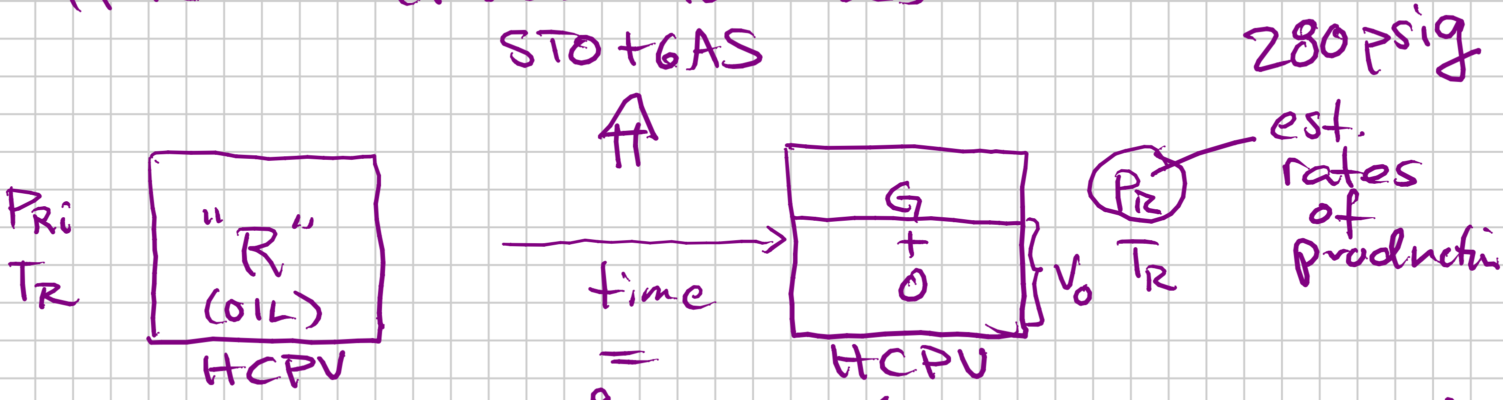
CLASS QUIZ:

- Oil Lab PVT Report (App. D)
- Ch. 6 + Lectures ⇒ Methods to determining and use B_o, R_s

- Application (Problem to Solve)



IOIP (N) = 10^9 STB (Stock Tank barrels)

Psc 1 atm

Tsc 60 °F (15.56 °C)

Cumulative Production

N_p = cum. OIL (STO) Prod = 10^8 STB

G_p = cum gas Prod = $0.5 \cdot 10^{12}$ scf

Q: Average Volumetric Reservoir Pressure ($\bar{P}_R$)

$(N - N_p)$ = Remaining STO in the R

= $900 \cdot 10^6$ STB (RF_o = 10%)

Conversion STB to Reservoir Barrels "B_o"

$$B_o = \frac{V_{oR}}{V_{\bar{o}}} = \frac{V_o}{V_{sto}}$$

$$V_o = (N - N_p)\, B_o$$

$$\uparrow$$

$$\frac{V_o}{V_{\bar{o}}} \leftarrow STO$$

Separator Test

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

$$\left[\frac{RB}{STB}\right] \quad \left[\frac{RB}{\cancel{res\ bbl}}\right] \quad \frac{\left[\frac{\cancel{RB}}{STB}\right]}{\left[\frac{\cancel{RB}}{\cancel{res\ bbl}}\right]}$$

Approx. Method of Conversion DLE ⇒ B_o, R_s use in engineering

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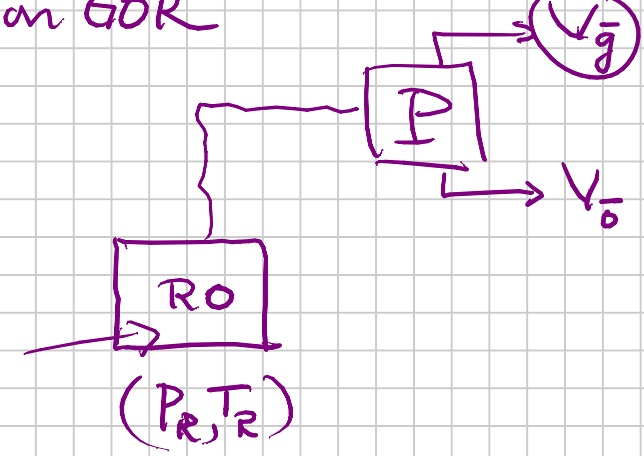
How to use $(R_s) = \dfrac{\text{gas remaining in solution in RO}}{STB}$

solution GOR



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

IGIP in our OIL Reservoir?

$$G = N \cdot R_{si} = N \cdot R_{sb}$$

same

1009 scf/STB

Gas Remaining in Reservoir (scf) ?

$$(G - G_p) = 1.009 \cdot 10^{12} - 0.5 \cdot 10^{12} \text{ scf}$$

$$= \underbrace{0.5 \cdot 10^{12} \text{ scf}}$$

(1) Still in solution in the Ro : $\underbrace{(N-N_p) \cdot R_s}$

\+

$\underline{\underline{V_g}}$ (2) "Free" Gas saturation (phase) in "RG"

$$V_g = \left[\overbrace{(G-G_p) - (N-N_p) R_{s(p)}}\right] \cdot B_{g(p)} \qquad \cancel{\text{scf}}\ \text{ft}^3$$

*

Convert scf → Reservoir ft^3 : B_g

$$\boxed{B_g} = \frac{V_g(p,T)}{V_{\bar{g}}}$$

$$* \quad R_{s(p)} = \overset{1009}{R_{sb}} - \left(\overset{1518}{R_{sd,b}} - R_{sd(p)}\right) \cdot \overset{\left(\frac{1.674}{2.075}\right)}{\left(\frac{B_{ob}}{B_{odb}}\right)}$$

$$B_g = \frac{p_{sc}}{T_{sc}} \cdot \frac{Z\,T_R}{p_R} \qquad \frac{ft^3}{scf}$$

$$5.615 \ ft^3/bbl$$

$$HCPV = N \cdot B_{oi} \qquad [RB]$$

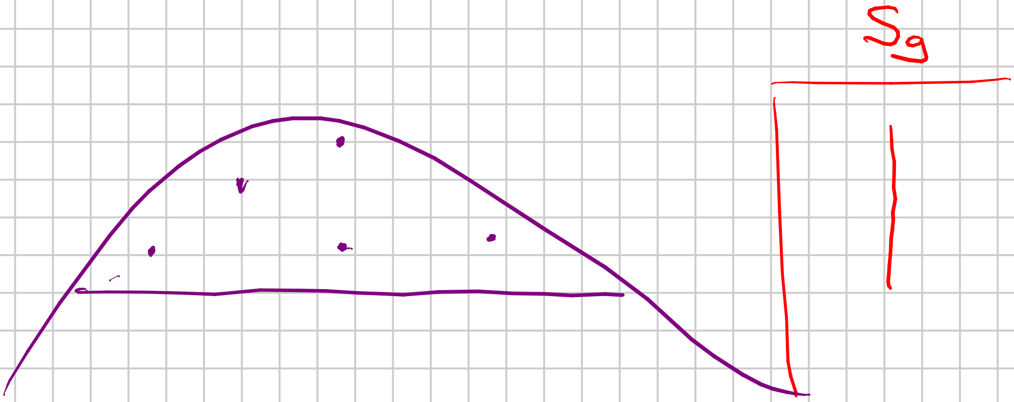
$$k_{ro} = S_{on}^{2.5}$$

$$k_{rg} = (1 - S_{on})^{2.5}$$

$$\frac{k_{rg}}{k_{ro}}(p) = \frac{(1-S_{on})^{2.5}}{S_{on}^{2.5}}$$

$$R_p = \underset{\left(\frac{scf}{STB}\right)}{\underset{\uparrow}{R_s}} + \underbrace{\overbrace{\left(\frac{k_{rg}}{k_{ro}}\right)\left(\frac{\mu_o B_o}{\mu_g B_g}\right)}^{vol/vol} \cdot \overset{\frac{ft^3}{bbl}}{\overset{\downarrow}{\underline{5.615}}}}_{\left(\frac{scf}{STB}\right)}$$

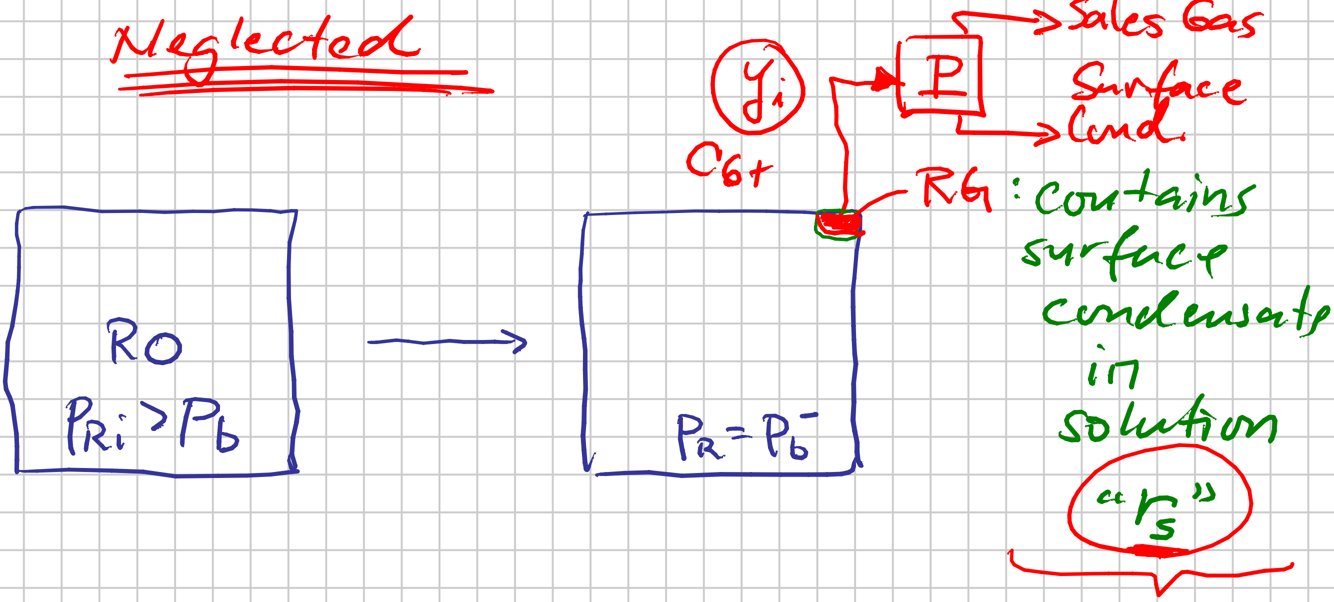
Uniform gas saturation distribution
thru out the reservoir



Assumed in the Quiz Solution:

- Surface Gas dissolved in Reservoir Oil ✓
- Surface Oil (Condensate) in solution in Reservoir Gas?

Neglected



Gas Condensate Discussion:

Gas Composition ⟺ • CGR
• OGR
• "Liquid yield"

y_i

C_{6+}

What DLE "data" indicates the magnitude of r_s?

(CGR)

"γ_{gDLE}"

$$M_{gR} = y_{\bar{g}} M_{\bar{g}} + \underbrace{(1-y_{\bar{g}})}_{\text{Cond.}} \cdot M_{\bar{o}}$$

$$\frac{M_{gR}}{M_{air}} = (1-y_o)\frac{M_{\bar{g}}}{M_{air}} + y_{\bar{o}}\frac{M_{\bar{o}}}{M_{air}}$$

$$\gamma_{gR} = \gamma_{gDLE} = (1-y_o)\,\gamma_{\bar{g}} + y_{\bar{o}} \cdot \frac{140}{28.97}$$

$$0.87 = (1-y_o)\,0.7 \uparrow$$

$M_{\bar{o}} \sim 140$ (120, 160)

Solve @ $p = 2938$ for $\boxed{y_{\bar{o}}}$

Mole frac. of RG becomes surface Condensate

Recall

$\rho\,[kg/m^3]$

Table 5.2 using $M_{\bar{o}} = 140$

$$(r_s) = CGR = \frac{y_{\bar{o}}}{(1-y_{\bar{o}})} \cdot \frac{(M_{\bar{o}}/\rho_{\bar{o}})}{\underbrace{(RT_{sc}/p_{sc})}_{23.64}}$$

Sm^3/Sm^3

$$\boxed{0.87 = (1-\underline{y_o})\,0.7 + \underline{y_o}\,\underbrace{\frac{140}{29}}_{4.83}}$$

$$0.87 = y_o(4.83-0.7) + 0.7$$

$$\frac{0.87-0.7}{4.83-0.7} = y_o$$

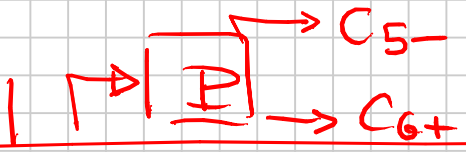
$$\frac{0.17}{4.13} = y_o$$

$$y_o = 0.041 = 4.1 \text{ mol-}\%$$

$M_o = 140$ (est.)

Table 5.2 ⇒ $\rho_o \sim 790$ kg/m^3

$(\gamma_o \sim 0.79)$



$$\boxed{CGR \cong \frac{\textcircled{0.041}}{1-0.041}\cdot\frac{(140/790)}{(23.64)}}$$

$$\left[\frac{Sm^3}{Sm^3}\right] = 3.22\cdot 10^{-4}$$

$$\textcircled{r_s} = 322\ Sm^3/10^6\ Sm^3$$

$$\textcircled{r_s} = 57\ STB/MMscf$$

@2938 psig first DLE stage

Returning to GAS CONDENSATE PVT

× Ch. 6

2 papers

* e-note GC-PVT

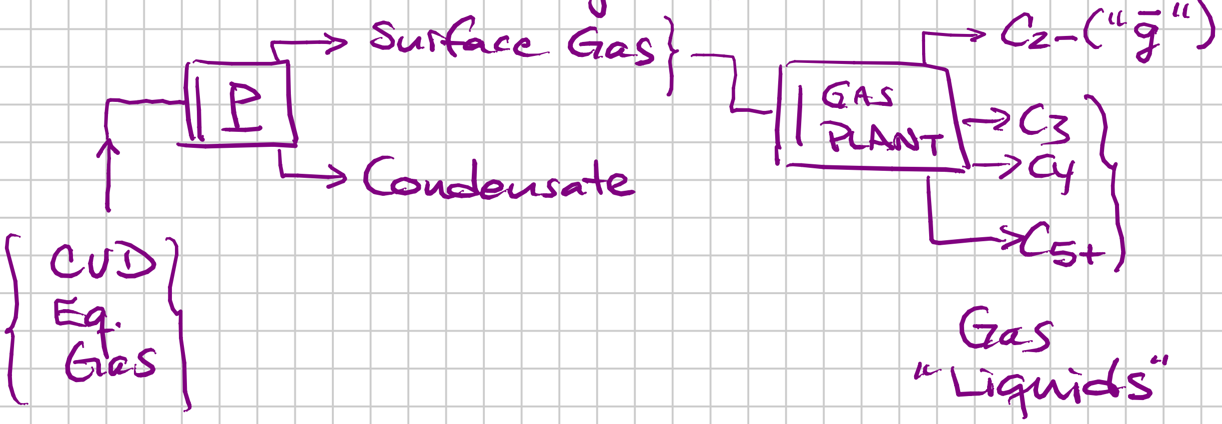
CVD

- Eq. Gas Removed
  - Amount mol-% of Initial Moles @ p_d
  - Composition
    - ! C_{6+} ⇒ Surface Condensate
    - Properties (M_{6+}, γ_{6+}) ⇒ convert moles ⇒ volume
  - Z-factor

Some Labs ||

Ch.6

  - Surface Process Analysis (calculations)



- Eq. Oil (Reservoir Condensate)
  - $V_o/V_d \simeq S_{on} = S_o/(1-S_w)$

    Very, very good approximation of

the reservoir average oil saturation

at $p_{CVD} \sim p_R$

! $\lambda_o = \frac{k_{ro}}{\mu_o} \sim 0 \quad << \quad \lambda_g$

- Final stage oil composition (highly recommended to obtain)
  - can and should be used to QC the lab GAS COMPOSITIONS (C6+ amounts) use the "backward material balance"

$$\underbrace{\left(1-\sum z_i K_i\right)}_{BP} \cdot \underbrace{\left(1-\sum z_i / K_i\right)}_{DP} = 0$$

$$CGR = \underbrace{r_{si} = r_{sd}}_{same} = \frac{y_{6+}}{1-y_{6+}} \cdot \frac{(M/\rho)_{6+}}{23.64}$$

$p > p_d$

$r_s = \text{const.}$

$\shortparallel$

$r_p = \text{const}$

$$\left(\frac{M}{\rho}\right)_{6+} \simeq \left(\frac{M}{\rho}\right)_{7+} = \left(\frac{143}{795}\right)$$

0.179

$$= \frac{0.0864}{1-0.0864} \cdot \frac{0.179}{23.64} \cdot 10^6$$

$$= \underline{716} \quad Sm^3/10^6 Sm^3$$

$$r_s(2900\ psig) = \frac{0.0593}{1-0.0593} \cdot \frac{(128/780)}{23.64} \cdot 10^6$$

$$= \boxed{438} \quad Sm^3/10^6 Sm^3$$

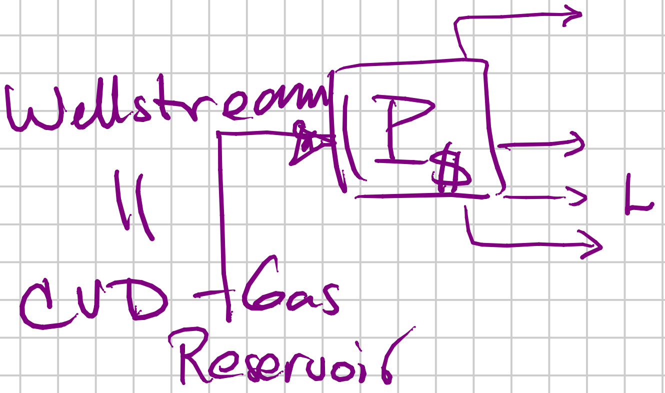
$STB/MMscf$

$$438 \cdot 10^{-6} \frac{\cancel{Sm^3}}{\cancel{Sm^3}} \cdot \frac{6.28\ STB}{\cancel{Sm^3}} \cdot \frac{\cancel{Sm^3}}{35.31\ scf}$$

$$= \underline{77.8 \cdot 10^{-6}} \frac{STB}{scf} \times \frac{10^6\ scf}{MMscf}$$

$$= \underline{77.8 \quad STB/MMscf}$$

r_s (2900 psig)



$$\begin{array}{c} RF_{iL} \\ \hline 30\%\ C_4 \\ 60\%\ C_5 \\ 100\%\ C_{6+} \end{array} \Bigg\} \text{Condensate}$$

$(M/\rho)_{cond}$?

$$\boxed{\Rightarrow 93\ \text{STB/MMscf}}\ ?$$

" weighed
u_i = mole fraction"

$$\rho_{cond} = \frac{\sum u_i M_i}{\{\sum u_i M_i/\rho_i\}} = \frac{\text{mass}}{\text{volume}}$$

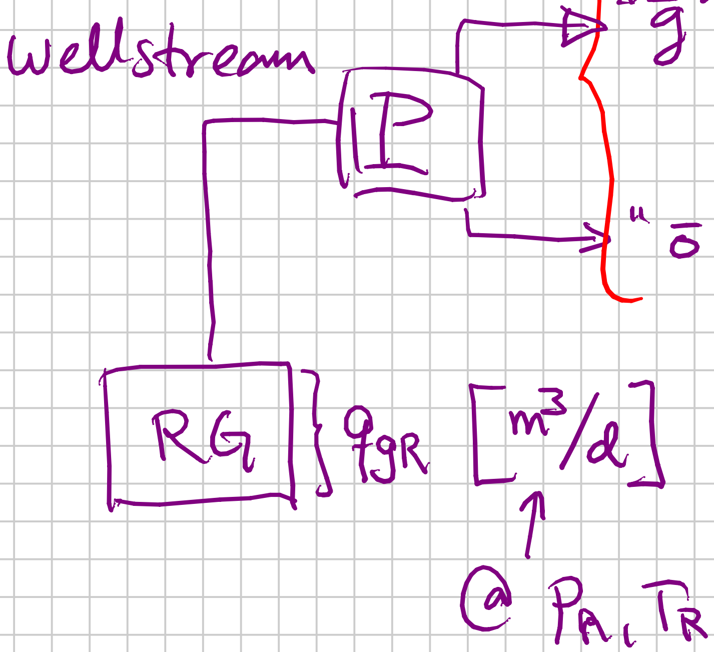
$$M_{cond} = \frac{\sum u_i M_i}{\sum u_i} = \frac{\text{mass}}{\text{moles}}$$

$$u_i = \underline{\underline{RF_{iL}}} \cdot \text{mole fraction of wellstream}$$

express it as a "<u>wet gas</u>"

"$\bar{g}$" $q_{\bar{g}}$? "dry gas"

"$\bar{o}$" (wetness removed) condensate



$$? \quad \boxed{B_{gd}} = \frac{V_g}{V_{\bar{g}}} = \frac{q_{gR}}{q_{\bar{g}}}$$

WANT & NEED

Dry Gas Formation Volume Factor

$$\boxed{B_{gw} = \frac{P_{sc}}{T_{sc}} \cdot \frac{Z\,T_R}{P_R}}$$

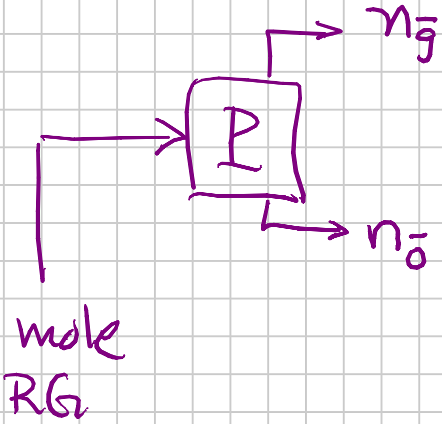
Wet Gas FVF

Reservoir Gas Becomes ONLY Surface Gas

$r_s = 0$

$$B_{gd} = \frac{V_{gR}}{V_{\bar{g}}}$$

$$\frac{V_{gR} = \dfrac{n \cdot \cancel{R} T_R Z_R}{P_R}}{V_{\bar{g}} = \dfrac{n_{\bar{g}} \cancel{R} T_{sc} \cancel{(1)}}{P_{sc}}} = B_{gd}$$



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

$$B_{gd} = \underbrace{\frac{P_{sc}}{T_{sc}} \cdot \frac{T_R Z_R}{P_R}}_{} \cdot \frac{1}{(n_{\bar{g}}/n)}$$

"B_{gw}"

$$\frac{n_{\bar{g}}}{n} = 1 - \frac{n_{\bar{o}}}{n} \cong 1 - C_{6+} \text{ mole frac}$$

$$= 1 - (z_w)_{6+}$$

$\uparrow$

wellstream
mole
fraction

$$B_{gd} = B_{gw} \cdot \frac{1}{1 - z_{w6+}}$$

2900 psig CVD Test:

B_{gw}

$Z_R = 0.748$

$\boxed{z_{w6+}} = y_{6+} = 0.0593$

$T_R = 186\,°F = 646\,°R$

$P_R = 2914.7$ psia

$$B_{gd} = \frac{14.7}{520} \cdot \frac{646\,(0.748)}{2915} \cdot \frac{1}{1 - 0.0593}$$

$$= \underline{0.00498} \ \ \text{ft}^3/\text{scf}$$

$$b_{gd} = 200 \quad \frac{scf}{ft^3} = \frac{1}{B_{gd}}$$

Problem 16 - Calc Upper Sat. Press.
Lower DP

$S_{BP}(p) \equiv$ BP Eq : $\boxed{1 - \sum y_i = 0}$

Know z_i, $K_i(p, p_K; T)$

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

$$\Rightarrow y_i = \underset{\checkmark}{z_i}\,\underset{\checkmark}{K_i}$$

$$y_i(p) = z_i \cdot K_i(p)$$

DP : $S_{DP}(p) = 1 - \sum x_i = 0$

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

$$x_i(p) = z_i / K_i(p)$$

Upper Sat Calc: $S_{BP} \times S_{DP} = 0$

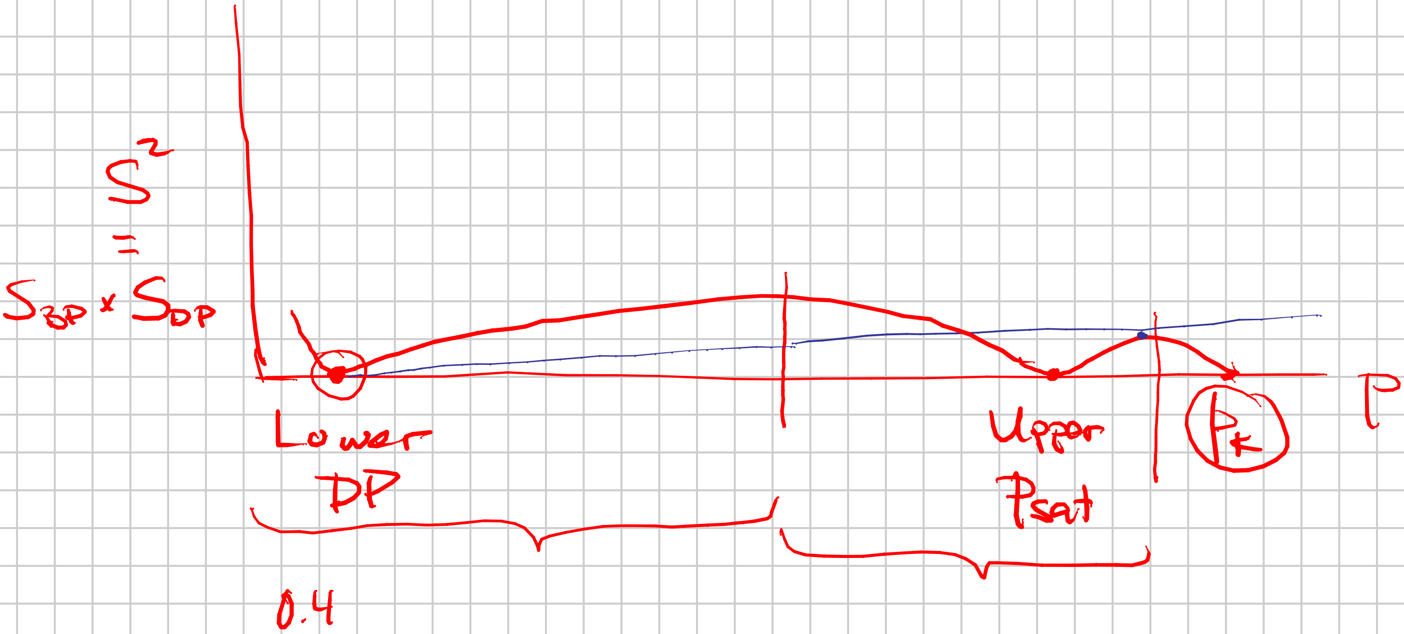
$\boxed{P}$ ← Variable in Solver

z_i	$K_i(p)$	z_iK_i	z_i/K_i
Fixed	↑ Modified Wilson Eq.	$\overline{}$	$\overline{}$

$\underbrace{S_{BP} \qquad S_{DP}}_{?}$ $\boxed{S^2}$

Target → ⓪

Solver



AT CONVERGENCE

Calculate DP

$$\boxed{y_i = z_i}$$

$$x_i = z_i/K_i = y_i/K_i$$

Calculate BP

$$\boxed{x_i = z_i}$$

$$y_i = z_iK_i = x_iK_i$$

DURING SEARCH

Estimate $\hat{x}_i = z_i / K_i$

Estimate $\hat{y}_i = z_i K_i$

Don't know DP or BP

⇓

Calc. both $\hat{x}_i$ & $\hat{y}_i$

Curtis Algorithm

DP

~~Discard $\hat{y}_i$~~

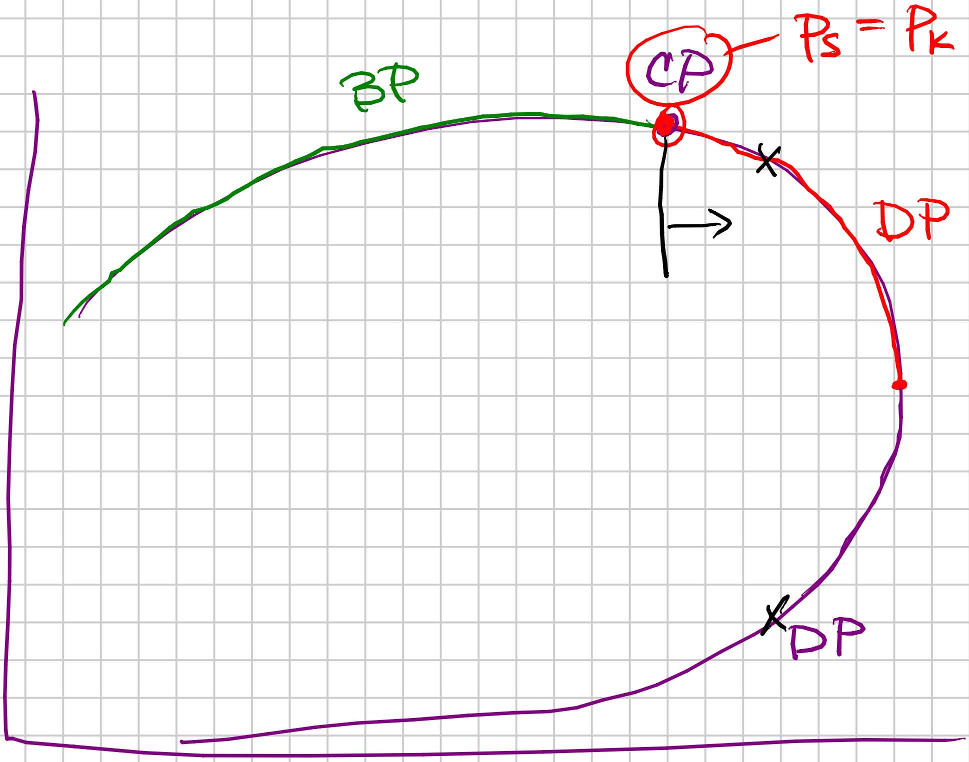
Use $\sum \hat{x}_i = 1$

If $S_{BP} \neq 1$

BP

~~Discard $\hat{x}_i$~~

Use $\sum \hat{y}_i = 1$



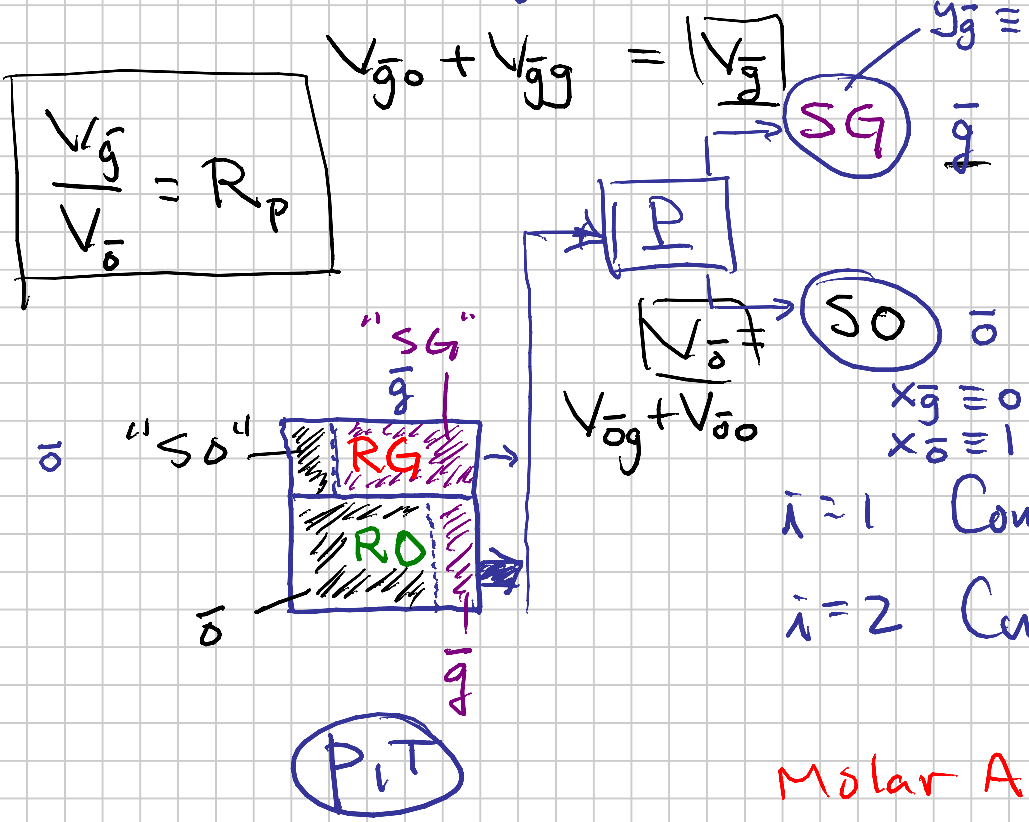
Ch. 7

Black-Oil PVT "Formulation"

Simplify our REAL fluids (100s of i) to a TWO-COMPONENT fluid desciption.

All phases (Gas and Oil) in the reservoir, or at surface consist of these two components.

$$\boxed{\frac{V_{\bar{g}}}{V_{\bar{o}}} = R_p}$$



Two Components ARE Surface Products

$i=1$ Component 1 : SG

$i=2$ Component 2 : SO

Molar Amounts

For example: RG $y_{\bar{g}} = 0.89$ (89%)

$y_{\bar{o}} = 0.11$ (11%)

$$r_p = \frac{V_{\bar{o}}}{V_{\bar{g}}} = \frac{1}{R_p}$$

RO $x_{\bar{g}} = 0.20$ (20%)

$x_{\bar{o}} = 0.80$ (80%)

Q? $K_{\bar{g}} = \frac{y_{\bar{g}}}{x_{\bar{g}}} = \frac{0.89}{0.2} \cong 4.5 \quad > 1$

$K_{\bar{o}} = \frac{y_{\bar{o}}}{x_{\bar{o}}} = \frac{0.11}{0.8} = 0.14 \quad < 1$

By definition @ Surface

SG: $y_{\bar{g}} = 1$, $y_{\bar{o}} = 0$

SO: $x_{\bar{g}} = 0$, $x_{\bar{o}} = 1$

At Reservoir Conditions: "Traditional" Black-Oil

$y_{\bar{o}} \simeq 0$ Assumption (<1975)

RG: $y_{\bar{g}} > 0 \quad y_{\bar{o}} > 0 \quad ; \quad y_{\bar{g}} + y_{\bar{o}} = 1$

RO: $x_{\bar{g}} > 0 \quad x_{\bar{o}} > 0 \quad ; \quad x_{\bar{g}} + x_{\bar{o}} = 1$

In applications we don't use mole or mass fractions (although you could).

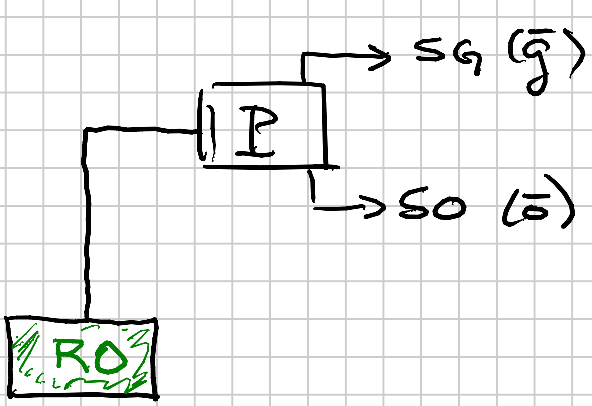
How do we quantify RG & RO "composition" without mass or mole fractions?

(SURFACE)

- USE VOLUME RATIOS

$[Sm^3/Sm^3]$

$[scf/STB]$



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

RO Source

Solution Gas-Oil Ratio of

$[Mscf/STB]$

RESERVOIR OIL

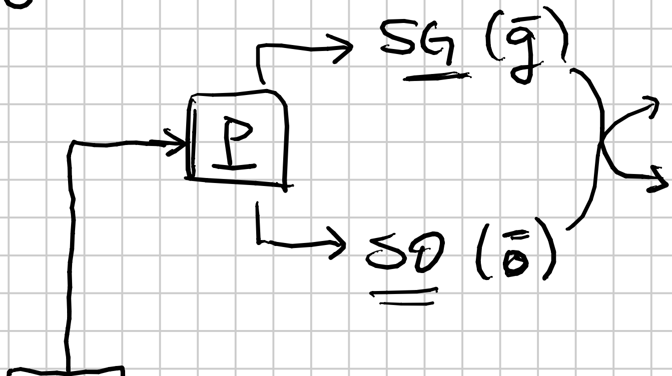
(x_i)

$$\underline{\underline{x_i}} \longleftrightarrow \boxed{R_s}$$

$$V_{og} = V_{\bar{o}g}$$

$[Sm^3/Sm^3]$

$[Sm^3/10^6 Sm^3]$



$$\frac{V_{\bar{o}g}}{V_{\bar{g}g}} \equiv r_s$$

Solution Oil-Gas Ratio of

RESERVOIR GAS

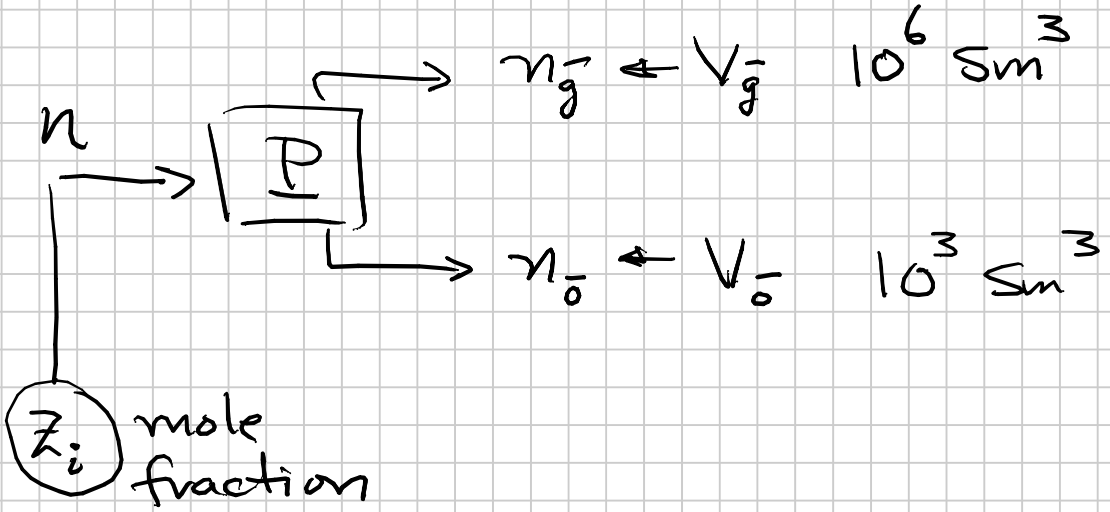
(y_i)

$[STB/scf]$

$[STB/MMscf]$

$$\underline{\underline{y_i}} \longleftrightarrow \boxed{r_s}$$

Conversion between solution GOR or OGR and molar composition.



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

$$V_{\bar{g}} \rightarrow n_{\bar{g}} \; : \; 23.64 \frac{\text{Sm}^3}{\text{kmol}} = \frac{RT_{sc}}{P_{sc}}$$

$$379 \frac{\text{scf}}{\text{lbmol}}$$

$$V_{\bar{o}} \rightarrow n_{\bar{o}} \; : \; n_{\bar{o}} = V_{\bar{o}} \cdot \left(\frac{\rho_{\bar{o}}}{M_{\bar{o}}}\right)$$

$$GOR = \frac{\left(\frac{RT_{sc}}{P_{sc}}\right) n_{\bar{g}}}{\left(\frac{M_{\bar{o}}}{\rho_{\bar{o}}}\right) n_{\bar{o}}} = \frac{\left(\frac{RT_{sc}}{P_{sc}}\right)}{\left(\frac{M_{\bar{o}}}{\rho_{\bar{o}}}\right)} \cdot \frac{n(1-z_{\bar{o}})}{n \cdot z_o}$$

$$z_i : \quad z_{\bar{g}} = \frac{n_{\bar{g}}}{n} = \frac{n_{\bar{g}}}{n_{\bar{g}} + n_{\bar{o}}} = 1 - z_{\bar{o}}$$

$$z_{\bar{o}} = \frac{n_o}{n} = 1 - z_{\bar{g}}$$

$$n_{\bar{o}} = z_{\bar{o}} \cdot n$$

$$n_g = n - z_{\bar{o}}\, n = n(1 - z_{\bar{o}})$$

$$GOR = \frac{(RT_{sc}/p_{sc})}{(M_o/\rho_{\bar{o}})} \cdot \frac{(1 - z_{\bar{o}})}{z_{\bar{o}}}$$

RO:

$R_s = GOR$

$z_i = x_i$

$$OGR = \underbrace{\frac{(M_{\bar{o}}/\rho_{\bar{o}})}{\left(\frac{RT_{sc}}{p_{sc}}\right)}}_{=(\text{"}C_{og}\text{"})^{-1}} \cdot \frac{z_{\bar{o}}}{(1 - z_{\bar{o}})}$$

RG:

$r_s = OGR$

$z_i = y_i$

To you ...

derive expressions for

$y_i = f(r_s) \qquad y_i \longleftrightarrow r_s$

$x_i = f(R_s) \qquad x_i \Longleftrightarrow R_s$

BLACK-OIL PVT FORMULATION

RG: $y_i \longleftrightarrow r_s$ (solution OGR)

RO: $x_i \longleftrightarrow R_s$ (solution GOR)

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

$$GOR = \left(\frac{RT_{sc}}{p_{sc}}\right)\left(\frac{\rho_{\bar{o}}}{M_{\bar{o}}}\right) \frac{1-u_{\bar{o}}}{u_{\bar{o}}}$$

u_i = molar composition $\{y_i \text{ or } x_i\}$

$$K_{\bar{g}} = \frac{y_{\bar{g}}}{x_{\bar{g}}} > 1$$

"g"

"methane-like component"

$$K_{\bar{o}} = \frac{y_{\bar{o}}}{x_{\bar{o}}} < 1$$

"decane-like component"

(may $\to \underset{0}{\epsilon}$)

total $R \to z_i$

$$\left.\begin{array}{l} R_s \to x_i \\ r_s \to y_i \end{array}\right\} K_i = \frac{y_i}{x_i} \Bigg\} RR \to$$

Phase Amounts (F_v)

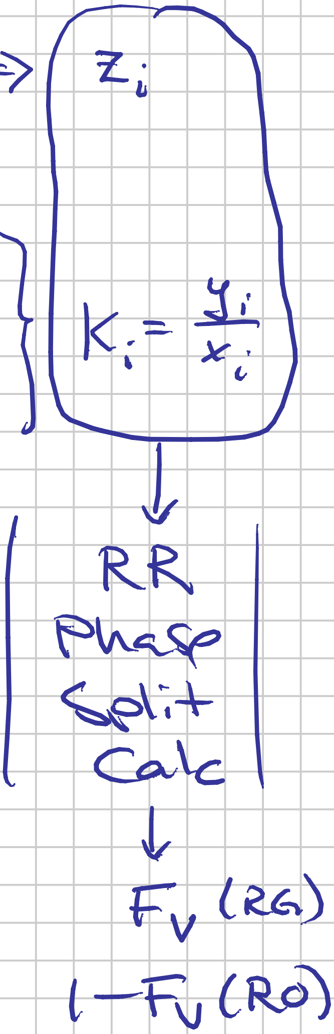
Example: $\gamma_{API} = 42$

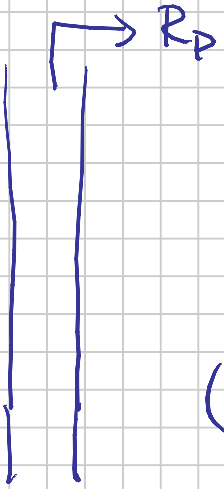
Well Producing $R_p = 300 \ Sm^3/Sm^3 \Rightarrow z_i$

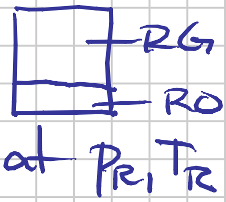
At reservoir $p_R = 300$ bar

$R_s = 180 \ Sm^3/Sm^3 \Rightarrow x_i$

$r_s = 200 \cdot 10^{-6} \ Sm^3/Sm^3 \Rightarrow y_i$







$\left(\frac{M_{\bar o}}{\rho_{\bar o}}\right)$: Table 5.2

Usually know

$\rho_{\bar o}$ (reported as γ_{API})

$$\frac{\rho_{\bar o}}{\rho_{\bar w}} \equiv \gamma_{\bar o} = \frac{141.5}{131.5 + \gamma_{API}}$$

$$\gamma_{\bar o} = \frac{141.5}{131.5+42} = 0.8155$$

$$\rho_{\bar o} = \gamma_{\bar o} \cdot \rho_{\bar w}$$

$$= 0.8155 \, (1000) \ \frac{kg}{m^3}$$

$$= 815 \ kg/m^3$$

$\Rightarrow$ Table 5.2

Est. Cragoe

Ch. 5

$$M_{\bar{o}} = \frac{6084}{\gamma_{API} - 5.9}$$

$$= 168 \text{ kg/kmol}$$

$$\Rightarrow \left(\frac{M_{\bar{o}}}{\rho_{\bar{o}}}\right) = 0.2068 \ \frac{Sm^3}{kgmol}$$

BO Model:

ARE ASSUMED TO

Surface Components have constant properties:

$$\begin{aligned} \rho_{\bar{g}} &= \rho_{\bar{a}} \cdot \gamma_{\bar{g}} \\ \rho_{\bar{o}} &= \rho_{\bar{w}} \cdot \gamma_{\bar{o}} \end{aligned}$$

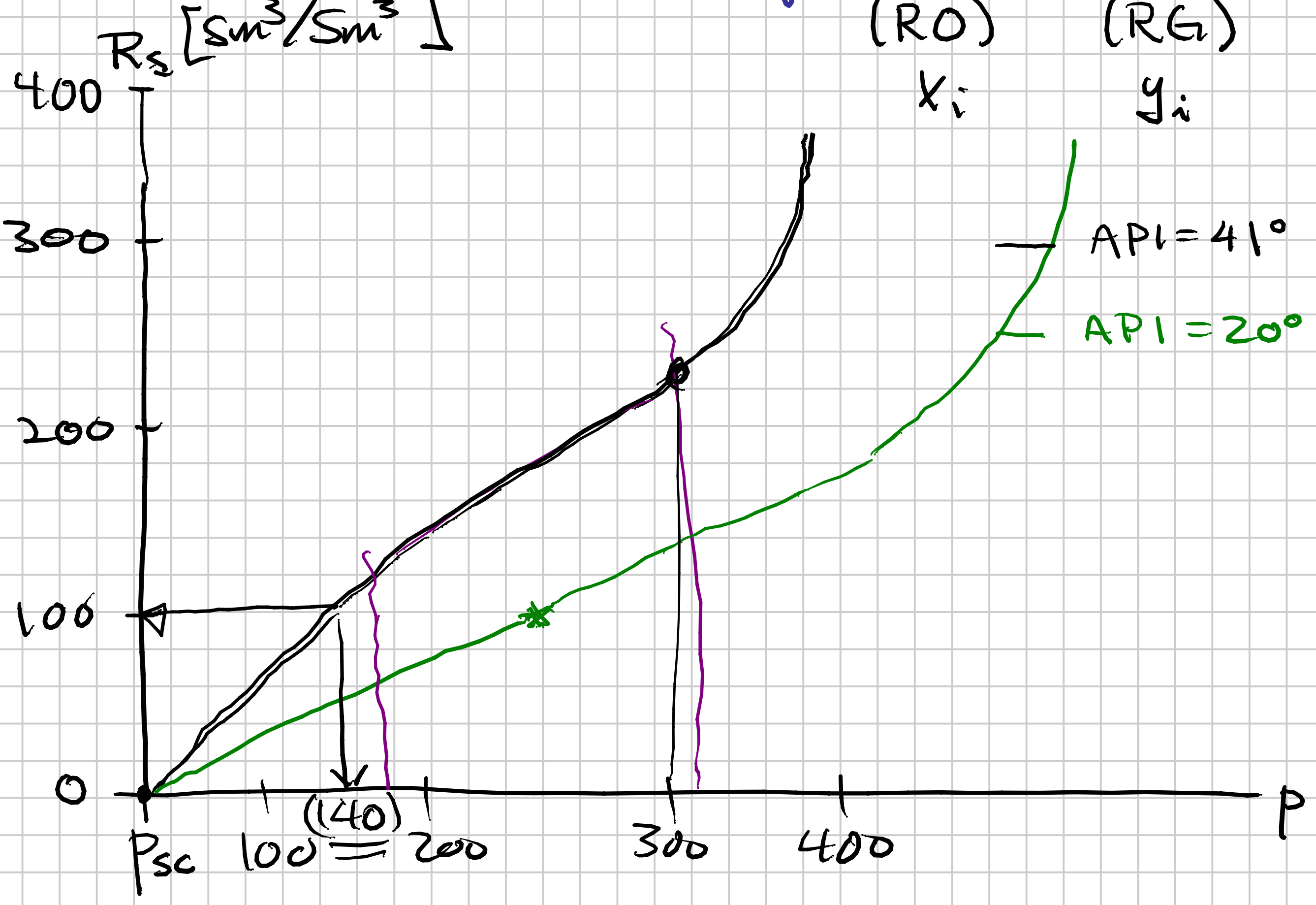
Input

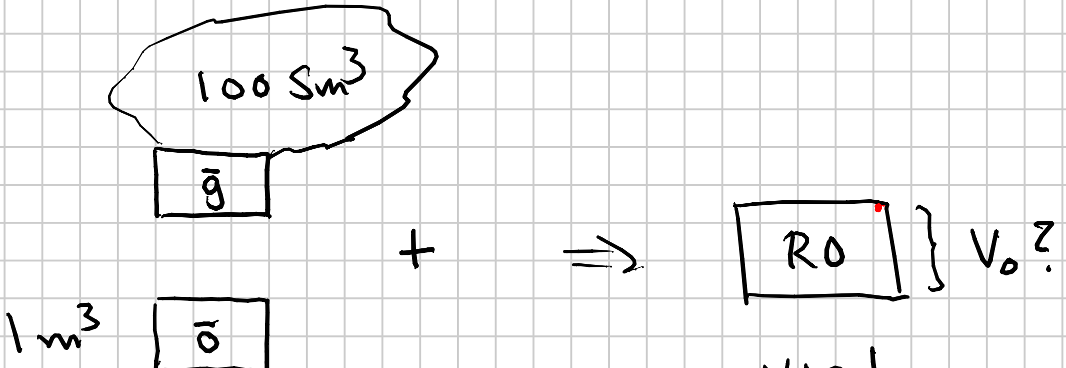
Known (reported)

Pressure Dependence of ✓ R_s & r_s

(RO) (RG)

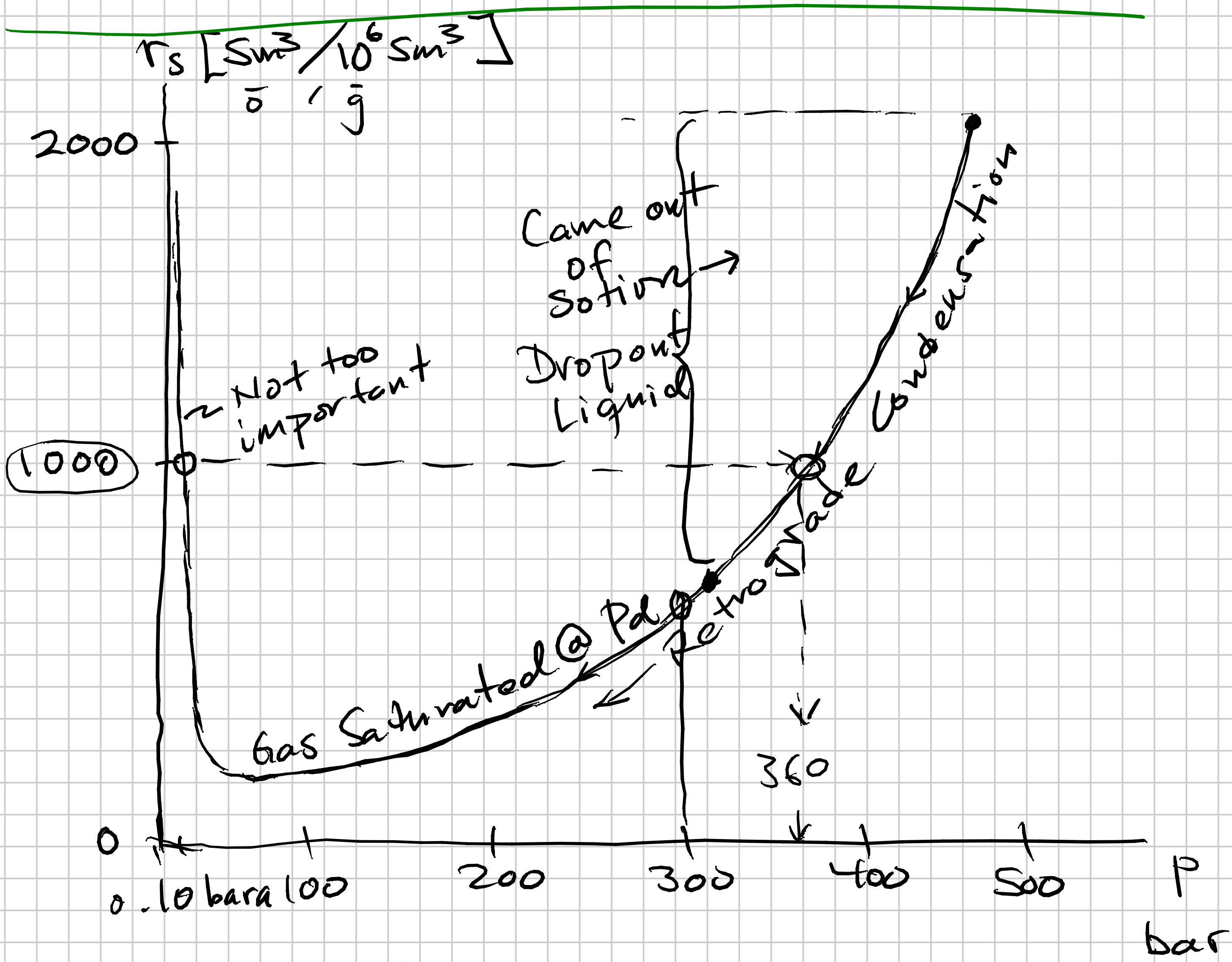
x_i y_i

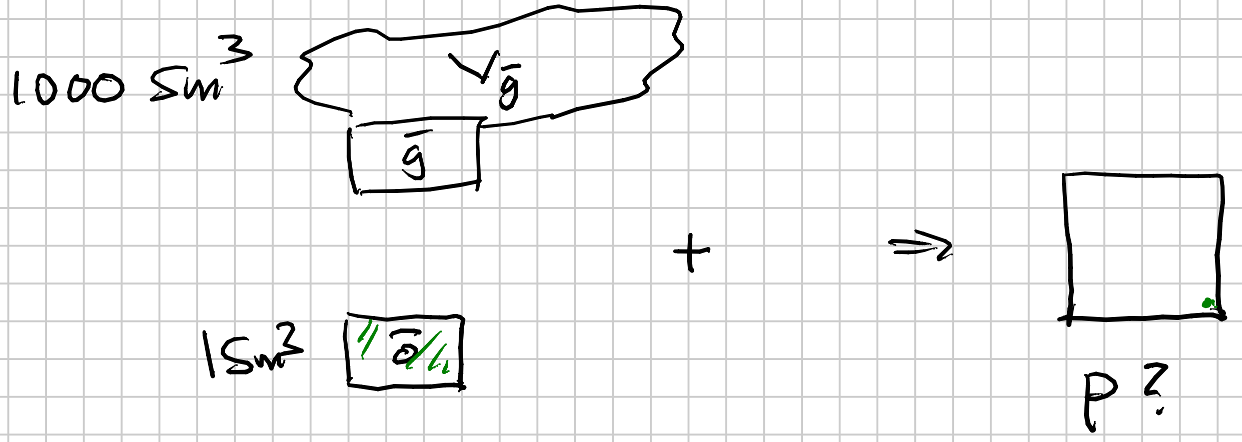




140 bara

P_b of RO



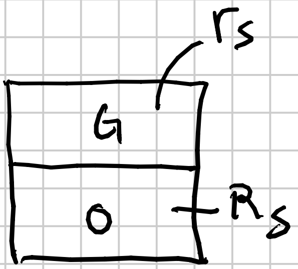


$OGR = \frac{1}{1000} = 0.001 = \underline{1000 \cdot 10^{-6}}\ Sm^3/Sm^3$

$\boxed{\text{"}z_i\text{"}}$

$\boxed{\text{"GOR"}}$ in every lego block at all times

Know:



$\{\overset{x_i}{R_s}, \overset{y_i}{r_s}$ curves$\} \Rightarrow \boxed{K_i}$

$\boxed{P}$

300 bar

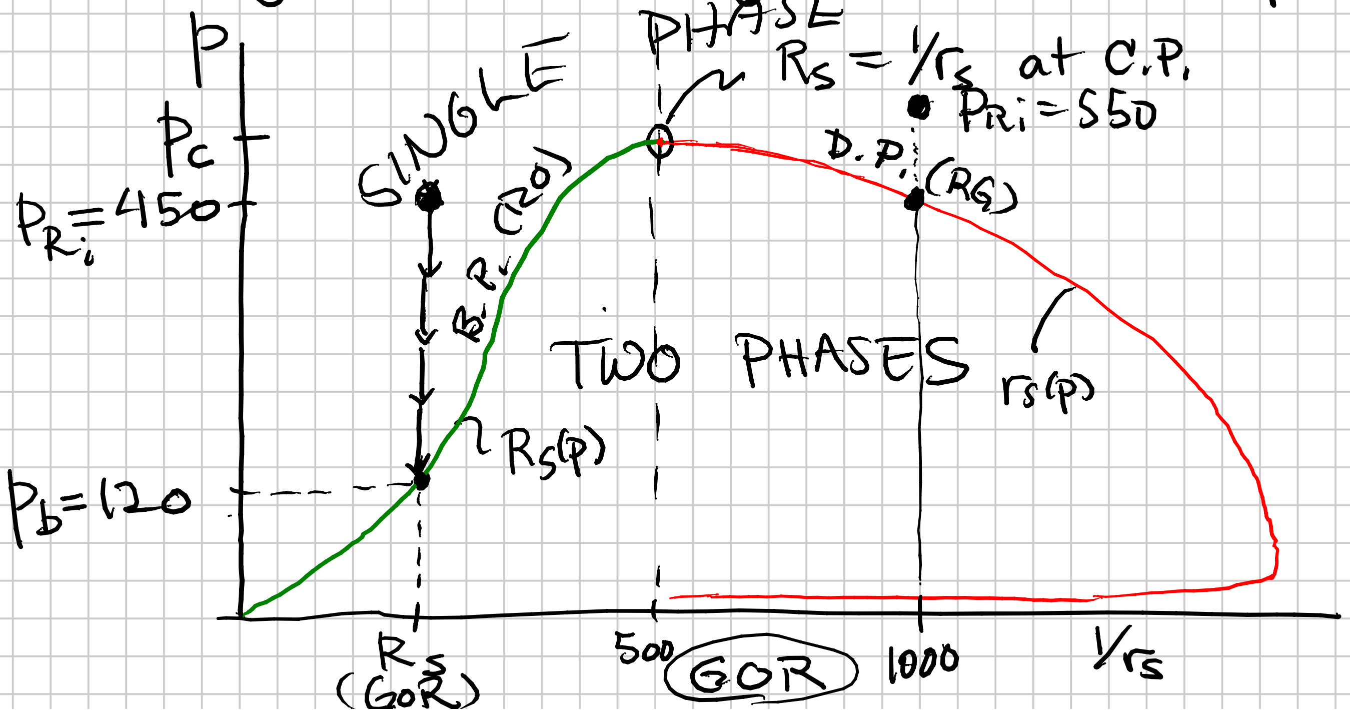
RR
- One Phase
  - → G
  - → O
- Two Phases
  - → Amounts

Discovery Well: GOR = 200 Sm^3/Sm^3

Q1. Is it a gas or an oil?

P_R = 450 bara

Combine the R_s and r_s curves on a single "phase diagram" GOR vs p_s



Q2. $GOR = 1000 \ Sm^3/Sm^3 \Rightarrow P_d = 450$ bara

$P_{Ri} = 550$ bara

$P_{Ri} > P_d$: $\underline{RG}$ undersaturated by ~ 100 bara

Q3. $GOR = \underline{\underline{600}} \ Sm^3/Sm^3$

$P_{Ri} = \underline{\underline{300}}$ bara

(a) G or O or G+O

(b) What are the

G : r_s =

O : R_s =

at $P_{Ri} = 300$ bara GOR vs P_s