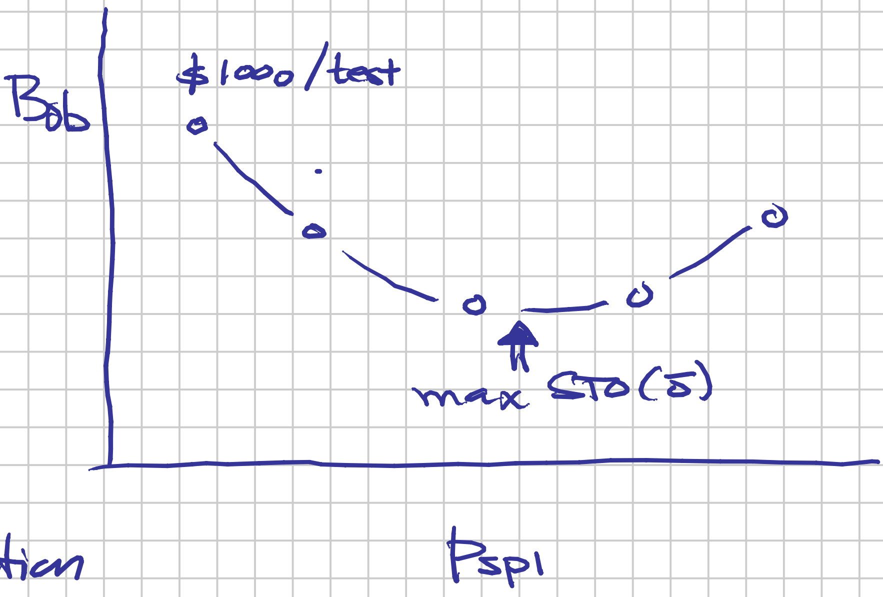
G.C.: $$\frac{V_{gd}}{V_{\bar{g}}} = \overset{\downarrow}{B_{gd}} = \text{Gas FVF}$$

b_{gd} = Gas 'Expansion' (E_g)

In the old days
(<1980)

P_{sp1}
↓
max $V_{\bar{o}}$

Today:
By flash calculation



Total Average Gas Specific Gravity $\bar{\gamma}_g$

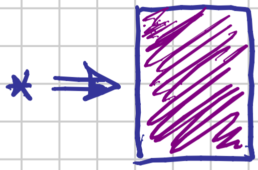
– Used in PVT Correlations

$$\bar{\gamma}_g = \frac{\sum_k GOR_k \cdot \gamma_{\bar{g}k}}{GOR_{total}}$$

CONSTANT COMPOSITION (MASS) EXPANSION – CCE

PVT Cell → "Visual" Cell (GOR ≳ 250 Sm^3/Sm^3)

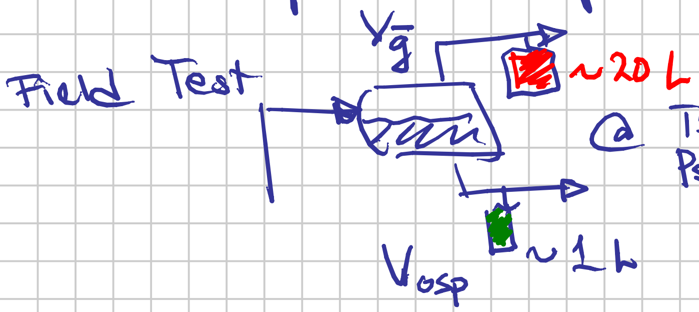
→ "Blind" Cell (lower-GOR oils) ≲ 250 Sm^3/Sm^3



Reservoir Fluid @ T_R

*(1) Bottomhole sample

(2) Physically Recombined Separator Samples



Recombined @ Test $GOR_{sp} = \frac{V_{\bar{g}}}{V_{osp}}$

CCE Test –

- Determine Saturation Pressure (p_b or p_d) @ T_R
- Volumetric behavior @ $p > p_s$ (@ undersaturated conditions)

① - Oils: ρ_o, $V^*_{ro} = (V_o/V_{ob})$ } @ $p \ge p_b$

② - Gases: Z_g @ $p \ge p_d$

$$c_o = -\frac{1}{V^*_{ro}}\frac{dV^*_{ro}}{dp} = \frac{1}{\rho_o}\frac{d\rho_o}{dp}$$

$$c_g = \frac{1}{p} - \frac{1}{Z}\frac{dZ}{dp}$$

$RF_{\bar{g}} = RF_{\bar{o}}$ @ $p_R \ge p_s$

the reservoir is producing a constant GOR (i.e. the same reservoir fluid) @ $p_R \ge p_s$

$$RF_{\bar{g}} = RF_{\bar{o}} = RF = f(c_{fluids}, c_{rock})$$

$\uparrow$

HCs, water

$\uparrow$

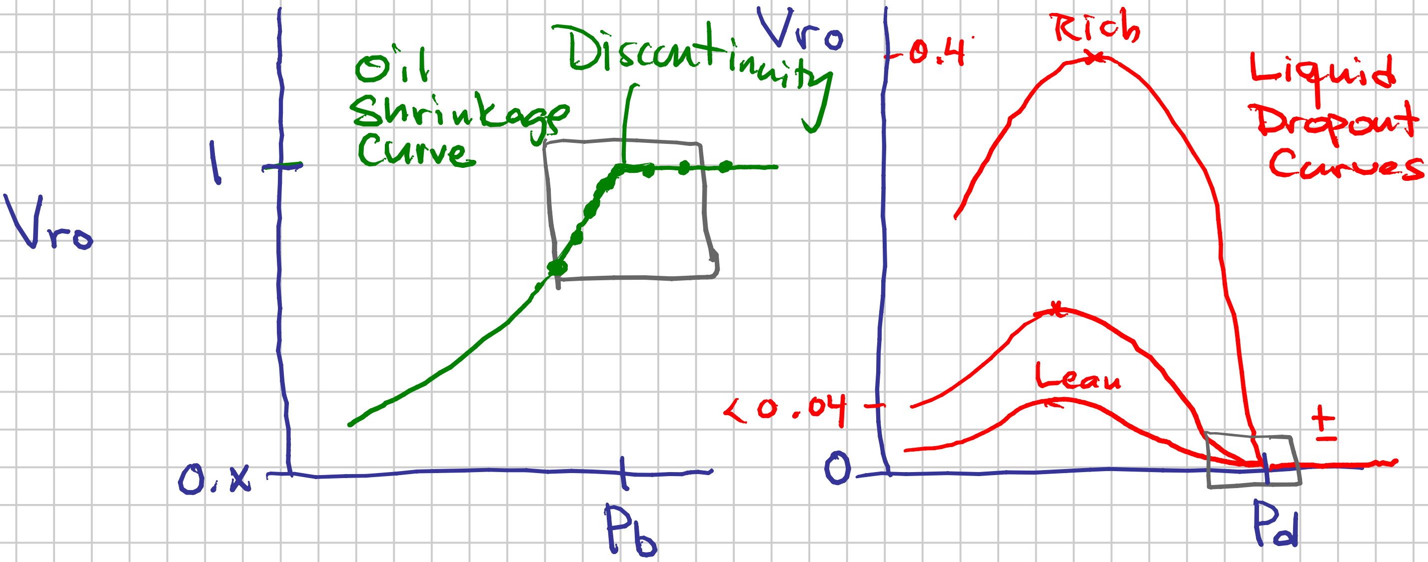
CCE

{ ③ – Higher-GOR fluids (GOR ≳ 250 Sm³/Sm³) }

- Window PVT Cell Tests
- Oil Volume @ $p < p_s$ $\Rightarrow$ $\dfrac{V_o(p)}{V_t(p)} = V_{ro}(p)$

in cell

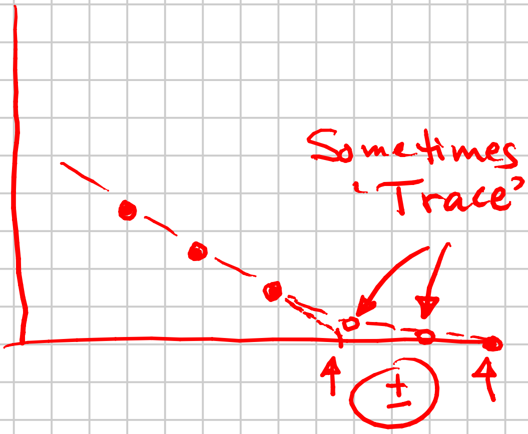
$$= \frac{V_o(p)}{V_o(p) + V_g(p)}$$



OILS

GAS CONDENSATES

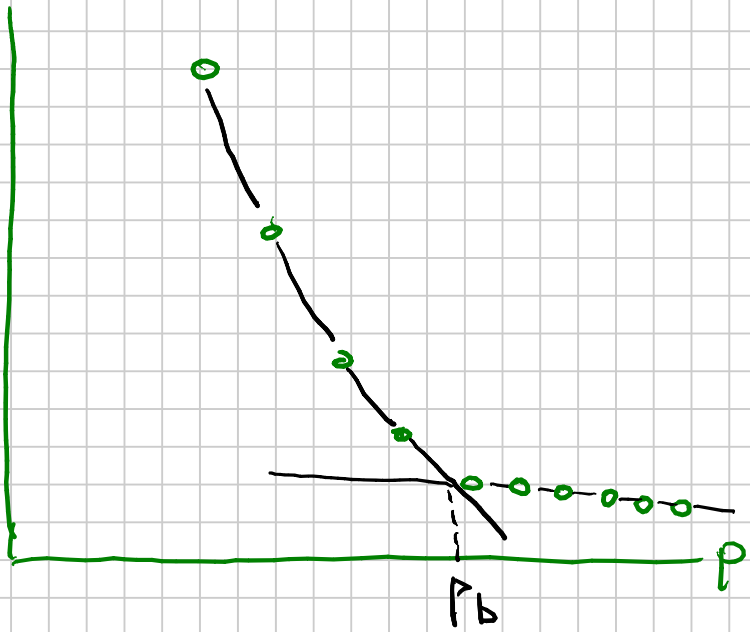
$V_{ro}(p)$ is used to 'determine' the saturation pressure.



OIL Systems GOR $\lesssim 250\ Sm^3/Sm^3$

- Blind PVT Cell

$$V_{cell} = V_t = \frac{(V_g + V_o)}{V_{ob}}$$



Preparation for this Wed.

- Ch. 6 Constant Volume Depletion test (CVD)

$\uparrow$

Accuracy $\propto \frac{1}{GOR}$

DEPLETION PVT TESTS (Ch. 6)

- 'Depletion' of pressure below the original saturation pressure.

  - Gas and oil (2-phases) in equilibrium

$$\boxed{\begin{array}{ll} \underline{y_i(p)} & \underline{x_i(p)} \\ \rho_g (Z_g, M_g) & \rho_o \\ \mu_g & \mu_o \\ \left\{\begin{array}{l} r_s \\ \\ B_g \end{array}\right. & \left.\begin{array}{r} R_s \\ \\ B_o \end{array}\right\} \end{array}} \qquad \underline{p < p_s}.$$

— Composition information in Bo PVT

$f(\underline{P})$

↑

Surface Process

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

Actual measured PVT data are either directly or indirectly providing this information.

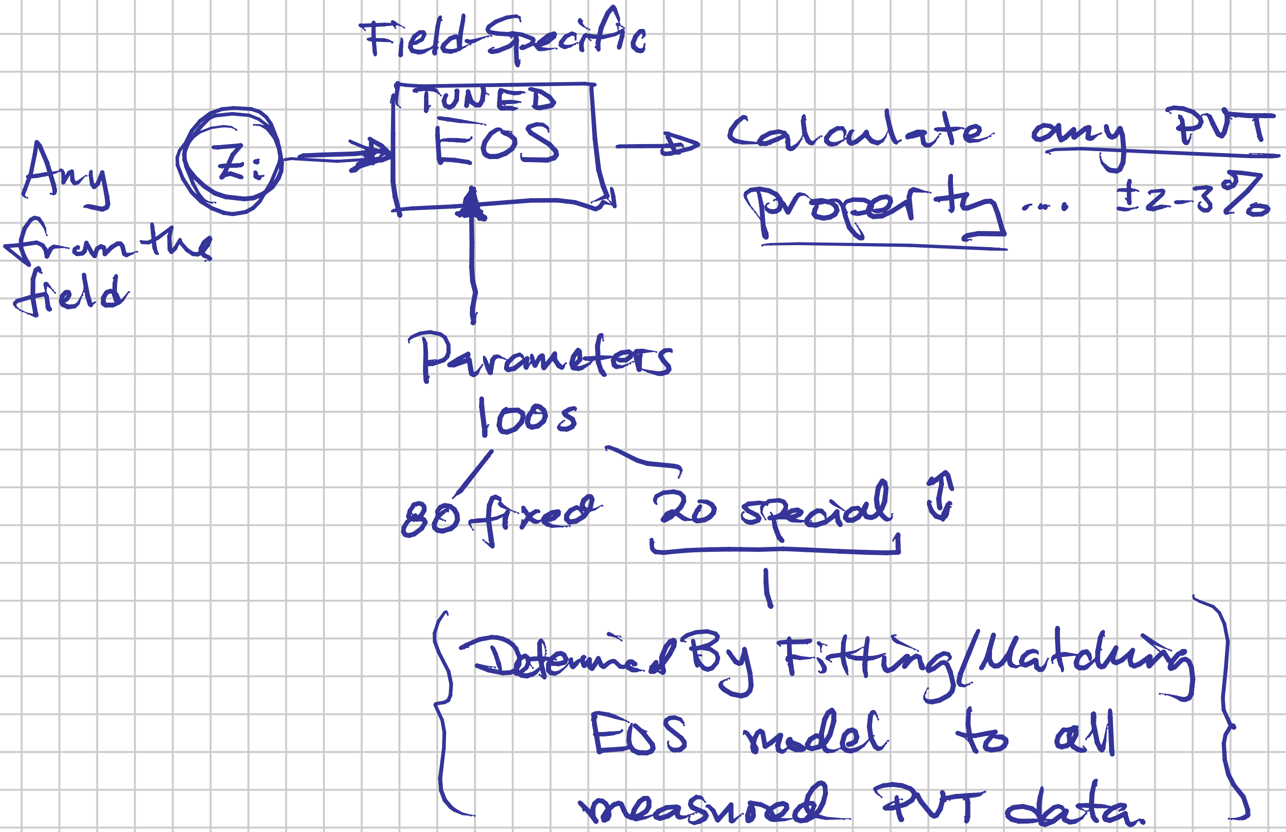
- How do we <u>use</u> these depletion data:

⇒ (1) Directly — e.g. $\rho_o \quad \rho_g \quad \mu_o \quad \mu_g$

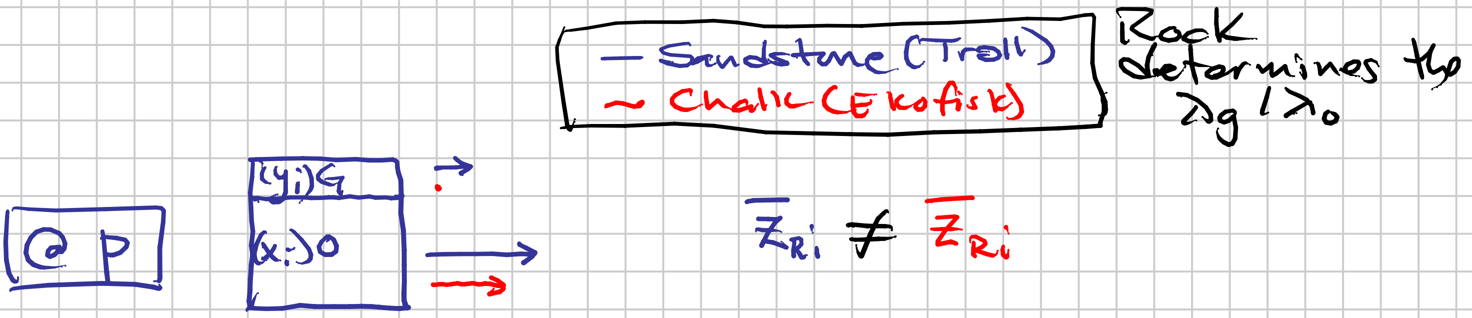
$R_s \quad r_s \quad B_g \quad B_o$: IGIP
IOIP

⇒ (2) To build PVT Models —
(Ch. 4) Equation of State models
(EOS)
with some PVT data tests on a few samples,

the model can be used to calculate PVT for a wide range of samples, conditions (R), and surface processing (P̲).

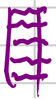


Do $y_i(p)$ & $x_i(p)$ depend on how we deplete or pressure?



ANSWER: N̲o̲ (not really)

$z^{\circ}_{Ri} \Rightarrow$ D

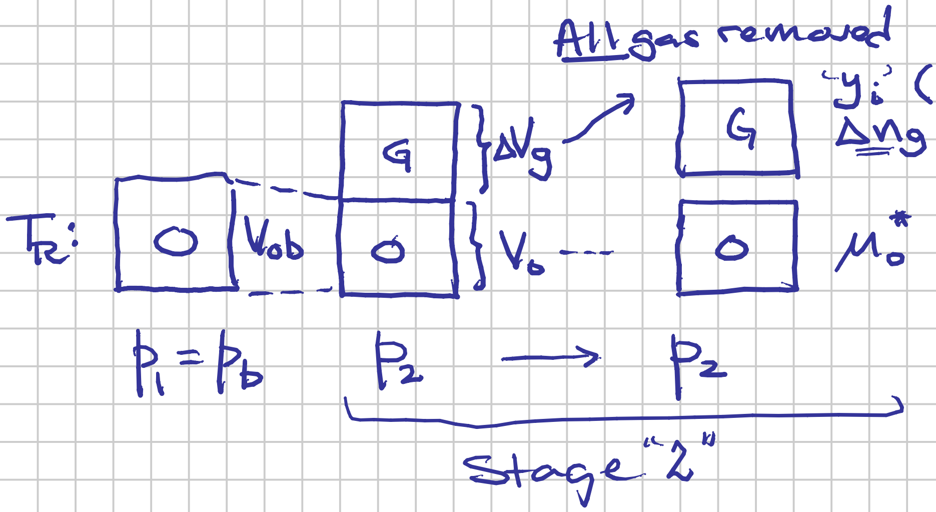


$y_i(p)$:

$x_i(p)$:

OIL Depletion Test:

Differential Liberation Test (DL)

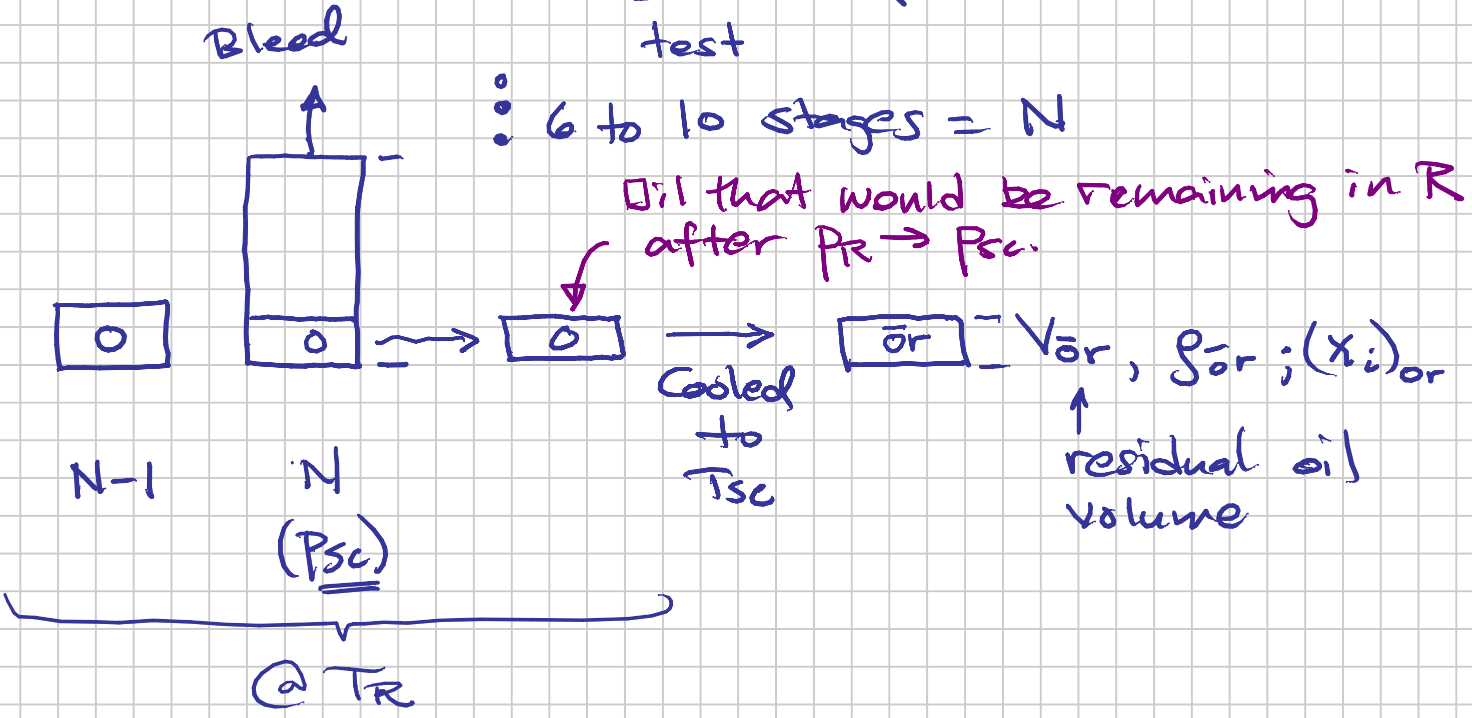


y_i $(M_g$ or $\gamma_g)$ $\Big\}$ $Z_g = \dfrac{p\,\Delta V_g}{\Delta n_g R T_R}$

$\Delta n_g \Rightarrow \Delta V_g$

* Same procedure, but in a parallel test

⋮ 6 to 10 stages = N



Report PVT Data:

$$B_{od} = \frac{V_o}{V_{\bar{o}r}}$$

$$R_{sd} = \frac{\sum_1 \Delta V_g}{V_{\bar{o}r}}$$

$\rho_{\bar{o}r}$

μ_o

$$\rho_o = \frac{\rho_{\bar{o}r} + R_{sd}\left(\frac{p_{sc}}{R T_{sc}}\right) M_g}{B_{od}}$$

$$Z_g = \frac{p\,\Delta V_g}{R T \Delta n_g}$$

$$M_g = \sum y_i M_i$$

M_o Cum Rem $\left[\left(\sum_1^N \Delta V_{\bar{g}}\right)/V_{\bar{o}r}\right]$ $R_{sd,b}$ − Cum Rem

scf/bbl $V_o/V_{or} = B_{od}$

Differential Liberation at 258°F

Gauge Pressure (psi) psig	Pressure/Volume Relation at 258 °F Relative Volume of Oil and Gas V/V_{ob}	Viscosity* of Oil at 258 °F (cp)	Gas/Oil Ratio Liberated/bbl Residual Oil	Gas/Oil Ratio In Solution/bbl Residual Oil	Relative Oil Volume V_o/V_{or}
$P_1 = P_b$ $\boxed{3,236}$	1.0000	$\boxed{0.093}$	0	$\boxed{1,518}$	$\boxed{2.075}$ bbl
3,200	1.0047				
3,141	1.0128				
3,110		$\boxed{0.095}$			
3,094	1.0192				
3,039	1.0273				
2,969	1.0387				
P_2 $\boxed{2,938}$			→ $\boxed{183}$ scf	1,335	1.970
2,882	1.0534				
2,800		$\boxed{0.104}$			
2,792	1.0697				
2,640	1.1025				
P_3 $\boxed{2,607}$			→ $\boxed{362}$	1,156	1.867
2,448	1.1517				
2,301			→ 506	1,012	1.787
2,300		0.118			
2,237	1.2177				
2,024	1.3003				
1,903			→ 670	848	1.698
1,825	1.3997				
1,800		0.134			
1,665	1.4994				
1,505			815	703	1.624
1,501	1.6244				
1,300		0.155			
1,261	1.8717				
1,092			957	561	1.544
1,078	2.1540				
900	2.5475				
800		0.179			
761	2.9926				
686			1,089	429	1.472
656	3.4741				
518	4.3966				
346			1,209	309	1.399
310		0.220			
200			1,262	256	1.367
97			1,328	190	1.311
0		0.700	1,518 scf	0	1.109
				at 60°F =	$\boxed{1.000}$ bbl

$\Delta V_{\bar{g}} = 362 - 183 = 179$ scf

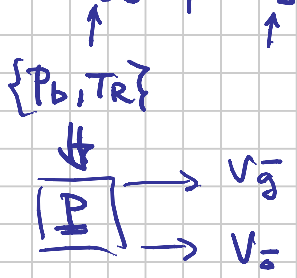
Oil Shrikage

Supplementary Differential-Liberation Data

Pressure (psig)	$\gamma_g = M_g$ Gas Gravity	ρ_o Oil Density (g/cm^3)	Z_g Deviation Factor Z
3,236		0.5773 ±1%	
2,938	0.870	0.5905	0.886
2,607	0.846	0.6055	0.879
2,301	0.833	0.6179	0.878
1,903	0.830	0.6326	0.884
1,505	0.835	0.6455	0.897
0	1.532	$\boxed{0.7340}$ $m_{\bar{o}r}$	

Calc'd: $$\rho_{o,k} = \frac{\left\{m_{\bar{o}r} + \sum_N^k \Delta m_{\bar{g}}\right\}}{V_{ok}} = \frac{m_{ok}}{V_{ok}}$$

Using B_{od} & R_{sd} to generate black-oil PVT B_o & R_s for engineering calcs. by using a multi-stage separator test ⇒ B_{ob} & R_{sb}



If $R_{sb} \lesssim 200$ Sm³/Sm³ (lesser volatile oils)

$$\Rightarrow B_o(p) = B_{od}(p) \cdot \frac{B_{ob}}{B_{od,b}}$$

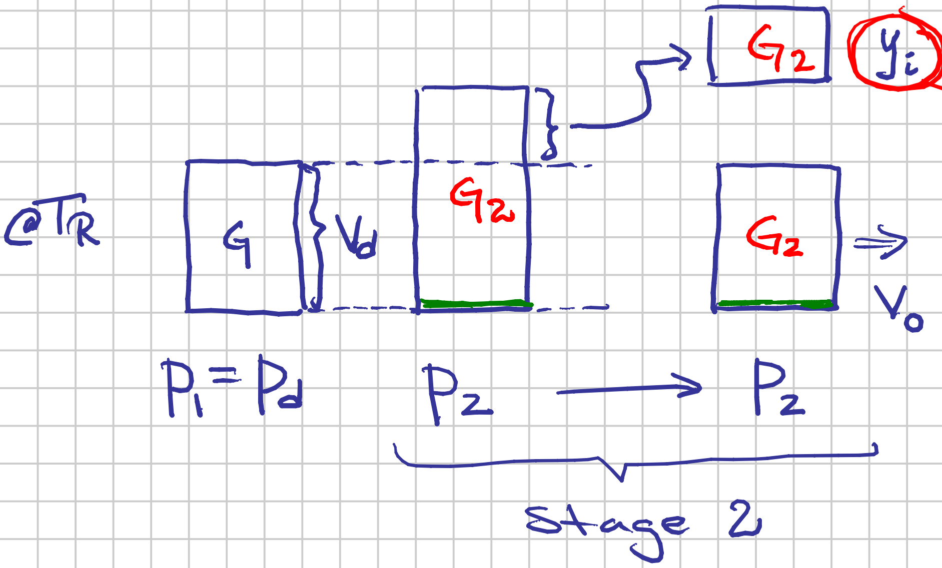
$$\Rightarrow R_s(p) = R_{sb} - \left(R_{sd,b} - R_{sd}(p)\right) \cdot \frac{B_{ob}}{B_{od,b}}$$

$$\circledast \Rightarrow B_g(p) = \frac{p_{sc}}{T_{sc}} \cdot \frac{T_R}{p} z_g$$

Assumes all R gas coming out of solution forms only sales gas – no condensate!

GAS CONDENSATE DEPLETION TEST

- CONSTANT VOLUME DEPLETION (CVD)



$\boxed{y_i}$ ΔV_g $\Delta n_g \Rightarrow Z_g = \frac{p\,\Delta V_g}{R T_R\, \Delta n_g}$

$\underbrace{C_{n+}\ (C_{6+}, C_{5+})}$ ⇒ forms a surface oil — sales condensate

$\boxed{y_{n+}}$ KEY data

⋮ 5–10 = N

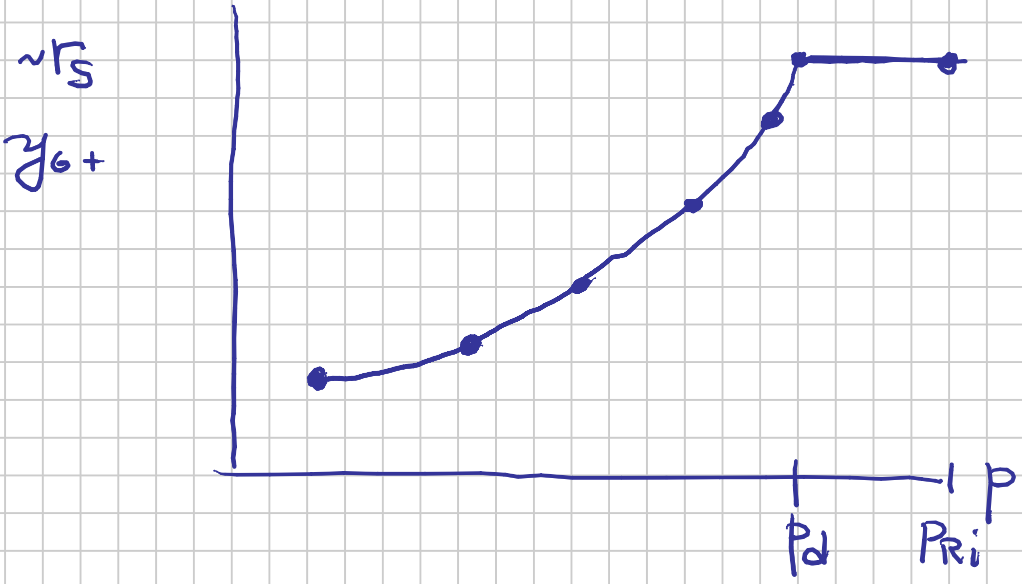
$$CGR = OGR = r_s \simeq \frac{(y_{n+})}{(1-y_{n+})} \cdot \frac{(M_{n+}/\rho_{n+})}{\left(\frac{R T_{sc}}{p_{sc}}\right)}$$

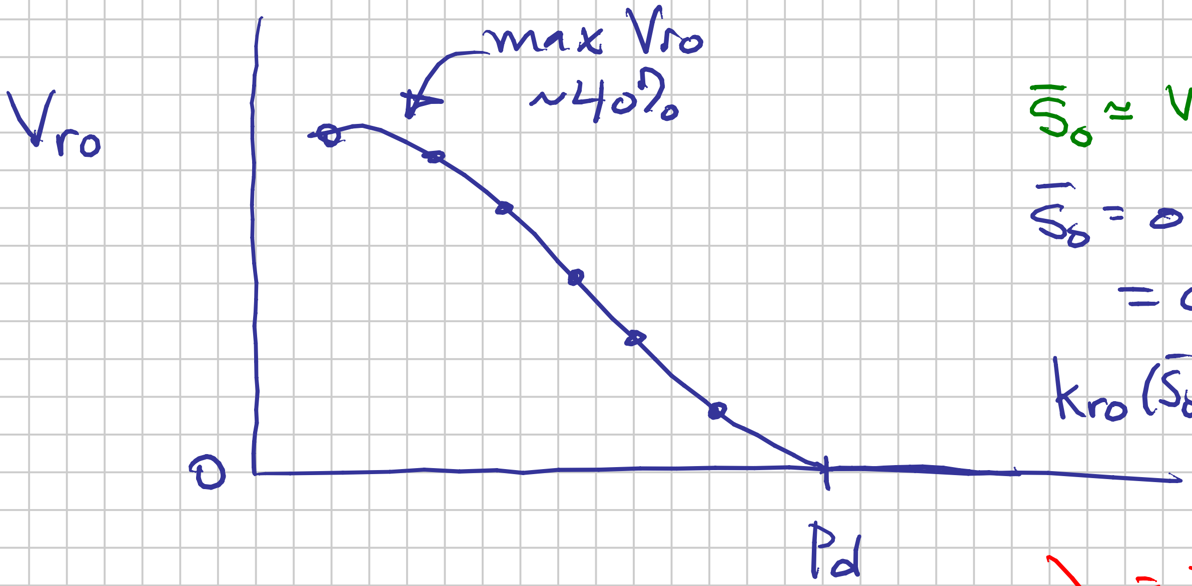
y_i

$$V_{ro} = \frac{V_o}{V_d}$$

$$\sum_1^i \frac{\Delta n_g}{n_d}$$ = Cumulative moles recovered as % of initial moles @ p_d

Z_g





$$\bar{S}_o \simeq V_{ro}(1-\bar{S}_w)$$

$$\bar{S}_o = 0.4(1-0.2)$$

$$= 0.32$$

$$k_{ro}(\bar{S}_o = 0.32)$$

$$= 0.0x$$

$$10 = \lambda_g = \frac{k_{rg}}{\mu_g} = \frac{0.2}{0.02}$$

$$\gg$$

$$0.1 = \lambda_o = \frac{k_{ro}}{\mu_o} = \frac{0.02}{0.2}$$

PROBLEM 13 SOLUTION (using App. D Oil PVT)

Problem 11

$$\boxed{p(z) = p(z_{ref}) + \rho g (z - z_{ref})}$$

Problem. An oil well produces at a total GOR of 900 scf/STB. Total gas gravity is 0.85 (air = 1). Stock-tank-oil gravity is 36°API. Calculate, using ideal-solution principles and apparent liquid density of the gas, the density of the reservoir oil at 3,300 psia and 190°F. If reservoir pressure is 3,300 psia at 7,200 ft subsea, what would the reservoir pressure be at a datum level of 6,000 ft subsea?

Static Fluid Column

Problem 12

$z \downarrow$

$$\frac{dp}{dz} = \rho g \; ; \; \rho \sim \text{constant over } z \text{ interval}$$

Problem. For the reservoir considered in Problem 11, use the Standing[10] bubblepoint correlation to estimate bubblepoint pressure. On the basis of this estimate, is it possible that a gas cap might be found between the test depth of 7,200 ft subsea and the structure top at 6,000 ft subsea? If so, at what depth?

Problem 13

Problem. If the hydrocarbon pore volume (HCPV) of the reservoir in Problem 11 is approximately 40×10^6 ft^3/ft reservoir thickness, estimate the original oil in place, *N*, and original gas in place, *G*. The water/oil contact (WOC) is at 7,300 ft subsea, the gas/oil contact (GOC) depth is given in Problem 12 as 6,500 ft subsea, and the top of the structure is at 6,000 ft subsea.

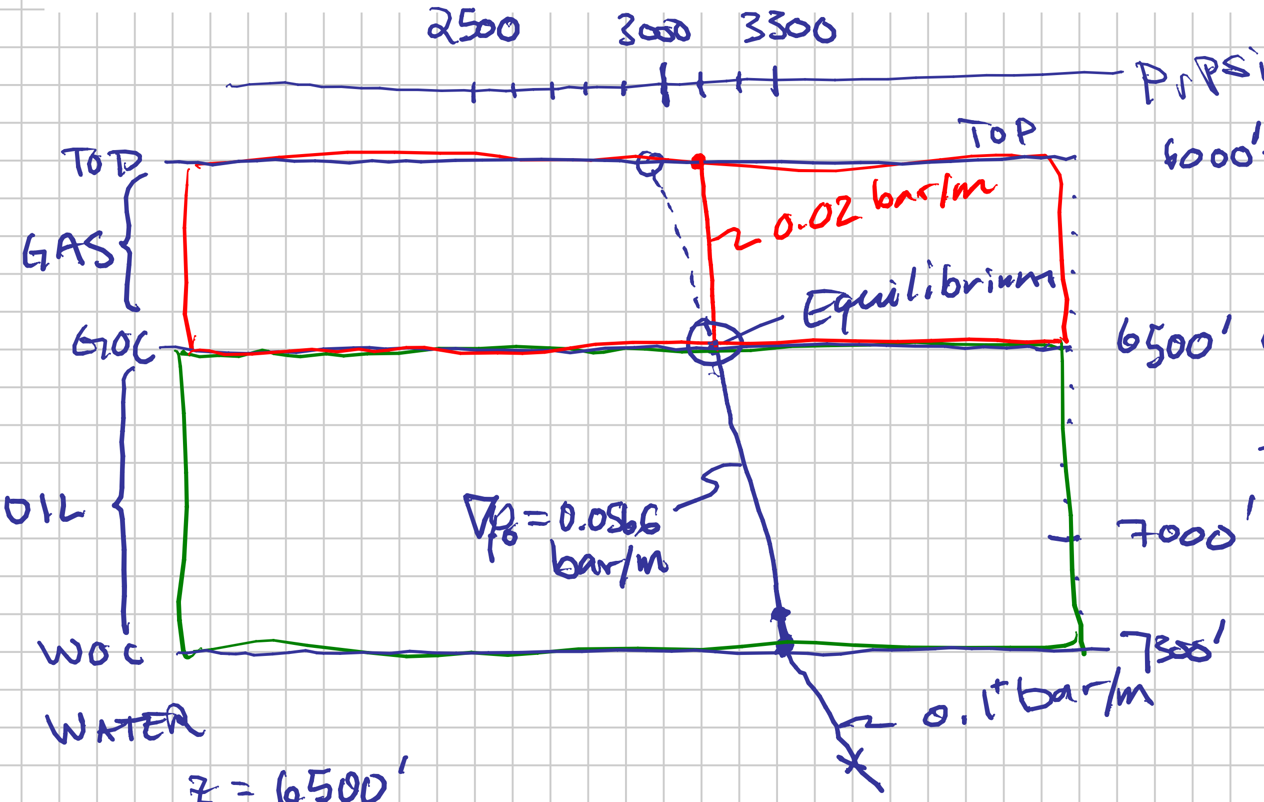
3. Compressibility of saturated oil at reservoir temperature: vol/vol-psi.

From 6,000 psi to 5,000 psi = 18.32×10^{-6}

From 5,000 psi to 4,000 psi = 22.33×10^{-6}

From 4,000 psi to 3,236 psi = 28.64×10^{-6}

4. Specific volume at saturation pressure: ft³/lbm 0.02772 at 258°F.



$HCPV_g = 500' \times 40 \cdot 10^6 \ ft^3/ft = 2 \cdot 10^{10} \ ft^3$

$HCPV_o = 800 \ ft \times 40 \cdot 10^6 = 3.2 \cdot 10^{10} \ ft^3$

$z = 6500'$

$p = \underset{@7200 ft}{3300 \text{ psia}} + \rho_o g (6500 - 7200)$

$= 227.53 \text{ bara} + \underbrace{\underset{\text{kg/m}^3}{(577.3)}\ \underset{\text{m/s}^2}{(9.8)}\ \underset{\text{m}}{(-213.4)}}_{\text{Pa}} \cdot \frac{\text{bar}}{10^5 \text{ Pa}}$

Table Pg 4

$= 227.53 - 12.07$

$= \underline{215.45 \text{ bara}}$ (3125 psia) @ GOC

Oil Gradient $\frac{\Delta p}{\Delta z} = \rho g = 0.0566$ bar/m

Supplementary Differential-Liberation Data

	Pressure (psig)	γ_g Gas Gravity	Oil Density (g/cm^3)	Z_g Deviation Factor Z
P_b	3,236	$\boxed{0.885}$ est	0.5773	$\boxed{0.895}$
	2,938	0.870	0.5905	0.886
	2,607	0.846	0.6055	0.879
	2,301	0.833	0.6179	0.878
	1,903	0.830	0.6326	0.884
	1,505	0.835	0.6455	0.897
	0	1.532	0.7340	

Incipient Gas Est.

Plot & Extrapolate

Plot & Extrap.

$$\rho_g = \frac{P_{GOC} \cdot M_g}{Z_g R T_R}$$

405 570 4359

$$= \frac{3300(28.97)(0.885)}{(0.895)(10.73)(258+460)}$$

$$= \underline{12.27} \quad lb/ft^3 = \underline{197} \quad kg/m^3$$

$$\left(\frac{\Delta p}{\Delta z}\right)_g = \rho_g g = 0.02 \quad bar/m$$

RG: $\overset{\checkmark}{B_{gdi}} \equiv \frac{V_g}{V_{\bar{g}g}} = \frac{HCPV_g^{\checkmark}}{G_g}$

$\uparrow$ $(IGIP)_{RG}$

$$\Rightarrow G_g = HCPV_g \cdot B_{gdi}^{-1}$$

IOIP Condensate $\quad N_g = G_g \cdot r_{si} \Leftarrow r_s = \frac{V_{\bar{o}g}}{V_{\bar{g}g}} = \frac{N_g}{G_g}$

$\uparrow$ Solution OGR

$\Rightarrow$ Est. B_{gdi}, r_{si} $\quad i$ @ GOC

Not reported in a traditional PVT study for an oil.

RO: Know $HCPV_o$

$$\text{PVT study} \Rightarrow B_{oi} = \frac{V_{oi}}{V_{\bar{o}o}} = \frac{HCPV_o}{\underset{\underset{IOIP_{RO}}{\uparrow}}{N_o}}$$

$$R_{si} = \frac{V_{\bar{g}o}}{N_{\bar{o}o}} \Rightarrow V_{\bar{g}o} = V_{\bar{o}o} \cdot R_{si}$$

$$\boxed{G_o = N_o \cdot R_{si}}$$

$\Rightarrow$ PVT Report: Get B_{oi}, R_{si}

Total Reservoir

Sm^3

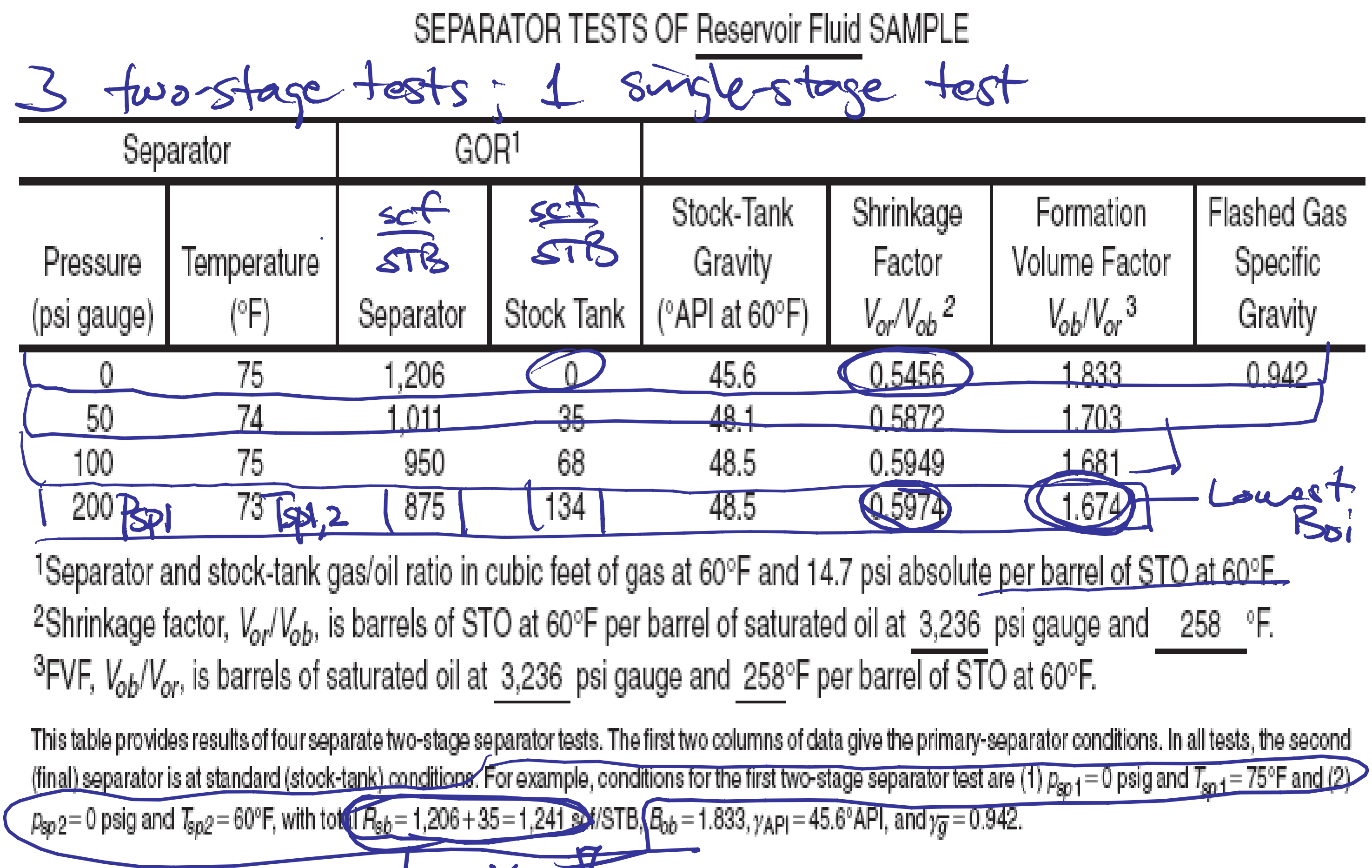
$$G = \underbrace{G_g}_{\text{Free Gas}} + \underbrace{G_o}_{\text{Solution Gas}}$$

$$N = \underbrace{N_g}_{\text{Solution Oil (Condensate)}} + \underbrace{N_o}_{\text{Free Oil}}$$

$$HCPV_g = 2\cdot 10^{10}\ ft^3 \times \frac{m^3}{35.31\ ft^3} = \underline{5.664\cdot 10^8}\ m^3$$

$$HCPV_o = 3.2\cdot 10^{10}\ ft^3 \times \frac{m^3}{35.31\ ft^3} = \underline{9.063\cdot 10^8}\ m^3$$

RO:



SEPARATOR TESTS OF Reservoir Fluid SAMPLE

3 two-stage tests ; 1 single-stage test

Separator		GOR[1]					
Pressure (psi gauge)	Temperature (°F)	scf/STB Separator	scf/STB Stock Tank	Stock-Tank Gravity (°API at 60°F)	Shrinkage Factor V_{or}/V_{ob}[2]	Formation Volume Factor V_{ob}/V_{or}[3]	Flashed Gas Specific Gravity
0	75	1,206	0	45.6	0.5456	1.833	0.942
50	74	1,011	35	48.1	0.5872	1.703	
100	75	950	68	48.5	0.5949	1.681	
200 P_{sp1}	73 $T_{sp1,2}$	875	134	48.5	0.5974	1.674 Lowest B_{oi}	

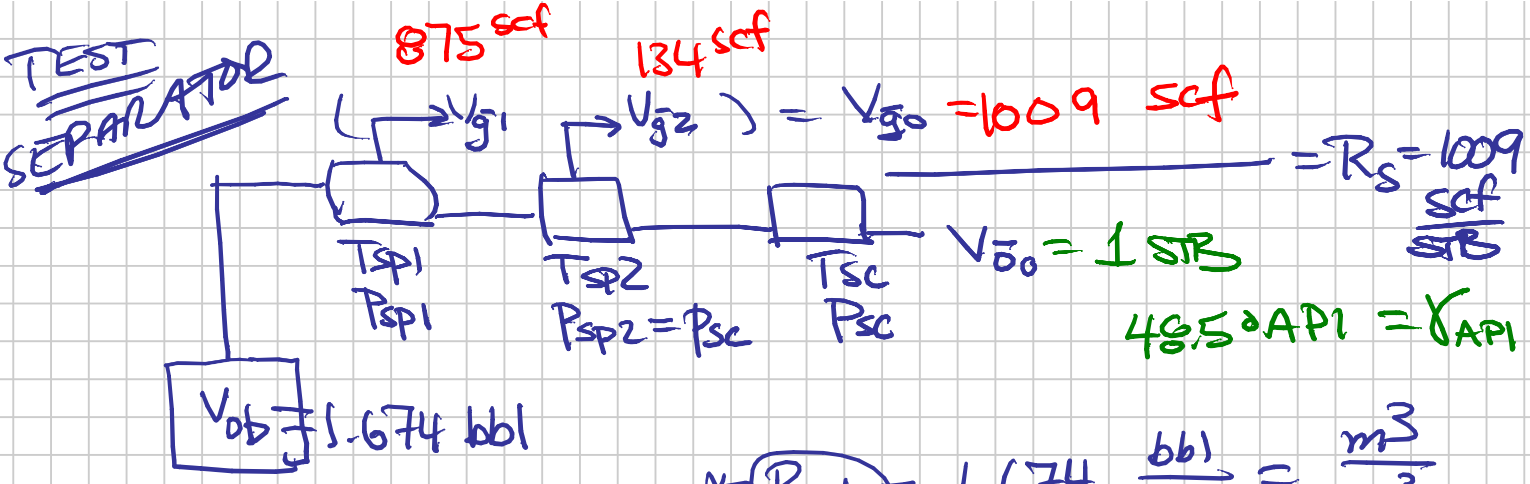
[1] Separator and stock-tank gas/oil ratio in cubic feet of gas at 60°F and 14.7 psi absolute per barrel of STO at 60°F.

[2] Shrinkage factor, V_{or}/V_{ob}, is barrels of STO at 60°F per barrel of saturated oil at 3,236 psi gauge and 258 °F.

[3] FVF, V_{ob}/V_{or}, is barrels of saturated oil at 3,236 psi gauge and 258°F per barrel of STO at 60°F.

This table provides results of four separate two-stage separator tests. The first two columns of data give the primary-separator conditions. In all tests, the second (final) separator is at standard (stock-tank) conditions. For example, conditions for the first two-stage separator test are (1) $p_{sp1} = 0$ psig and $T_{sp1} = 75$°F and (2) $p_{sp2} = 0$ psig and $T_{sp2} = 60$°F, with total $R_{sb} = 1{,}206 + 35 = 1{,}241$ scf/STB, $B_{ob} = 1.833$, $\gamma_{API} = 45.6$°API, and $\gamma_{\bar{g}} = 0.942$.

WRONG!



NOT the Differential Test Data! (App. D)

$$* \boxed{B_{ob}} = 1.674 \frac{bbl}{STB} = \frac{m^3}{Sm^3}$$

$$* \boxed{R_s} = 1009 \frac{scf}{\cancel{STB}} \times \frac{\cancel{STB}}{5.615\ scf} = 180 \frac{Sm^3}{Sm^3}$$

$$N_o = 9.063 \cdot 10^8\ m^3 \Big/ 1.674 \frac{m^3}{Sm^3}$$

$$= 5.414 \cdot 10^8\ Sm^3$$

$$= 541.4 \cdot 10^6\ Sm^3$$

$$= 3.4 \cdot 10^9\ STB$$

$$G_o = 5.414 \cdot 10^8\ Sm^3 \times 180 \frac{Sm^3}{Sm^3}$$

$$= 9.745 \cdot 10^{10}\ Sm^3$$

$$= 3.441\ Tcf$$

RG

We don't know the gas cap "composition" y_i

"r_s"

Estimate r_s

What do we know about the RG

① All RG → $V_{\bar{g}g}$; $V_{\bar{o}g} = 0$

Traditional GasPVT "B_{gw}"

$$\frac{V_{gR}}{V_{\bar{g}w}} = \boxed{B_{gi} = \left[\left(\frac{p_{sc}}{T_{sc}}\right)\cdot \frac{Z_g R T_R}{p_{Ri}}\right]} \checkmark = \text{"}B_{gw}\text{"}$$

Ficticous "wet" Gas Volume

$$G_g = \frac{HCPV_g}{B_{gi}} = \frac{5.664\cdot 10^8\ m^3}{0.0600\ Sm^3/m^3}$$

$$= 1.01\cdot 10^{11}\ Sm^3$$

$$= 3.578\ \text{Tcf}\ \checkmark$$

$$N_g = 0$$

② Guess (est.)

8 mol-% → $\underline{0.08}$ → $f_{\bar{o}g}$

1-15%

99-85%

$$B_{gd} = B_{gw}\cdot\left[\frac{1}{1-f_{\bar{o}g}}\right] = \frac{V_{gR}}{V_{\bar{g}g}}$$

① assumes $r_s = 0$; $y_{\bar{o}} = 0$

$$\frac{V_{\bar{g}R}}{V_{\bar{g}w}(1-0.08)}$$

$$\boxed{V_{\bar{g}g}} = \boxed{V_{\bar{g}w}} \times (1 - \underset{0.08}{f_{\bar{o}g}})$$

$$(1.01 \cdot 10^{11}\ Sm^3)$$

$$G_g = \underbrace{(0.92)}_{\text{frac of Reservoir Gas} \rightarrow \text{Surface Gas}} (3.578\ Tcf) = 0.9 \cdot 10^{11}\ Sm^3 = 3.292\ Tcf$$

$$N_g \overset{?}{=} \boxed{r_s} \cdot G_g$$

$$\frac{Sm^3}{Sm^3}$$

$$\boxed{y_{\bar{g}} = \frac{1}{1 + r_s \cdot \underbrace{\left(\frac{\rho_{\bar{o}}}{M_{\bar{o}}}\right)\left(\frac{M_{\bar{g}}}{\rho_{\bar{g}}}\right)}_{\frac{600}{100} \times 23.68 \,=\, 150}}}$$

$$\frac{\rho}{M} = \frac{p_{sc}}{RT_{sc}} = 23.68\ \frac{Sm^3}{kgmol}$$

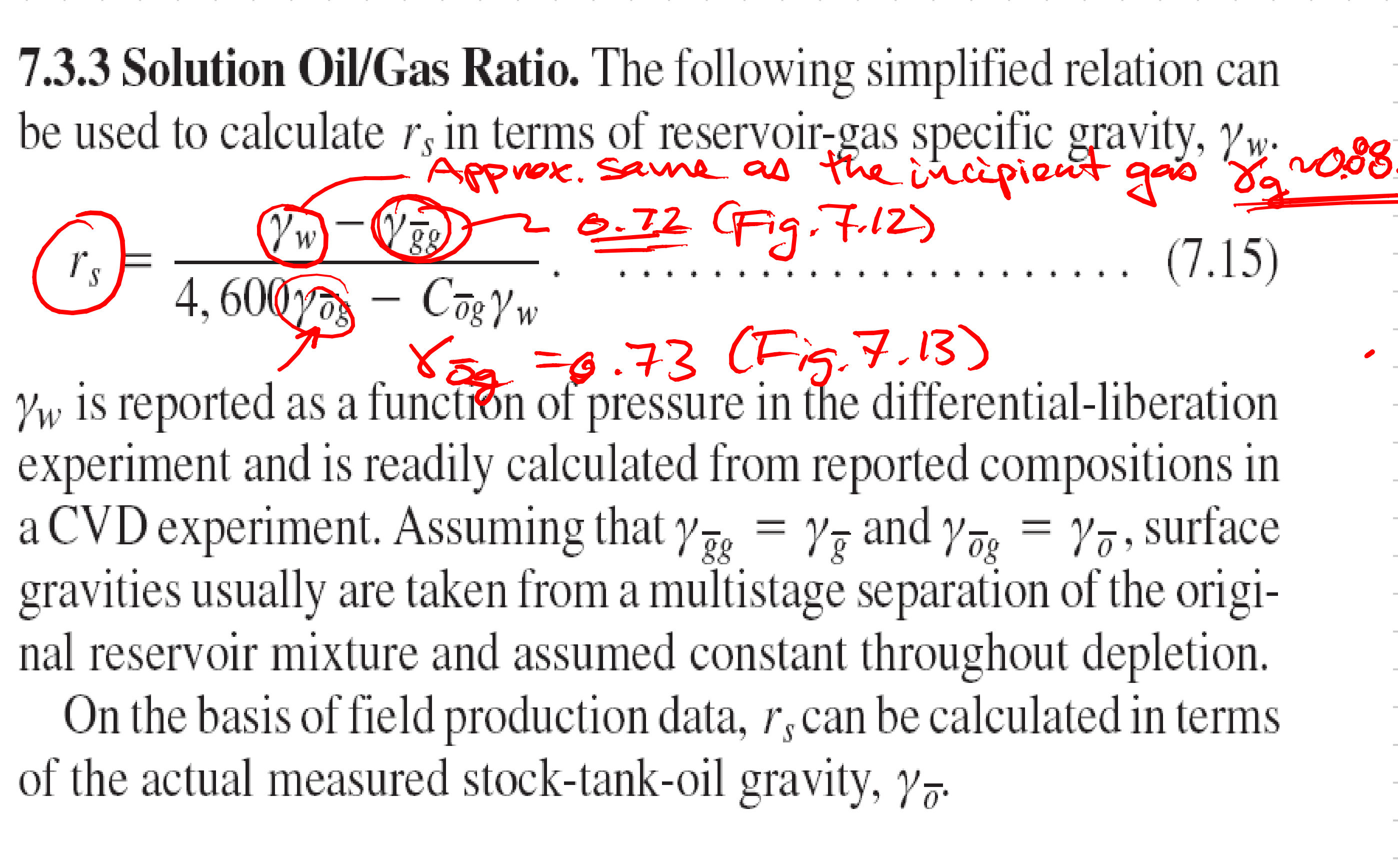
$$y_{\bar{g}} + 150\, y_g\, r_s = 1$$

$$r_s = \frac{1 - y_{\bar{g}}}{150 \cdot y_g} = \frac{0.08}{150(0.92)} = 0.00058\ Sm^3/Sm^3$$

$= 580 \ Sm^3/10^6 \ Sm^3$

$$N_g = G_g \cdot r_s$$
$$= 0.9 \cdot 10^{11} (0.00058)$$
$$= 5.874 \cdot 10^7 \ Sm^3$$
$$= 3.689 \cdot 10^8 \ STB$$

③ Ch. 7



7.3.3 Solution Oil/Gas Ratio. The following simplified relation can be used to calculate r_s in terms of reservoir-gas specific gravity, γ_w.

Approx. same as the incipient gas $\gamma_g \sim 0.885$

$$r_s = \frac{\gamma_w - \gamma_{\bar{g}g}}{4,600\gamma_{\bar{o}g} - C_{\bar{o}g}\gamma_w} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7.15)$$

$\gamma_{\bar{g}g}$ ~ 0.72 (Fig. 7.12)

$\gamma_{\bar{o}g} = 0.73$ (Fig. 7.13)

γ_w is reported as a function of pressure in the differential-liberation experiment and is readily calculated from reported compositions in a CVD experiment. Assuming that $\gamma_{\bar{g}g} = \gamma_{\bar{g}}$ and $\gamma_{\bar{o}g} = \gamma_{\bar{o}}$, surface gravities usually are taken from a multistage separation of the original reservoir mixture and assumed constant throughout depletion.

On the basis of field production data, r_s can be calculated in terms of the actual measured stock-tank-oil gravity, $\gamma_{\bar{o}}$.

$r_s \rightarrow \gamma_{\bar{g}}$ to calculate B_{gd}

$$B_{gd} = \frac{p_{sc}}{T_{sc}} \cdot \frac{Z_g T_R}{p_R} \cdot \left(\frac{1}{\gamma_{\bar{g}}}\right)$$

EXAM - COURSE Qs & As

EXAM PREPARATION

1. Study course notes, lectures
   - Emphasize problems solved in class (exam will be number crunching)
   - Don't understand lectured material,
     - look in monograph (other) for better explanations
     - talk with other students
     - ask Curtis

2. Study Problems solved in course as homework – and Problems 11 & 13 in App. B.

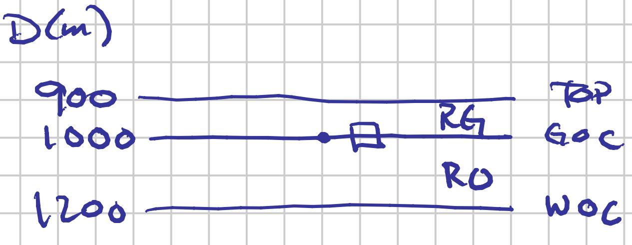
3. Previous Exams
   - If it doesn't look familiar (and you know what was lectured this year!) then it is <u>not</u> a relevant 2009 exam Q.
   - If it looks familiar, know how to solve it.

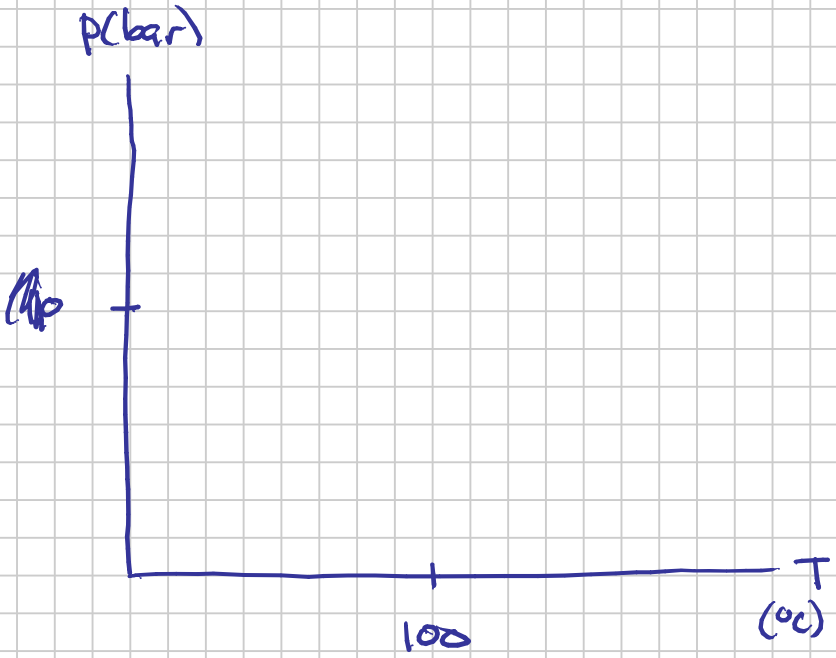
p-T Diagram 2008 Exam

GOC @ 1000 m

P_{GOC} = 100 bar

T_{GOC} = 100 °C





Problem 4a - 2006

Total Reservoir Gas-Oil Ratio

$$\boxed{R} = \frac{IGIP}{IOIP} = \frac{237 \cdot 10^9 \text{ scf}}{126 \cdot 10^6 \text{ STB}} = 1.8 \cdot 10^3 \frac{\text{scf}}{\text{STB}}$$

$$\boxed{1800 \text{ scf/STB}}$$

$$= \frac{10^6}{1800} = 555 \frac{\text{STB}}{10^6 \text{scf}}$$

PVT Table at P_R : 4000 psig

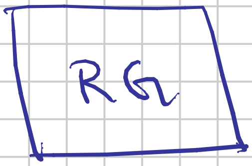
823 = R_s = solution GOR of saturated oil @ P_R

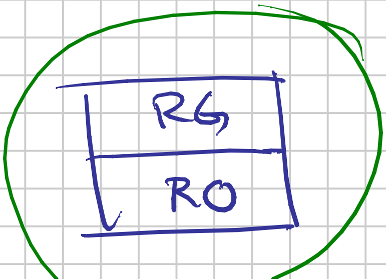
$\boxed{33.76}\ 10^{-6}$ STB/scf = r_s = solution OGR of saturated gas @ P_R

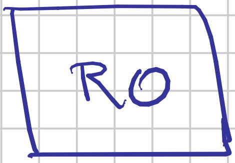
30 000 $\frac{\text{scf}}{\text{STB}}$ = $\frac{1}{r_s}$ = solution GOR ———— " ————

↑

min GoR still a RG

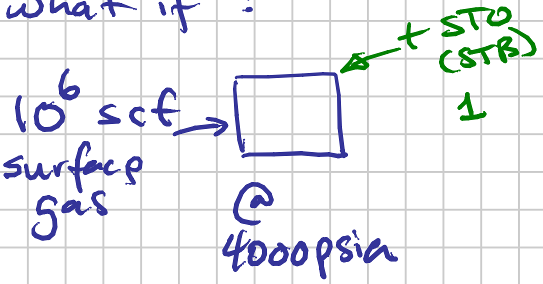






✓

what if ?



How many STB <u>max</u> = r_s can I add to my 10^6 scf surface gas and still remain as a Reservoir Gas?

$$\min GOR = \frac{1}{r_s}$$ and still be RG

No José

↓

what if ?

max GOR and still be an OIL is $R_s @ 4000 = 823 \frac{scf}{STB}$

X

No way José

2008 Exam   Problem 1 (n)

Test Tubing : $d_T = 3.5$ in

Production Tubing : $d_T = 5$ in

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

$$\uparrow$$

Test : $(C_T) = 16579 = \dfrac{(q_g)_T}{\left(p_w^2 - p_t^2\right)_T^{0.5}}$

Fetkovich paper :

$$\boxed{C_T \propto d_{tubing}^{2.6}}$$

$$\underline{\underline{(C_T)_{new}}} = (C_T)_{old} \cdot \frac{\left(d_{tubing}\right)_{New}^{2.6}}{\left(d_{tubing}\right)_{old}^{2.6}}$$

$$= 16579 \cdot \left(\frac{5}{3.5}\right)^{2.6} = 42000$$

* * *

$$Bq_g^2 + A q_g - \left(p_c^2 - p_t^2\right) = 0$$

If R: D=0 (only Darcy eq.)

then $B = \dfrac{1}{C_T^2} = \dfrac{1}{\left(5.69 \cdot 10^{-10}\right)^2} = 42000$ ✓

$P_c^2 - P_w^2 = \frac{1}{C_R} q$ OR $P_c^2 - P_w^2 = B_R q^2 + A_R q$

$P_w^2 - P_t^2 = \frac{1}{C_t^2} q^2$

$$P_c^2 - P_t^2 = \underset{\overset{\uparrow}{B_R + \frac{1}{C_t^2}}}{B} q^2 + A q$$