

3rd-year Norwegian MS

- + Visiting
- + Intl MS program

CURTIS WHITSON

Tues 10-13

Wed 8-10

- Stud. Assistant Mohsin Siddique
- Buy the book (bring it;
- Its Learning
- Bring calculator + book
- UNITS

Phase Behavior
Whitson - Beuler

- Field (USA-based)
- SI
 - pure (not used)
 - SPE (bar; days; ...)

} practice & work at

- Its Learning
 - Browser

www.ntnu.no

- intranett (ask Tone Sanne)

2nd floor of Gløshaugen Room 202 - ask

- send your Name (First Last) by email
to siddique@stud.ntnu.no

PHASE BEHAVIOR REVIEW

"Petroleum" Technology

Oil & Gas (& Water) phases

Oil & Gas mixtures : composition or compounds making up the mixtures

non-HC $\left\{ \begin{array}{l} N_2 \\ CO_2 \\ H_2S \end{array} \right\}$ found mainly in the gas phase, can also be in sig. amount in oil phase

HC's

- C₁ methane
- C₂
- C₃
- i C₄ butanes
- n C₄
- i C₅
- n C₅
- C₆ (not benzene)
- C₇ (includes benzene)
- many isomers ↓
- complex: C₇₊ $\left\{ \begin{array}{l} \text{paraffins (alkanes)} \\ \text{naphthenes} \\ \text{aromatics} \end{array} \right\}$ PNA

Can be very important in surface production facilities.

H₂O (Water) - usually "removed" when reporting composition - BUT always present in gas & oil mixtures! ✓

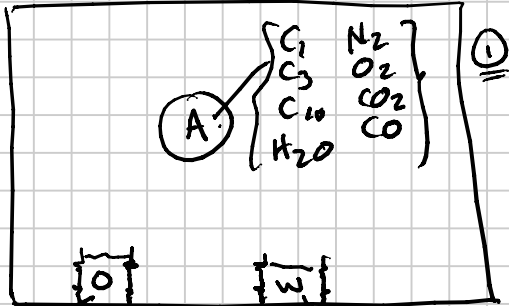
Thermodynamic "State" of phases

- saturated
- undersaturated

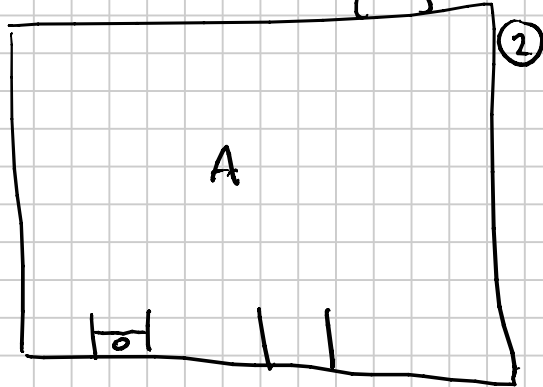
with respect to another phase

"Phase Equilibrium"

O: C₁
C₃
C₁₀
W: H₂O



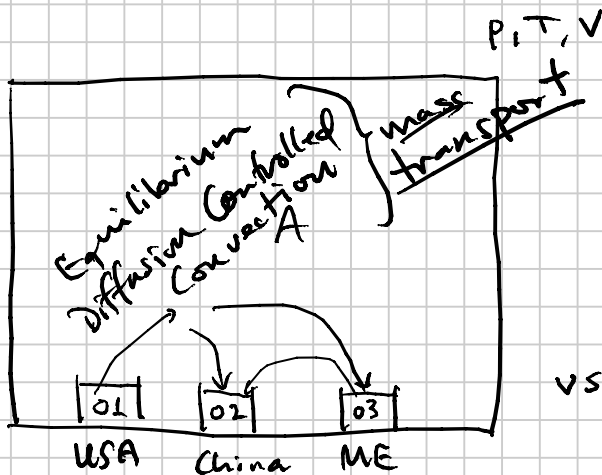
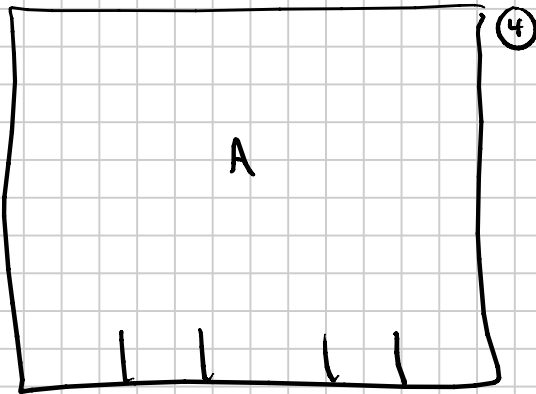
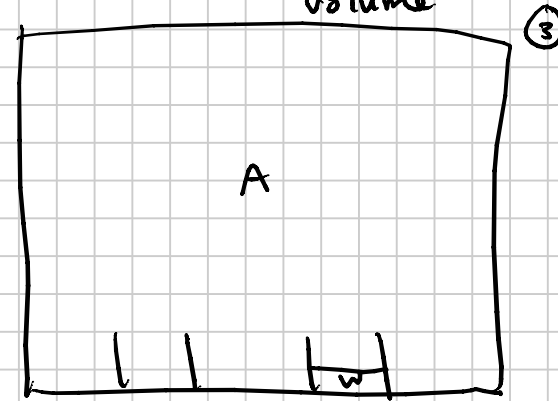
{ C₁ N₂
C₃ O₂
C₁₀ CO₂
H₂O CO }



Outcomes

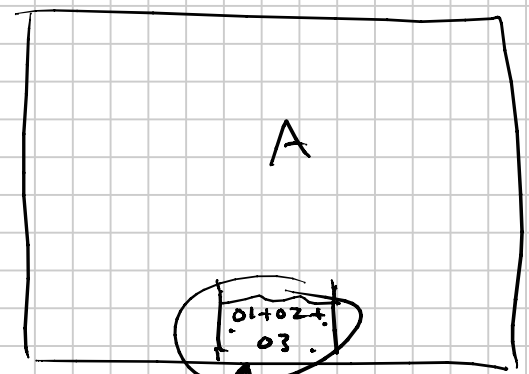
	A	O	W
1. \checkmark O, \checkmark W, \checkmark A	S_{Ow}	S_{Aw}	S_{AO}
2. O A	S_O	S_A	
3. W A	S_W		S_A
4. A	(u - or - $S_w S_o$)		
5. O W			
6. O			
7. W			

X Why?
Can't fill total volume

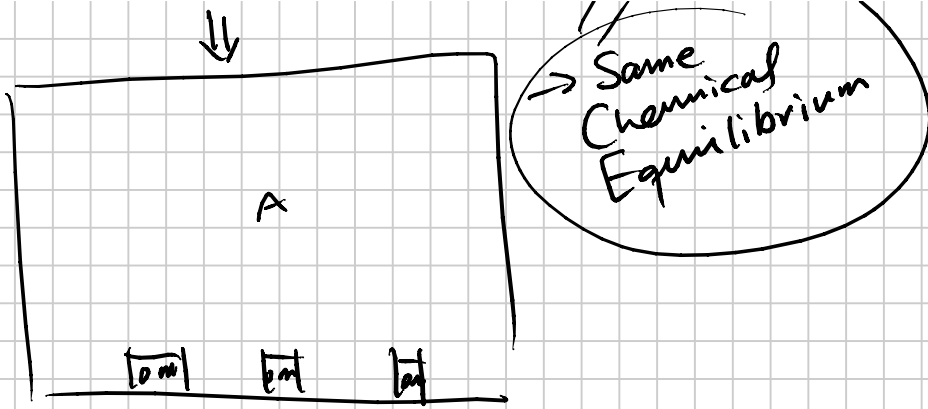


wait a long time...

vs

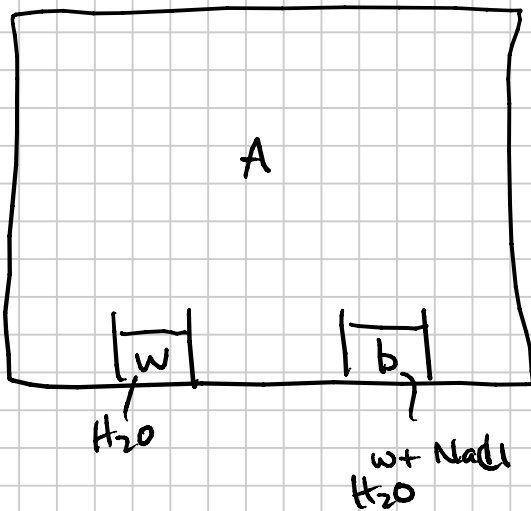
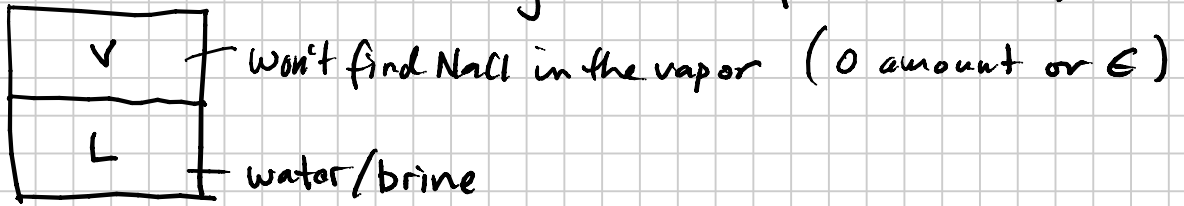


Three oils mix "miscibly" om



Examples of non-partitioning compounds

-e.g. salt compounds (NaCl)



To get access to ItsLearning

- (1) Go to 2nd floor in S32 with student ID (Intranet access)
- (2) Send your First Name, Last Name to Mohsin at
siddique@stud.ntnu.no

Phase (Vapor/Liquid) Equilibrium

VLE

- Several Phases (V, L1, L2)
- States of the Phases (Saturated; Undersaturated)
w.r.t. another phase
- Mixtures (many components; non-HC + HCs — 100s
1000s)
+ H₂O + NaCl

Engineering Goal/Task/Job: at P, T for a given mixture.

- (1) How many phases is our mixture
- (2) How much of each component is found in each phase
- (3) Properties of each phase (μ, ρ, c, \dots, P_s)

How?

- (1) Graphical Charts (based on experimental measurement) Ch. 3
- (2) Equations
 - Empirical (best-fit to our data) ~ 1980 Ch. 3
 - Theoretical (Equations of State) Ch. 4
EOS
- (3) (Strange) Petroleum Models Ch. 7
Stabilized Oil differences "Ch. 5"
- (4) Laboratory measurements Ch. 6

TABLE 2.1—COMPOSITION AND PROPERTIES OF SEVERAL RESERVOIR FLUIDS

Component	Composition (mol%) <u>mass %</u>					
	Dry Gas	Wet Gas	Gas	Near-Critical	Oil	Black Oil
CO ₂	0.10	1.41	2.37		1.30	0.93
N ₂	2.07	0.25	0.31		0.56	0.21
C ₁	86.12	92.46	73.19	(69.44	58.77
C ₂	5.91	3.18	7.80		7.88	7.57
C ₃	3.58	1.01	3.55	↔	4.26	4.09
✓ i-C ₄	1.72	0.28	0.71		0.89	0.91
✓ n-C ₄		0.24	1.45		2.14	2.09
✓ i-C ₅	0.50	0.13	0.64		0.90	0.77
✓ n-C ₅		0.08	0.68		1.13	1.15
✓ C _{6(s)}		0.14	1.09		1.46	1.75
C ₇₊		0.82	8.21		10.04	21.76
Properties						
M _{C₇₊}		130	184		219	228
γ _{C₇₊}		0.763	0.816		0.839	0.858
K _{wC₇}		12.00	11.95		11.98	11.83
GOR, scf/STB	∞	105,000	5,450		3,650	1,490
OGR, STB/MMscf	0	10	180		275	
γ _{API}		57	49		45	38
γ _g		0.61	0.70		0.71	0.70
p _{sat} , psia		3,430	6,560		7,015	5,420
B _{sat} , ft ³ /scf or bbl/STB		0.0051	0.0039		2.78	1.73
ρ _{sat} , lbm/ft ³		9.61	26.7		30.7	38.2

mass ↔ mole
MW
(M)

SI: molar mass

$$M \left(\frac{\text{mass}}{\text{mole}} \right)$$

Units of mass:

kg, g, lb_m,

Units of moles:

mol ≡ gmol

kmol ≡ kgmol

lbmol

C₁: M = 16.04

$$M = 16.04 \frac{\text{g}}{\text{gmol}} \leftarrow$$

$$16.04 \frac{\text{kg}}{\text{kgmol}} \leftarrow$$

$$16.04 \frac{\text{lb}}{\text{lbmol}} \leftarrow$$

Mass "fractions"
(Weight)

w_i: overall mixture
w_{gi}: gas phase
w_{oi}: oil phase

Mole "fractions"

z_i: overall mixture
y_i: gas phase
x_i: liquid (oil) phase

Appendix A

$$M_i \equiv \frac{m_i}{n_i}$$

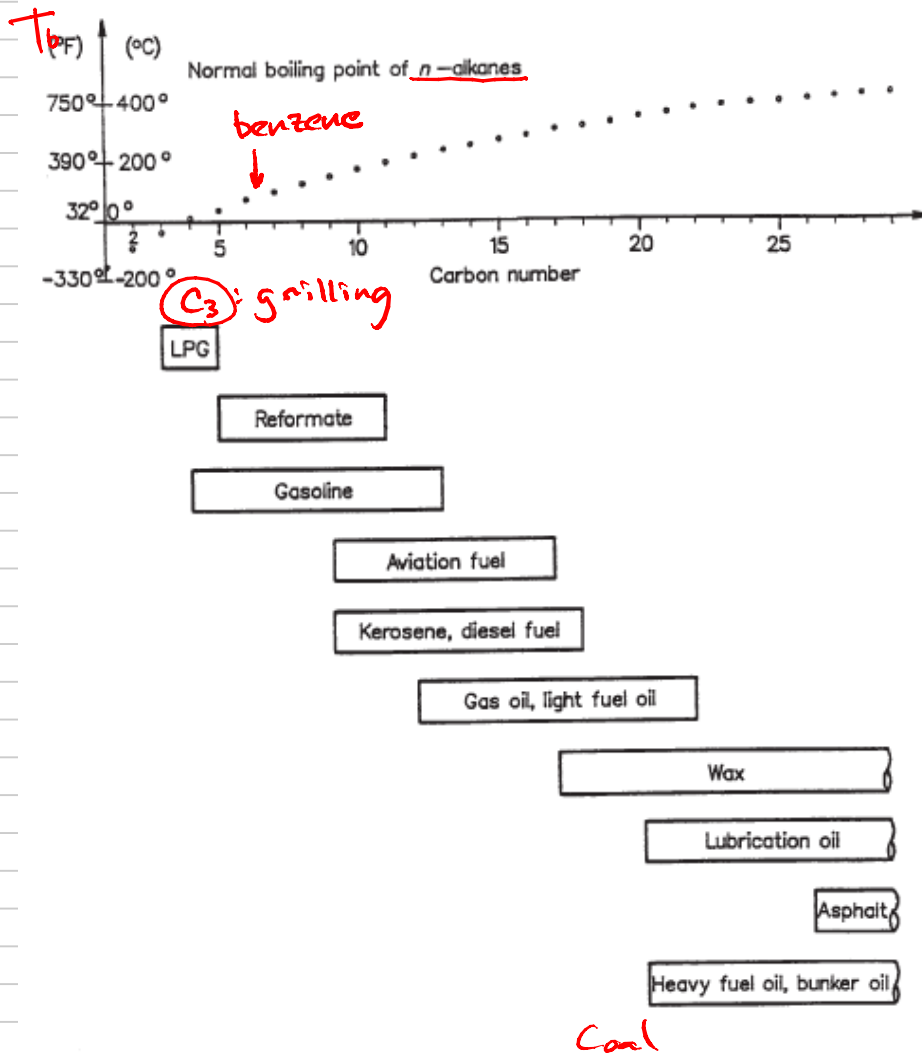
$$z_i \equiv \frac{n_i}{\sum_{j=1}^n n_j} = \frac{n_i}{n}$$

n_i = moles of component i

n = total (sum) of all moles

$$\sum z_i = 1$$

$$w_i = \frac{m_i}{\sum_j m_j} = \frac{m_i}{m} \leftarrow \begin{matrix} \text{mass of } i \\ \text{total mass} \end{matrix}$$



$n-C_6$ 342

$T_b > 342$

Benzene: $T_b = 80^\circ C$

+ 273

353 K

"G" n-

n-C7 371 K

Products, sold from refineries

Fig. 2.1—Petroleum products identified according to carbon number.

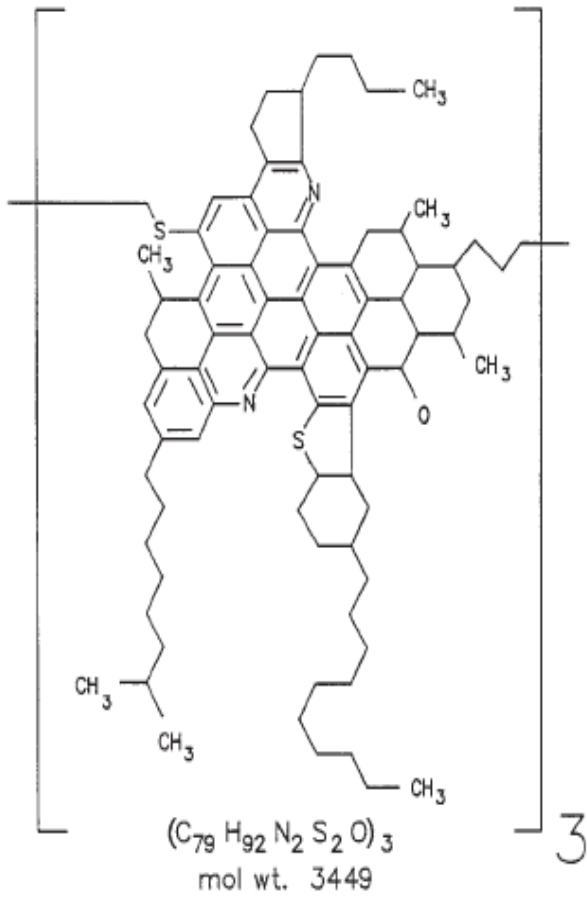


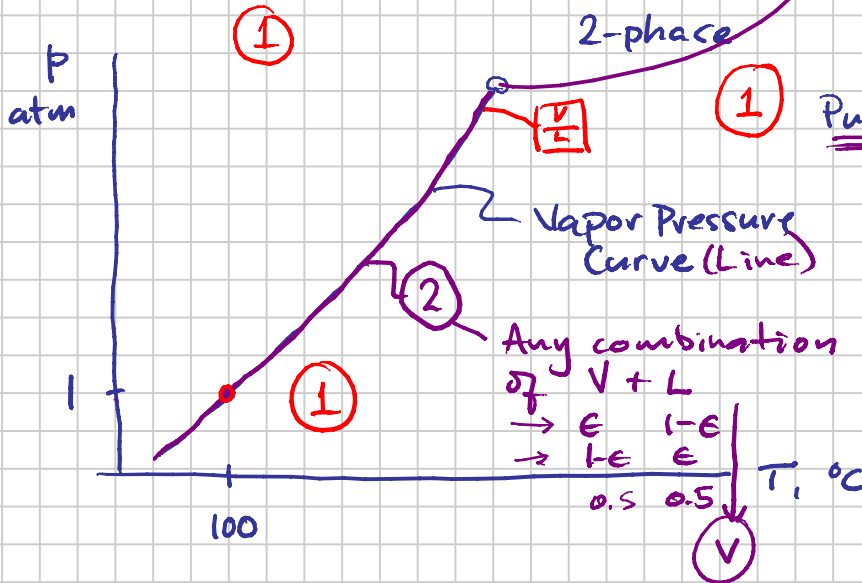
Fig. 2.3—Hypothetical structure of a petroleum asphaltene (after Speight and Moschopedis¹⁴).

Phase Diagrams

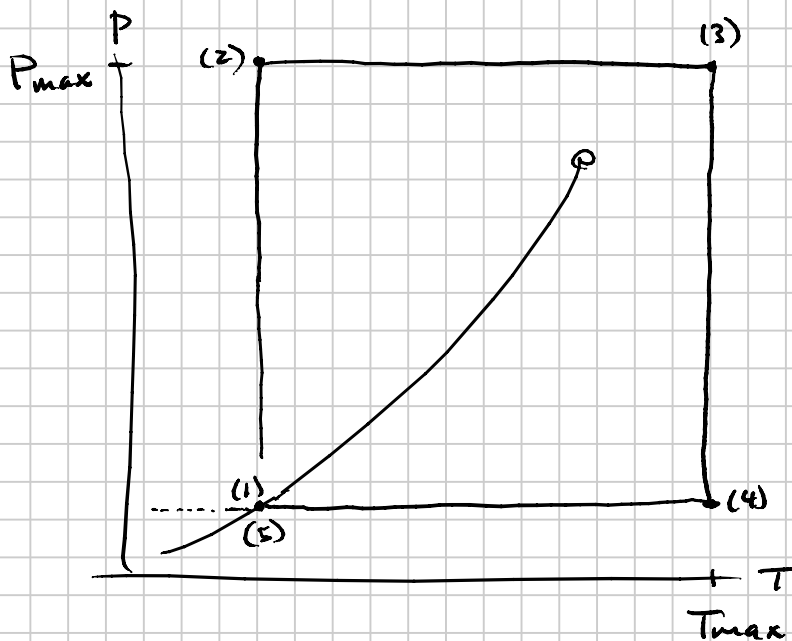
P-T-V

P-T P-V (T-V)

Maps the region(s) of 1-phase

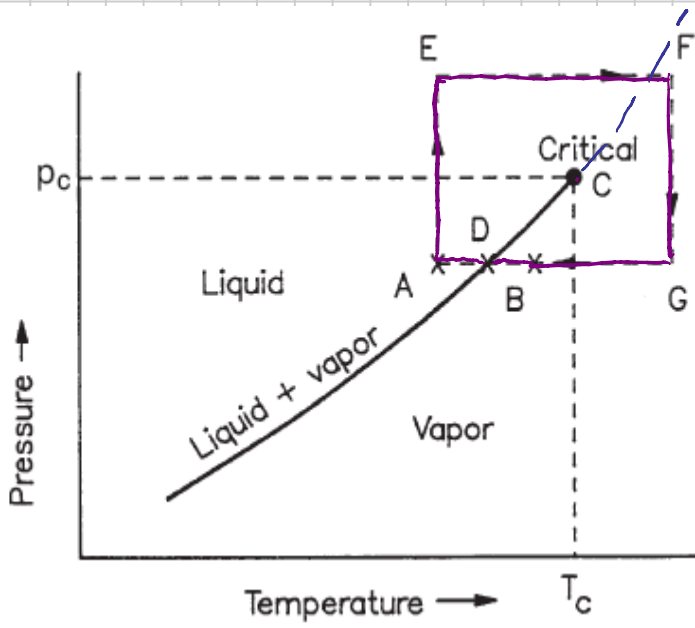


At 1 atm ~ 1.0135 bar
~ 14.7 psia

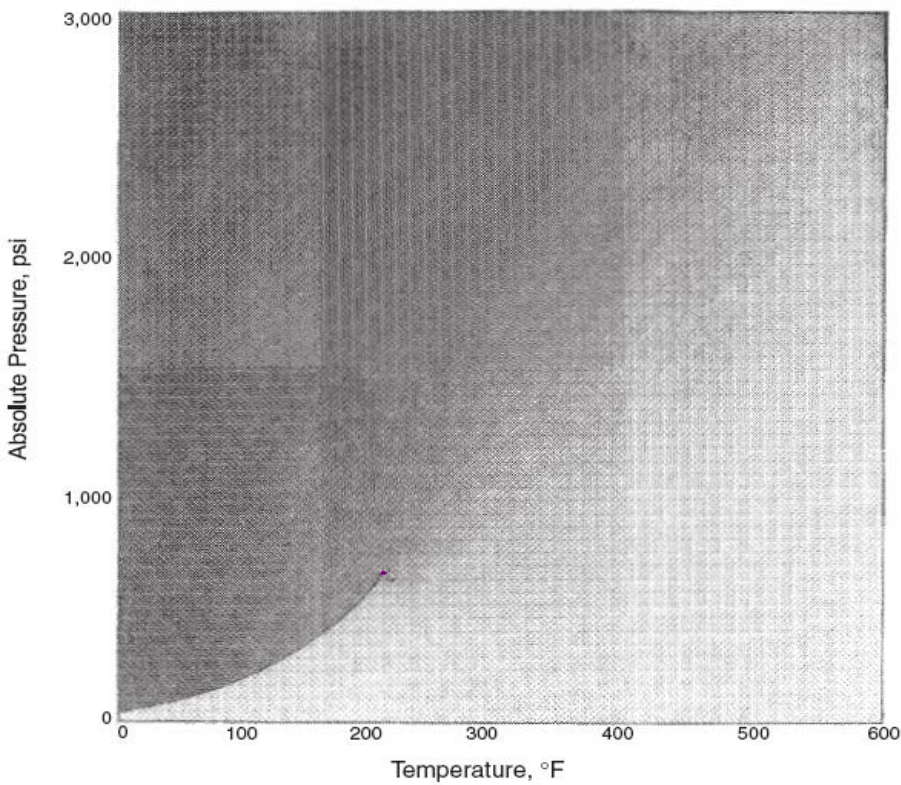
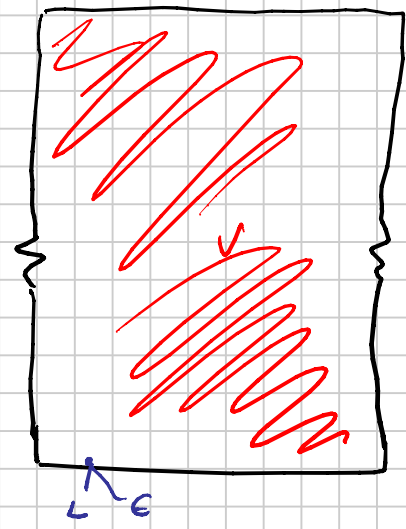


- (1) 1st bubble of steam
- (2) Pressurize @ 100°C
- (3) Heat at P_{max}
- (4) Reduce P @ T_{max} to 1 atm
- (5) Cool at 1 atm to 100°C

[Red scribbled text]



D⁻
A
E
G
B
D⁺



Shading $\propto \rho$

Single Component p-V

H₂O
T = 100°C

T = T_c T > T_c

Liquid Like
slope: "compressibility" $c \equiv -\frac{1}{V} \left(\frac{\partial V}{\partial p} \right)_{T,n}$

$\left(\frac{p_c v_c}{RT_c} \right) \sim \frac{1}{3}$ all compounds

$\frac{dp}{dv} = \frac{d^2p}{dv^2} = 0$ | vander Waals
Critical Criterion

T > T_c
monotonically decreasing

$pV = RT$

$pV = nRT$

"Ideal Gas" Behavior

$v = \frac{V}{n}$

molar volume

SC "standard" conditions

Density: $\text{Mass } \rho = \frac{m}{V} = \frac{M}{v}$
Molar $\rho_m = \frac{n}{V} = \frac{1}{v}$

Ethane: Saturated Liquid Density at 60°F

ρ kg/m³
 ρ_m kg-mol/m³

Fig. 2.7

P_v at 60°F in bar

14.50377 $\frac{\text{psi}}{\text{bar}}$

$^{\circ}\text{C} = (^{\circ}\text{F} - 32) \frac{5}{9}$

$\left[\frac{62.37 \text{ lb/ft}^3}{1000 \text{ kg/m}^3} \right]$

1

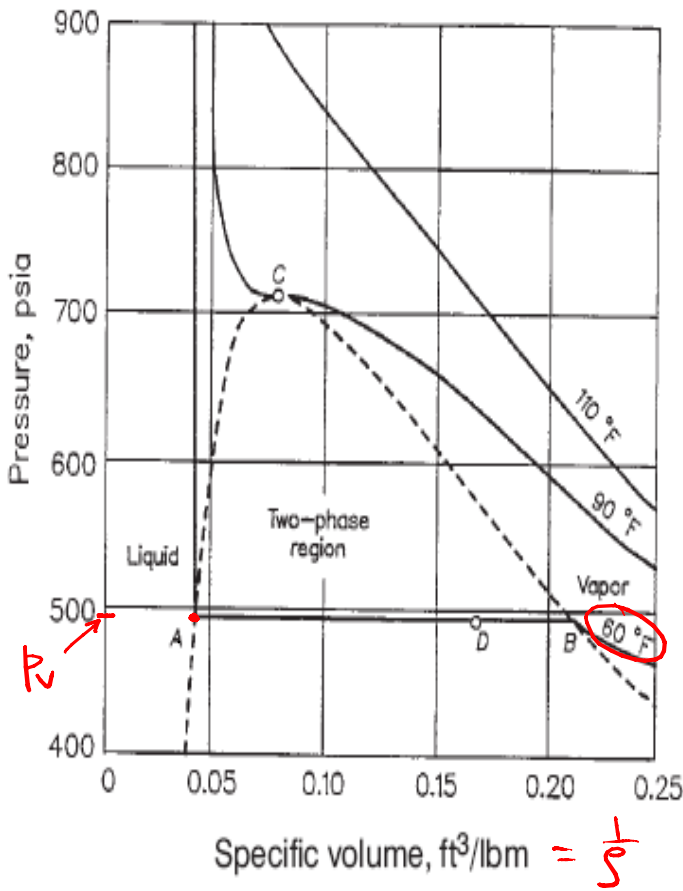


Fig. 2.7— p - V diagram for ethane at three temperatures (from Standing²⁶).

$$\frac{1}{\rho_{SL}} = 0.04 \frac{\text{ft}^3}{\text{lb}}$$

$$\rho_{SL} = 25 \frac{\text{lb}}{\text{ft}^3} \quad \text{lb}_m \text{ lb}_m \text{ "mass"}$$

$$\rho_{SL} = \frac{25 \left(\frac{\text{lb}}{\text{ft}^3} \right)}{\left(\frac{62.37}{1000} \right) \frac{\text{kg}}{\text{m}^3}} = 400.8 \frac{\text{kg}}{\text{m}^3}$$

$$M_{C2} = 30.04 \text{ kg/kg-mol}$$

$$\begin{aligned} (\rho_m)_{SL} &= \frac{400.8 \text{ kg/m}^3}{30.04 \text{ kg/kg-mol}} \\ &= 13.34 \text{ kg-mol/m}^3 \end{aligned}$$

$$p_v = 495 \text{ psia} \leftarrow \text{absolute}$$

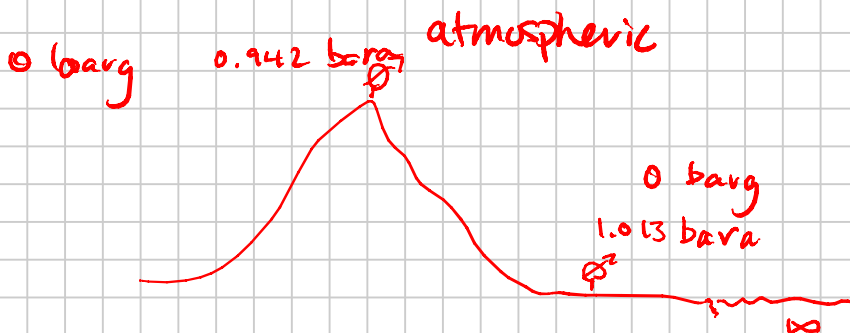
lb_f per in²

Pressure measurement in petroleum:

- absolute
- "gauge" = absolute

$$495 \text{ psia} \cdot \frac{\text{bar}}{14.504 \text{ psi}}$$

$$p_v = 34.1 \text{ bara}$$



psig
psia

62 psi $\left\{ \begin{array}{l} \text{psig} \\ \text{psig} \end{array} \right.$
13 bar $\left\{ \begin{array}{l} \text{barg} \\ \text{barg} \end{array} \right.$

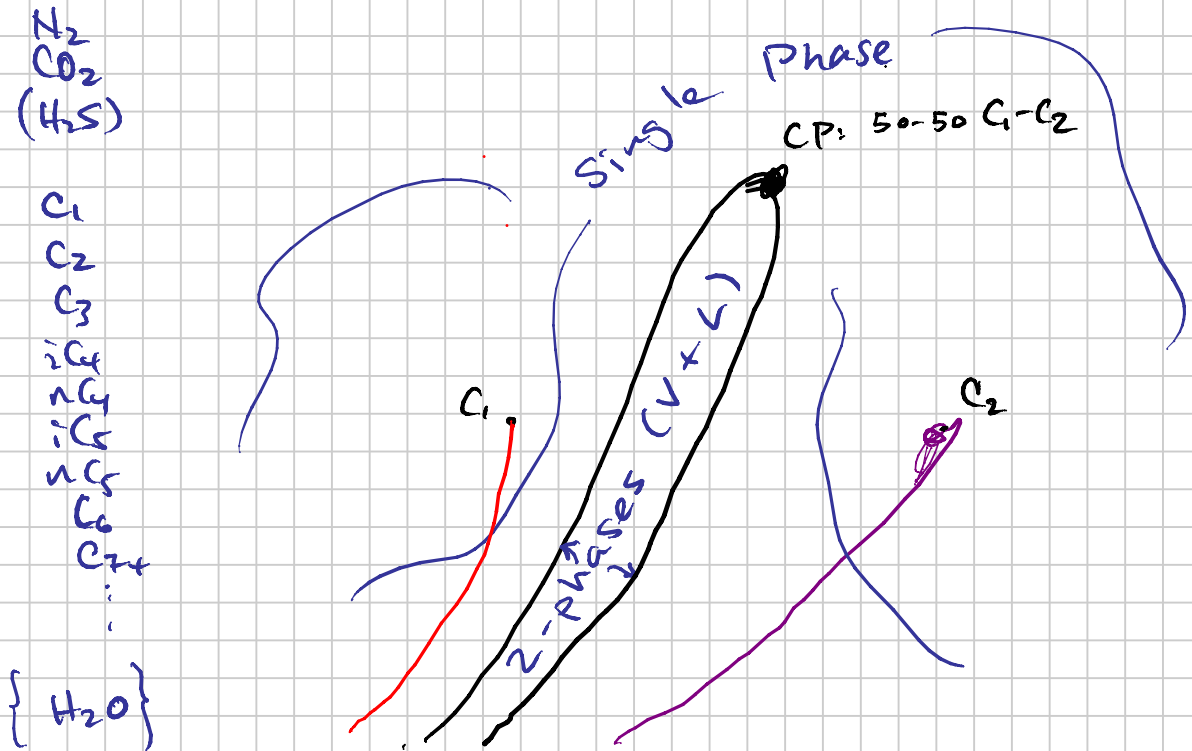
902 bar

Multicomponent Phase Behavior

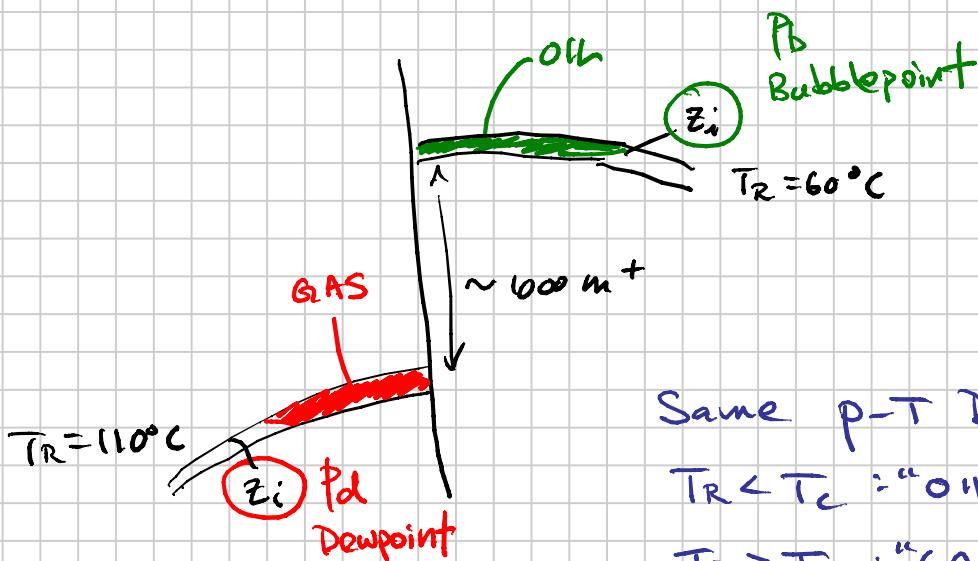
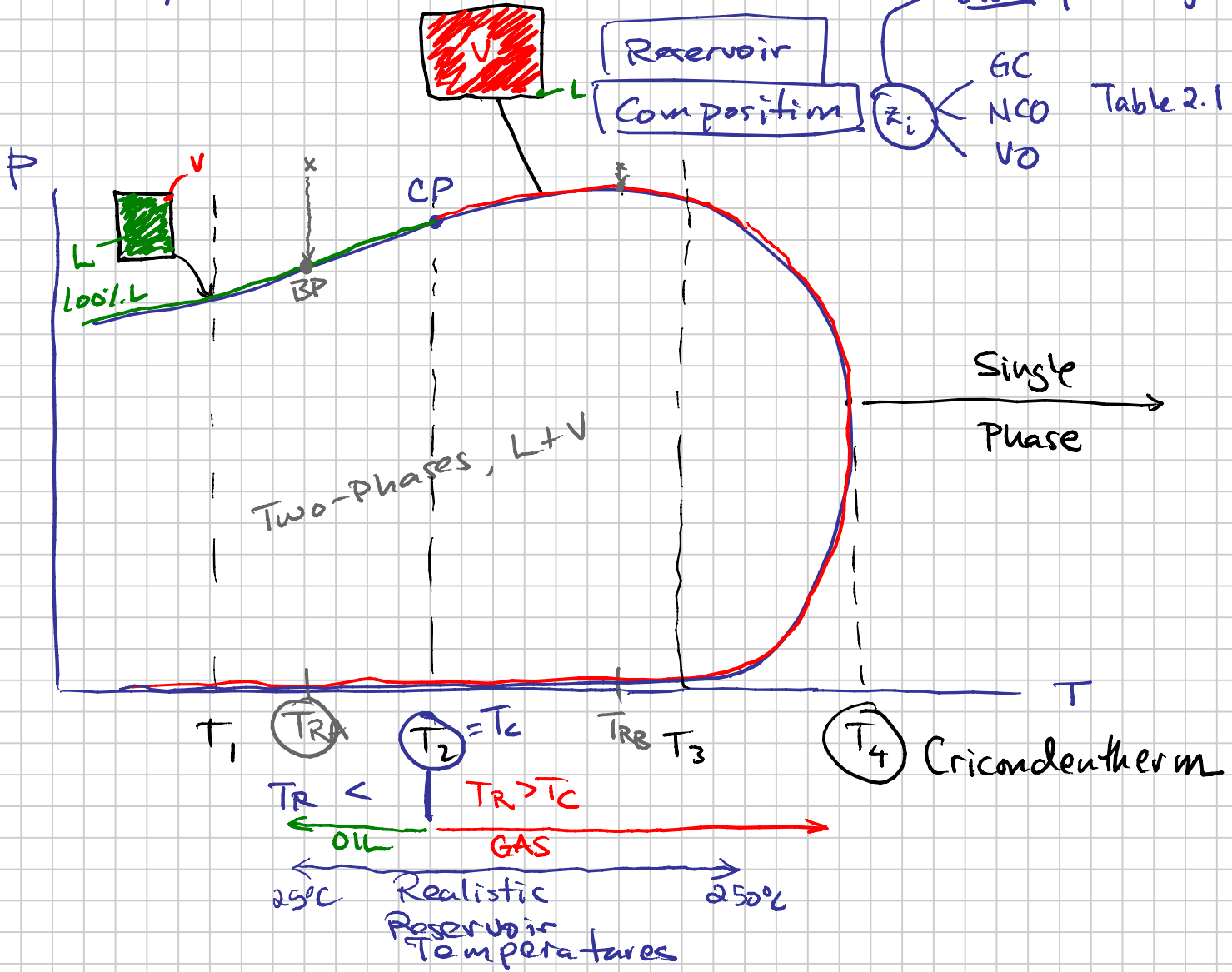
$p-T$ $p-V$ } $\left\{ \begin{array}{l} \text{Total Mixture} \\ \text{Each Phase Separately} \end{array} \right.$
 Phase Definition

Reservoir Fluid "Types" (Labels)

Multiple Components:



"Average" Petroleum Mixture,



Same p-T Diagram.

$T_R < T_c$: "OIL"

$T_R > T_c$: "GAS"

even though the reservoir mixtures are "identical" same composition.

IMPORTANT:

Sissel: Samples

⊗ A given mixture defined by its composition has a unique p-T diagram.

z_i

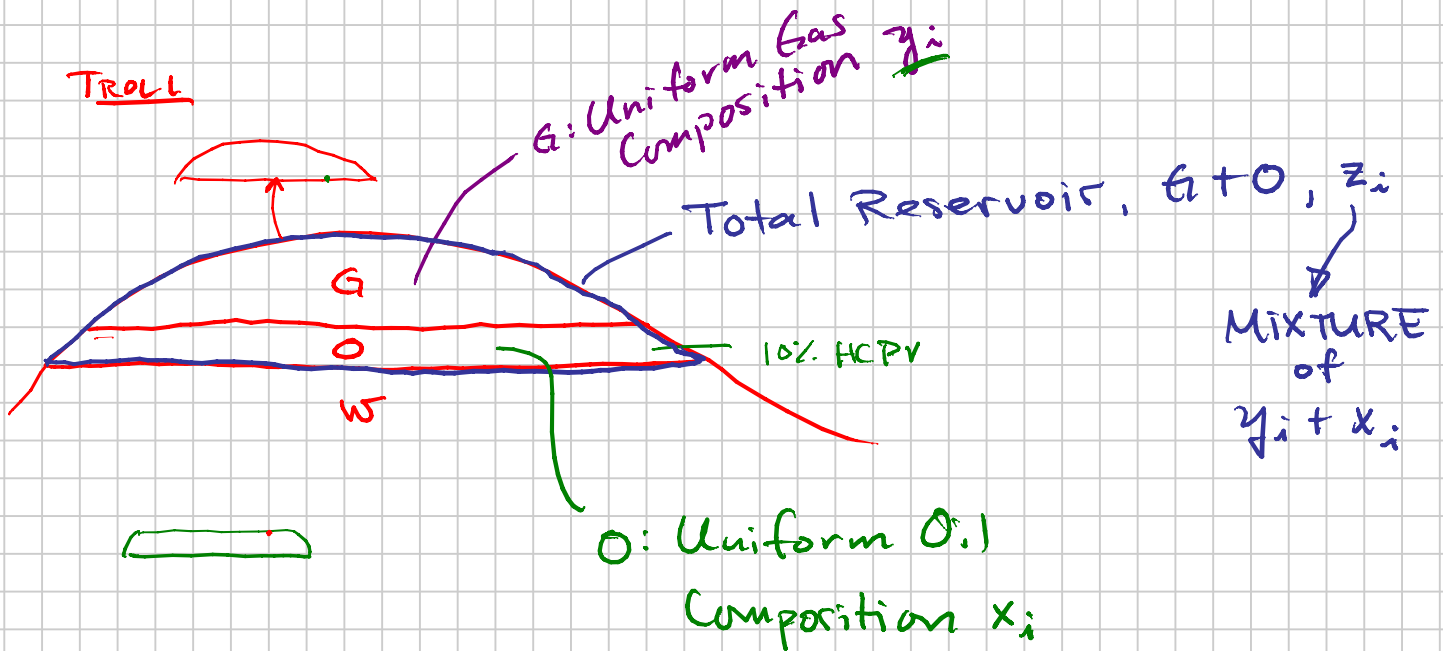
Sol. A single phase reservoir with uniform composition z_i ; then

OIL: $T_R < T_c$ (of z_i)

GAS: $T_R > T_c$ (of z_i)

Other Sol. (more complex reservoir fluids)

- Simple, Saturated, Two-Phase (G+O) reservoir

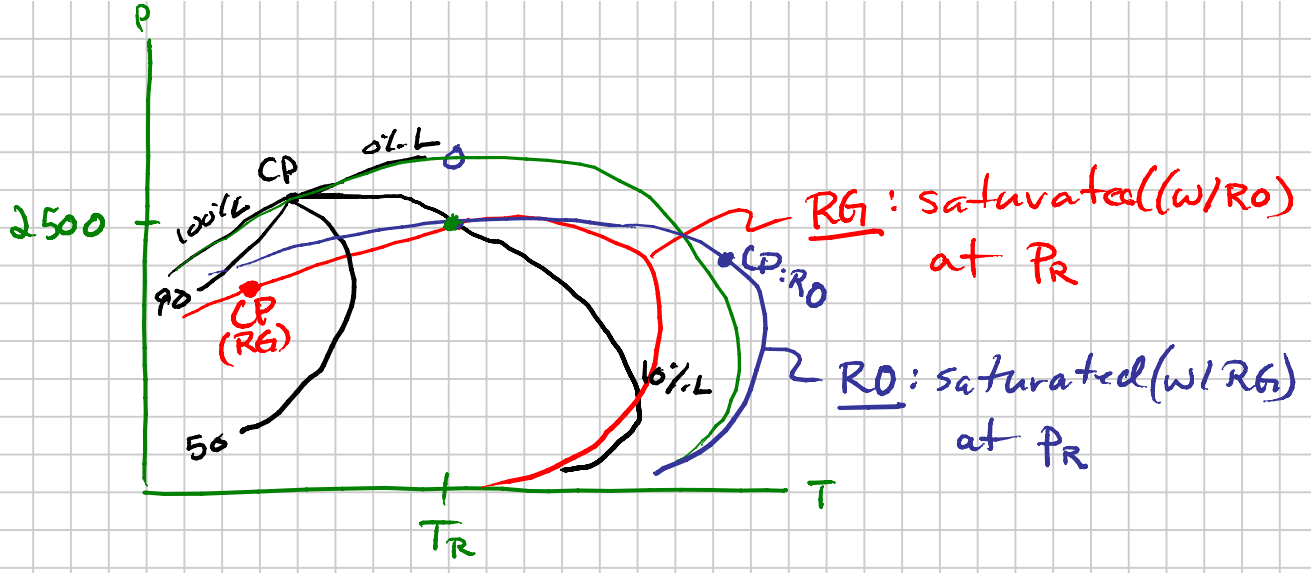


$P_R = 2500$ psia (?)

$T_R = \text{constant}$

(1) Total Mixture:	p_s ?	> 2500	} psia	BP or \textcircled{DP}
(2) Res. Gas (RG):	p_s ?	2500		BP or \textcircled{DP}
(3) Res. Oil (RO):	p_s ?	2500		\textcircled{BP} or DP

Sketch of p-T diagram of each: z_i, y_i, x_i



Reservoir Mixtures - Review

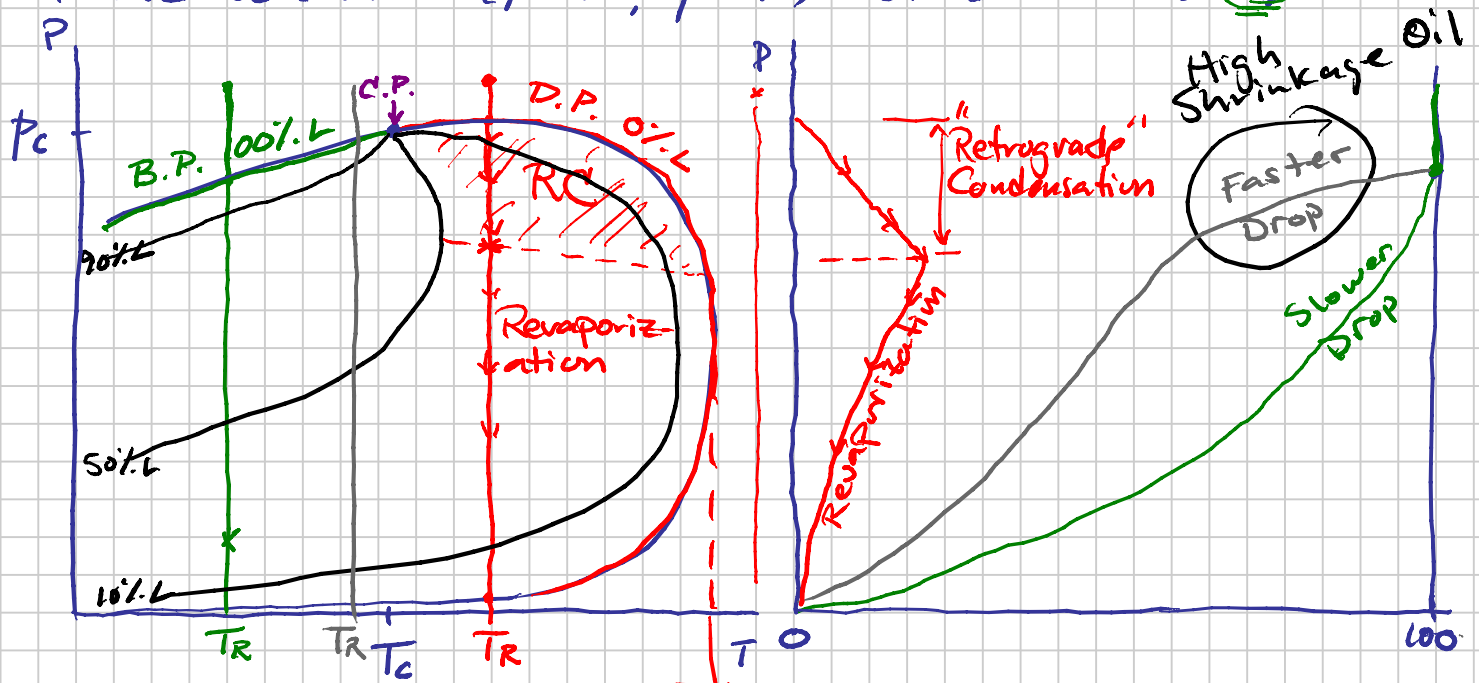
Note Title

9/4/2007

Molar Composition (z_i)
 Mole Fraction
 mol-%
 (Mass amount)
 Water-free basis

- non-HCs (N_2, CO_2, H_2S)
- HCs ($C_1, C_2, C_3, iC_4, nC_4, iC_5, nC_5, C_6, C_7, C_7, C_8 \dots C_{30+}$)
- H_2O (+ salts)

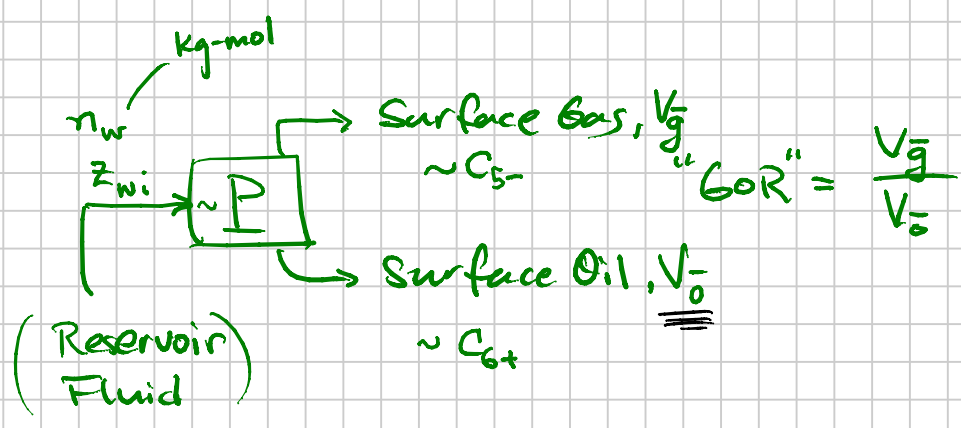
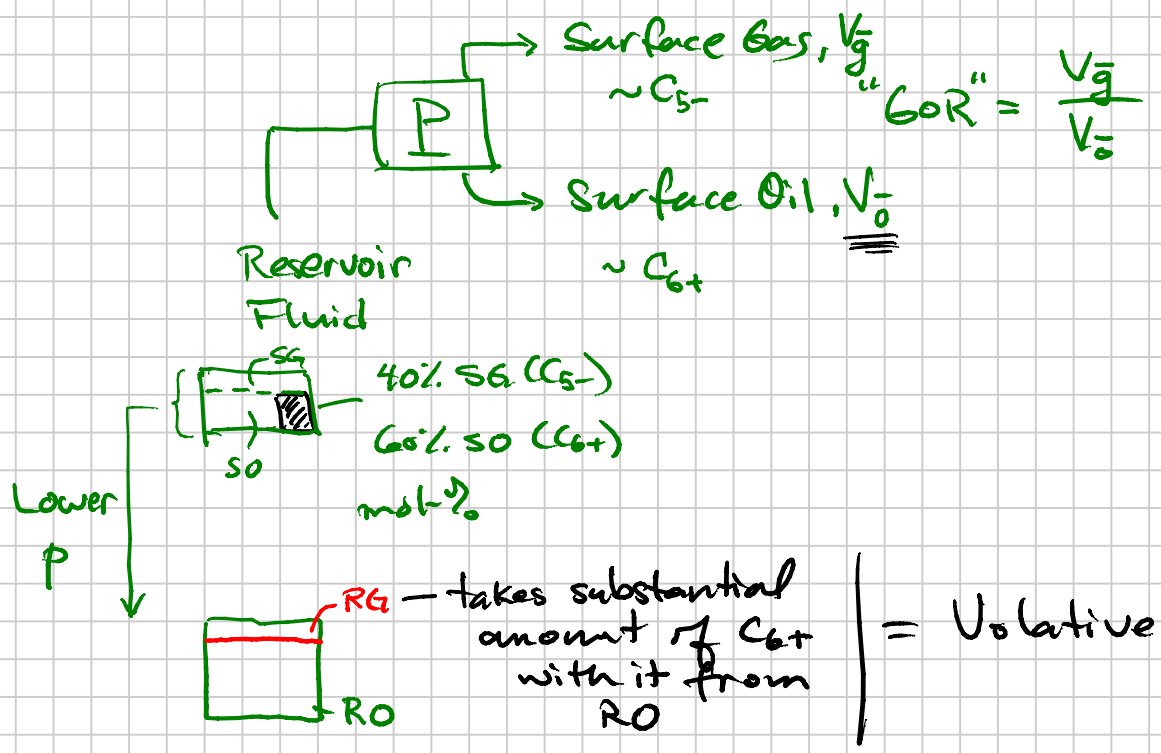
Phase Behavior (p-T, p-V) of a MIXTURE (z_i)



$T_R < T_c$
 OIL
 BLACK OIL | VOLATILE OIL
 "GOR"
 $< 120 \text{ Sm}^3/\text{Sm}^3$
 -140
 Rule of Thumb

$T_R > T_c$
 GAS
 Retrograde
 • $T_c < T_R < T_{crit}$: "Gas Condensate"
 • ($T_R > T_{crit}$)
 - Wet Gas (get SO surface condensate, in \boxed{P})
 - Dry Gas ($\rightarrow \boxed{P}$) $\rightarrow \sim 0$ Surf. Cond.

"Volatile" means is that the RO_i

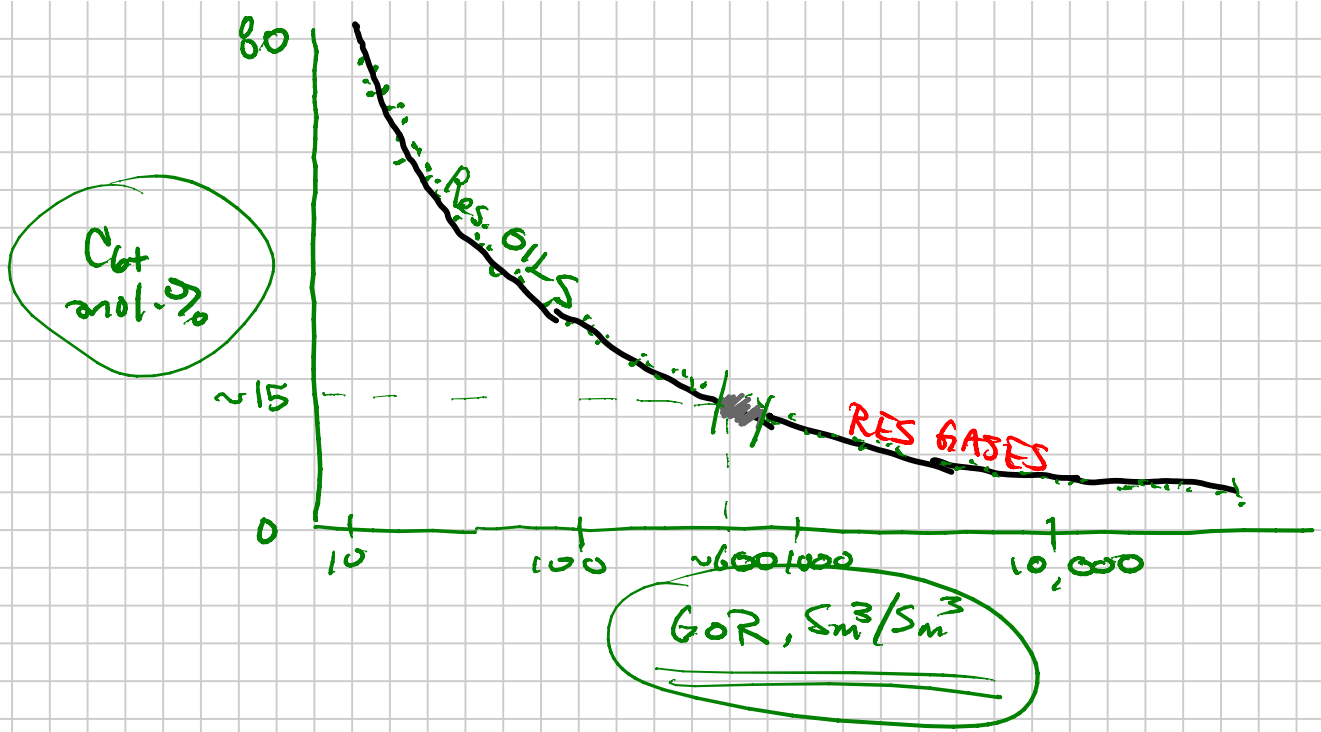


$$GOR = \frac{n_g \cdot \left(\frac{RT_{sc}}{P_{sc}}\right)}{n_o \cdot \left(\frac{M}{\rho}\right)_o}$$

$$\sim [P]: \quad n_g = n \cdot z_{C5-} = n(1 - z_{C6+})$$

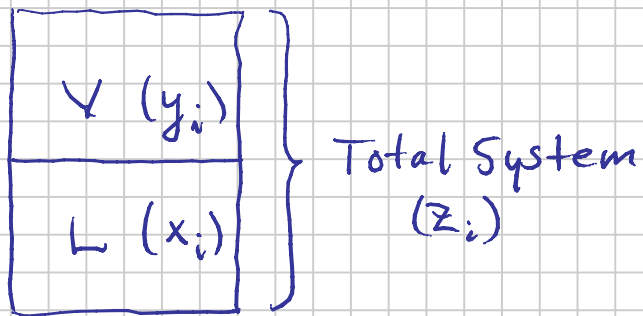
$$n_o = n \cdot z_{C6+}$$

$$GOR \approx \underbrace{\left(\frac{RT_{sc}}{P_{sc}}\right) \left(\frac{\rho}{M}\right)_o}_{\sim \text{Constant}} \cdot \frac{1 - z_w C_{6+}}{z_w C_{6+}} \quad \frac{Sm^3}{Sm^3}$$



VAPOR-LIQUID EQUILIBRIA (VLE)

Computation Phase Equilibria



TASK:

Given P, T, z_i

Want:

- ⊙ Amount of each Phase
- ⊙ Composition of each Phase

Equilibrium

(Revisit thermodynamics)

Gibbs, Helmholtz, van der Waals
...

Michelsen

Nature wants to distribute the components in a mixture (z_i) at (P, T) in such a way that the total energy of the mixture is minimized.

→ How many phases

→ How to partition the components in the phase

μ_i = chemical energy of component i in a phase

$\mu_{i,v}$

$\mu_{i,l}$

μ_i total mixture

$$\text{Minimize } \mu_i = n_v \mu_v + n_l \mu_l$$

$$\mu_V = \sum y_i \mu_{iV}$$

$$\mu_L = \sum x_i \mu_{iL}$$

$$\mu_{iV} = \mu_{iL} \quad \text{all } i \Rightarrow \text{Comp } i \text{ is "happy"}$$

Gibbs: $\mu_i (P, T, V, \text{phase composition}, i)$

Ch. 4
Equations

fugacity (units - pressure)

$$\mu_i \equiv RT \cdot \ln f_i \quad \left(+ \lambda_i \right)$$

↑
const.

To solve the equations of phase equilibrium most (normal) people introduce a "variable"

K-value, equilibrium ratio

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

y_i
x_i

$K_{ci} = 2$ "partitioning factor"

$> 1 \Rightarrow$ comp. "prefers" being in the V

$< 1 \Rightarrow$ — " — — — — — " — L

Characteristics of K_i

- $K_i > 1$

- $K_i < 1$

- $K_i (P, T, z_i)$
 \uparrow
 overall mixture

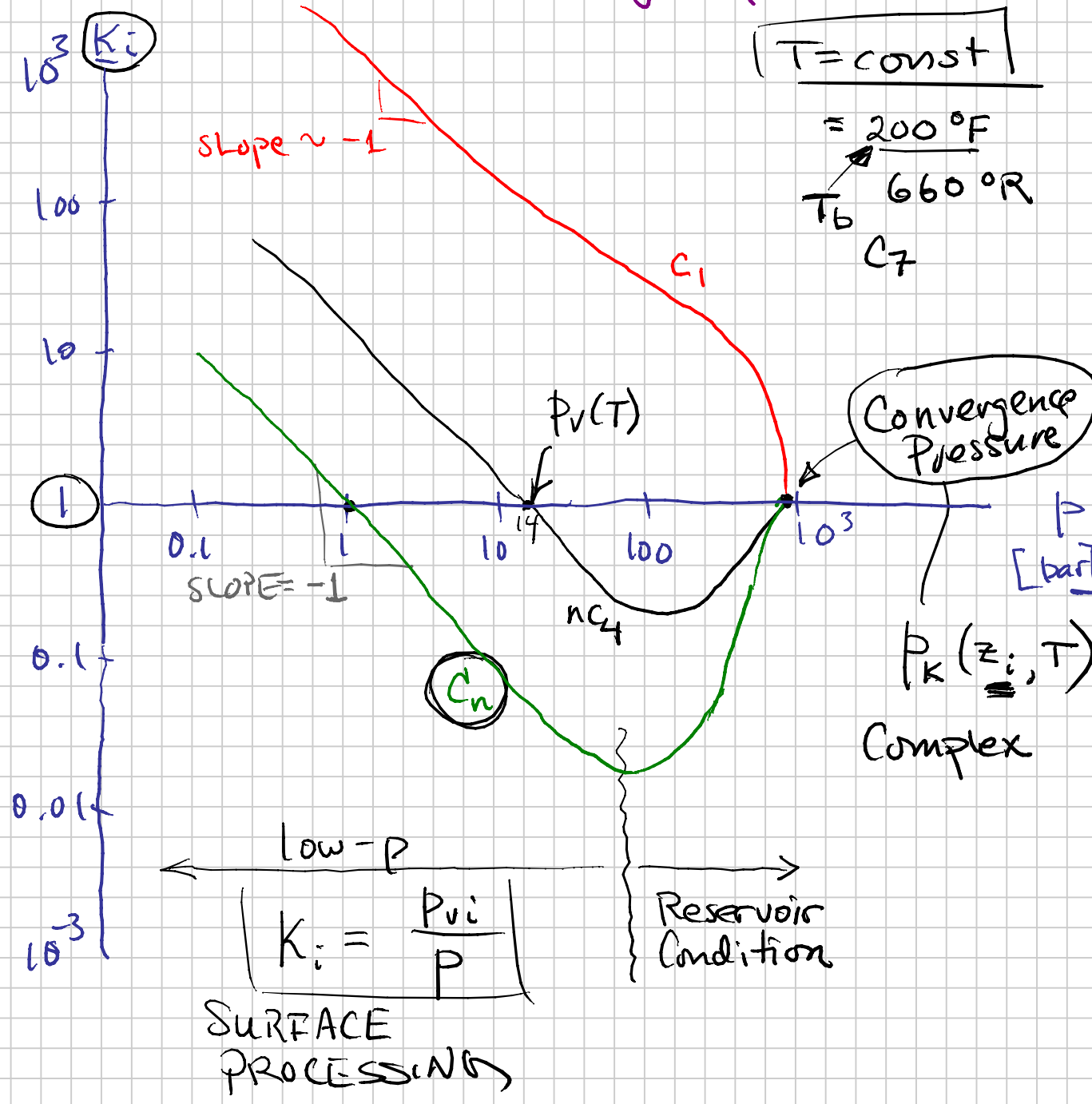
GENERAL

- At "lower" pressures ($\sim 50^+$ bar \rightarrow 100 bar)

$$K_i \approx \frac{P_{vi}(T)}{P}$$

$$K_i (P, T, i)$$

- All $K_i \rightarrow 1$ at some "higher pressure"



Ch. 3: K-value equations:

Wilson Eq. low-p

General:

$$\log p_v = a + \frac{b}{T}$$

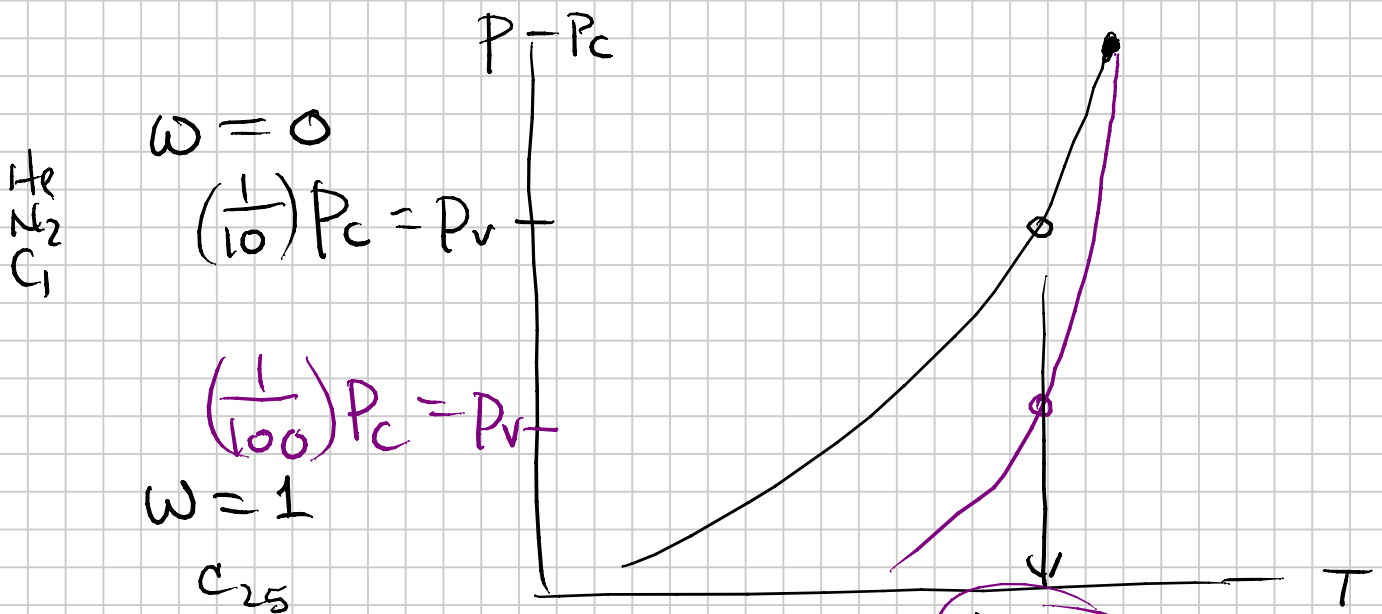
It is interesting to note that the well-known Wilson^{102,103} equation,

$$K_i = \frac{\exp 5.37(1 + \omega_i)(1 - T_{ri}^{-1})}{P_{ri} P/P_c} \dots \dots \dots (3.157)$$

$$K_i = \frac{P_{vi}}{P}$$

$$\Rightarrow P_{vi} = f(T_r, P_c, \omega)$$

Table, Comp. value
 ↑
 Acentric Factor



$$\text{Pitzer: } \omega \equiv -1 - \log \left(\frac{P_v(0.7T_c)}{P_c} \right)$$

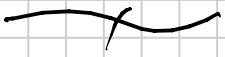
$\omega \sim$ slope of $P_v(T)$ near T_c

Low-p $K_i(P, T)$

Need $\underline{P_{vi}(T)}$ using $K_i = \frac{P_{vi}(T)}{P}$

or

Wilson : P_{ci}, T_{ci}, ω_i



High-p K-values

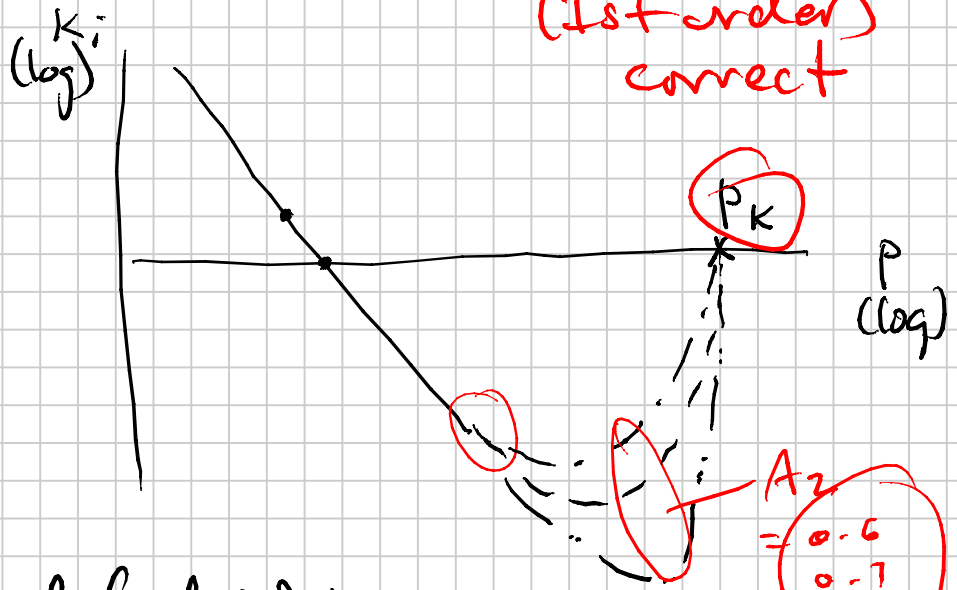
(1) $K_i \rightarrow 1$, all i , as $P \rightarrow P_K$

Parameter
= $f(Z_i, T)$

(2) Connect with the low-p
 $K_i(P, T)$

Semi-quantitatively
(1st order)
correct

Graphical:



Equation: Modified Wilson

$$K_i = \frac{\left(\frac{P_{ci}}{P_K}\right)^{A_1+1} \exp\left[5.37 A_1 (1 + \omega_i) \left(1 - \frac{T}{T_{ri}}\right)\right]}{P/P_{ci} \dots \dots \dots} \quad (3.159)$$

P_K ; $A_1(P)$

$$A_i(P) = 1 - \left(\frac{P}{P_K} \right)^{A_2} \quad ; \quad A_2 \sim 0.5 - 0.8$$

(0.7)

... K_i estimation - dare deal

$$\underbrace{T_{ci}, P_{ci}, \omega_i}_{\text{App. A}}$$

$$; \quad \frac{P_K, (A_2)}{}$$

? vary from Res to Res

$$(P, T)$$

How to use what we know?

$$\begin{cases} \hookrightarrow z_i \\ \hookrightarrow K_i(P, T) \end{cases}$$

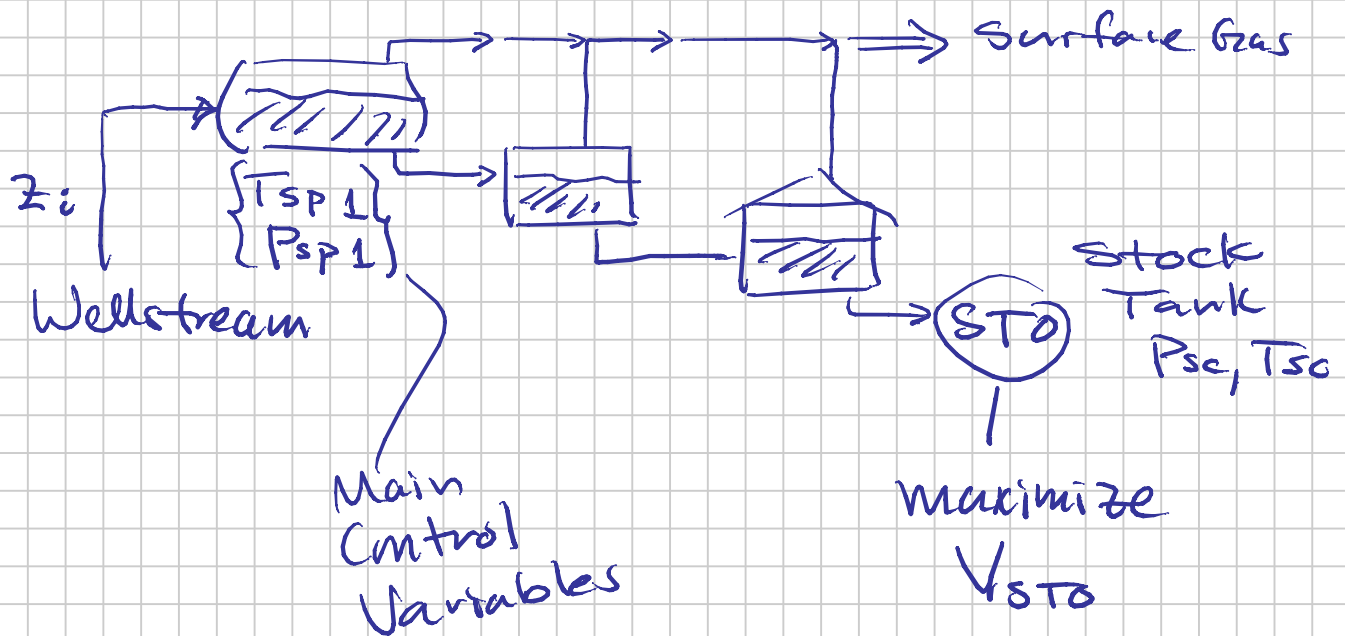
We can find

- Amount of each phase
- Composition of each phase

"Phase Split Problem" (Ch. 4)

Solutions:

1949: Muskat-McDowell (short footnote)



1952: Exxon ("Rachford-Rice")

same solution, just not quite
as comp. efficient MM

Problem: N components

Know $z_i, K_i (= \frac{y_i}{x_i})$

Want n_v, n_L, y_i, x_i

Comp. Material Balance

$$z_i \cdot n = y_i \cdot n_v + x_i \cdot n_L$$

$$n = n_v + n_L$$

$$\sum z_i = 1$$

| Given

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

| Constraint

Definitions:

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

(β^u)

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

Trick \rightarrow $h \equiv \sum (y_i - x_i) = 0$ Eq. (1)

Drive the function $h \rightarrow 0$
by changing the main
unknown, F_v

$$h = \sum y_i - x_i$$

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

$$= \sum K_i x_i - x_i$$

$$y_i = K_i x_i$$

↑
know

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

↑
use comp. matr. bal.

$$z_i = F_v \cdot y_i + (1 - F_v) x_i$$

Know ↑

$$z_i = F_v (y_i - x_i) + x_i$$

$$= F_v (K_i x_i - x_i) + x_i$$

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

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

$$\Rightarrow x_i = \frac{z_i}{F_v (K_i - 1) + 1}$$

RR

$$h = \sum \frac{z_i (K_i - 1)}{F_v (K_i - 1) + 1} = 0$$

Solve for F_v to drive $h \rightarrow 0$

MM

$$c_i \equiv \frac{1}{K_i - 1} \quad ; \quad c_i = 0, K_i = 1$$

$$h = \sum \frac{z_i}{F_v + c_i} = 0$$

What are the characteristics of $h(F_v)$?

(1) Multiple solutions, N or $N-1$ solutions

(2) Only ONE of the solutions

$$\Rightarrow \begin{matrix} x_i \\ y_i \\ \uparrow \\ z_i \end{matrix} > 0 \quad (\text{physical requirement})$$

$$\underbrace{\frac{1}{1-k_{\max}}}_{F_{\min} < 0} < F_v^* < \underbrace{\frac{1}{1-k_{\min}}}_{F_{\max} > 1}$$

Know that the physical solution $0 \leq F_v \leq 1$ always lie between F_{\min} and F_{\max}

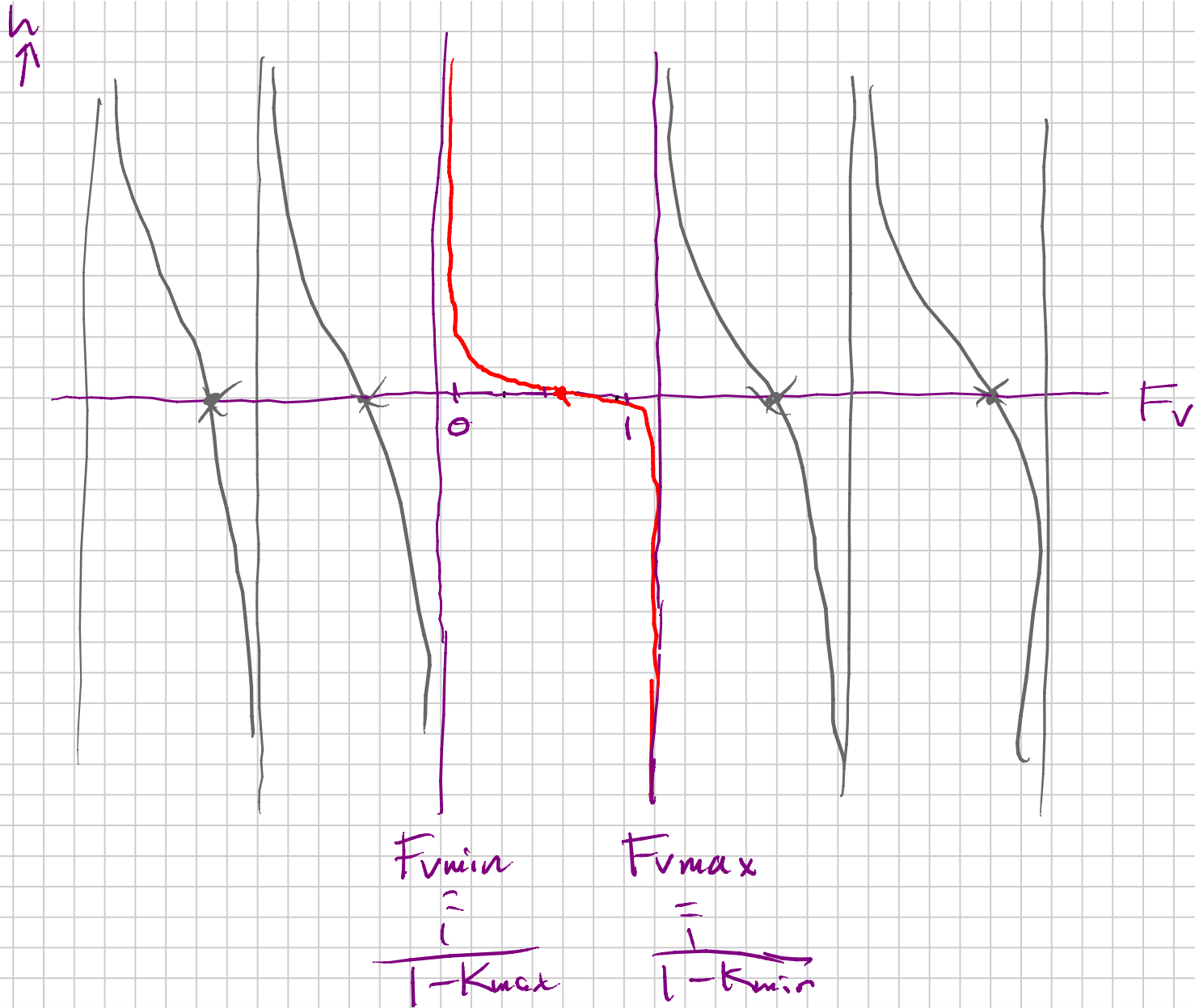
(3) $h(F_v)$ monotonic

(4) $h(F_{\min})$ asymptote
 $h(F_{\max})$ — " —

(5) $h(F_v)$ highly non-linear and prone to numerical roundoff errors

Challenge

for cases with $z_k \sim \epsilon$ and $k_k \sim \epsilon$ or $\frac{1}{\epsilon}$



Solution Algorithm:

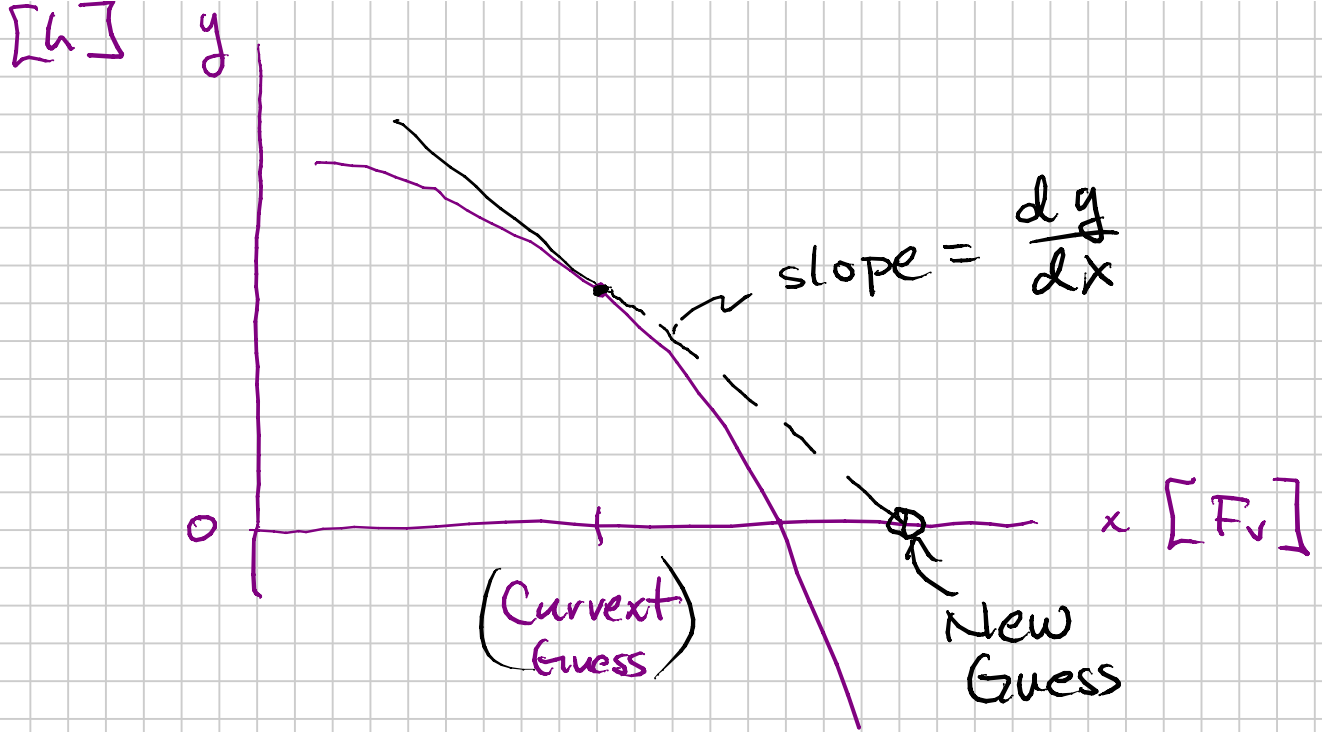
(0) Calc. F_{vmin} , F_{vmax} (search bounds)

(1) Guess $F_v = 0.5$

(2) Calc. $h(F_v)$

(3) If $|h| >$ tolerance for convergence
 10^{-10}

(a) New est. of F_v
 using Newton-Raphson



$$x^{new} = x^{current} - \frac{y @ x^{current}}{\left(\frac{dy}{dx}\right)_{x^{current}}}$$

BUT

$$x^{new}$$

$$F_{vmin} < F_v^{new} < F_{vmax} \quad ; \text{restraint}$$

$$F_v^{new} = F_v^{current} - \frac{h(F_v^{current})}{h'(F_v^{current})}$$

(b) Converged if $|h| < \text{tolerance}$

Calc. from Z_i , K_{ij} and F_v

$$X_i = \quad \checkmark$$

$$y_i = \quad \checkmark$$

4.3 Two-Phase Flash Calculation

The isothermal two-phase flash calculation is the workhorse of most EOS applications. The problem consists of defining the amounts and compositions of equilibrium phases, usually liquid and vapor, given the pressure, temperature, and overall composition. An inherent obstacle to solving this problem is not knowing whether two equilibrium phases form at the specified pressure and temperature. The mixture may exist as a single phase or may split into two or more phases.

In 1949, Muskat and McDowell³⁸ proposed a solution to the two-phase split calculation that is basically the same as the one proposed by Rachford and Rice³⁵ but numerically more efficient. Introducing the quantity $c_i = 1/(K_i - 1)$, where $c_i = \infty$ for $K_i = 1$, Muskat and McDowell proposed the following form of the function $h(F_v)$.

$$h(F_v) = \sum_{i=1}^N \frac{z_i}{F_v + c_i} = 0, \quad \dots \dots \dots (4.39)$$

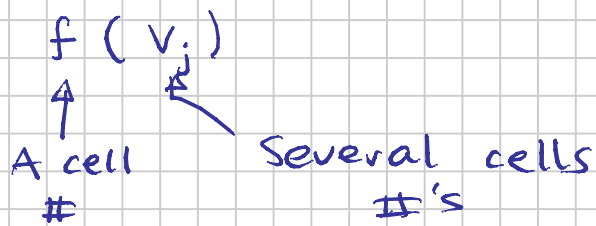
$$\text{where } \frac{dh}{dF_v} = - \sum_{i=1}^N \frac{z_i}{(F_v + c_i)^2}. \quad \dots \dots \dots (4.40)$$

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

..... (3.159)

where A_1 = a function of pressure, with $A_1 = 1$ at $p = p_{sc}$ and $A_1 = 0$ at $p = p_K$. The key characteristics of K values vs. pressure

SOLVER in Excel

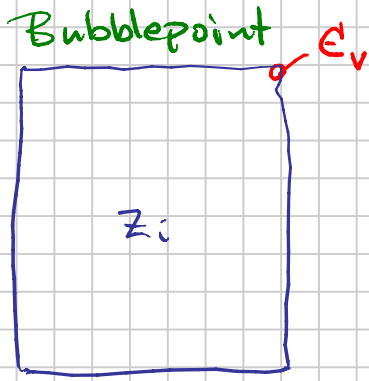


- Minimize $f(V_j)$
- Maximize $f(V_j)$
- Set Equal $f(V_j)$

Allows:

Set Constraints on V_j | Highly Recommended

SATURATION PRESSURE CALCULATION

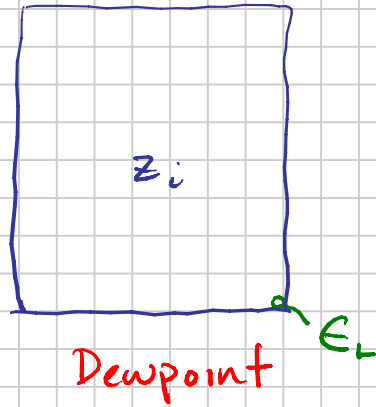


T_1

B.P.

At what pressure

is $F_v = \epsilon$

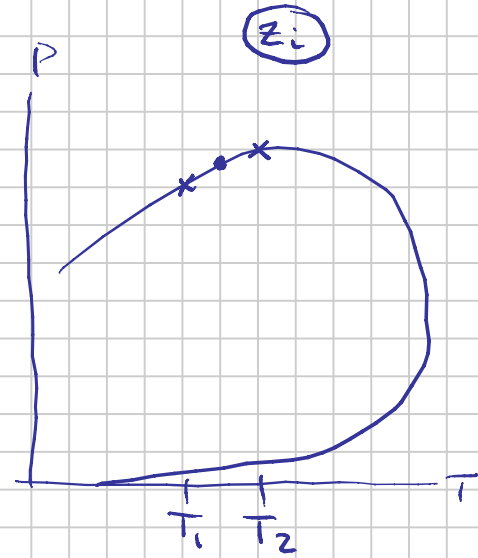


T_2

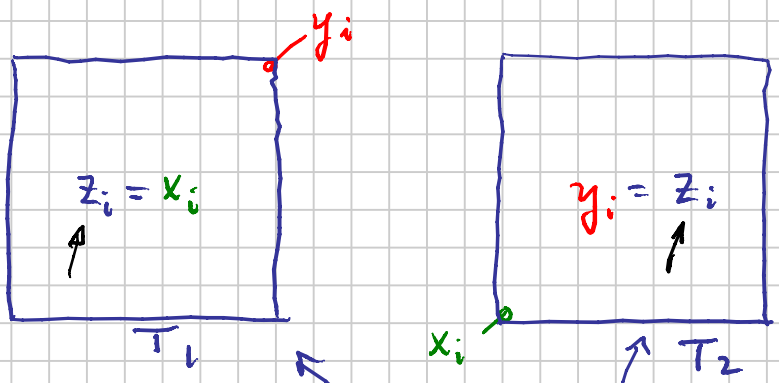
D.P.

At what p

is $1 - F_v = \epsilon$



Short Review of Saturation Pressure Calculation

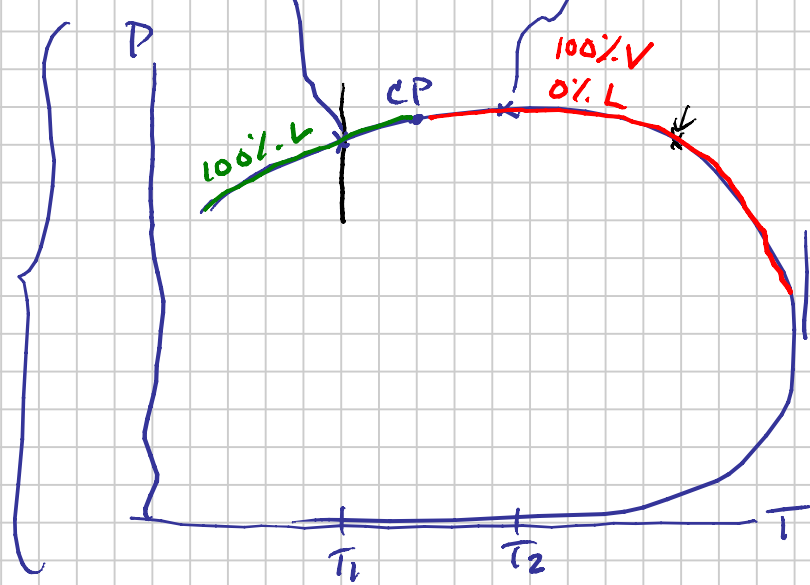


Q1. $Is(x_i)_{T_1} = (x_i)_{T_2}$
NO

Q2. $P_s(T_1) = P_s(T_2)$
NO

Q3. $x_i(T_1) = y_i(T_2)$
YES

Valid for z_i



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

BP: $x_i = z_i$

$y_i = K_i x_i$
↑
Know

$y_i = K_i \cdot z_i$

$= z_i \cdot K_i(T_1, p, \text{composition})$

↑
Know

↑
Fixed

↑
"PK"
Guess or
Fix the
Value

↑
Guess or
Fix the
Value

$> P_s(T_1)$

"Incipient"
Bubble

$$y_i = z_i \cdot K_i(T_1, P_K, P) \Rightarrow y_i(P)$$

Known or Fixed

Unknown
= "saturation"
pressure

Material Balance Constraint

$$\text{B.P.} \quad \sum y_i = 1 = \sum z_i K_i(T_1, P_K, P_B)$$

Dewpoint : Incipient Drop of Liquid

$$y_i = z_i$$

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

$$\sum x_i = 1$$

$$K_i(T_2, P_K, P)$$

$$\text{D.P.} \quad \sum \frac{z_i}{K_i(T_2, P_K, P_d)} = 1$$

Variable Unknown

P_K is a simplified (empirical) term used to define the composition dependence of K_i using (e.g.) the modified Wilson equation.

$P_K(\underline{z}_i, T)$: Estimate some way or another

General Solution:

(1) BP or DP ?

- User specifies

✓ - Solution tells

(2) Multiple Solutions

Avoid - Always lower DP
(not interested in this solution)

✓ - Search only upper sat. pressure

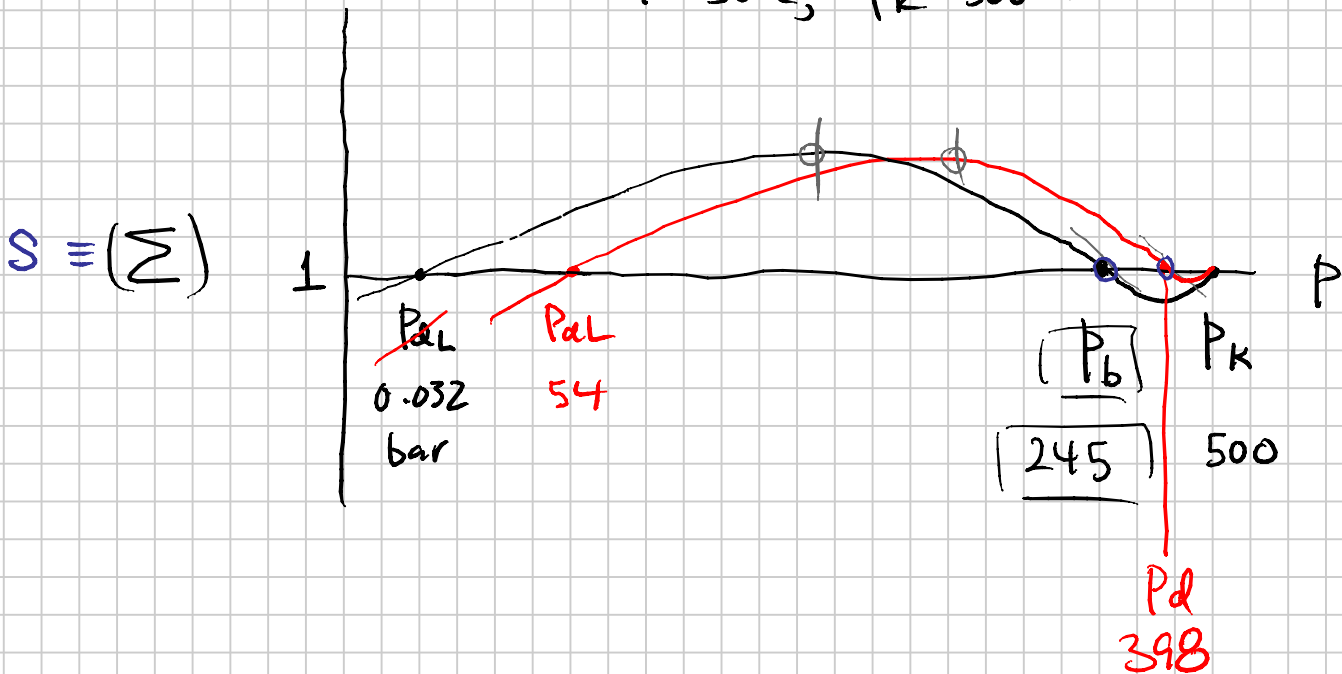
Avoid • $P_s = P_k$ solves the constraint eq.
"trivial" solution

- It is the correct solution, if $T = T_c$

• May (I think) have BP \neq DP
solution existing ?? Let's assume
a problem

$T = 300^\circ\text{C}$, -"-

$T = 50^\circ\text{C}$, $P_k = 500$ bar



$$\left(\frac{dS}{dp}\right)_{\text{Upper } P_0} < 0$$

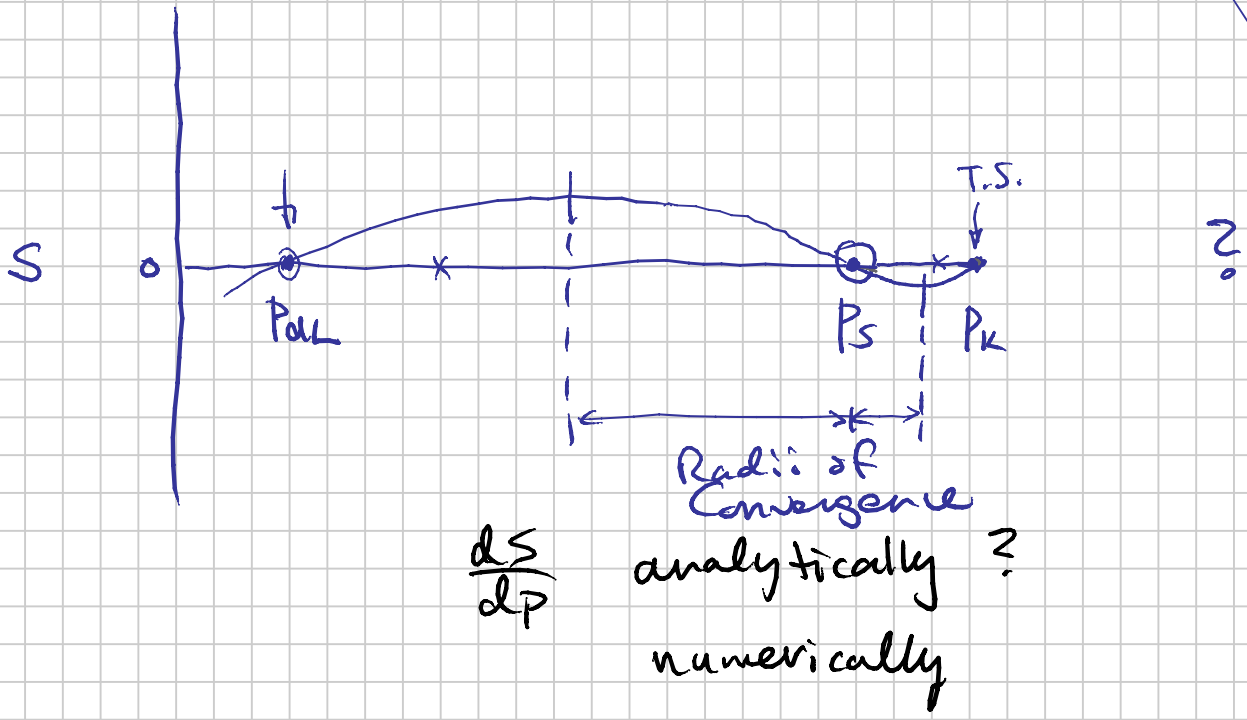
at the solution

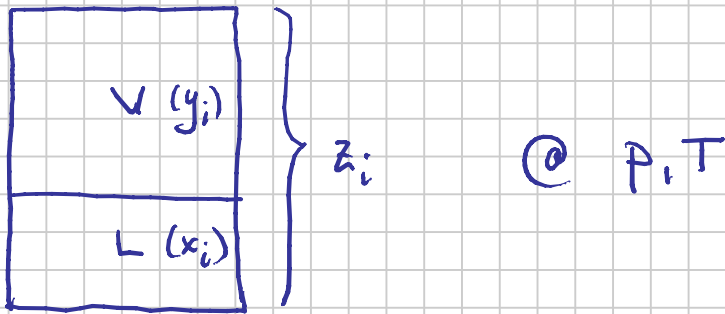
$$\left. \begin{aligned} S_{BP} &= \sum z_i K_i \rightarrow 1 \\ S_{DP} &= \sum z_i / K_i \neq 1 \\ S &= 0 @ BP \\ S_{BP} &\neq 1 \\ S_{DP} &= 1 \\ S &= 0 @ DP \end{aligned} \right\} \text{at a BP}$$

What if Use

$$S = (S_{BP} - 1) \cdot (S_{DP} - 1) \rightarrow 0$$

Don't need to know BP vs DP when solved





Estimate $K_i (= J_i/x_i)$ and knowing z_i ,

- ⇒ (1) # phases and amounts
 (2) phase compositions

Verification of our calculations based on a "more-rigorous" thermodynamic model.

Gibbs Energy Minimization } =
 Equal Chemical Potential

Component Chemical Energy inverse molar "density" = $\frac{S}{M}$
 $v = \frac{M}{\rho}$

$\mu_{i,p}$ (composition, p, T, v_p)
 from an

Fugacity (surrogate)

$$\mu_i = RT \cdot \ln f_i + (\lambda_i) \text{ Equation of State (EOS)}$$

\uparrow pressure units \uparrow p-T-v equation

Vapor and Liquid states must be described by the SAME EOS model, that will also guarantee consistency in single-phase regions and at critical states

$$L \equiv V$$

Constant T ; Fixed p
Equilibrium of Two Phases

ALL i

$\mu_{iL} = \mu_{iV}$
 $\rightarrow f_{iL} = f_{iV}$ } Chemical

Diffusion Process

Approximation

$$q_i = D_i \frac{dc_i}{dx}$$

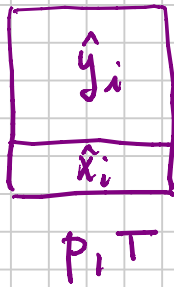
$$q_i = D_i \frac{d\mu_i}{dx}$$

Fick's law

$$q_i = D_i \frac{d\phi_i}{dx}$$

$$\phi_i = \underline{\underline{\mu_i + M_i g}}$$

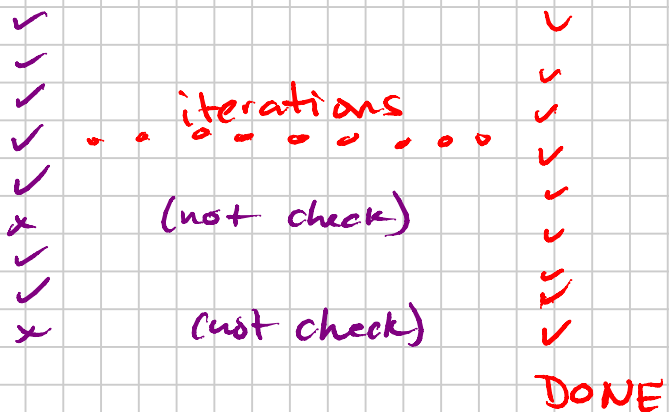
Check on our approximate Phase Split Calculation



(1) Vapor Phase $(\hat{y}_i, p, T) \Rightarrow \text{EOS}_V \Rightarrow \mu_{iV}$
 $(v_v) \quad f_{iV}$

(2) Liquid Phase $(\hat{x}_i, p, T) \Rightarrow \text{EOS}_L \Rightarrow \mu_{iL}$
 $(v_L) \quad f_{iL}$

(3) $\mu_{iV} = \mu_{iL} \quad \underline{\underline{\text{all}}}$ $i \quad (f_{iV} = f_{iL})$



(4) New set of K_i estimates

$$K_i^{\text{new}} = K_i^{\text{old}} \cdot \left(\frac{f_{Li}}{f_{Vi}} \right)$$

(5) Resolve RR problem using K_i^{new}

\Rightarrow New phase amounts
 New y_i and x_i

Back to step (1)

EQUATION OF STATE used

- Process
- Reservoir
- Production

Pet. Eng. disciplines ?

1870's van der Waals

$$p = \frac{RT}{v-b} - \frac{a}{v^2}$$

"R" "A"

"Cubic" EOS

- Two constants a, b ✓
- volume being "cubic" ✓

$$p = \frac{RTv^2 - a(v-b)}{[(v-b)v^2]}$$

↖
Cubic in volume

$$C_3 v^3 + C_2 v^2 + C_1 v + C_0 = 0$$

1870's: vdW

1949: Redlich-Kwong (RK)

$$p = \frac{RT}{v-b} - \frac{a \cdot \alpha(T)}{[v(v+b)]}$$

↙ Correction Term

1972: Soave - RK (SRK)

$\alpha(T, \text{component})$

⇒ EOS now could predict very accurately the vapor pressure curve of all components

$K_i \iff p_{vi} \quad @ \quad p < 50 + b_{ara}$

1977: Peng - Robinson (PR)

$$p = \frac{RT}{v-b} - \frac{a \cdot \alpha}{[v^2 + 2bv - b^2]}$$

$\alpha(T, \text{component})$

- Process
 - Reservoir
 - Production
- } Ref. Eng. disciplines ?

1870's van der Waals

$$p = \frac{RT}{v-b} - \frac{a}{v^2}$$

"R"
"A"

"Cubic" EOS

- Two constants a, b ✓
- volume being "cubic" ✓

$$p = \frac{RTv^2 - a(v-b)}{[(v-b)v^2]}$$

↗ Cubic in volume

$$c_3 v^3 + c_2 v^2 + c_1 v + c_0 = 0$$

1870's: vdW

1949: Redlich-Kwong (RK)

$$p = \frac{RT}{v-b} - \frac{a \cdot \alpha(T)}{\underbrace{[v(v+b)]}_A}$$

↖ Correction Term

1972: Soave - RK (SRK)

$\alpha(T, \text{component})$

⇒ EOS now could predict very accurately the vapor pressure curve of all components

$K_i \iff p_{vi} \quad @ \quad p < 50 \text{ bara}$

1977: Peng - Robinson (PR)

$$p = \frac{RT}{v-b} - \frac{a \cdot \alpha}{[v^2 + 2bv - b^2]}$$

$\alpha(T, \text{component}) : a \text{ (a Soave)}$
 $\Rightarrow p_{vi}(T)$

1982: Peneloux, Rauzy, Freze

Fixed the problem of SRK & PR

p_L off by 5-35% (low)

Volume
 Translation
 (Shift)

Ch. 4 recommended reading:

4.1 - Intro

4.2 - Cubic's

less 4.2.4

4.3 - Two-Phase Flash

4.6 - Intro section only

No Problems related to EOS material

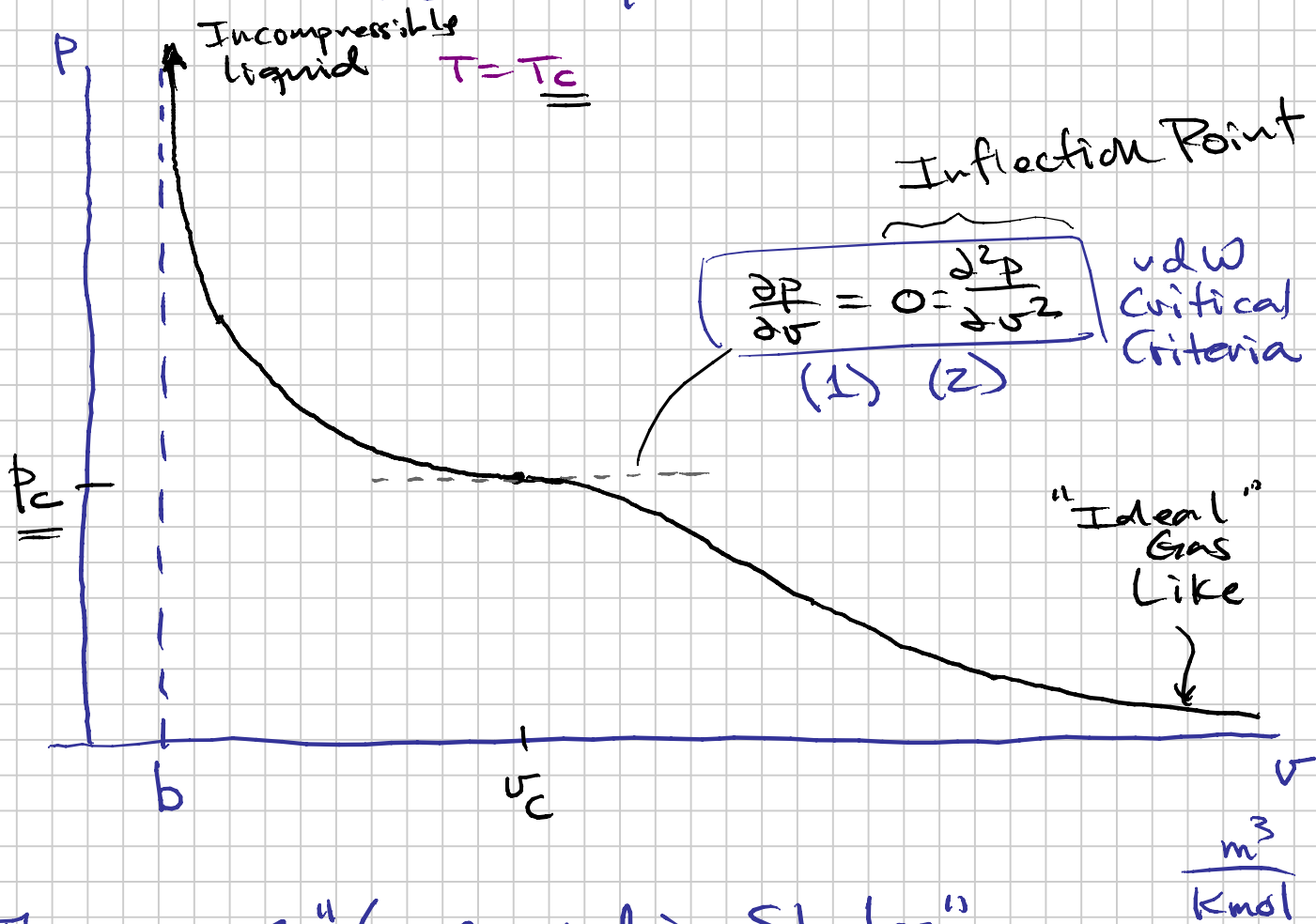
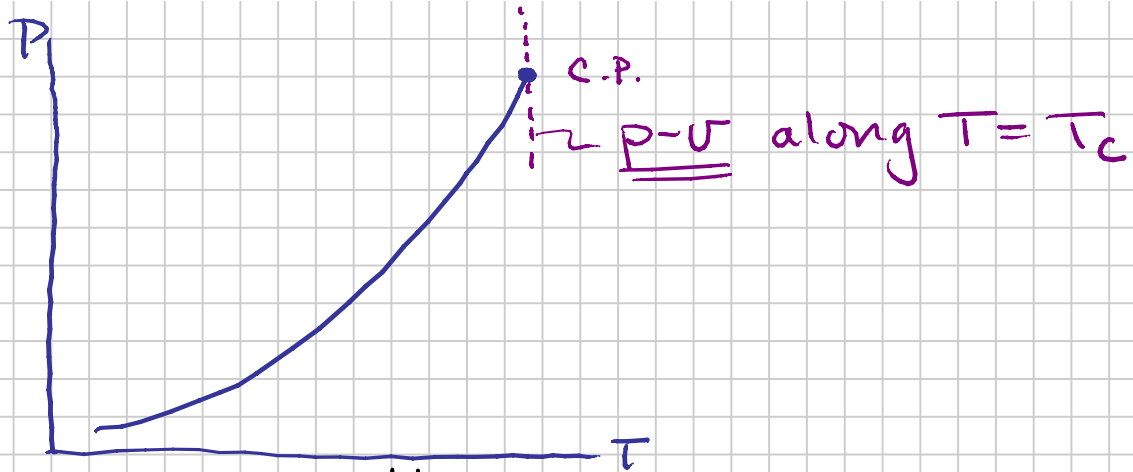
vdW: Constants a & b

Exp. data $P-T-v$ (e.g. H_2O)

① Best-fit to P_{SL} }
--- all P 's } $\Rightarrow a, b$
--- P_{SV} }
1960s: Alami-Kenedy

② vdW: General observation

Any compound $H_2O, CH_4, \dots C_{10} \dots$
has "similar" behavior around its
critical point.



Theorem of "Corresponding States"

$$p = \frac{RT}{v-b} - \frac{a}{v^2}$$

As $v \rightarrow \infty$, $a/v^2 \ll \frac{RT}{v-b}$

and $\frac{RT}{v-b} \rightarrow \frac{RT}{v} = p$

vdW Equations for a & b

$$a = \underbrace{\Omega_a}_{\sim 0.4} \frac{R^2 T_c^2}{P_c}$$

$$b = \underbrace{\Omega_b}_{\sim 0.1} \frac{R T_c}{P_c}$$

Ω_a = number specific to the EOS

Ω_b = _____ " _____

To use EOS: we need T_c & P_c of all components in our mixtures:

- App. A

- Ch. 5 C_7, C_8, \dots, C_{45}

How to use Cubic EOS for mixtures:

Phase with molar composition u_i (z_i, y_i, x_i)

$$\bar{a} = \sum_i \sum_j u_i u_j (a_i a_j)^{1/2}$$

$$\bar{b} = \sum_i u_i b_i$$

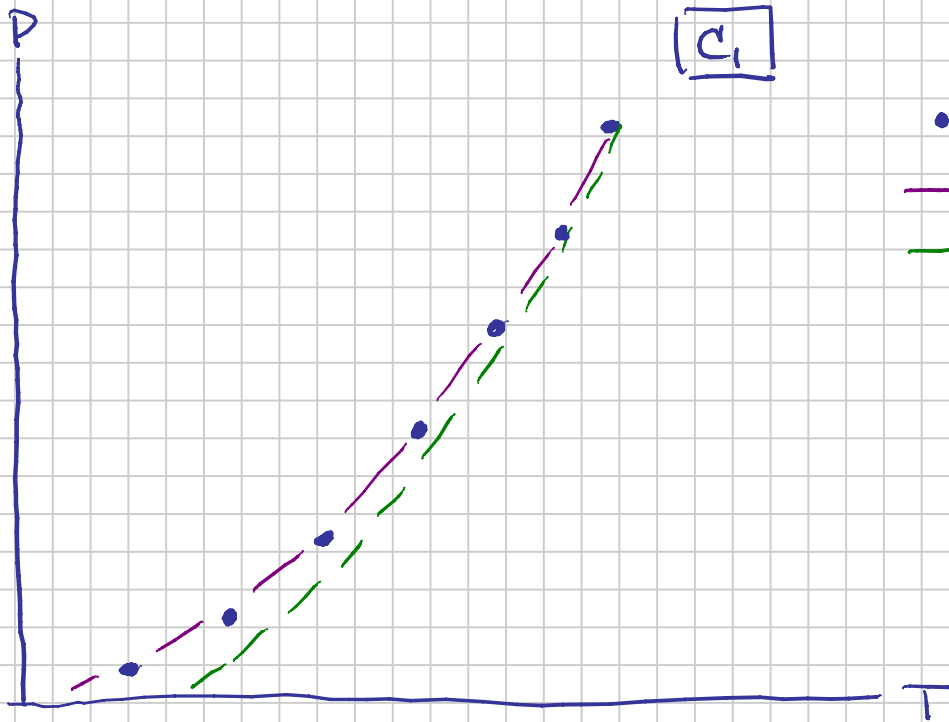
$$p = \frac{RT}{v - \bar{b}} - \frac{\bar{a}}{v^2}$$

Mixture
(Phase)

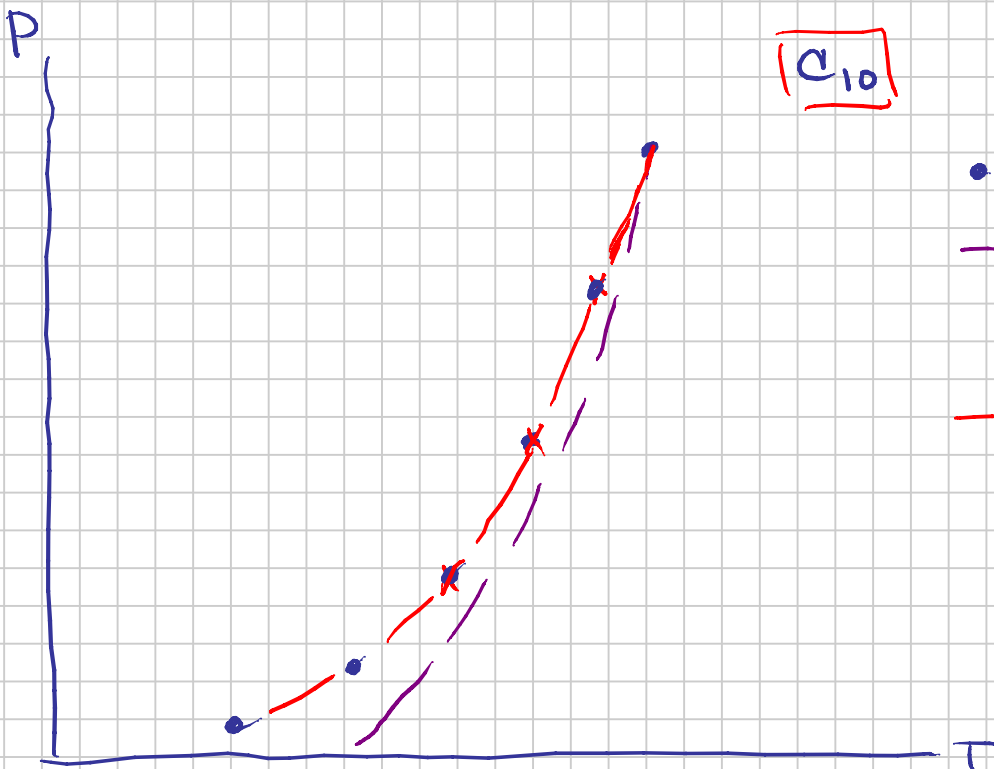
$p-v-T$

vdW

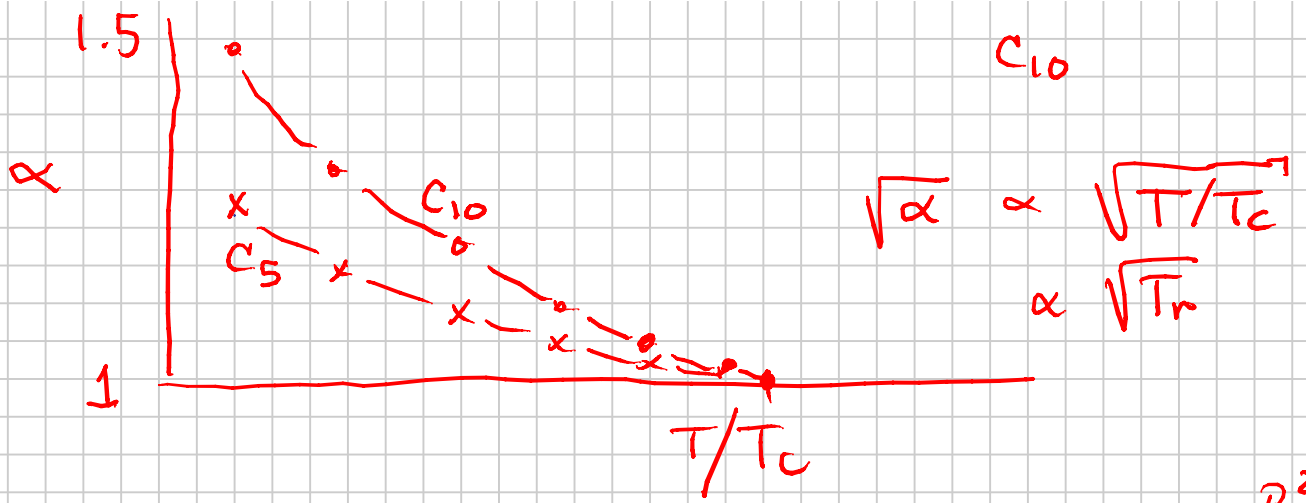
Soave's EOS Improvement



- Exp. data
- RK
- vdW



- Exp. Data
- RK (not good)
- SRK



$$a = a_{RK} \cdot \alpha_{SRK}$$

$$j a_{RK} = \int a \cdot \frac{R^2 T_c^2}{P_c}$$

$$\alpha^{1/2} = 1 + \underline{m} (1 - \sqrt{T_r})$$

Slope of $\sqrt{\alpha}$ vs $\sqrt{T_r}$

different for each component i

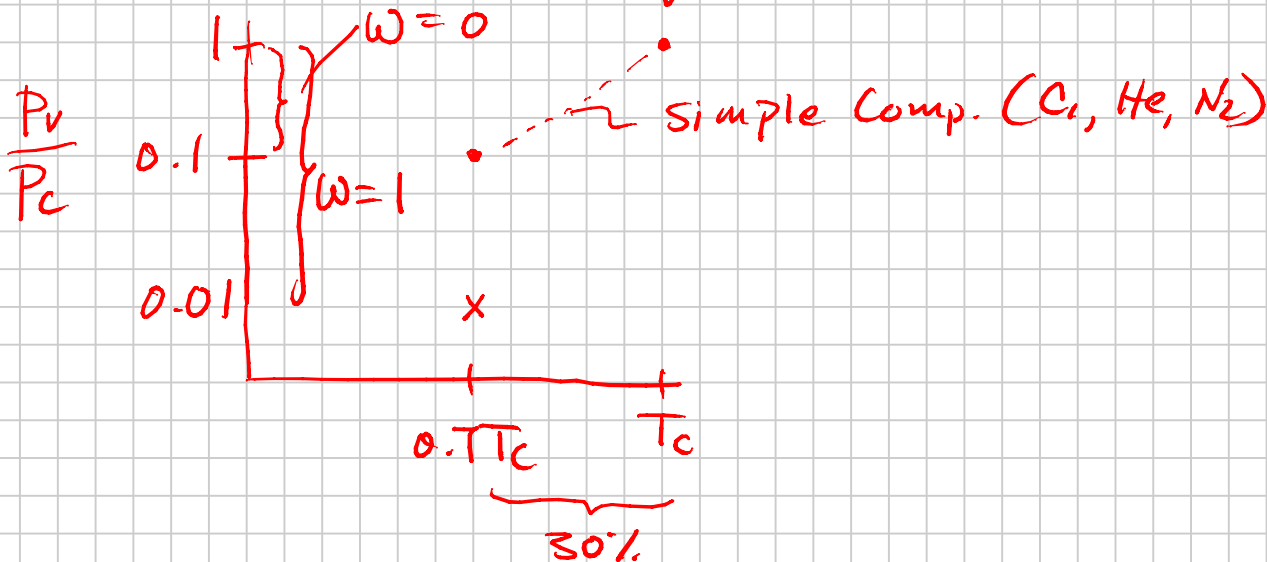
Soave: $m(\omega) = m_0 + m_1 \omega + m_2 \omega^2$

Correlating m with "Component"

Used "acentric factor" ω (App. A, Ch. 5)

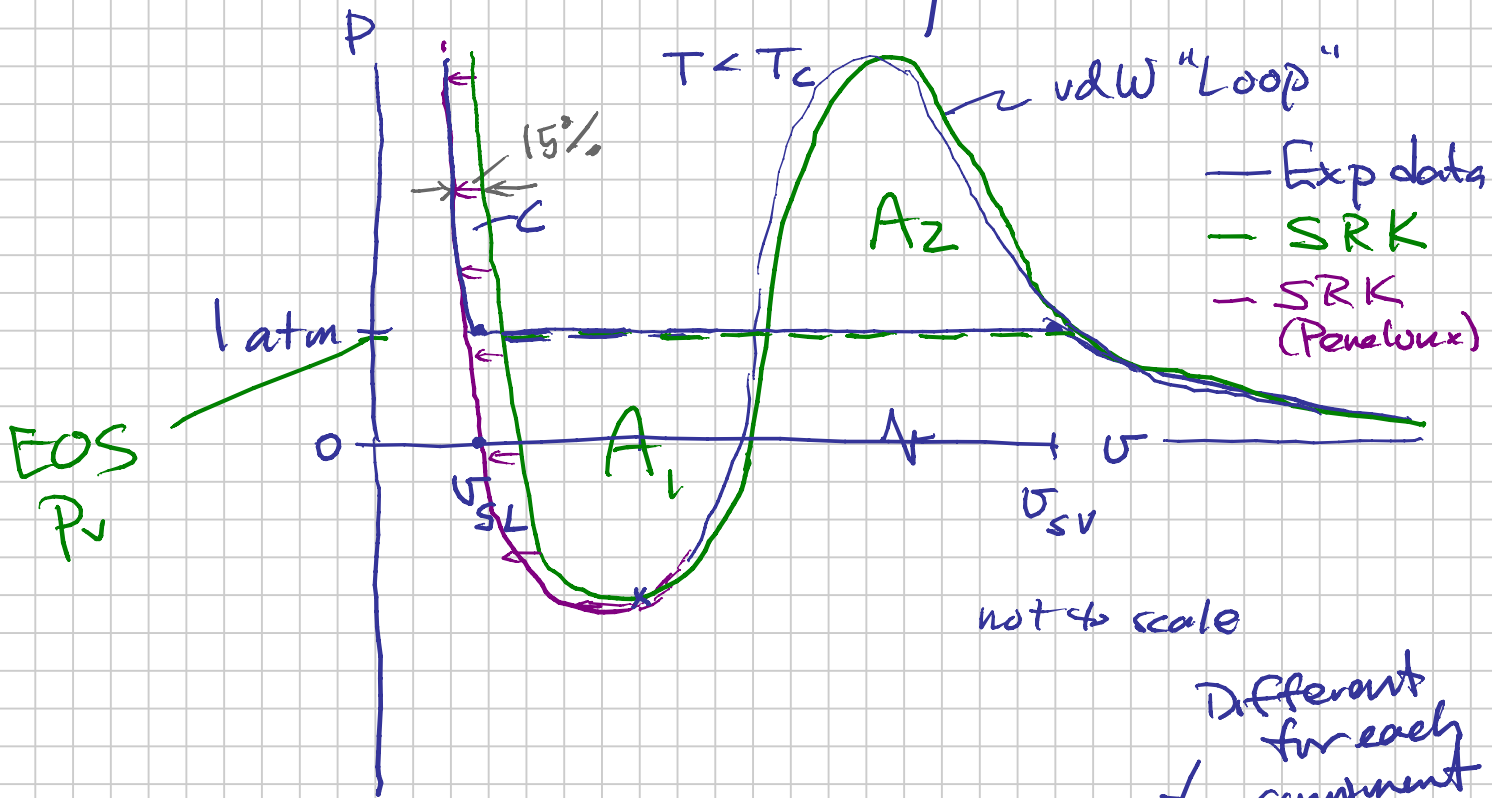
Pitzer (ω)

related to the slope of $P_r(T)$ near C.P.



$$\omega = -1 - \log_{10} \frac{P_v(0.7T_c)}{P_c}$$

Cubic EOS "calculate" $P_v(T)$?



$$V = V_{SRK} - \frac{c}{\text{Different for each component (EOS)}}$$

- does NOT affect EOS (P_v)
- Fixes (V_{SL})
- Has little effect on V_{SV} (which was ok in the original SRK)

Need to Use EOS:

Each Component:

T_c

P_c

ω

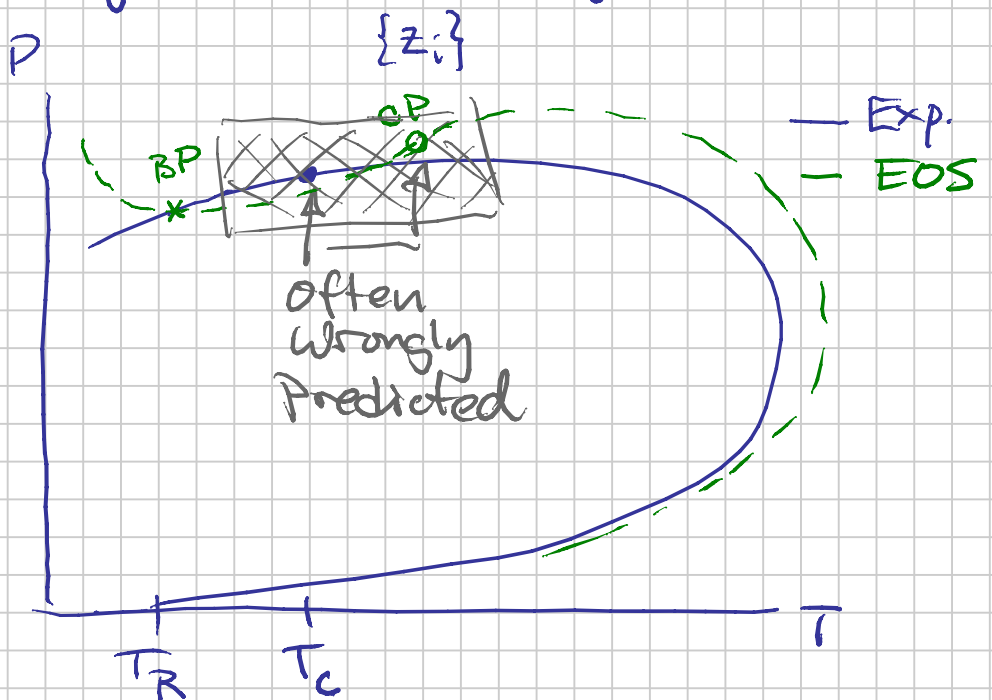
c [s] [$"s" \equiv c/b$] dimensionless
"c" shift

M ; convert $v \rightarrow g$

SRK with VT
PR with VT

(similar)
same set of component
 $\{T_c, P_c, \omega, M\}$
different s values

Neither EOS usually predicts c.p. of mixtures accurately.



Improve Mixture VLE (K-values)

(y_i, x_i, F_v)

How?

y_i
x_i

$$\bar{a}_v = \sum_i \sum_j y_i y_j (a_i a_j)^{1/2} (1 - k_{ij})$$

$$\bar{a}_L = \sum_i \sum_j x_i x_j (a_i a_j)^{1/2} (1 - k_{ij})$$

\bar{a} VERY important to calc'd $\mu_{i,v}$ for
 $\mu_{i,L}$ for

k_{ij} is the "binary (i-j) interaction parameter"

BIP

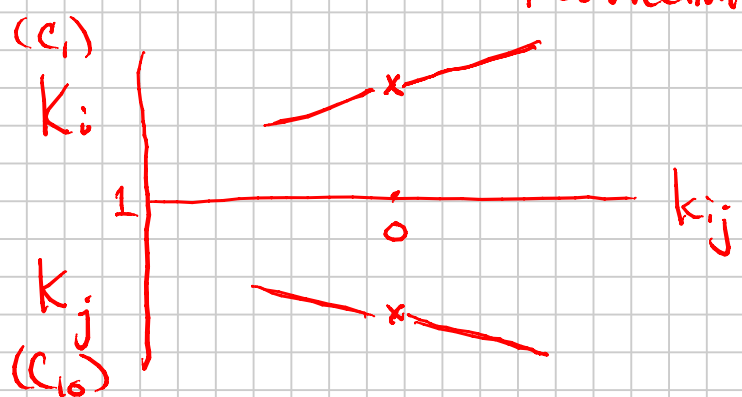
• Symmetric: $k_{ij} = k_{ji}$ |

• Diagonal: $k_{ii} = 0$ |

• Magnitude: -0.1 to +0.3
(usual)

10-30%
Correction

• Semi-quantitatively



• SRK & PR

non-HC $\left\{ \begin{array}{l} \text{N}_2\text{-HC} \\ \text{CO}_2\text{-HC} \\ \text{H}_2\text{S-HC} \end{array} \right\}$ BIPs $\sim +0.1$ (0.05-0.15)

• SRK : HC-HC default $k_{ij} = 0$
(C₁-C₇₊)

PR : C₁ - C₇₊ "default" $k_{ij} \sim \underline{0.05-0.15}$

• k_{ij} IMPACT $K_i \& K_j$
key to VLE

LABORATORY PVT EXPERIMENTS (Ch. 6)

• SAMPLE ANALYSIS

- QC Samples - Leakage Well \rightarrow Lab?
- Compositional Analysis (mole, mass amounts)
- Physical Recombination

• SATURATION PRESSURE

- BP or DP @ T_R

2 methods
- \pm

• CONSTANT COMPOSITION (MASS) EXPANSION (CCE)

- $P-V$ @ T_R ; $P > P_s \Rightarrow \underline{\underline{S}}$

• DEPLETION TEST (@ T_R)

- $P < P_s \Rightarrow$ 2-phases (G + O)

- Remove some gas at each "stage"

- OILS: Remove ALL gas

"Differential Liberation Exp." (DLE)

- GAS CONDENSATES: Remove "some" of the Gas

"Constant Volume Depletion" (CVD)

D.P. Volume

• "SURFACE" MULTISTAGE SEPARATOR TEST (SEP)

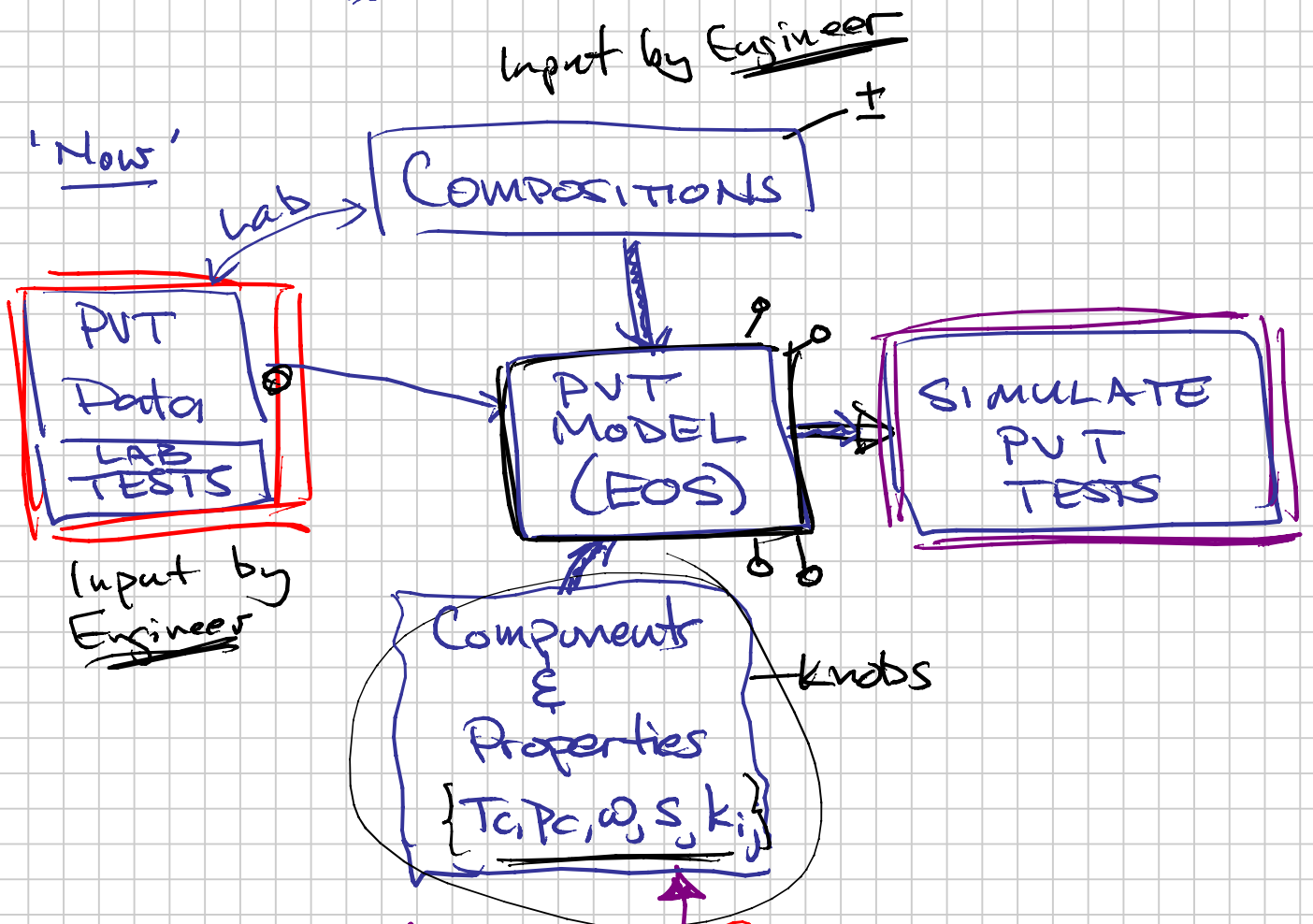
- 2 or 3 STAGES \rightarrow p_{sc}, T_{sc}

\Rightarrow Phase Amounts, Compositions, Properties
 F_v y_i x_i ρ μ c

'Old Days'

Used directly (or indirectly) measured lab PVT data to make engineering calcs.

- ⇒ $q(t)$
- Material Balance (\bar{P}_R vs RF)!
 - Flow (Darcy) Calcs
 - $\mu, \rho, \text{Shrinkage}(o) \text{ or Expansion}(G_i)$
 - Decline Curve Methods
 - Reservoir Simulation
 - ...
- ↑
 Recovery Factor
 Surface Gas
 Surface Oil



(1) Guess/estimate $\left(\begin{matrix} + \\ - \end{matrix} \right) C_7+$ Properties

Compare Lab PVT data vs EOS PVT data

$P_s, S, V_g, V_o, S_g, S_o \dots y_i, x_i$

$$SSQ = \sum_i \left(\frac{d_{lab} - d_{eos}}{d_{ref}} \right)^2 \cdot W_i$$

↓
 low: good fit
 high: bad fit

"scaling"
 Weight Factors

minimize
 by changing
 C_7+
 $T_c, P_c, w \dots$

SAMPLE ANALYSIS

- QC Samples - Leakage Well → Lab?
- Compositional Analysis (mole, mass amounts)
- Physical Recombination

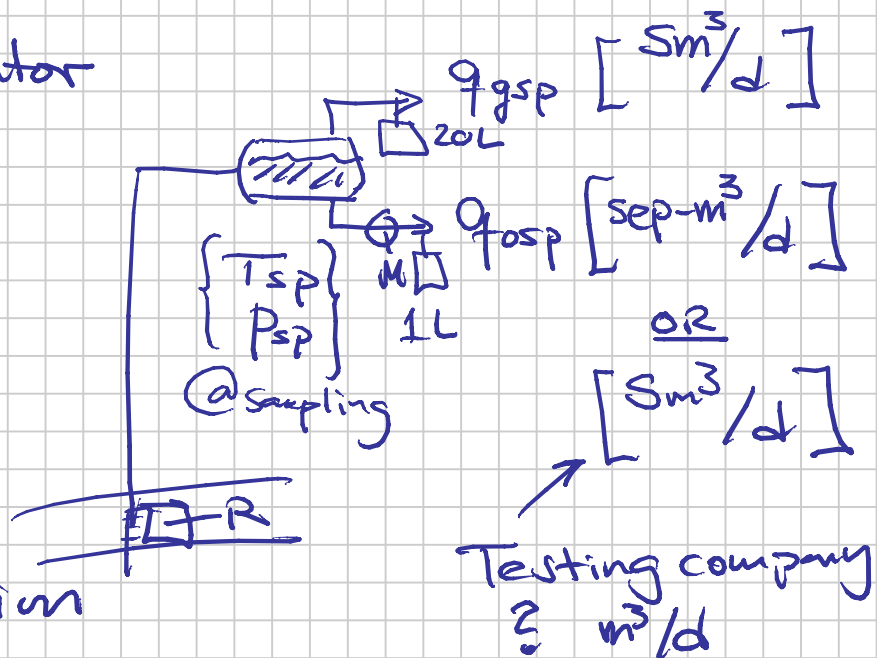
Two Types of Samples:

① Surface Separator

Lab needs


$$GOR_{sp} = \begin{cases} q_{gsp} [Sm^3] \\ q_{osp} [sep-m^3] \end{cases}$$

to make the physical recombination

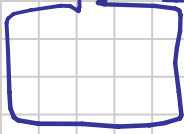


QC: Gas, in the lab

(1) they heat to T_{sp}

(2)  open $P \sim P_{sp} \pm 5-10\%$

QC

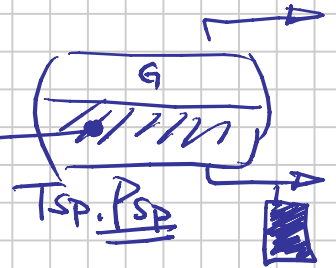


ASK and NEVER assume

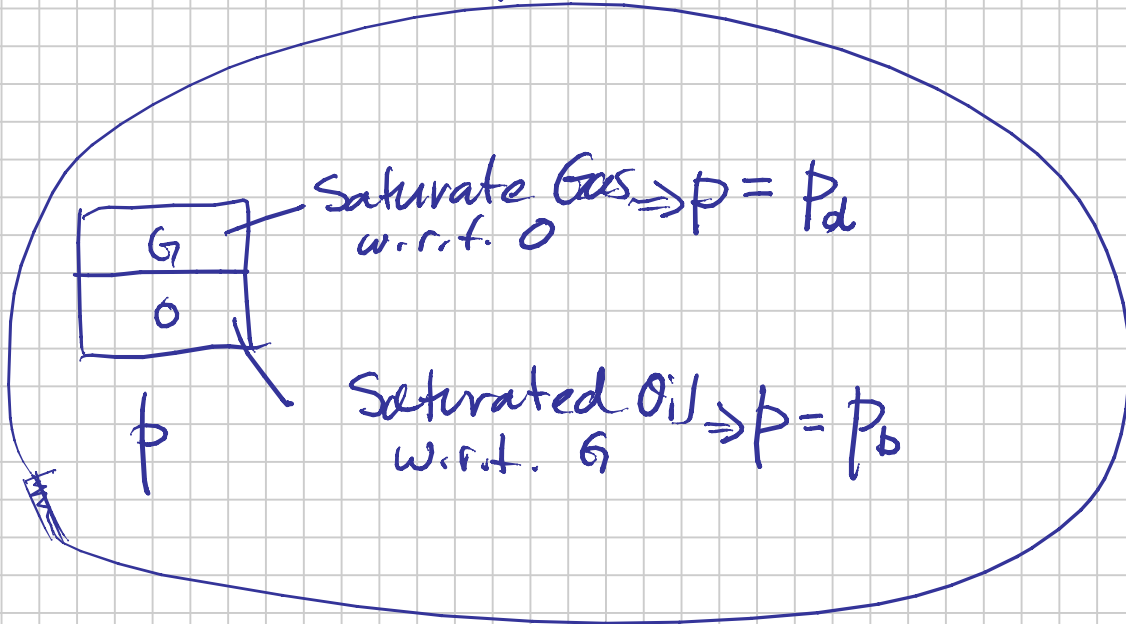
Sep. Oil (1) Heat to T_{sp}

QC

(2) Measure P_b (Sep Oil) @ T_{sp}



Saturated?

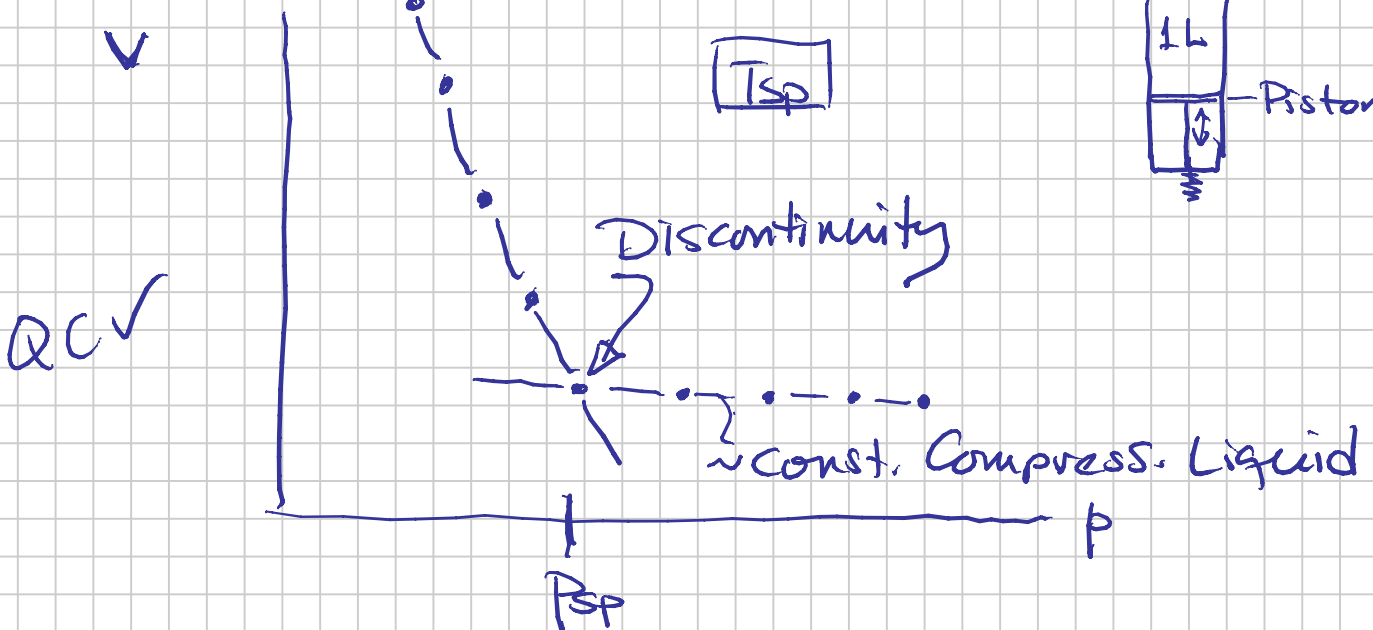


e.g.

$P_b = 20 \text{ bar}$
 $P_{sp} = 60 \text{ bar}$

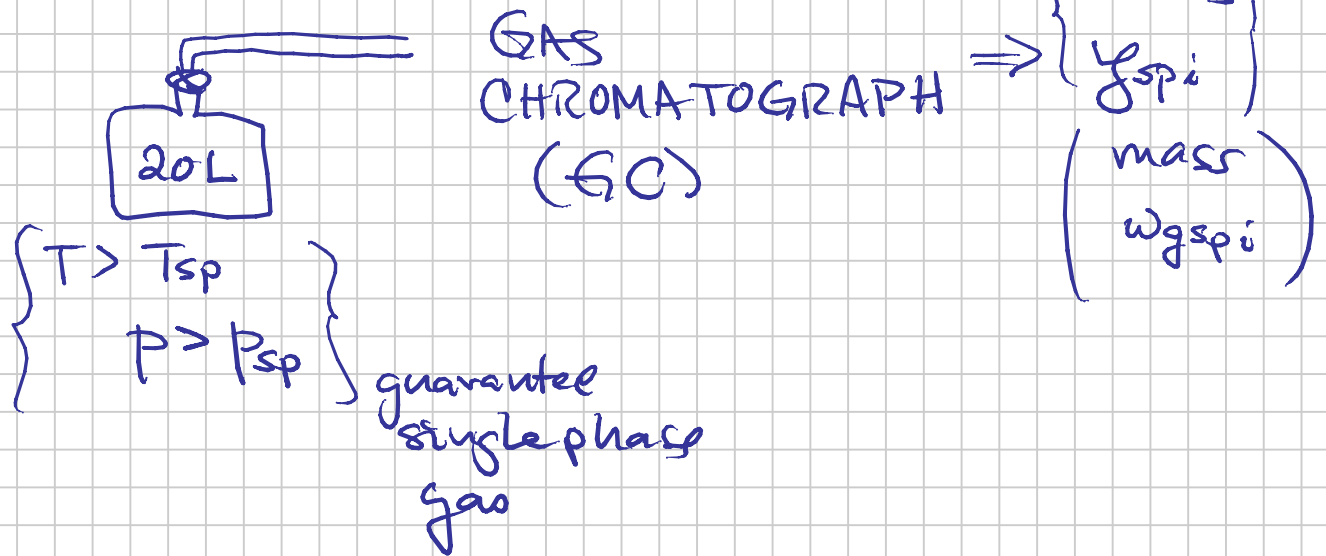
Leakage

Sep. Oil BP Measurement

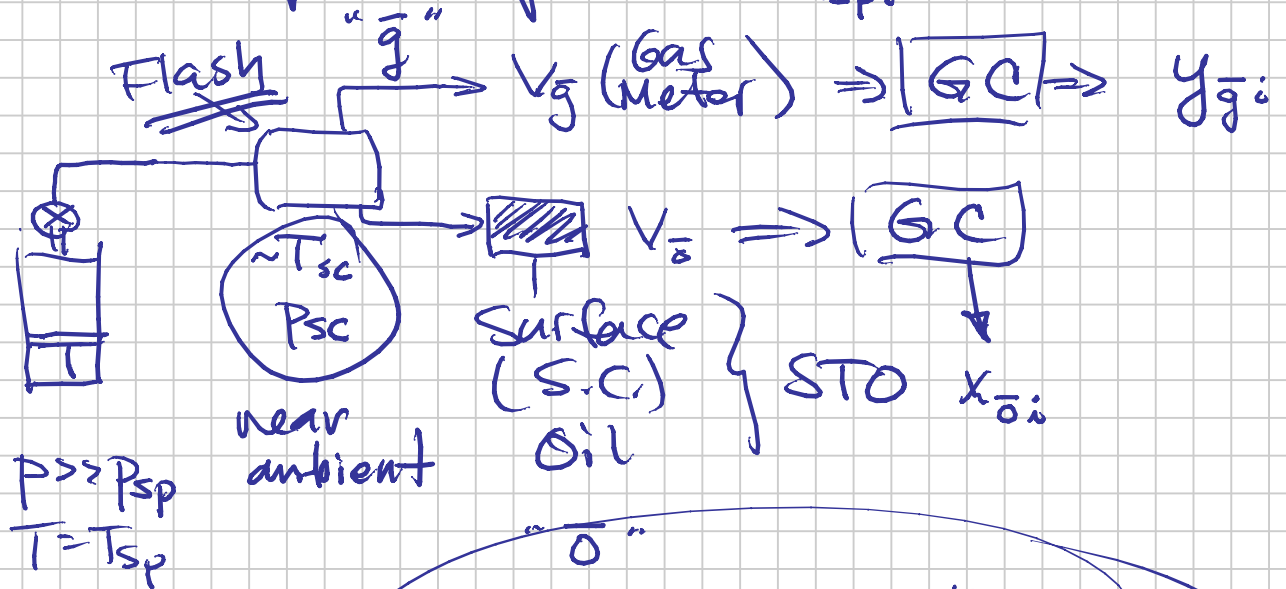


QC ✓

Separator Sample Compositions



Sep. Oil Sample Composition x_{spi}



Mathematically Recombined $\bar{g} + \bar{o}$

$$x_{spi} = F_{\bar{g}} y_{gi} + (1 - F_{\bar{g}}) x_{oi}$$

Check $F_{\bar{g}} = \frac{V_{\bar{g}}}{V_{\bar{o}}} ; S_{\bar{o}}, M_{\bar{o}}$

Sep. Gas & Oil Comp.

(1) Mathematical Recombination

Z_{wi} = wellstream composition entering the separator

$GOR \left[\frac{\text{Sm}^3}{\text{sep-m}^3} \right]$
 $\rho \left[\frac{\text{kg}}{\text{m}^3} \right]$
 $M \left[\frac{\text{kg}}{\text{kg-mol}} \right]$

$$Z_{wi} = F_{gsp} y_{spi} + (1 - F_{gsp}) x_{spi}$$

$$F_{gsp} = \frac{GOR_{sp}}{GOR_{sp} + \left(\frac{\rho_{osp}}{M_{osp}} \right) \left(\frac{RT_{sc}}{P_{sc}} \right)}$$

$$\frac{RT_{sc}}{P_{sc}} = 23.64 \frac{\text{Sm}^3}{\text{kgmol}}$$

$$= \frac{n_{gsp}}{n_{gsp} + n_{osp}}$$

Ch. 6 uses Field Units:

$$GOR_{sp} = \frac{V_{gsp}}{V_{osp}} \left[\frac{\text{Sm}^3}{\text{sep-m}^3} \right]$$

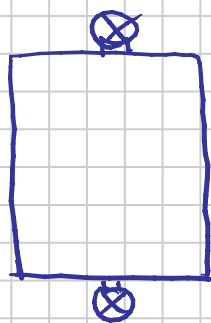
$\frac{\text{scf}}{\text{sep-bbl}}$

$$\frac{\rho_{osp}}{M_{osp}}$$

Torkel Ristebrotten

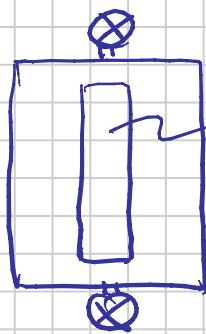
(Physical Recombination of Sep. Samples)

"Blind"



High-P
High-T
PVT
Cell

"Windowed"



Sapphire
Window

100-1000 cc

Volume Control

- (1) Hg injection (bottom \updownarrow) OLD
- * (2) Piston

Fill PVT Cell with sep-gas + sep-oil
in the CORRECT proportions.

— Lab ^{ONLY} needs the actual GOR_{sp} @
time of sampling.

$$\frac{\uparrow \text{Sm}^3}{\text{sep-m}^3}$$

② BOTTOMHOLE SAMPLE

- Openhole ("MDT" or "RCI" ...)
"Formation Testing Tool"
 - Before Casing is "set"

- Cased-hole, "traditional" BHS



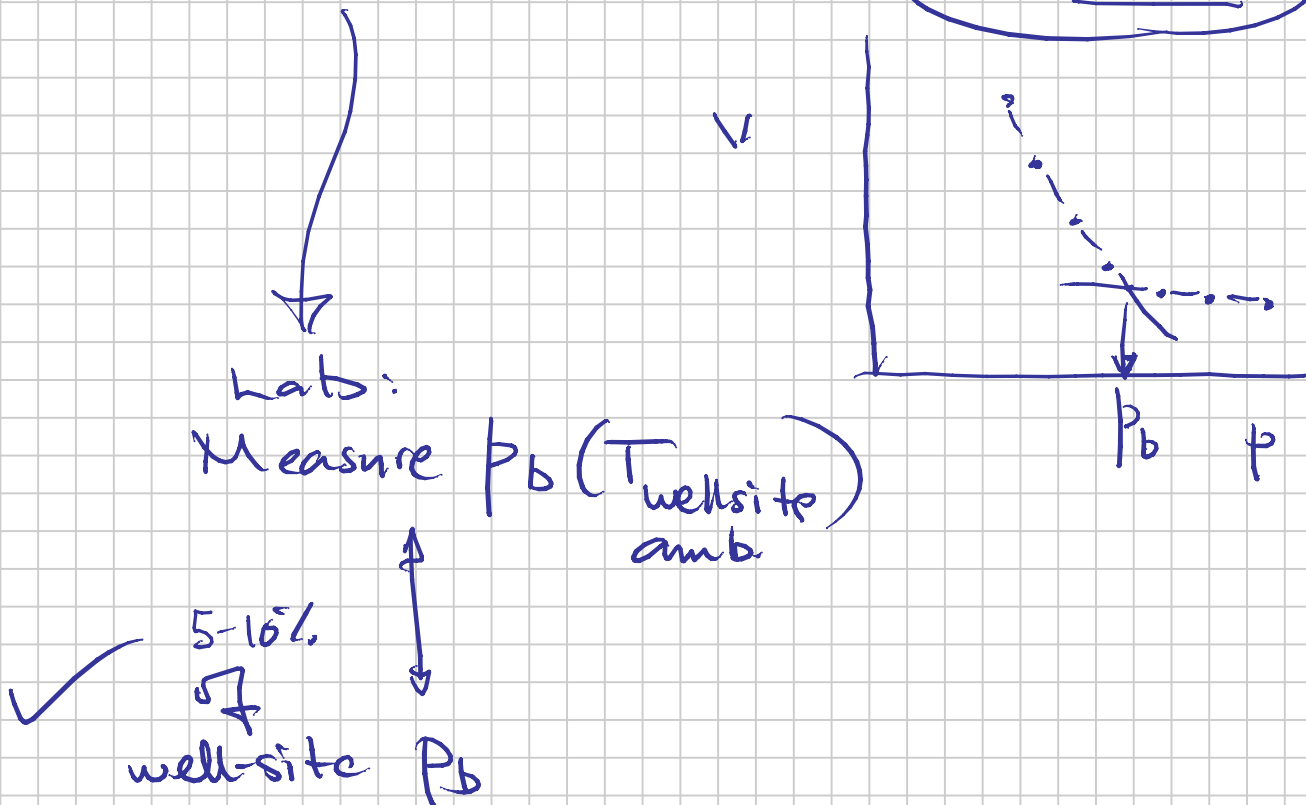
QC of BHS:

- Some Oils (GOR $\approx 150 \frac{\text{Sm}^3}{\text{Sm}^3}$)

50 cc -
500 cc

On the wellsite:

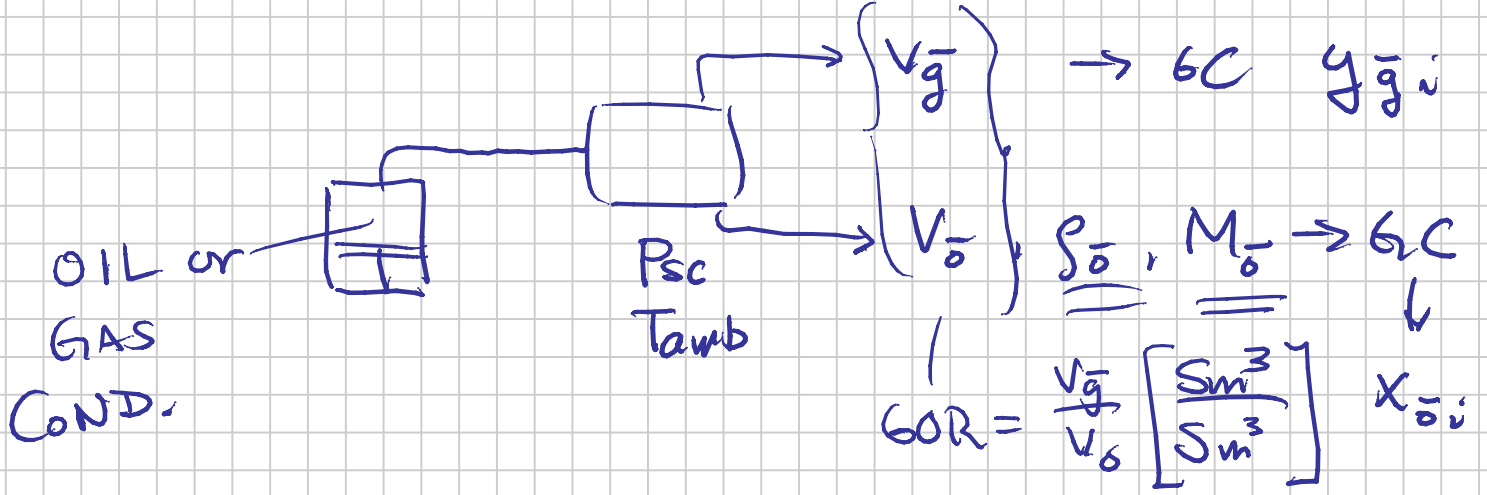
p-V_g curve
@ T_{ambient}



Charge Directly the BHS to the
PVT Cell for PVT measurements

Composition of BHS?

Measured using "Flash-GC" method
(same as we used sep-oil)



Lab usually reports ONLY $\{z_i\}$

$$z_i = F_g y_{g,i} + (1 - F_g) x_{o,i}$$

$$F_g = \frac{GOR}{GOR + \left(\frac{\rho_o}{M_o}\right) \left(\frac{RT_{sc}}{P_{sc}}\right)}$$

Ask for Flash-GC details

Sm^3 / Sm^3

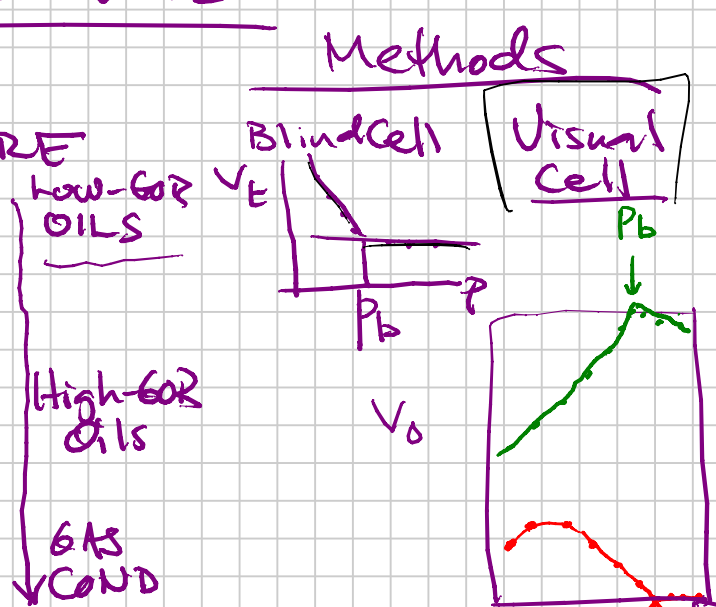
$\rho [kg/m^3]$

$\frac{RT_{sc}}{P_{sc}} = 23.64 \frac{Sm^3}{kgmol}$

PVT Measurements

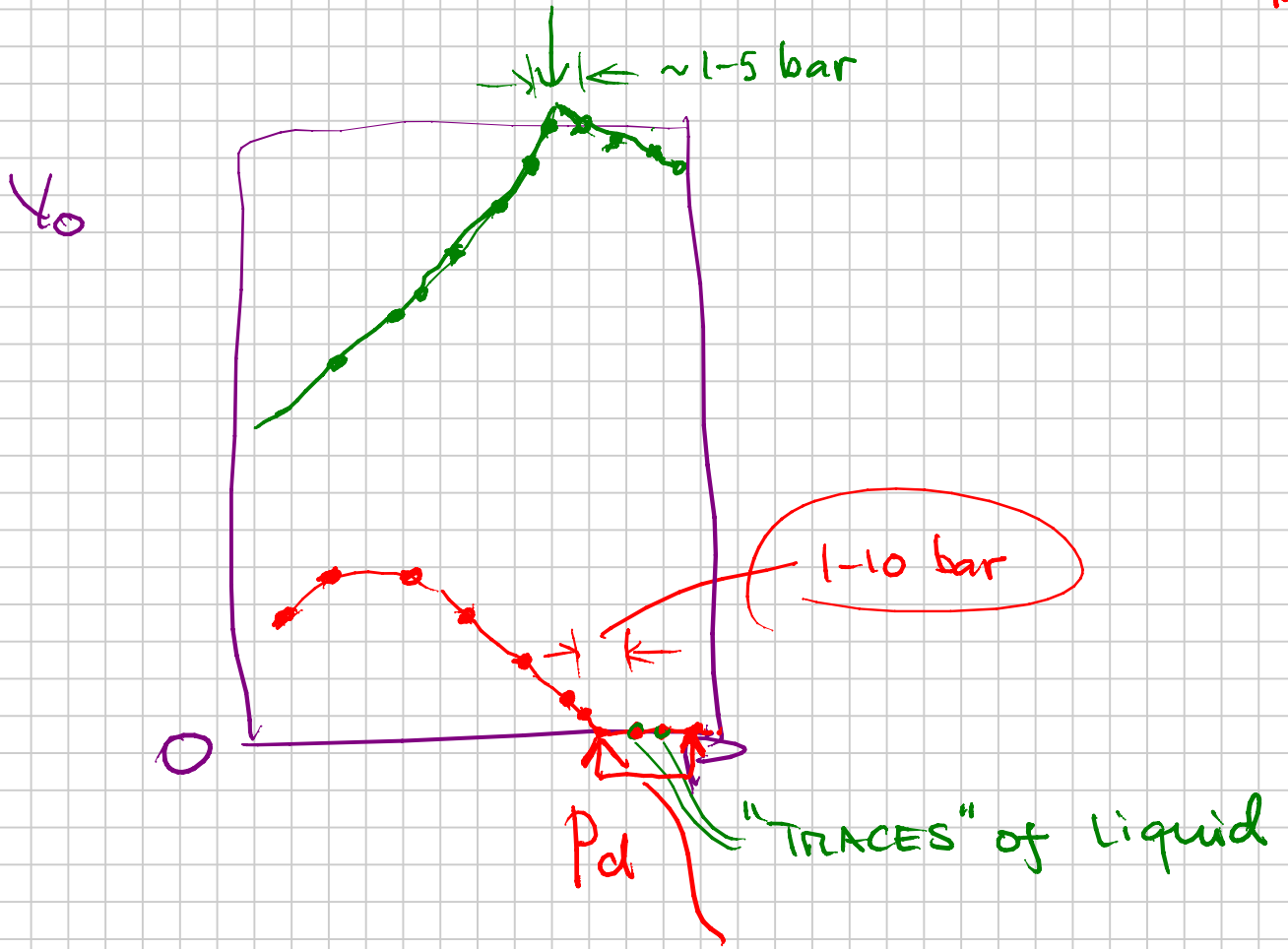
• SATURATION PRESSURE

- Bubblepoint @ T_R
- Dewpoint @ T_R



$P_b @ V_{o,max}$

P_d



CCE

Reporting data $p-V$ when measuring the saturation pressure:

T_R

p

V_t

$\{V_o\}$

GASES

Z_g

$\{P_g\}$

$\frac{V_o}{V_{ref}}$

lab-to-lab

P_s

(-)>DP

0



- = V_d
- = V_t

<u>P</u>	<u>V_t</u>	<u>{V_o}</u>	<u>OILS</u> <u>V_t / V_b</u>	<u>ρ_o</u>	<u>V_o / V_{ref}</u> <small>V_b or V_t</small>
			< 1	---	< 1
			1	(-)BP	↑ <u>1</u> _{max}
<u>P_b</u>			> 1		< 1

Sampling Conditions

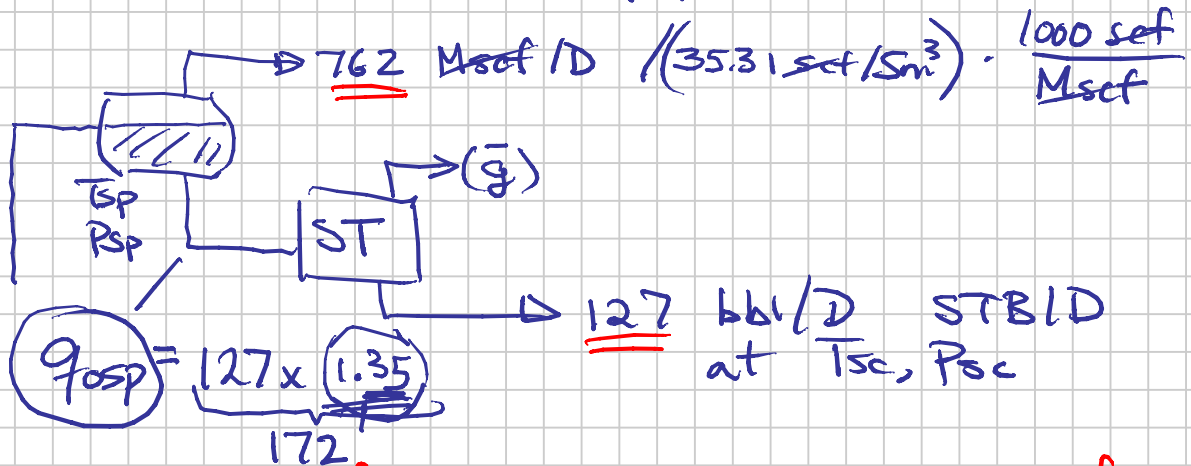
Flowing tubing pressure, psig	3,375
FBHP, psig	5,500
Primary-separator pressure, <u>psig</u>	<u>300</u>
Primary-separator temperature, °F	62
Secondary-separator pressure, psig	20
Secondary-separator temperature, °F	60
Field stock-tank-liquid gravity at 60°F, °API	58.5
Primary-separator-gas production rate, Mscf/D	762.14
Pressure base, psia	14.696
Temperature base, °F	60
Compressibility factor, F_{pv}	1.043
Gas gravity (laboratory)	0.737
Gas-gravity factor, F_g	0.902
Stock-tank-liquid production rate at 60°F, B/D	<u>127.3</u> STBL/D
Primary-separator-gas/stock-tank-liquid ratio	5,987
In scf/bbl	167.0
In bbl/MMscf	
Sampled by	

315 psia
~ 20 bar

bbl? $\frac{STB}{sep. bbl}$?

STBL/D
 $\frac{scf}{STB}$

Recombination GOR = q_{gsp} / q_{osp} ?



Check $\frac{762,000 \text{ scf}}{127 \text{ bbl}} = 6000 = \frac{scf}{STB} = 5987$

(Note: An arrow points from the 127 bbl in the denominator to a question mark below it.)

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

Component	Separator Products Hydrocarbon Analysis				
	Separator Liquid (mol%)	Separator Gas		Wellstream	
	x_{pi}	y_{spi}	(gal/Mscf)	(mol%)	(gal/Mscf)
CO ₂	Trace	0.22		0.18	
N ₂	Trace	0.16		0.13	
Methane	7.78	75.31		61.92	
Ethane	10.02	15.08		14.08	
Propane	15.08	6.68	1.832	8.35	2.290
iso-butane	2.77	0.52	0.170	0.97	0.317
n-butane	11.39	1.44	0.453	3.41	1.073
iso-pentane	3.52	0.18	0.066	0.84	0.306
n-pentane	6.50	0.24	0.087	1.48	0.535
Hexanes	8.61	0.11	0.045	1.79	0.734
Heptanes plus	34.33	0.06	0.028	6.85	3.904
Total	100.00	100.00	2.681	100.00	9.159

Heptanes-Plus Properties		
Oil gravity, °API	46.6	
Specific gravity at 60/60°F	0.7946	0.795
Molecular weight	143	103

Parameters	
Calculated separator gas gravity (air = 1.000)	0.735
Calculated gross heating value for separator gas at 14.696 psia and 60°F, BTU/ft ³ dry gas	1,295
Primary-separator-gas*/separator-liquid* ratio, scf/bbl at 60°F	4,428
Primary-separator-gas/stock-tank-liquid ratio at 60°F, bbl at 60°F/bbl	1,352
Primary-separator-gas/wellstream ratio, Mscf/MMscf	801.66
Stock-tank-liquid/wellstream ratio, bbl/MMscf	133.9

*Primary separator gas and liquid collected at 300 psig and 62°F.

$$F_{gsp} = Z = \frac{z-x}{y-x}$$

$$= \frac{8.35 - 15.08}{6.68 - 15.08}$$

$$= 0.801 \checkmark$$

$$\frac{4428 \text{ scf}}{\text{sep-bbl}} = \frac{762000 \text{ scf}}{q_{gsp}}$$

$$\Rightarrow q_{gsp} = 172 \frac{\text{sep-bbl}}{\text{D}}$$

separator

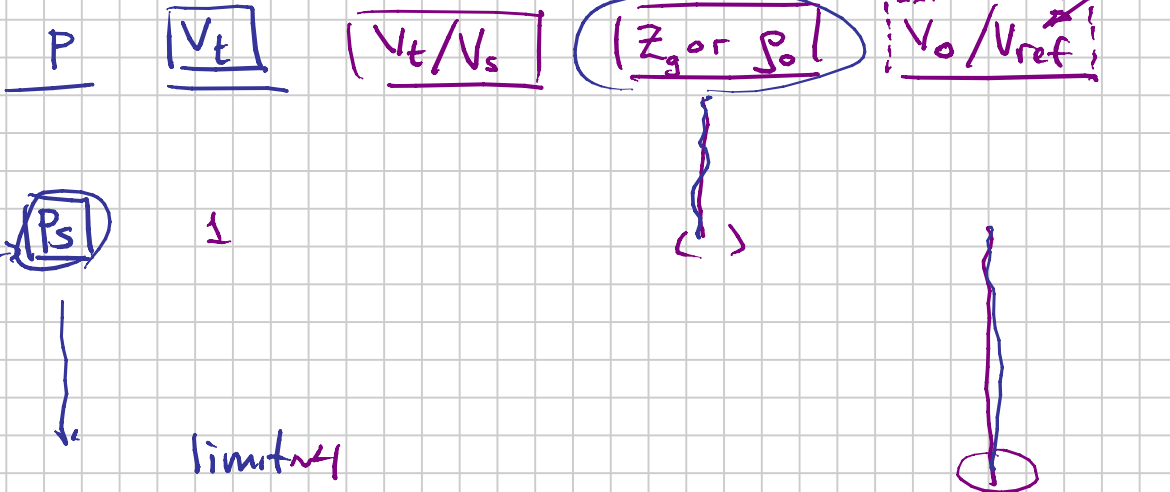
$$F_{gsp} = \frac{n_{gsp}}{n_{\text{wellstream}}} \times \frac{\left(\frac{RT_{sc}}{P_{sc}}\right) (10^{-3}) \text{ Mscf}}{\left(\frac{RT_{sc}}{P_{sc}}\right) (10^{-6}) \text{ MMscf}}$$

$$F_{gsp} = \frac{801.66}{10^3} = 0.80166 \checkmark$$

$$Z_{wi} = F_{gsp} \cdot y_{spi} + (1 - F_{gsp}) \cdot x_{spi}$$

CCE Test

Always Measured
Reported



Depletion Tests:

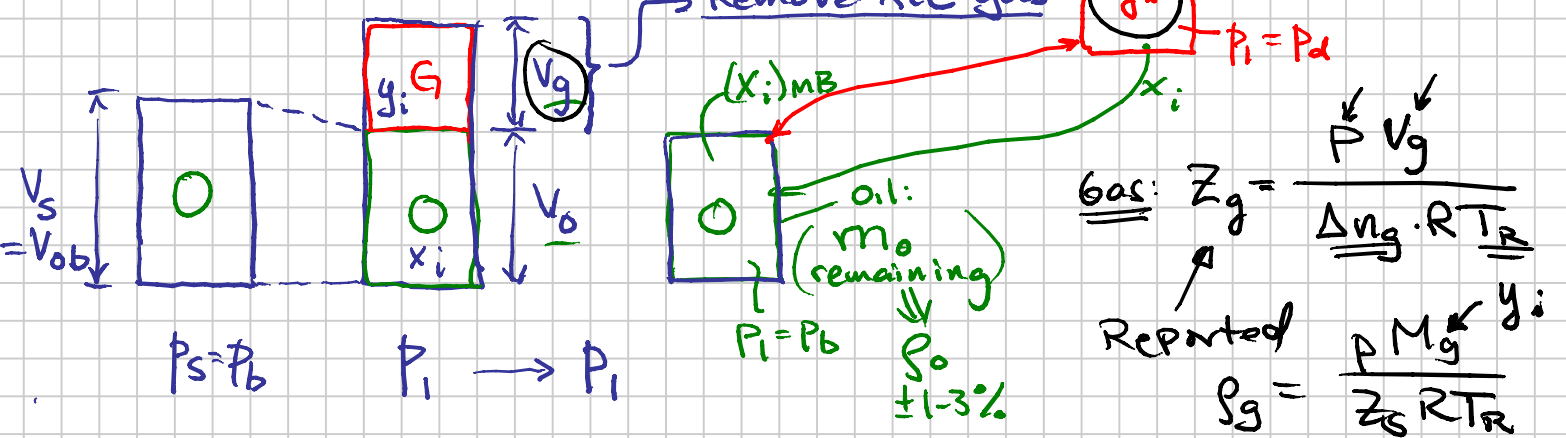
OILS: DLE (Differential Liberation) APP. D (DLE + SEP)

GAS CONDENSATES & (HIGH-GOR OILS) : CVD (Constant Volume Depletion)
Ch. 6 - details

Ps starts the test

forming two (gas/oil) equilibrium phases

DLE @ $T_R = \text{const.}$



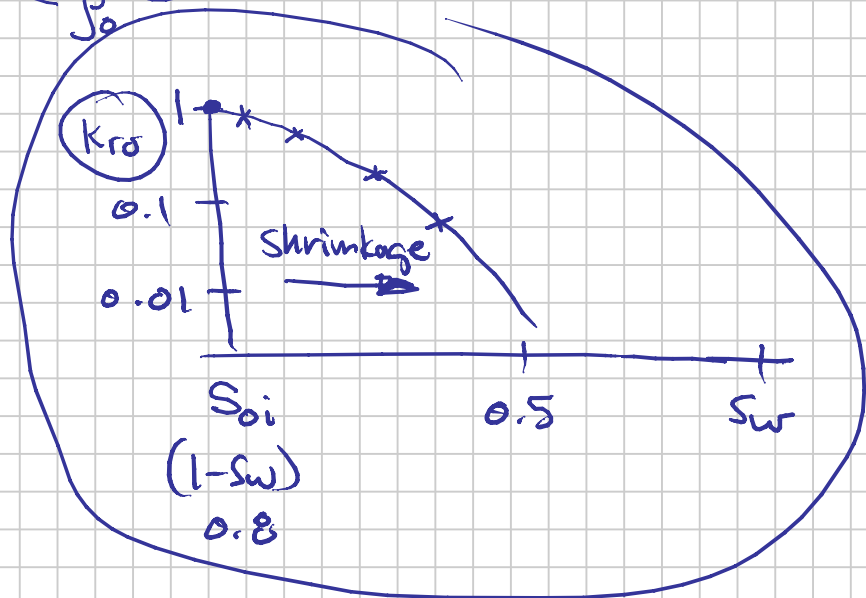
∴ (1) Shrinkage of oil as gas comes out of solution ($\Rightarrow \lambda_o$)

(2) Change in oil density, $\rho_o = m_o/V_o$

$$q_o = v_o = \frac{k_{ro} k}{\mu_o} \cdot \nabla(p + \Delta \rho g) \quad ; \quad \lambda_o = \frac{k_{ro} \cdot k}{\mu_o}$$

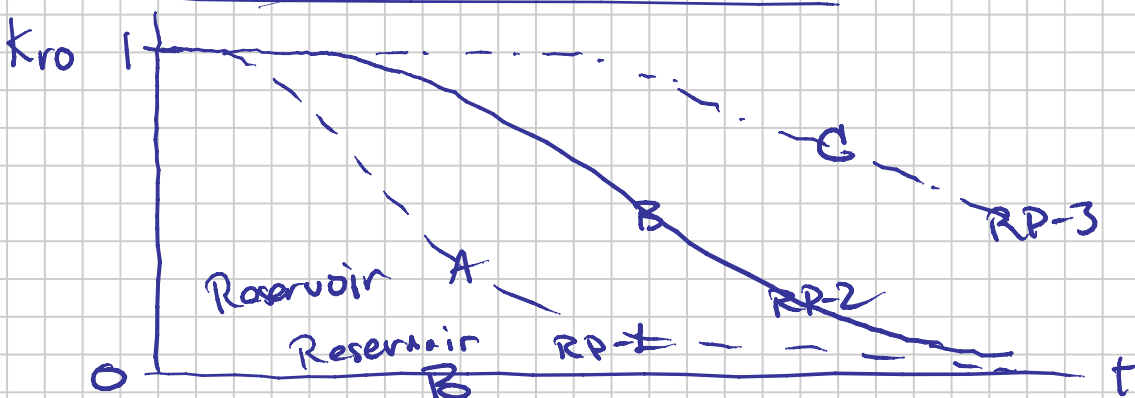
$k_{ro} \propto S_o$ $n \sim (2-4)$

$S_o = \left(\frac{V_o}{V_{ob}} \right)^n$



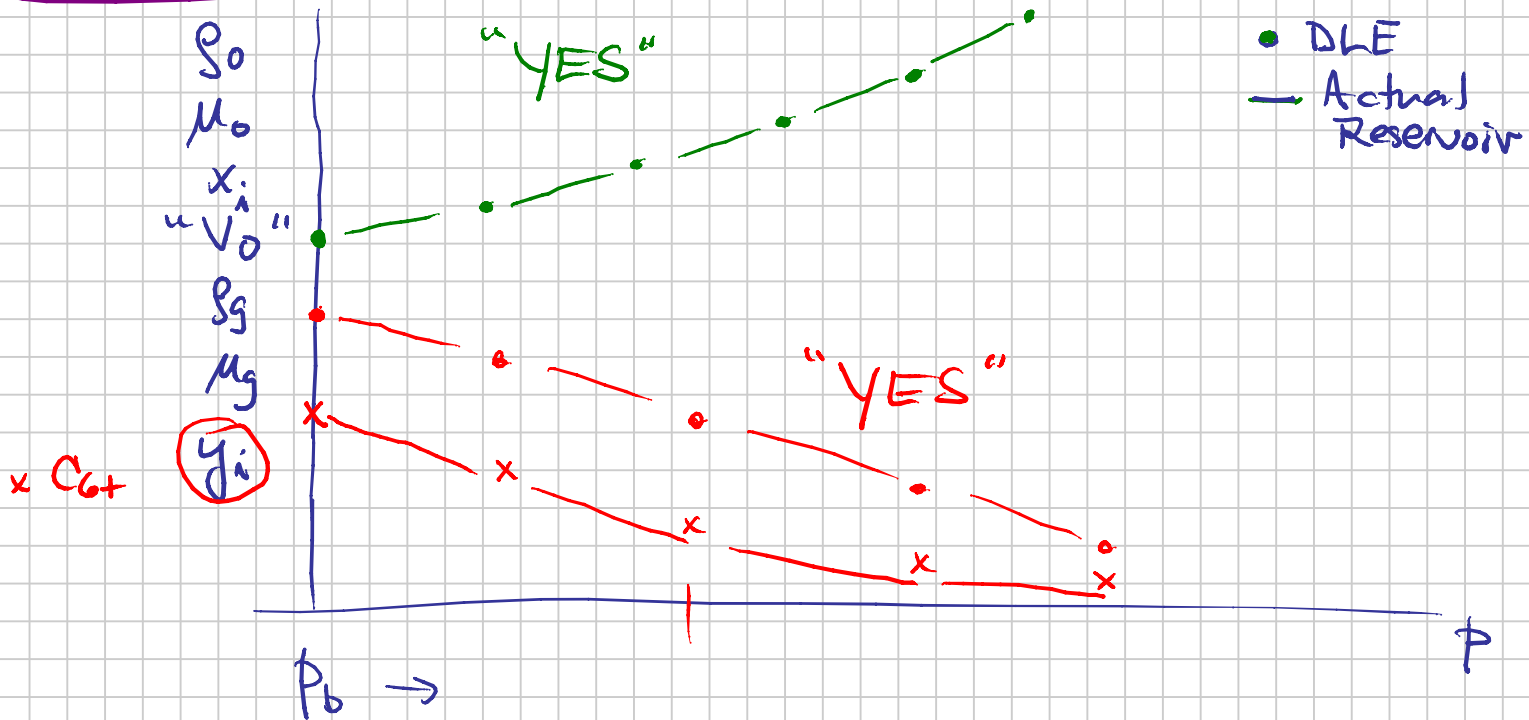
DLE: Does this test represent what goes on IN the reservoir? No

$(k_{ro})_{DLE} = 0$



The PVT Data measured in DLE, are they "useful" or "not"; are they similar to PVT Data in the Reservoir (e.g., @ \bar{P}_R)

INTENSIVE



TODAY : GAS CONDENSATE PUT - LAB DATA (CVD)

TOMORROW : WORK A QUIZ IN CLASS

- App. D . OIL PUT Reports



GAS CONDENSATE PUT - Recommend Study
 "Evaluating CVD Data"

Whitson-Torp

Troll: Gas 45 Tscf
 (10¹² scf)

• (optional)

-> Austad et al.

supplement ; not required

North Field : 900 Tcf
 (Qatar)

(35-40 $\frac{STB}{MMscf}$)

Condensate
 "Yield"

Condensate-
 Gas Ratio
 (CGR)

• E-note GC-PUT

Carbonate
 Khuff formation
 (25-65 STB/MM)

South Pars : 300-400 Tcf
 (350 est)

NF+SP : Initial Condensate in Place ①
 (35 STB/MMscf)

\$ 70/STB } ② Initial Value of Gas
 \$ 7/Mscf } & Condensate
 Mscf = 10³ scf Tcf = 10¹² scf

(10^9 billion STB)

VALUE (billion USD)

Row	ICIP	COND	GAS
1	"	"	"
2	"	"	"
3	"	"	"
4	43.75	(3062) _{25%}	(8750) _{75%}
5	"	"	"
6	"	"	"
7	"	"	"
8	"	"	"
9	"	"	"

$$\text{GAS: } (900 + 350) \cdot 10^{12} \text{ scf} \times \frac{\text{Mscf}}{10^3 \text{ scf}} \times 7 \frac{\text{USD}}{\text{Mscf}} = 8750 \cdot 10^9 \text{ USD}$$

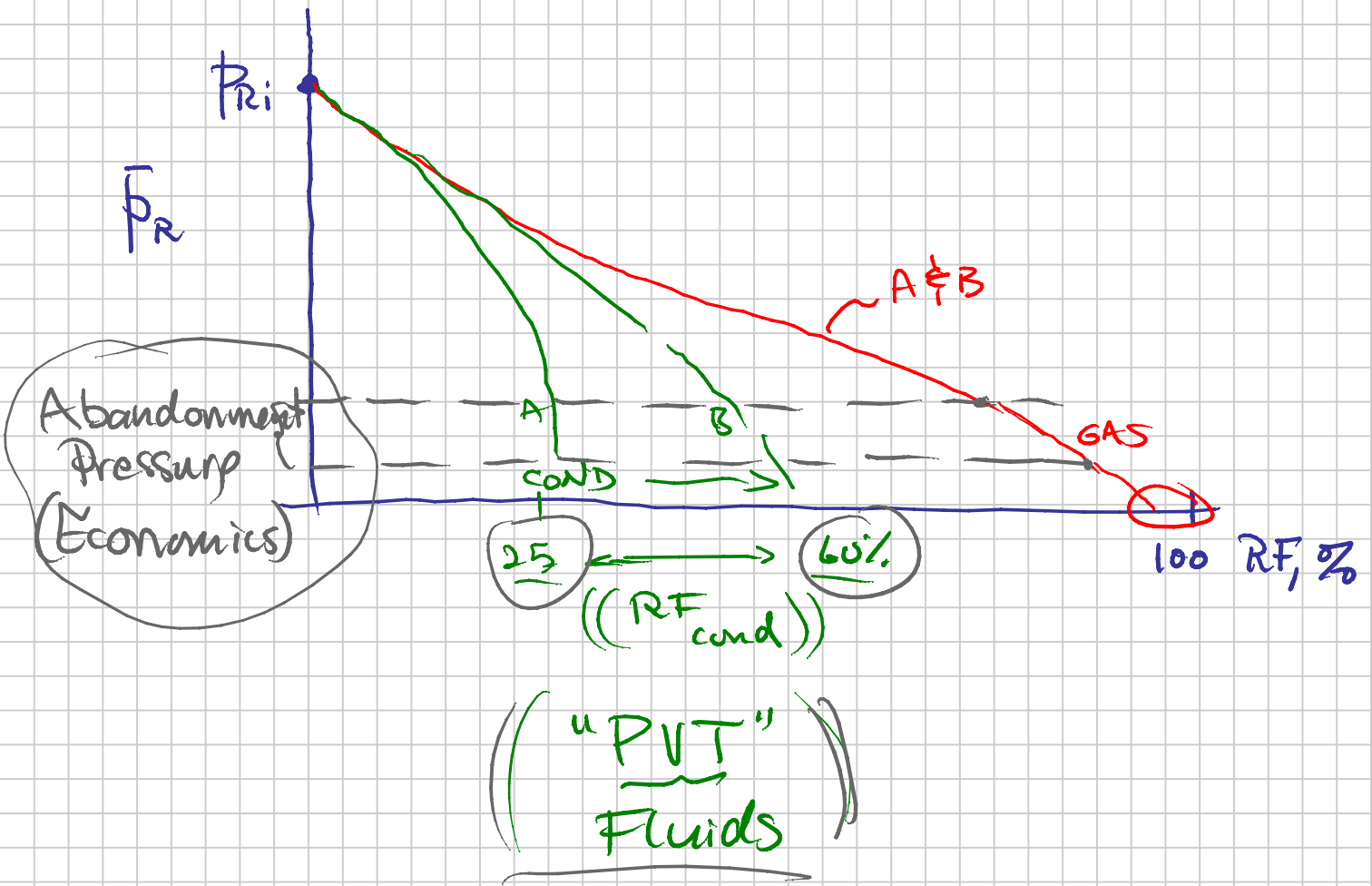
$$\text{OIL: } (900 + 350) \cdot 10^{12} \text{ scf} \cdot 35 \frac{\text{STB}}{\text{Mscf}} \cdot \frac{\text{Mscf}}{10^6 \text{ scf}} = \boxed{43.75 \text{ STB}}$$

$$\text{OIL VALUE: } \frac{43.75 \cdot 10^9 \text{ STB}}{\text{STB}} \cdot 70 \frac{\text{USD}}{\text{STB}} = \underline{\underline{3062 \cdot 10^9 \text{ USD}}}$$

2012 : 10^6 NOK / Norw. | in the oil fund

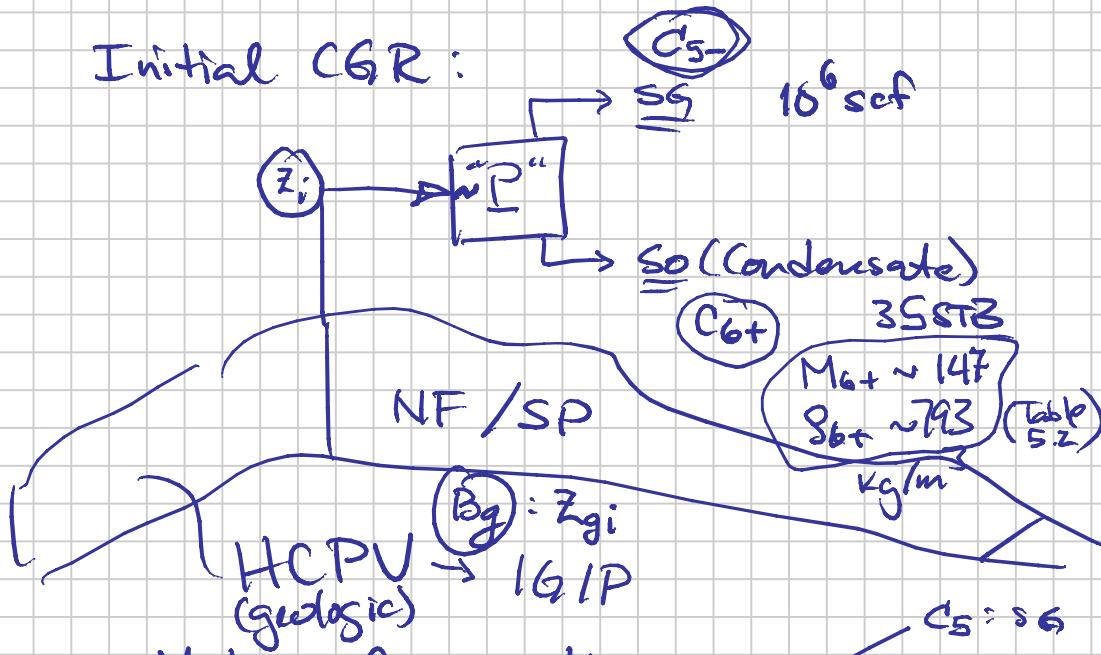
$$175 \text{ 000 USD} \times 4 \cdot 10^6 = \boxed{\underline{\underline{700 \cdot 10^9 \text{ USD}}}}$$

Recovery Factors Expected from GC

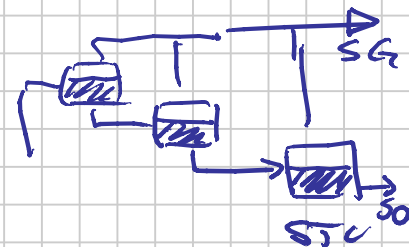


G.C. PUT

Initial CGR:



Approximate Description of a “Multi-Stage” Separation



Molar Composition z_i

$C5 = S6$

$C6+ = S0$

\bar{g} ($S6$)

\bar{o} ($S0$)

\Rightarrow Convert into \sim Surface Products

$$\begin{aligned}
 \text{CGR} &= \frac{V_o}{V_g} = \frac{35 \text{ lbt}}{10^6 \text{ ft}^3} \times \frac{\text{m}^3}{6.28 \text{ lbt}} \times \frac{35.31 \text{ ft}^3}{\text{m}^3} \\
 &= 196 \cdot 10^{-6} \frac{\text{Sm}^3}{\text{Sm}^3} \quad 5.6 \\
 &= 196 \frac{\text{Sm}^3}{10^6 \text{ Sm}^3}
 \end{aligned}$$

$$\text{CGR} = \frac{(z_{G+}) \cdot M_{G+} \cdot \frac{1}{S_{G+}}}{(1-z_{G+}) \left(\frac{RT_{sc}}{P_{sc}} \right)} = \frac{z_{G+} \left(\frac{147}{793} \right)}{(1-z_{G+}) 23.64}$$

$$z \text{ [kg-mol]}$$

What is the average NF (SF C_{G+} content) in mol-%? (z_{G+})

$$196 \cdot 10^{-6} = \frac{147}{(23.64)(793)} = \frac{z}{1-z}$$

$$a = \frac{z}{1-z}$$

$$a - az - z = 0$$

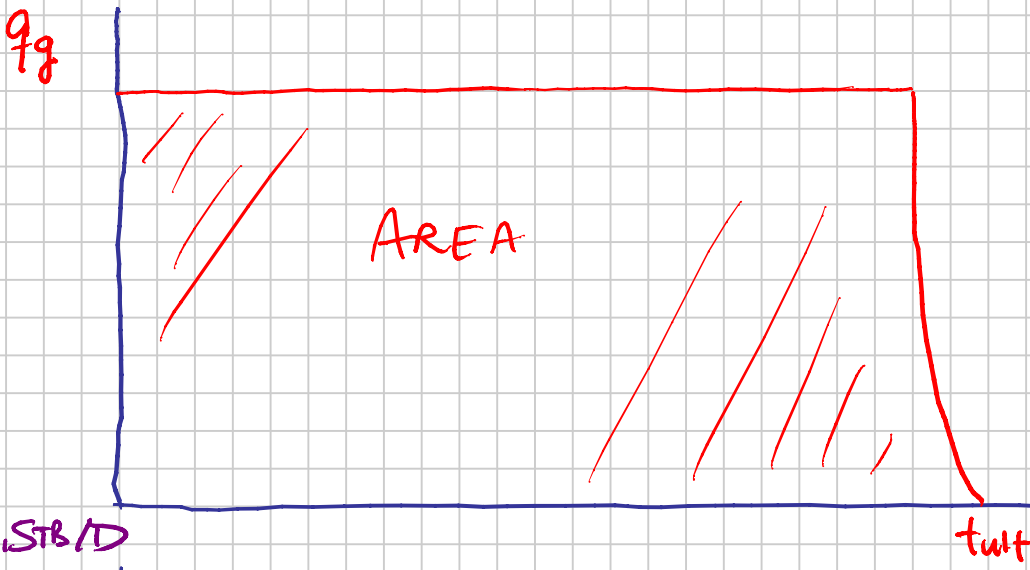
$$z(a+1) = +a$$

$$z = \frac{a}{a+1}$$

$$z_{G+} = 2.43 \text{ mol-\%}$$

C₆₊ variation with pressure \Rightarrow RF₀

Given producing composition (C₆₊ amount) \Rightarrow CGR \sim



q_0 STB/D

2.5

C₆₊ mol-%
in
Produced
Wellstream

AREA
 $N_p = \int q_0 dt$

CGR
+ 35 (196)
STB/MM
(Sm³/10Sm³)

$$q_0 = q_g \cdot \text{CGR}$$

IF
CGR = constant
 \Rightarrow RF₀ = RF_g

RF₀ $\equiv \frac{N_p = \int q_0 dt}{N}$

LOIP
ICIP

RF_g $\equiv \frac{G_{\text{Total}} = \int_0^{t_{\text{ult}}} q_g dt = \text{Cumulative Gas Produced}}{G}$
LOIP

$C_{6+}(\bar{P}_R)$ determines RF_0 .

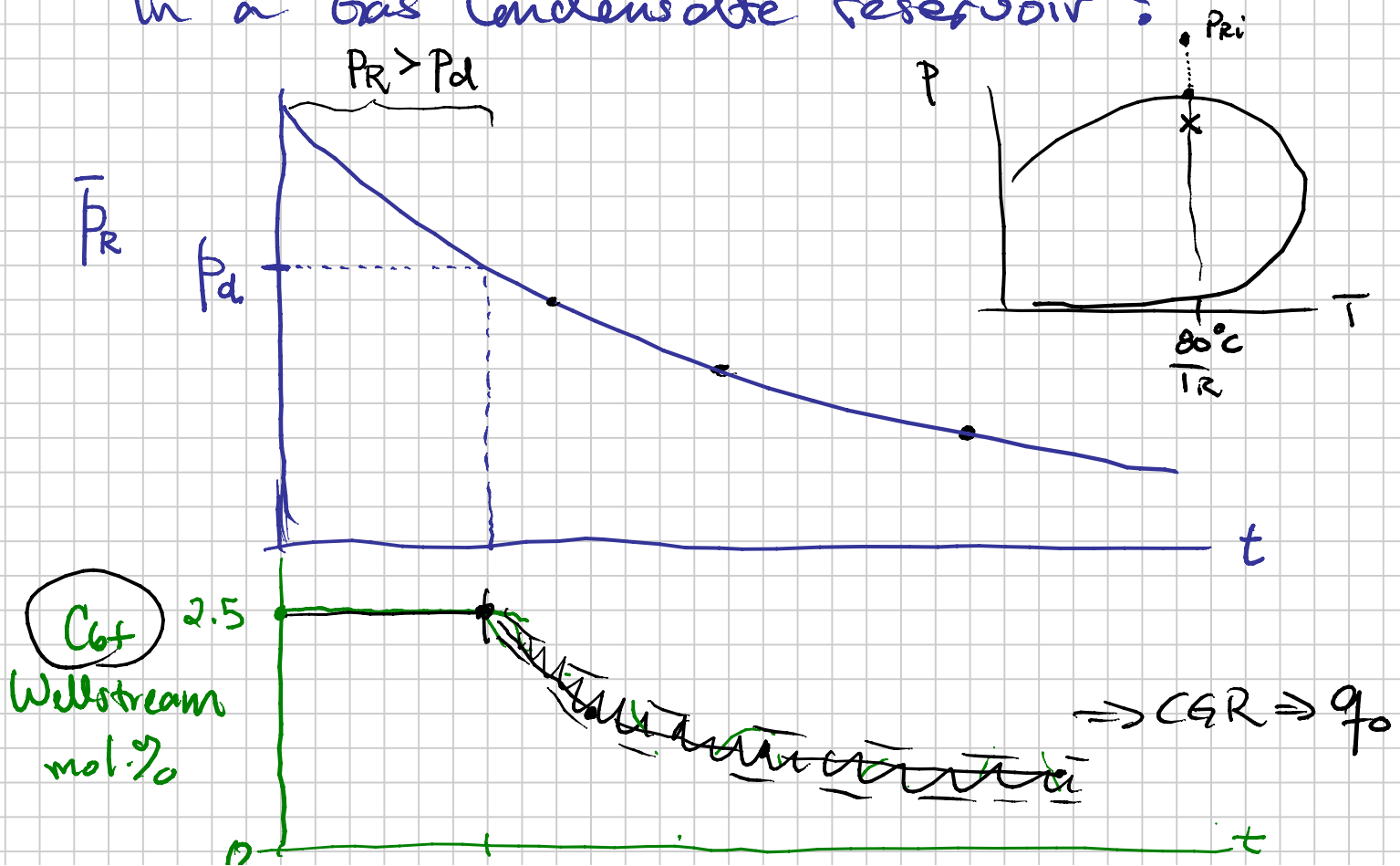
↑
in produced wellstream

$$CGR = A \left(\frac{z_{6+}}{1 - z_{6+}} \right) \Rightarrow \underline{\underline{CGR \propto C_{6+}}}$$

G.C.: C_{6+} range (initially) 1-15 mol.-%

MF/SP: 2-3.5
Smeđrbuk South
steepness 7%

How does the C_{6+} amount vary in a Gas Condensate reservoir?



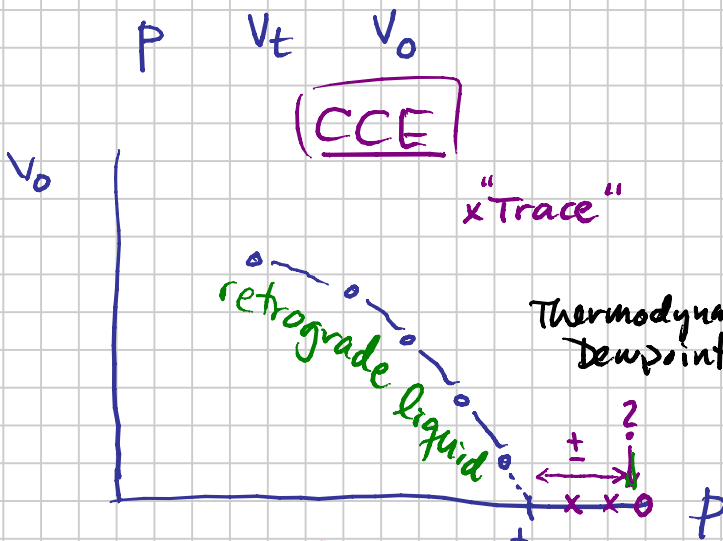
$$\lambda_{OR} = 0$$

How do we "determine" the dewpoint of a gas?



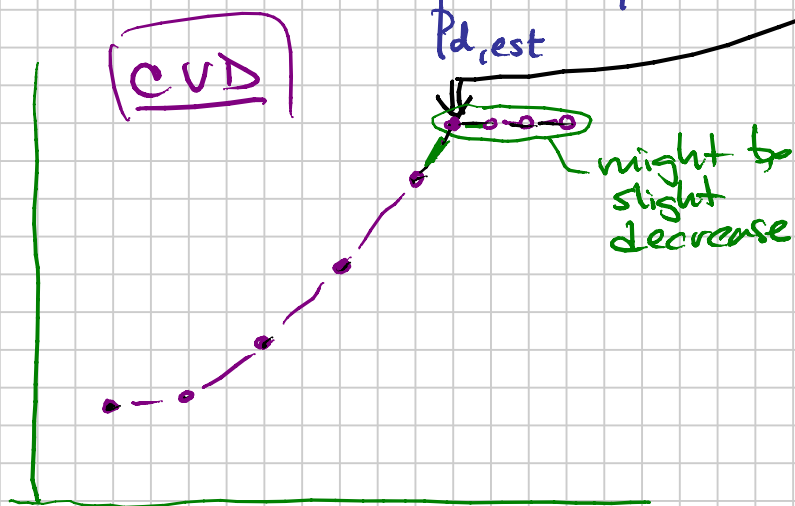
At the pressure where liquid first appears.

Extrapolate $V_0(P)$
 $\lim V_0 \rightarrow 0$



"Engineering" (Economics) Dewpoint

"CGR"
 C₆₊
 in
 CVD
 Gas



C₆₊ in Gas \rightarrow CGR \rightarrow "q₀ or N_p" \rightarrow RF₀

e-note

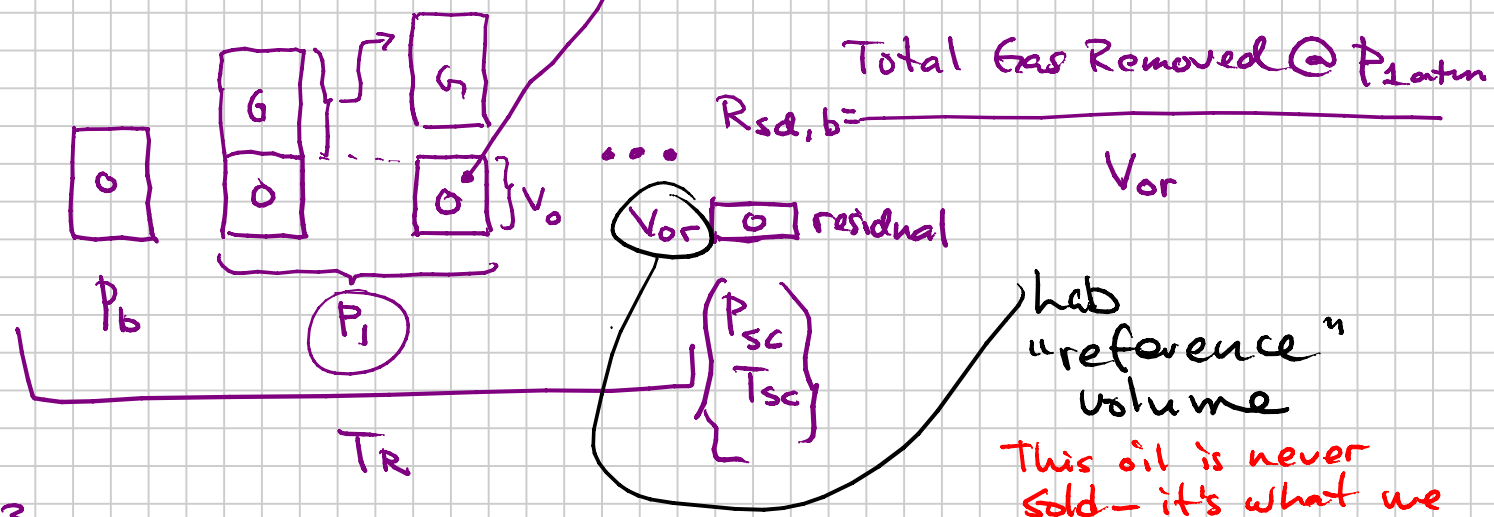
"Gas Cond PVT -
 What's Important
 & Why"

OIL PUT (App. D)

DLE:

$$B_{od} = \frac{V_o}{V_{or}}$$

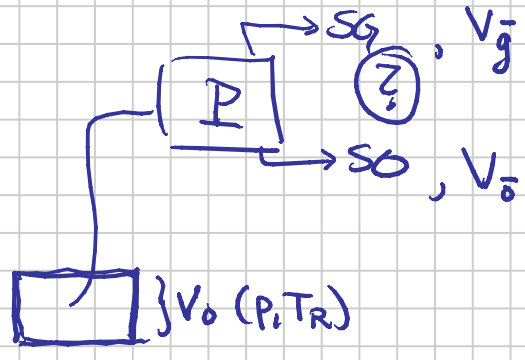
$$R_{sd} = \frac{\text{Remaining Gas in Solution}}{V_{or}}$$



Sm³
scf

$$\left\{ \text{Removed Gas (p)} \right\} = \frac{R_{sd,b}}{V_{or}} - \frac{R_{sd}(p)}{V_{or}}$$

App. D (Ch. 6): Convert B_{od} & R_{sd} to "engineering" usable quantities - in terms of reservoir oil volume V_o and the surface volumes which result by processing that oil at surface conditions.

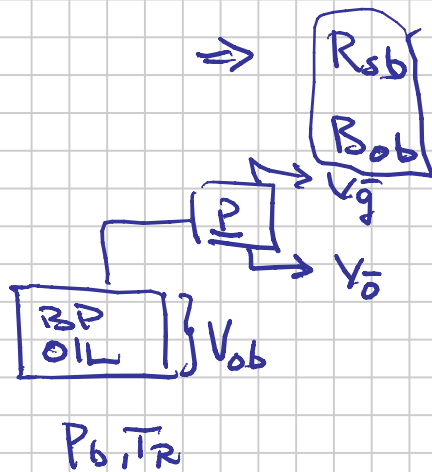


Need:

$$R_s \equiv \frac{V_g}{V_o}$$

$$B_o \equiv \frac{V_o}{V_o}$$

Lab provides only one set of R_s, B_o ,
 from \boxed{P} of the bubblepoint (original) oil.



$$DHE: \underbrace{\begin{Bmatrix} R_{sd}(P) \\ B_{od}(P) \end{Bmatrix}}_{\text{Lab}} + \underbrace{\begin{Bmatrix} R_{sb} \\ B_{ob} \end{Bmatrix}}_{\text{Lab}} \Rightarrow \underbrace{\begin{Bmatrix} R_s(P) \\ B_o(P) \end{Bmatrix}}_{\text{Engineering}}$$

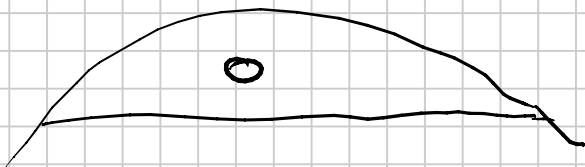
Q: How to use $R_s(P)$ and $B_o(P)$ in solving an engineering problem.

Use App. D
 PVT Data.

$$N(10IP) = 10^9 \text{ STB}$$

$$\text{In Solution: } G(1GIP) = N \cdot R_{si} = N \cdot R_{sb} = 10^{12} \text{ scf}$$

$$R_{sb} = 1000 \text{ scf/STB}$$



$$\left\{ \begin{array}{l} N_p = 10^8 \text{ STB (10\%)} \\ G_p = 5 \cdot 10^{11} \text{ scf (50\%)} \end{array} \right\} \text{ Historical Production}$$

$\boxed{P_R ?}$

Bubblepoint Oil

SEPARATOR TESTS OF Reservoir Fluid SAMPLE

$T_{sp2} = T_{sc} \quad 60^\circ\text{F}$

$P_{sp2} = P_{sc} \quad 1 \text{ atm}$

(4)

2-stage Separator Tests

Separator		GOR ¹		Bob			
P_{sp1} Pressure (psi gauge)	T_{sp1} Temperature (°F)	Separator	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
① 0	75	1,206	① 1206	45.6	0.5456	1.833	0.942
② 50	74	1,011	35 1046	48.1	0.5872	1.703	
③ 100	75	950	68 1018	48.5	0.5949	1.681	
④ 200	73	875	134 1009	48.5	0.5974	1.674	

USE →

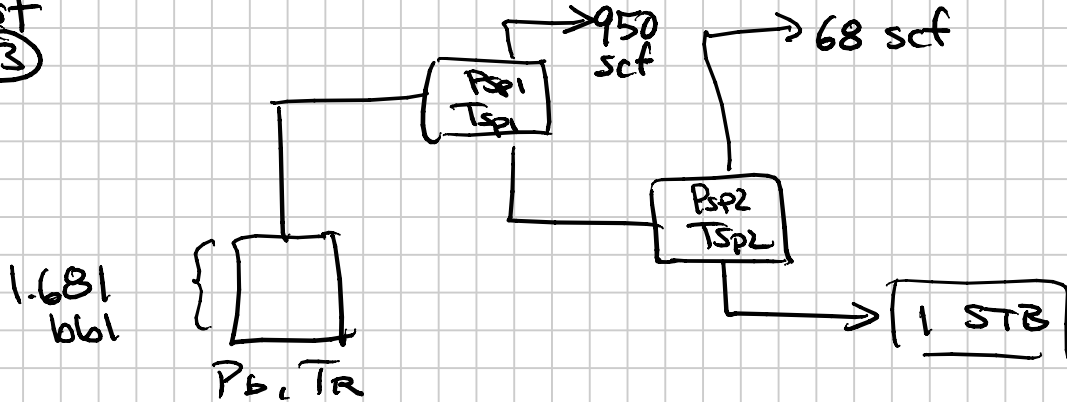
¹ Separator and stock-tank gas/oil ratio in cubic feet of gas at 60°F and 14.7 psi absolute per barrel of STO at 60°F.

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 $T_{sp1} = 75^\circ\text{F}$ and (2) $p_{sp2} = 0$ psig and $T_{sp2} = 60^\circ\text{F}$, with total $R_{sb} = 1,206$ scf/STB, $B_{ob} = 1.833$, $\gamma_{API} = 45.6^\circ\text{API}$, and $\gamma_g = 0.942$.

Test (3)



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

$$1.970 \times \left\{ \frac{1.681}{2.075} \right\} = 1.595 \frac{\text{bbl}}{\text{STB}}$$

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

$$1009 - (1518 - 1335) \cdot \left\{ \frac{1.681}{2.075} \right\}$$

$$= 861 \text{ scf/STB}$$

	P (psig)	B_o ($\frac{bbl}{STB}$)	R_s ($\frac{scf}{STB}$)	...	↓	↓	↓	↓
P_b	3236	1.681	1009					
	2938	1.595	861					
	⋮							

Problem Solution:

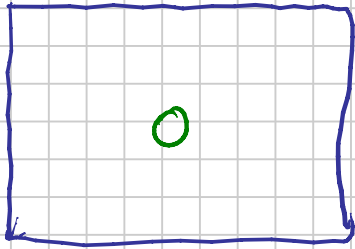
Hints -

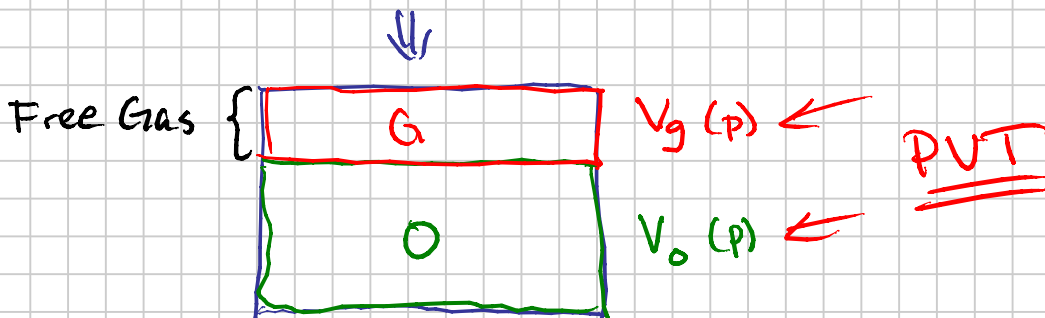
① $N - N_p = \text{oil (STB) remaining}$ $N = \text{Initial oil in place}$

② $(N - N_p) \cdot R_s = \text{gas (scf) remaining in solution}$ $N_p = \text{cumulative oil produced}$

③ Geometric distribution of "free" gas makes no difference

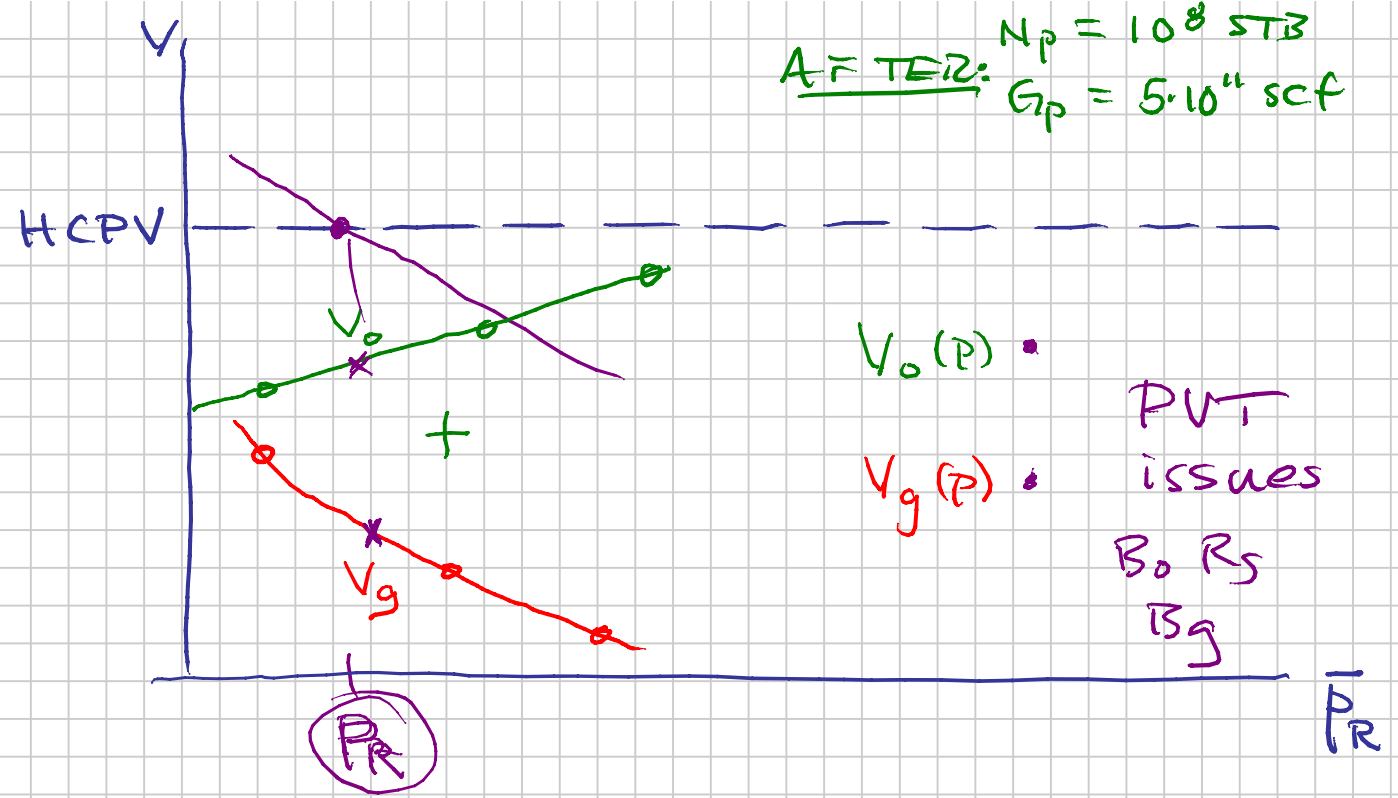
④ Saturated system (assume) $P_R < P_b$

⑤  $HCPV = N \cdot B_{oi}$
 $= \text{constant}$ } constraint



⑥ Total remaining gas = free gas + gas in solution

$N_p = 10^8 \text{ STB}$
 $G_p = 5 \cdot 10^{11} \text{ scf}$
AFTER:



$$\left. \begin{aligned}
 k_{ro} &= S_o^{2.5} \\
 k_{rg} &= (1 - S_o)^{2.5}
 \end{aligned} \right\}$$

Ignore $S_w (=0)$

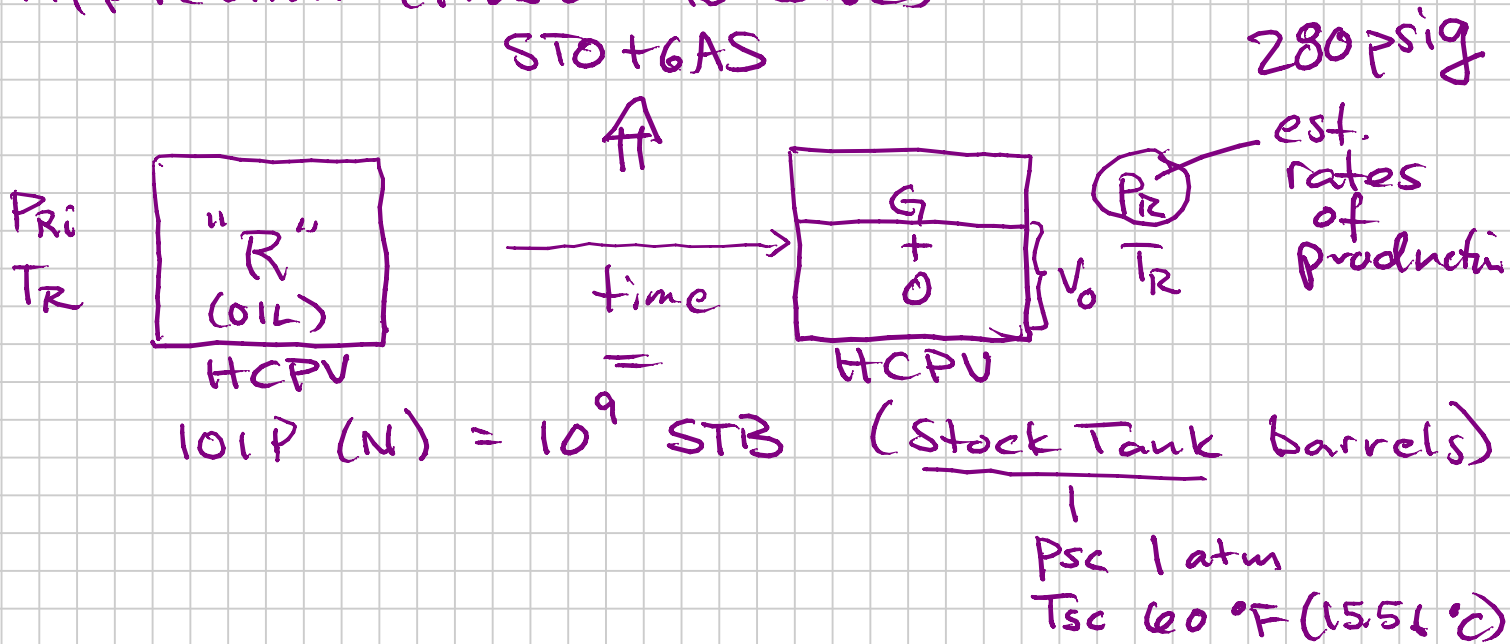
S_o from solution above = $\frac{V_o}{V_o + V_g}$

CURRENT
 \Rightarrow Producing GOR = $R_s + \left(\frac{k_{rg}}{k_{ro}} \cdot \frac{\mu_o B_o}{\mu_g B_g} \right) @ \bar{P}_R$

CLASS QUIZ:

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

- Application (Problem to solve)



Cumulative Production

$N_p = \text{cum. oil (STO) Prod} = 10^8 \text{ STB}$

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

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

$(N - N_p) = \text{Remaining STO in the R}$
 $= 900 \cdot 10^6 \text{ STB} \quad (RF_o = 10\%)$

Conversion STB to Reservoir Barrels
 "B_o"

$$B_o = \frac{V_{OR}}{V_o} = \frac{V_o}{V_{sto}}$$

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

$$\frac{V_o}{V_o} \leftarrow STO$$

Separator Tests

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

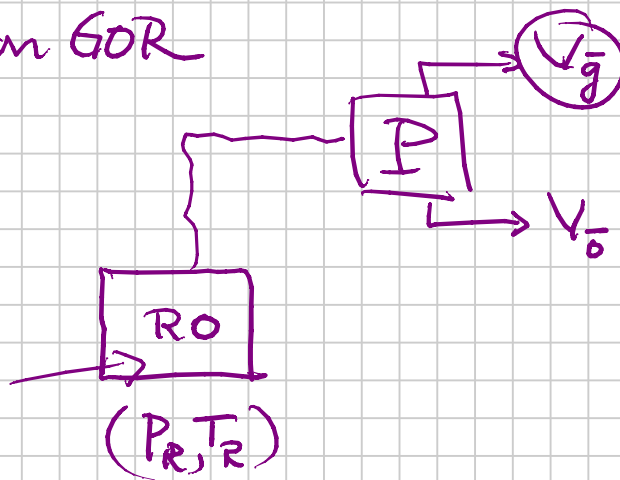
$$\left[\frac{RB}{STB} \right]$$

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

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

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

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



$$\Rightarrow R_s = \frac{V_g}{V_o}$$

IGIP in our OIL Reservoir?

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

\uparrow \uparrow
 same
 1009 scf/STB

Gas Remaining in Reservoir (scf)?

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

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

(1) Still in solution in the RO: $(N - N_p) \cdot R_s$

+

(2) "Free" gas saturation (phase) in "RG"

V_g

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

Convert scf \rightarrow Reservoir ft^3 : B_g

$$B_g = \frac{V_g(P, T)}{V_{g_i}}$$

$$\left(\frac{1.674}{2.075} \right)$$

$$* R_{s(p)} = R_{sb} - (R_{sd,b} - R_{sd(p)}) \cdot \left(\frac{B_{ob}}{B_{og,b}} \right)$$

\uparrow \uparrow \uparrow

$$B_g = \frac{P_{sc}}{T_{sc}} \cdot \frac{Z T_R}{P_R} \quad \frac{\text{ft}^3}{\text{scf}}$$

$$5.615 \text{ ft}^3/\text{bbl}$$

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

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

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

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

$$R_p = R_s + \underbrace{\left(\frac{k_{rg}}{k_{ro}} \right) \left(\frac{\mu_o B_o}{\mu_g B_g} \right)}_{\text{vol/vol}} \cdot \underbrace{5.615}_{\frac{\text{ft}^3}{\text{bbl}}}$$

\uparrow $\left(\frac{\text{scf}}{\text{STB}} \right)$ $\left(\frac{\text{scf}}{\text{STB}} \right)$

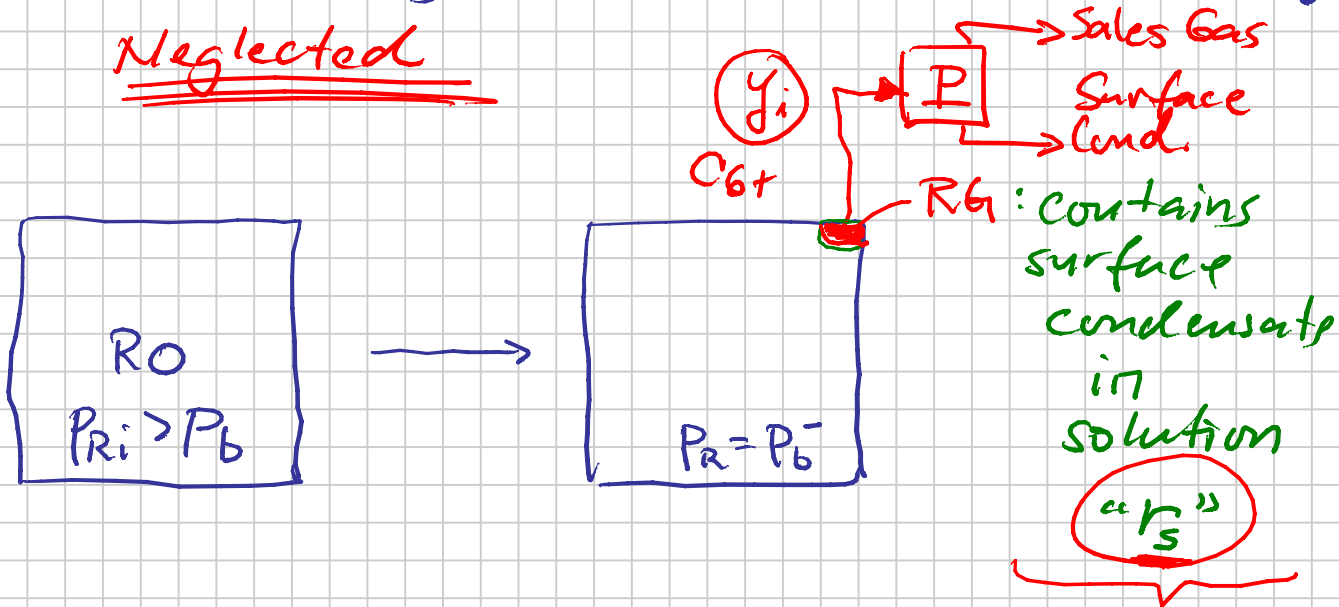
Uniform gas saturation distribution
turn out the reservoir



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 \leftrightarrow C_{GR}
 \bullet O_{GR}
 \bullet "Liquid Yield"
 y_i
 C_{G+}

What DLE "data" indicates the magnitude of r_s ?
 (C_{GR})

" γ_{gDLE} "

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

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

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

$$0.87 = (1-y_{\bar{o}}) \cdot 0.7 \quad M_{\bar{o}} \sim 140 \begin{matrix} 120 \\ 160 \end{matrix}$$

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

\uparrow
Mole frac. of
RG becomes
Surface Condensate

Recall

$$(r_s) = C_{GR} = \frac{y_{\bar{o}}}{(1-y_{\bar{o}})} \cdot \frac{(M_{\bar{o}}/P_{\bar{o}})}{(RT_{sc}/P_{sc})}$$

ρ [kg/m³] \swarrow Table 5.2 Using $M_{\bar{o}} = 140$

23.64

S_m^3 / S_m^3

$$0.87 = (1-y_0) \cdot 0.7 + y_0 \cdot \frac{140}{29}$$

$\frac{140}{29} = 4.83$

$$0.87 = y_0 (4.83 - 0.7) + 0.7$$

$$\frac{0.87 - 0.7}{4.83 - 0.7} = y_0$$

$$\frac{0.17}{4.13} = y_0$$

$$y_0 = 0.041 = 4.1 \text{ mol-\%}$$

$$M_0 = 140 \text{ (est.)}$$

$$\text{Table 5.2} \Rightarrow \rho_0 \sim 790 \text{ kg/m}^3$$



$$G_R \approx \frac{0.041}{1 - 0.041} \cdot \frac{(140/790)}{(23.64)}$$

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

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

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

@ 2938 psig
first DLE
stage

Returning to GAS CONDENSATE FWT

x Ch. 6

2 papers

* e-note GC-FWT

CVD

- Eq. Gas Removed

- Amount mol-% of Initial Moles @ P_d

- Composition

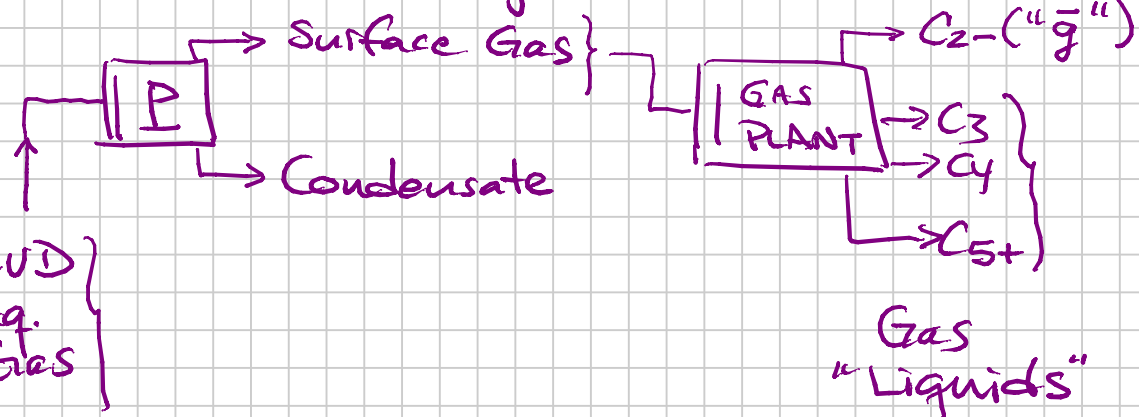
- ↓ C_{6+} ⇒ Surface Condensate

- Properties (M_{G+} , ρ_{G+}) ⇒ convert moles ⇒ volume

- Z-factor

Some Labs

- Surface Process Analysis (calculations)



Ch. 6

- Eq. Oil (Reservoir Condensate)

- $V_o/V_d \approx S_{on} = S_o/(1-S_w)$

Very, very good approximation of

the reservoir average oil saturation

at $p_{cud} \sim p_R$

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

- 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"

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

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

$$\begin{aligned} p &> p_d \\ \frac{p}{r_s} &= \text{const.} \\ \frac{p}{r_p} &= \text{const.} \end{aligned}$$

$$\begin{aligned} \left(\frac{M}{P}\right)_{6+} &\approx \left(\frac{M}{P}\right)_{7+} \\ &= \left(\frac{143}{795}\right) \end{aligned}$$

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

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

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

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

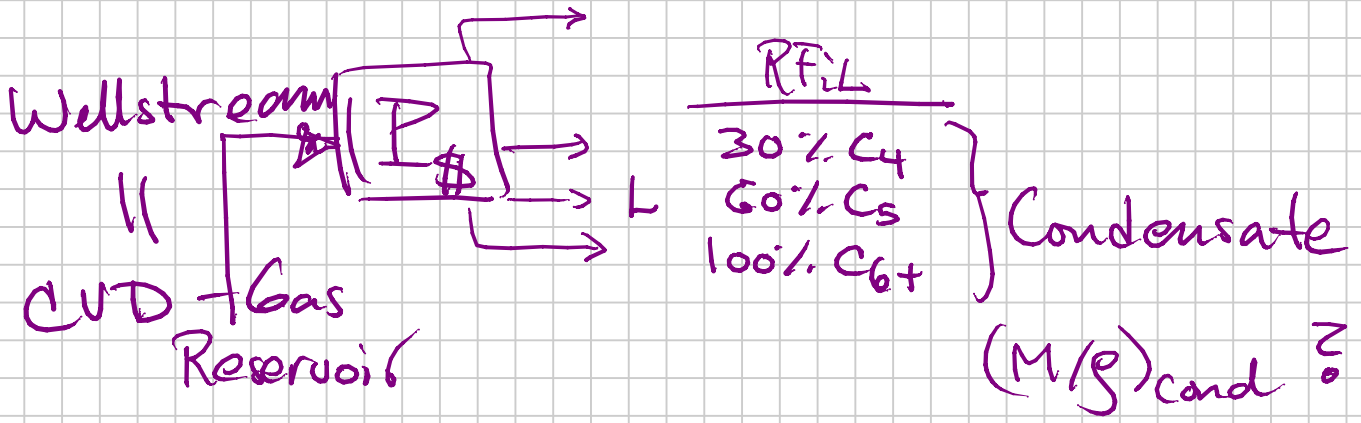
STB / MMscf

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

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

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

t_s (2900 psig)



"weighed"
 $u_i = \text{mole fraction}$ "

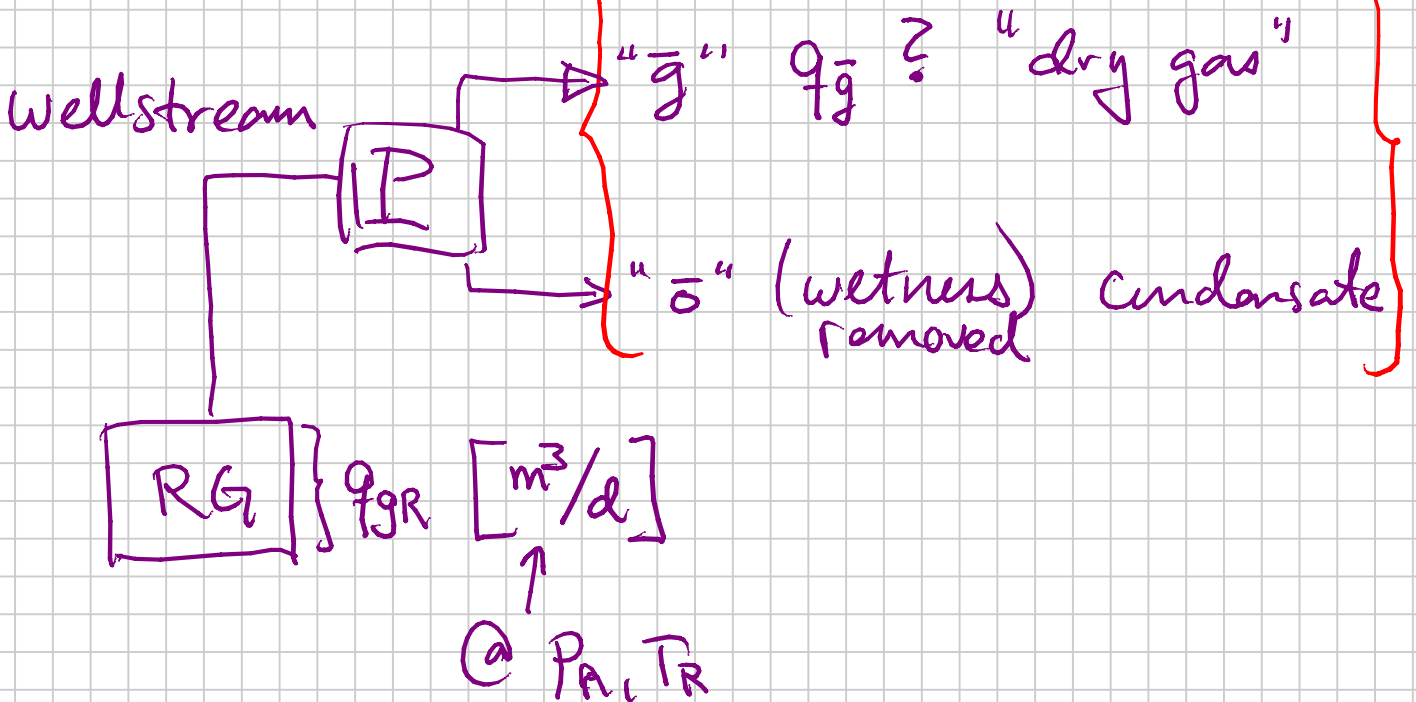
$$\Rightarrow 93 \text{ STB/MMscf} ?$$

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

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

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

express it as a "wet gas"



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

Dry Gas
Formation
Volume
Factor

WANT
&
NEED

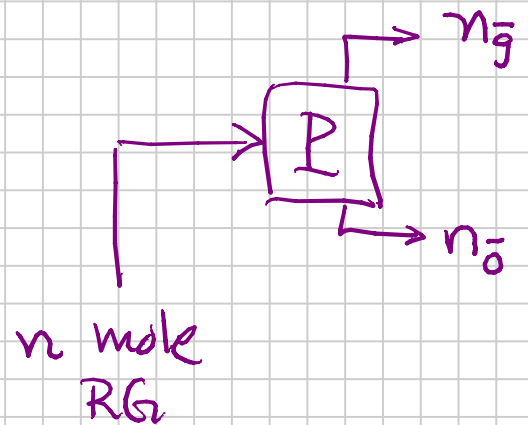
$$B_{gw} = \frac{p_{sc}}{T_{sc}} \cdot \frac{z_{TR}}{p_R}$$

Wet Gas FVF

Reservoir Gas
Becomes
ONLY
Surface
Gas
 $r_s = 0$

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

$$V_{gR} = \frac{n \cdot R T_R z_R}{p_R}$$



$$\frac{V_{gR}}{V_{\bar{g}}} = \frac{\frac{n \cdot R T_R z_R}{p_R}}{\frac{n_{\bar{g}} R T_{sc}}{p_{sc}}} = B_{gd}$$

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

$$B_{gd} = \underbrace{\frac{p_{sc}}{T_{sc}} \cdot \frac{T_R z_R}{p_R}} \cdot \frac{1}{(n_{\bar{g}}/n)}$$

"B_{gw}"

$$\frac{n_g}{n} = 1 - \frac{n_o}{n} \approx 1 - C_{6+} \text{ mole frac}$$
$$= 1 - (z_w)_{6+}$$

↑
wellstream
mole
fraction

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

2900 psig CVD Test:

$$z_R = 0.748$$

$$(z_{w6+}) = y_{6+} = 0.0593$$

$$T_R = 186^\circ\text{F} = 646^\circ\text{R}$$

$$P_R = 2914.7 \text{ psia}$$

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

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

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

Problem 16 - Calc Upper Sat. Press.

Lower DP

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

Know $z_i, K_i(P, P_k; T)$

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

$$\Rightarrow y_i = z_i \cdot K_i$$

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

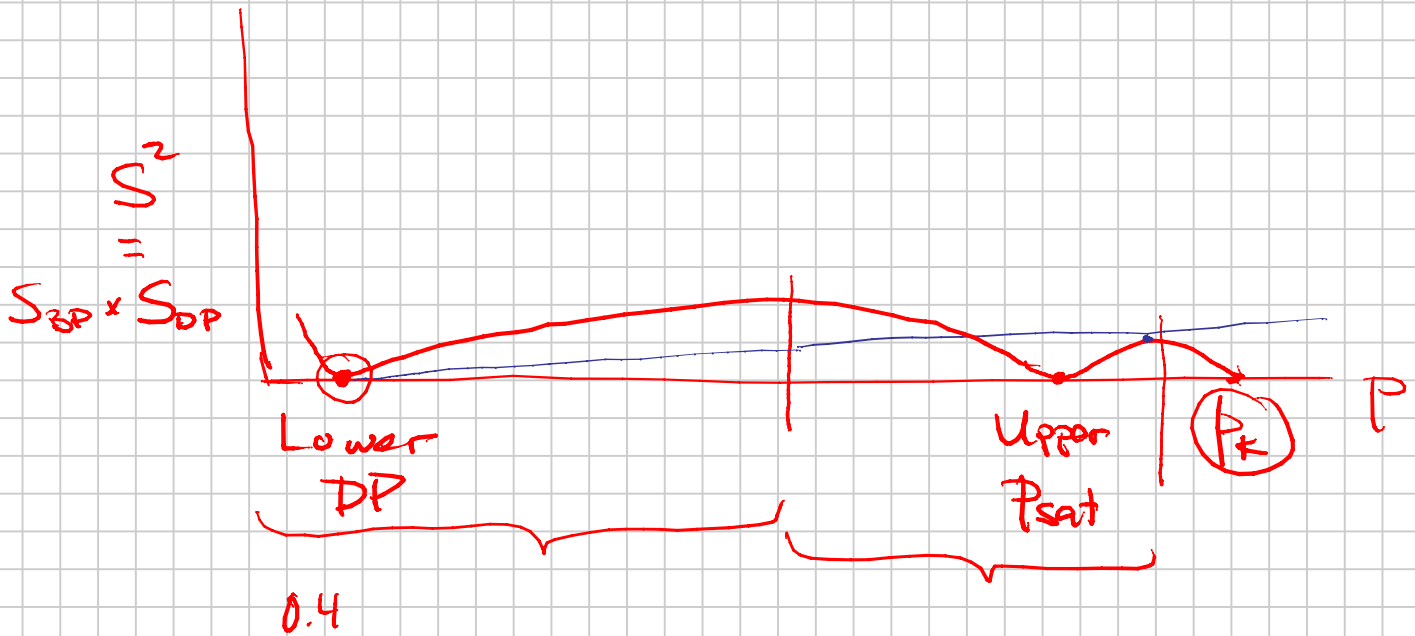
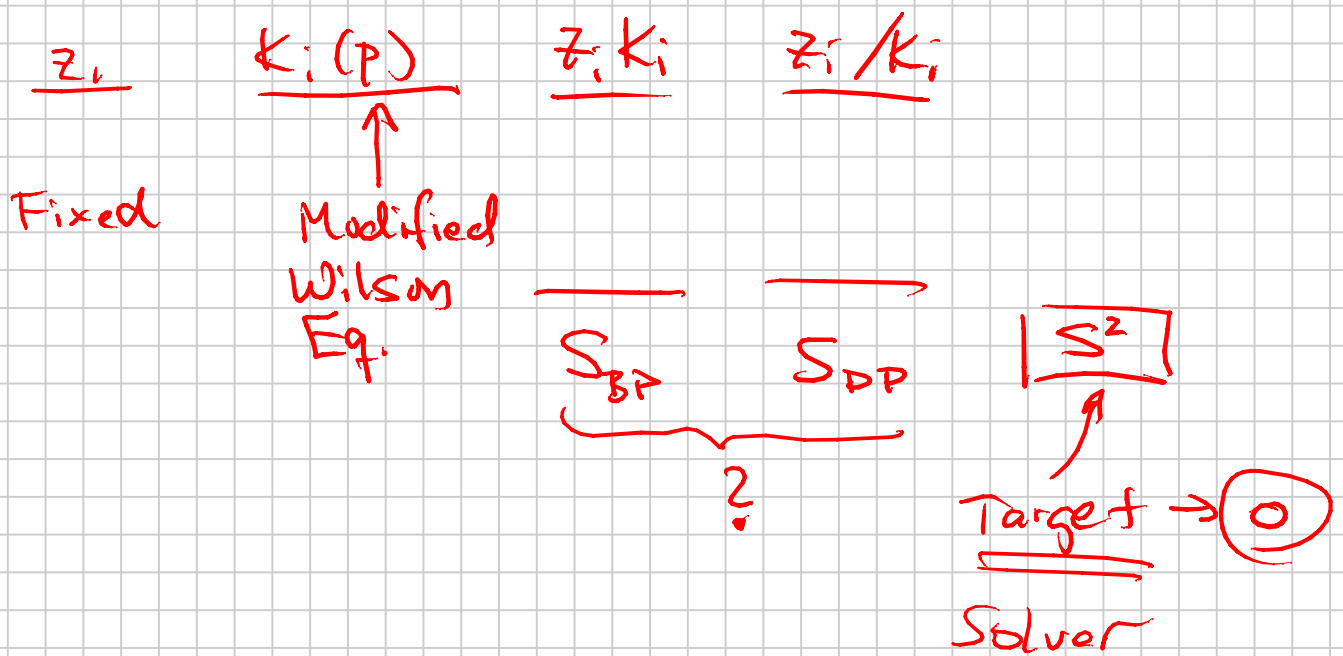
$$DP : S_{DP}(P) = 1 - \sum x_i = 0$$

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

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

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

→ P Variable in Solver



AT CONVERGENCE

Calculate DP

$$y_i \equiv z_i$$

$$x_i = z_i / k_i = y_i / k_i$$

Calculate BP

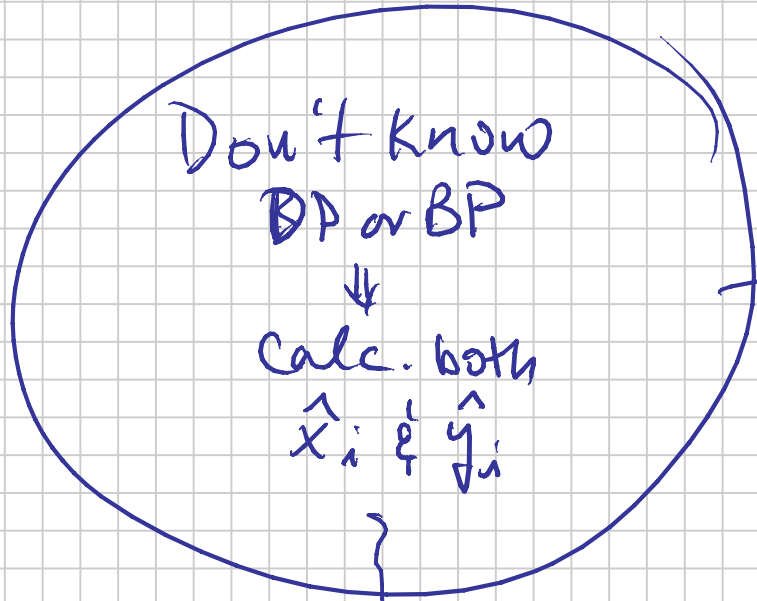
$$x_i \equiv z_i$$

$$y_i = z_i k_i = x_i k_i$$

DURING SEARCH

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

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



Curtis
Algorithm

DP

Discard

\hat{y}_i

If $S_{BP} \neq 1$

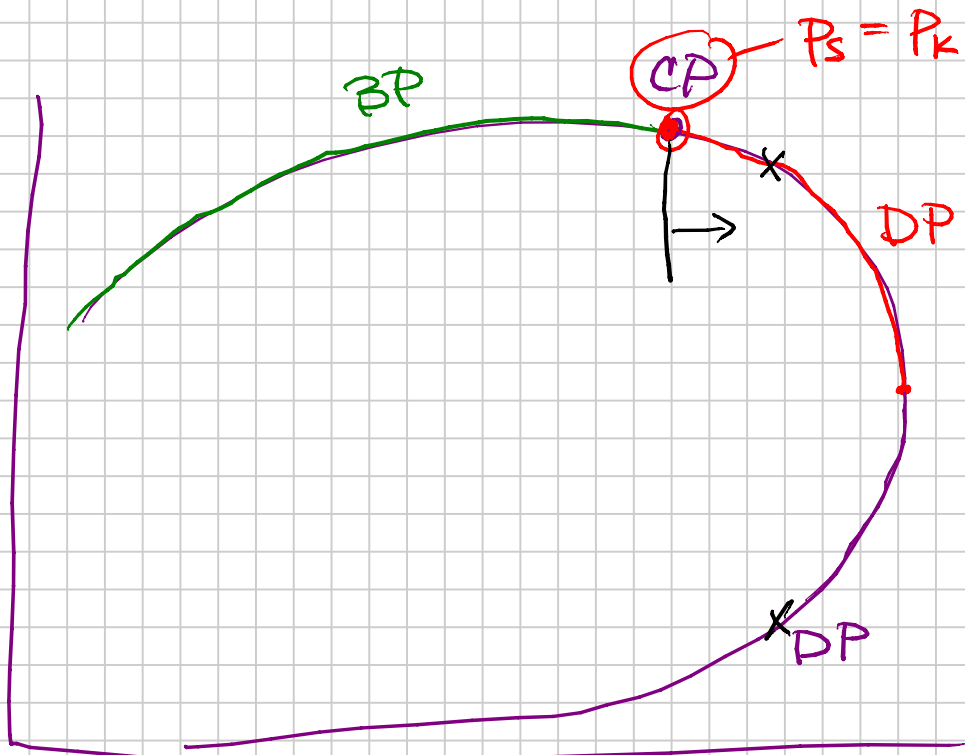
Use $\sum \hat{x}_i = 1$

BP

Discard

\hat{x}_i

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



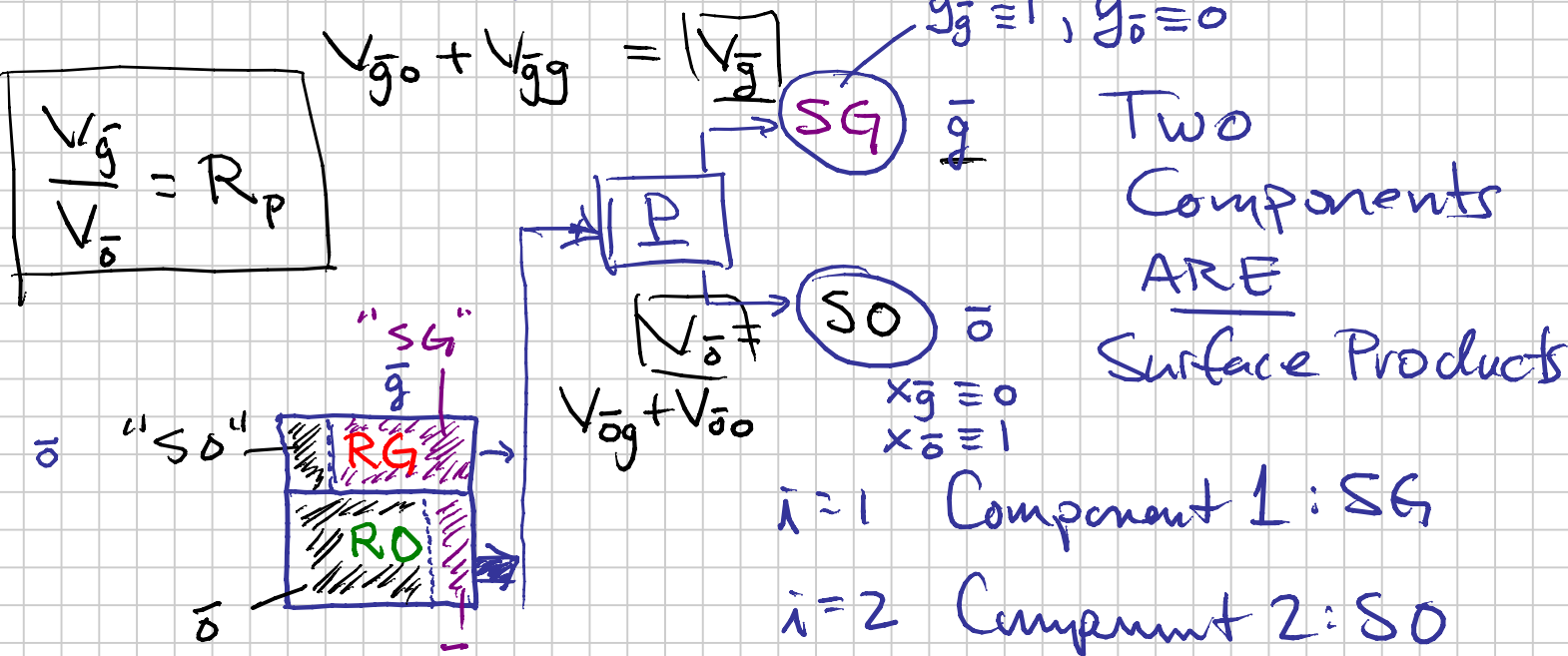
Ch. 7

Black-Oil PVT

"Formulation"

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

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



For example: RG $y_{g1} = 0.89$ (89%)

$y_{o1} = 0.11$ (11%)

RO $x_{g2} = 0.20$ (20%)

$$r_p = \frac{V_{o1}}{V_{g1}} = \frac{1}{R_p}$$

$$x_o = 0.80 \quad (80\%)$$

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

$$K_o = \frac{y_o}{x_o} = \frac{0.11}{0.8} = 0.14 < 1$$

By definition @ Surface

$$SG: \quad y_{\bar{g}} \equiv 1, \quad y_o \equiv 0$$

$$SO: \quad x_{\bar{g}} \equiv 0, \quad x_o \equiv 1$$

At Reservoir Conditions: "Traditional" Black-oil

$y_o \approx 0$ Assumption (< 1975)

$$RG: \quad y_{\bar{g}} > 0$$

$$y_o > 0; \quad y_{\bar{g}} + y_o = 1$$

$$RO: \quad x_{\bar{g}} > 0$$

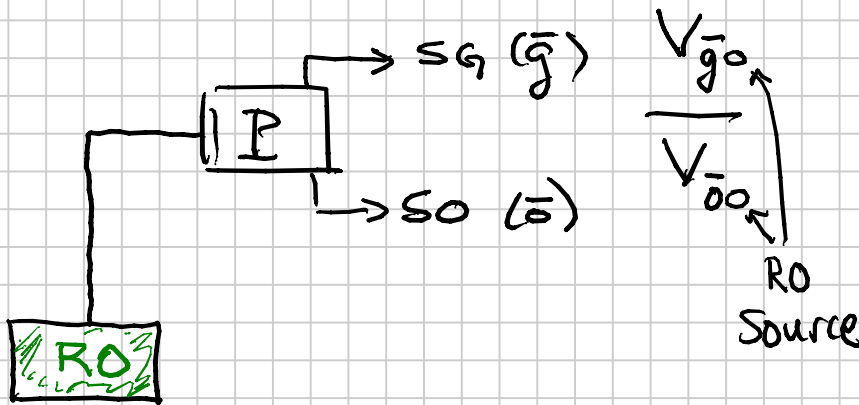
$$x_o > 0; \quad x_{\bar{g}} + x_o = 1$$

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

How do we quantify R_G & R_O "composition" without mass or mole fractions?

(SURFACE)

- USE VOLUME RATIOS



$$\frac{V_{go}}{V_{oog}} \equiv R_s$$

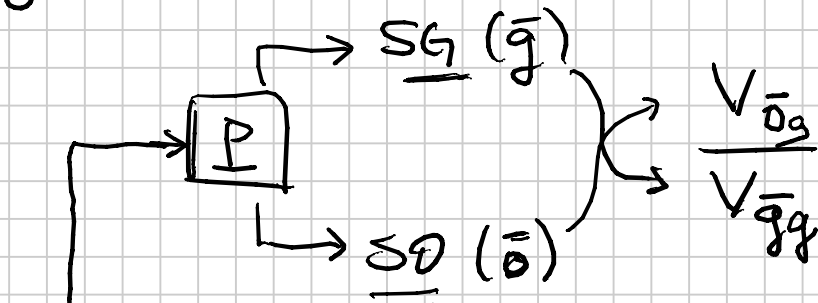
Solution Gas-Oil Ratio of

$$\left[\frac{\text{Mscf}}{\text{STB}} \right]$$

RESERVOIR OIL (x_i)

$$x_i \leftrightarrow R_s$$

$$V_{og} = V_{og}$$



$$\frac{V_{oog}}{V_{gg}} \equiv r_s$$

Solution Oil Gas Ratio of

$$\left[\frac{\text{STB}}{\text{scf}} \right]$$

$$\left[\frac{\text{STB}}{\text{MMscf}} \right]$$

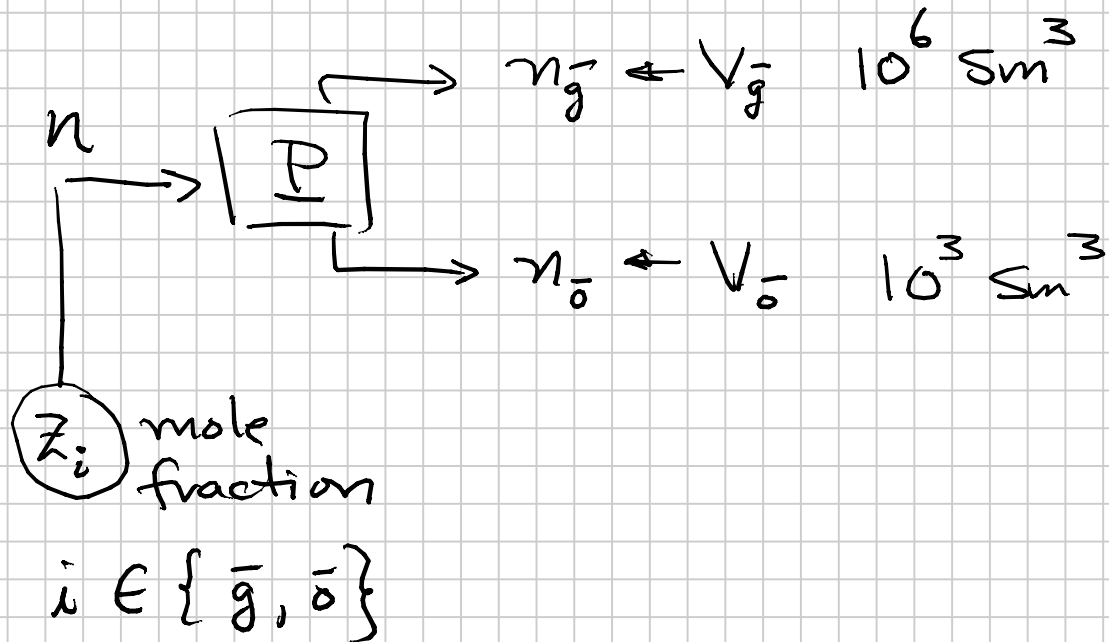
RESERVOIR GAS (y_i)

$$y_i \leftrightarrow r_s$$

$$\left[\frac{\text{Sm}^3}{\text{Sm}^3} \right]$$

$$\left[\frac{\text{Sm}^3}{10^6 \text{Sm}^3} \right]$$

Conversion between solution GOR or OGR and molar composition.



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

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

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

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

$$z_i: \quad z_g = \frac{n_g}{n} = \frac{n_g}{n_g + n_o} = 1 - z_o$$

$$z_o = \frac{n_o}{n} = 1 - z_g$$

$$n_o = z_o \cdot n$$

$$n_g = n - z_o n = n(1 - z_o)$$

$$\text{GOR} = \frac{\left(\frac{RT_{sc}}{P_{sc}}\right)}{\left(\frac{M_o}{P_o}\right)} \cdot \frac{(1 - z_o)}{z_o}$$

RO:

$$R_s = \text{GOR}$$

$$z_i = x_i$$

$$\text{OGR} = \frac{\left(\frac{M_o}{P_o}\right)}{\left(\frac{RT_{sc}}{P_{sc}}\right)} \cdot \frac{z_o}{(1 - z_o)}$$

RG:

$$r_s = \text{OGR}$$

$$z_i = y_i$$

$$= \left(\text{"C}_{\text{og}} \right)^{-1}$$

To you ...

derive expressions for

$$y_i = f(r_s)$$

$$y_i \leftrightarrow r_s$$

$$x_i = f(R_s)$$

$$x_i \leftrightarrow R_s$$

BLACK-OIL PVT FORMULATION

$$RG: y_i \leftrightarrow r_s \quad (\text{solution OGR})$$

$$RO: x_i \leftrightarrow R_s \quad (\text{solution GOR})$$

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

$$GOR = \left(\frac{RT_{sc}}{P_{sc}} \right) \left(\frac{\rho_o}{M_o} \right) \frac{1 - u_o}{u_o}$$

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

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

" \bar{g} "
"methane-like
component"

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

"decane-like
component"

(may $\rightarrow \epsilon$)
0

$$\text{total } R \rightarrow z_i$$

$$R_s \rightarrow x_i$$

$$r_s \rightarrow y_i$$

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

$$\left. \begin{array}{l} R \rightarrow z_i \\ R_s \rightarrow x_i \\ r_s \rightarrow y_i \end{array} \right\} RR \rightarrow \text{Phase Amounts } (F_v)$$

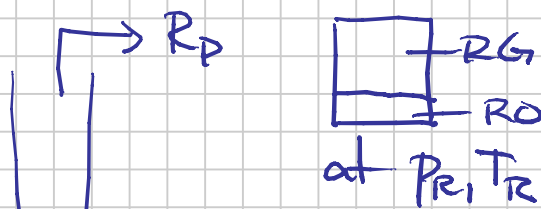
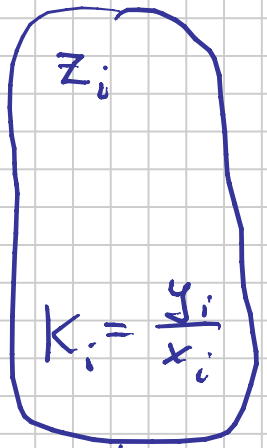
Example: $\gamma_{API} = 42$

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

At reservoir $p_r = 300 \text{ bar}$

$R_s = 180 \text{ Sm}^3/\text{Sm}^3 \Rightarrow x_i$

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



$\left(\frac{M_o}{\rho_o}\right)$: Table 5.2

Usually know

ρ_o (reported as γ_{API})

$$\frac{\rho_o}{\rho_w} \equiv \gamma_o = \frac{141.5}{131.5 + \gamma_{API}}$$

$$\gamma_o = \frac{141.5}{131.5 + 42} = 0.8155$$

$$\rho_o = \gamma_o \cdot \rho_w$$

$$= 0.8155 (1000)$$

$$= 815 \text{ kg/m}^3$$

\Rightarrow Table 5.2

$\frac{\text{kg}}{\text{m}^3}$

Est.
Cragoe

$$M_o = \frac{6084}{\gamma_{API} - 5.9}$$

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

Ch. 5

$$\Rightarrow \left(\frac{M_o}{\rho_o} \right) = 0.2068 \frac{\text{m}^3}{\text{kgmol}}$$

BO Model:

ARE ASSUMED TO

Surface Components have constant properties:

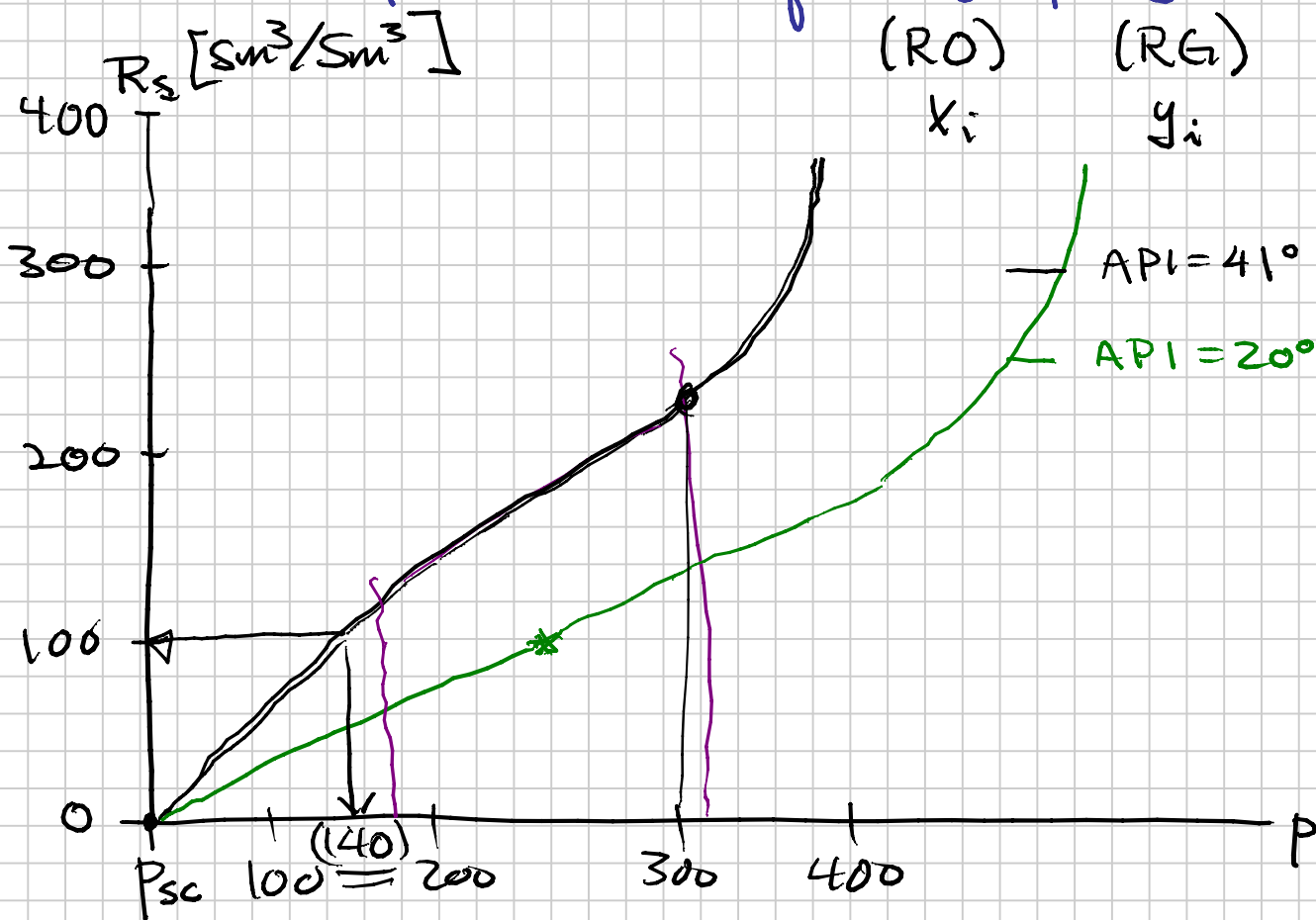
$$\begin{aligned} \rho_{\bar{g}} &= \rho_{\bar{a}} \cdot \gamma_{\bar{g}} \\ \rho_{\bar{o}} &= \rho_{\bar{\omega}} \cdot \gamma_{\bar{o}} \end{aligned}$$

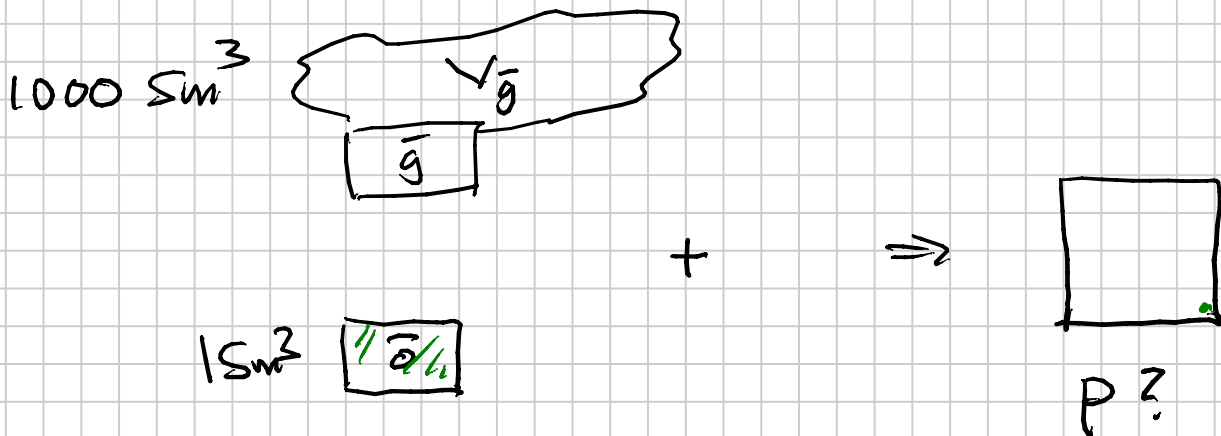
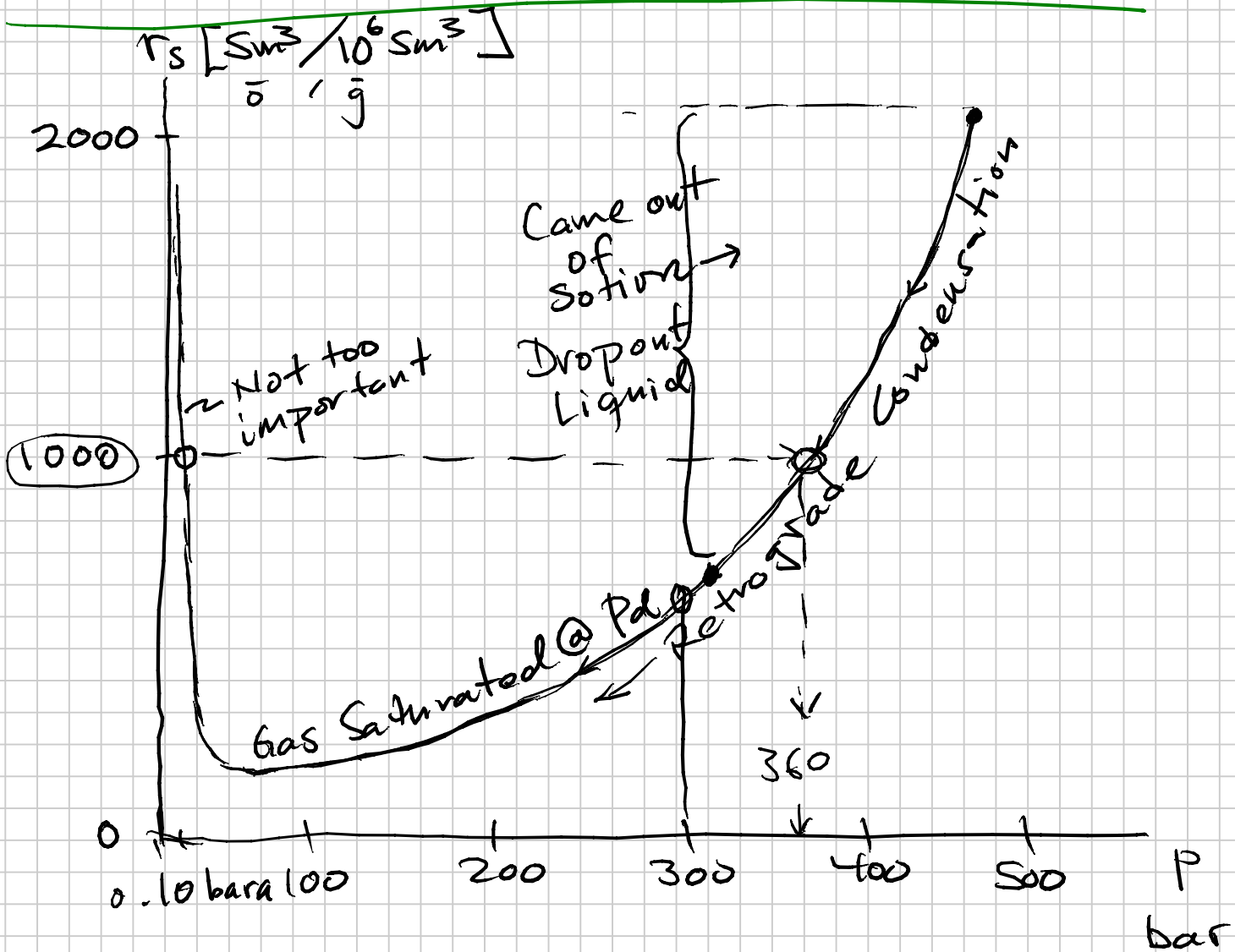
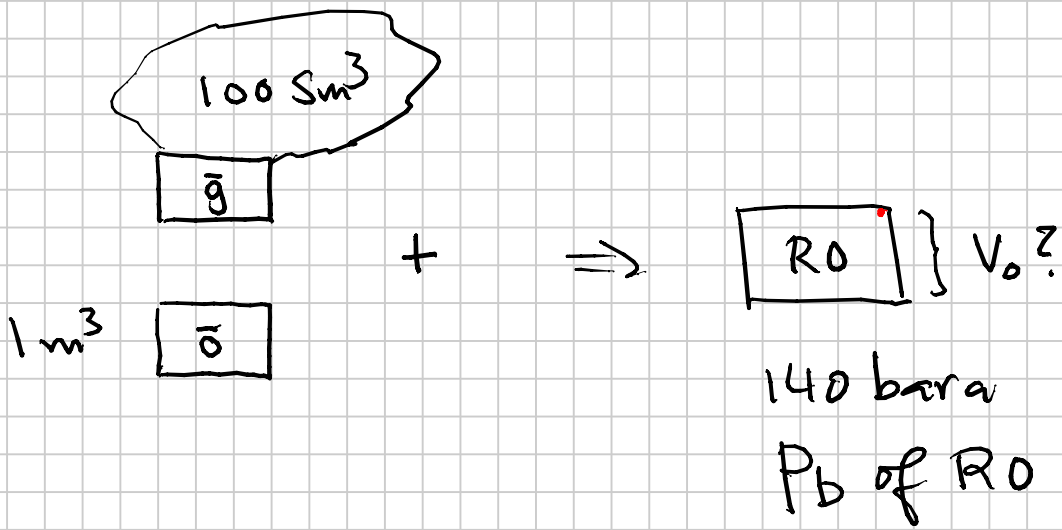
Input \leftarrow (points to $\rho_{\bar{g}}$ and $\rho_{\bar{o}}$)

Known (reported) \leftarrow (points to $\gamma_{\bar{g}}$ and $\gamma_{\bar{o}}$)

Pressure Dependence of

R_s & Γ_s
(RO) & (RG)
 x_i & y_i



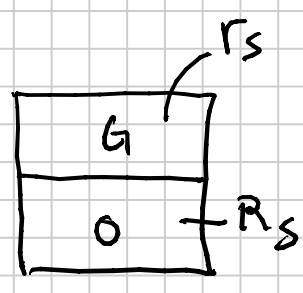


$$GOR = \frac{1}{1000} = 0.001 = \underline{1000} \cdot 10^{-6} \text{ Sm}^3/\text{Sm}^3$$

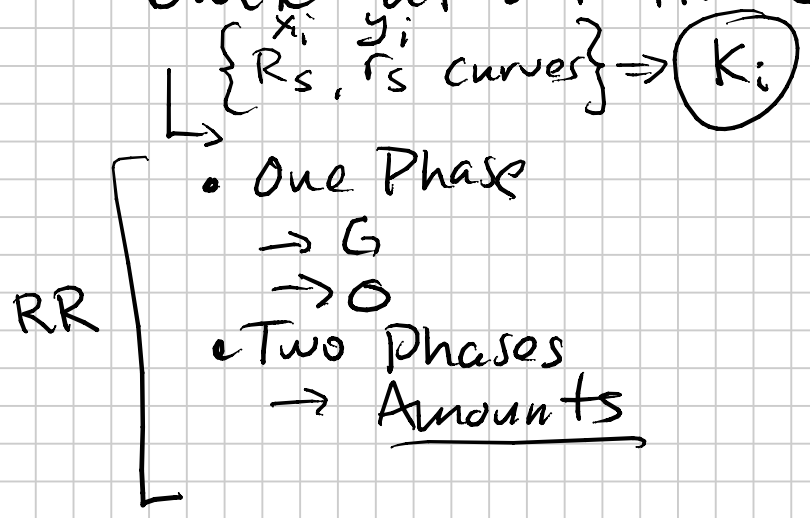
"z_i"

"GOR" in every lego block at all times

KNOW:



(P)
300 bar

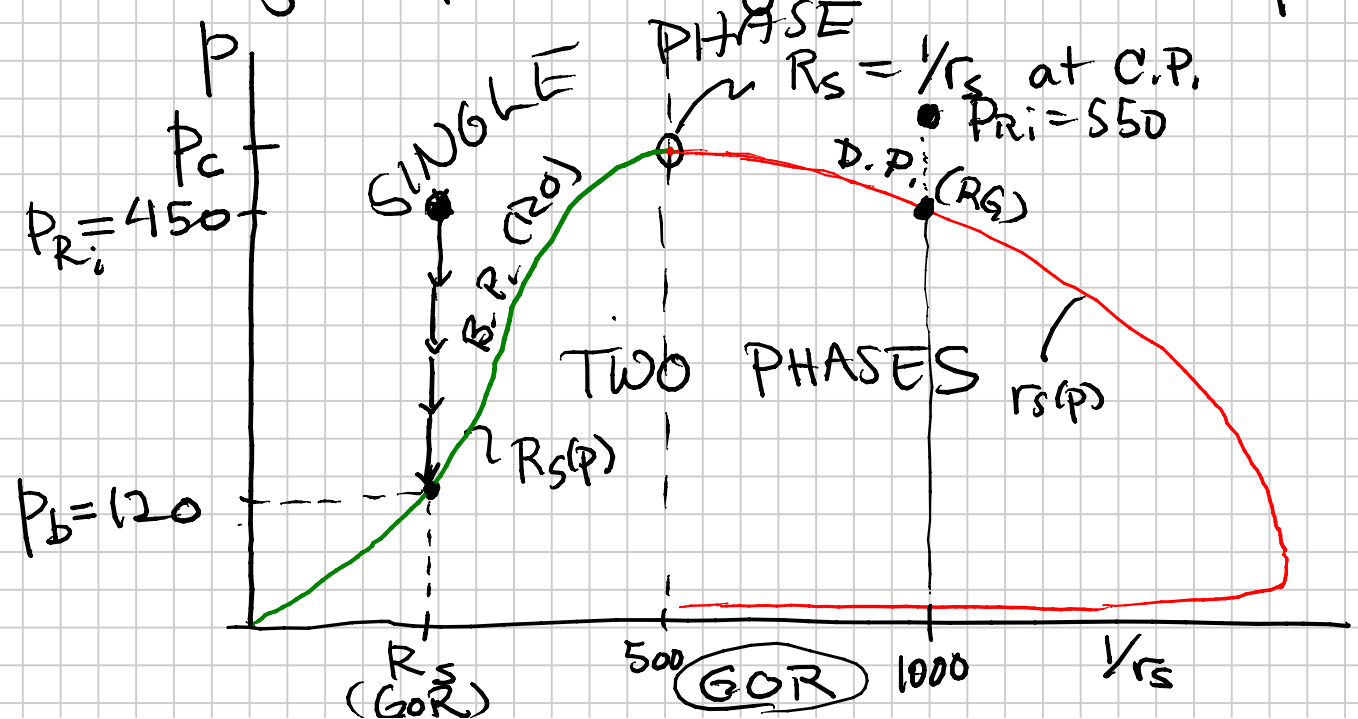


Discovery Well: GOR = 200 Sm³/Sm³

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. $GOR = 1000 \text{ Sm}^3/\text{Sm}^3 \Rightarrow P_d = 450 \text{ bara}$

$P_{R_i} = 550 \text{ bara}$

$P_{R_i} > P_d = \underline{RG}$ undersaturated
by $\sim 100 \text{ bara}$

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

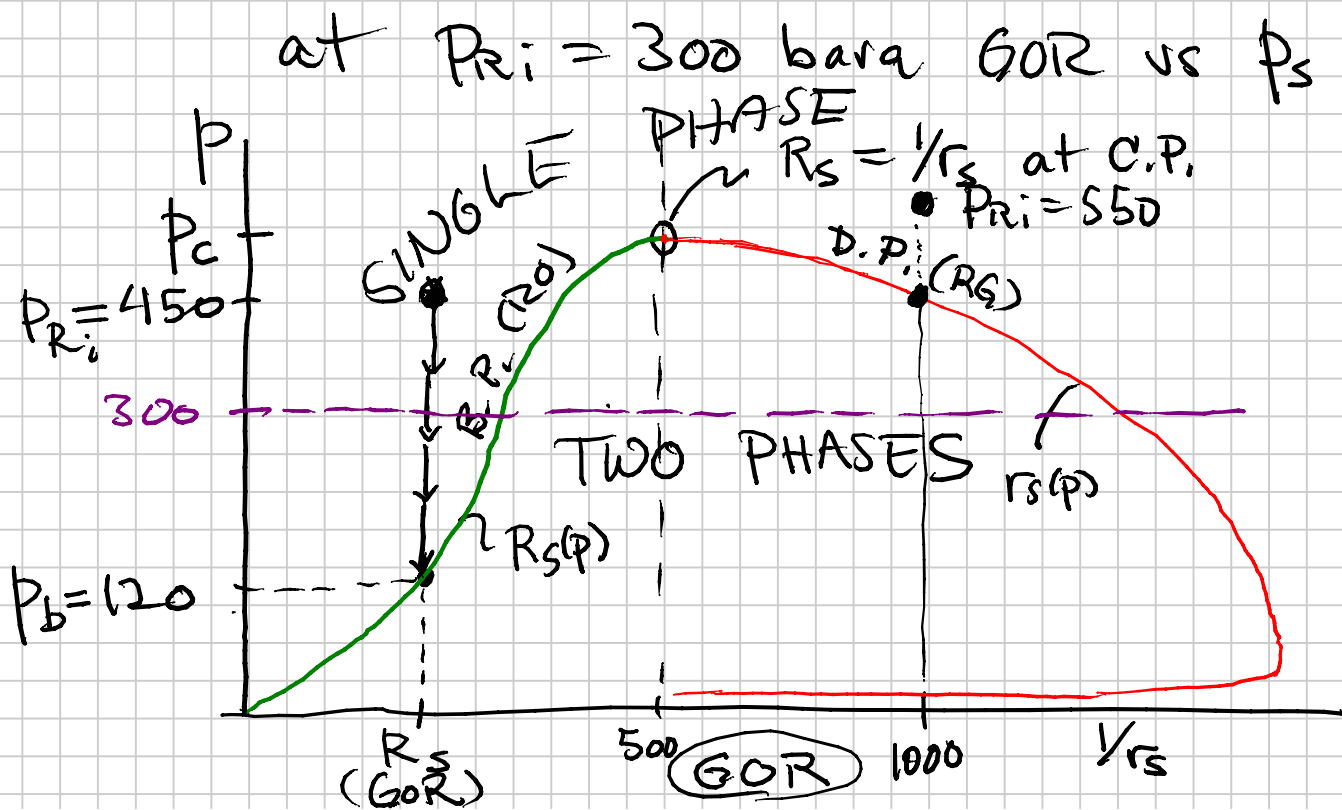
$P_{R_i} = \underline{300} \text{ bara}$

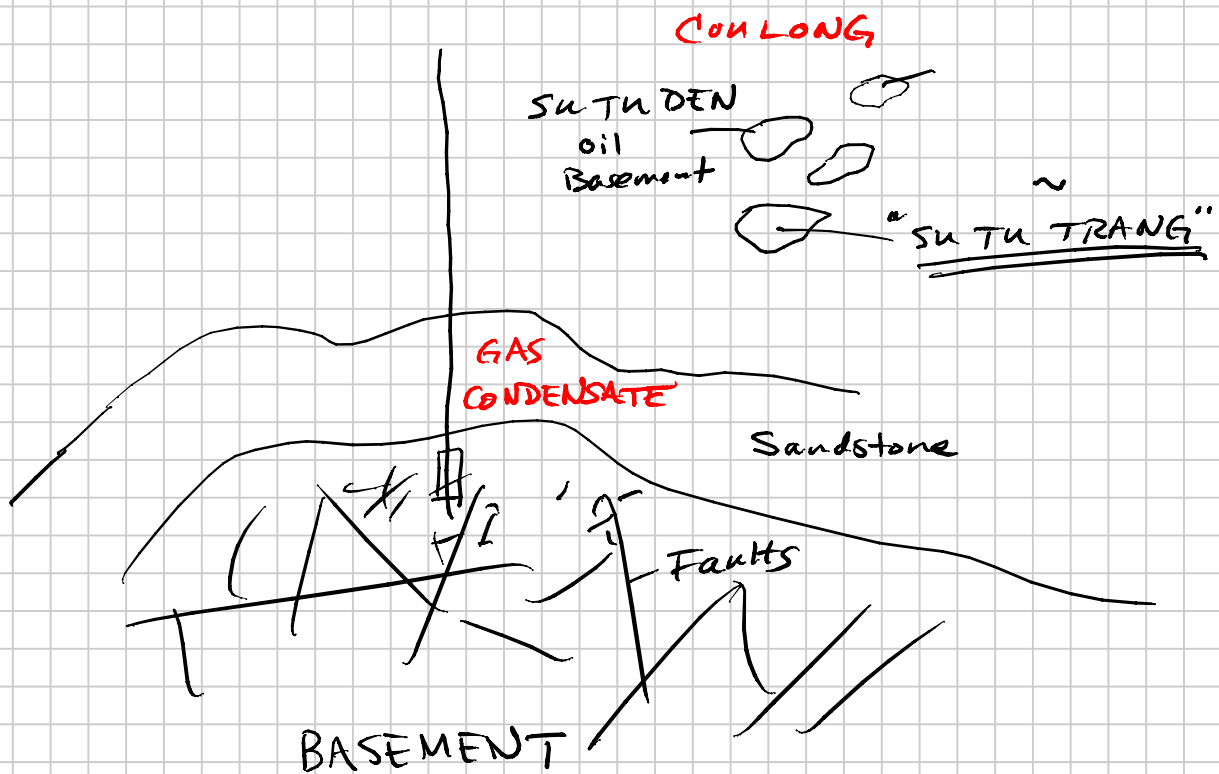
(a) G or 0 or G+O

(b) What are the

G : $r_s =$

O : $R_s =$





Final Topics (Next Three Weeks)

① Gas Rate Equation (Reservoir / Tubing)

- (R) {
- "Inflow Performance Relation" (IPR)
 - Backpressure Equation
- Darcy's Law or Forchheimer Eq.

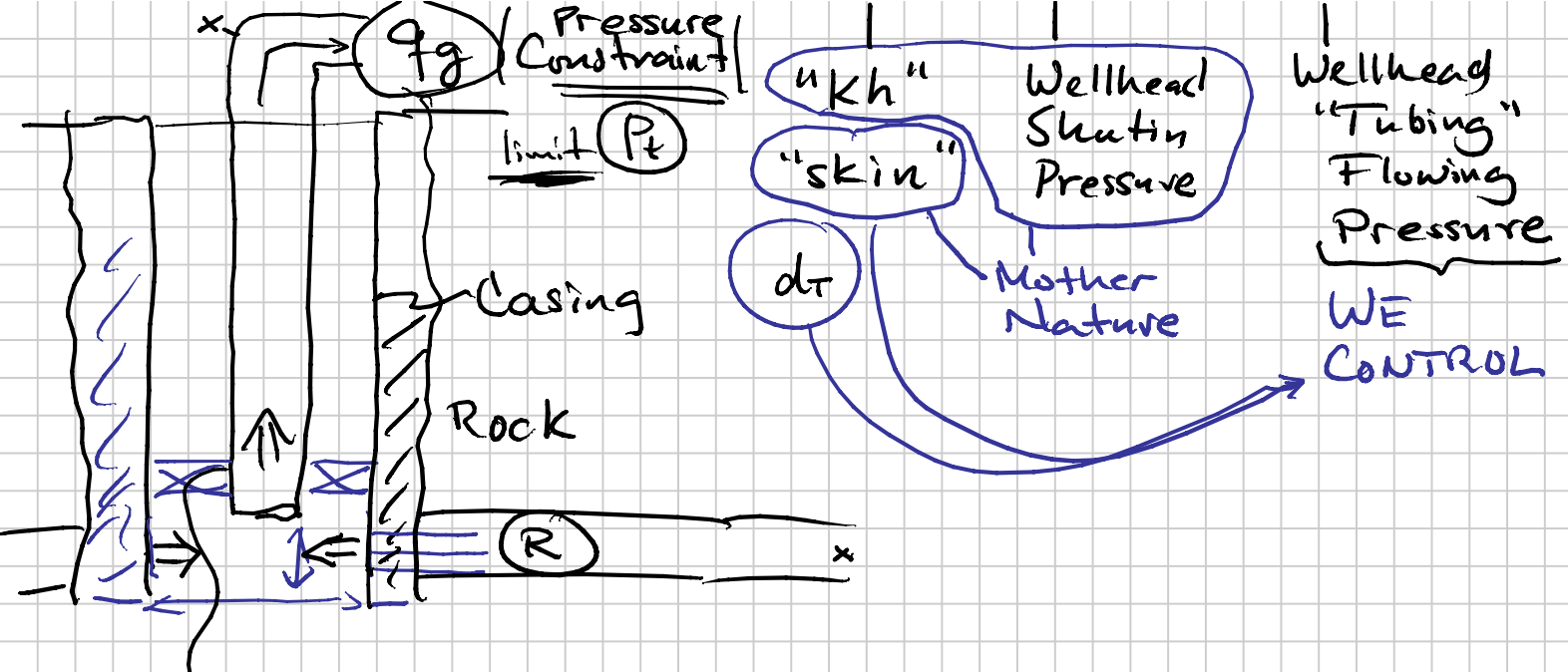
(T)

- Tubing Flow
- "Vertical Lift Curve" (VLC)

• Composite (R+T)

- "Wellhead Backpressure Equation" 0.5-1

$$\underline{(q_g)_{well}} = C_{WH} (P_c^2 - P_t^2)^{\eta_{WH}}$$



Tubing (O.D. $2\frac{3}{8}" \rightarrow 7" \rightarrow 9\frac{5}{8}" \rightarrow 13"$)
 d_t We control

Baku
 "Old Technology"
 - Casing
 - Hanging Tubing

RESERVOIR RATE EQUATION

Darcy's Law:

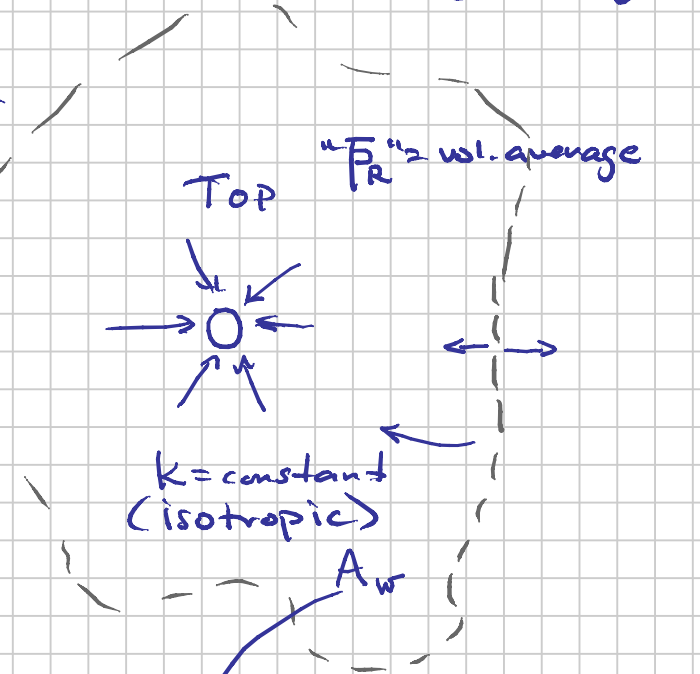
$$v = \frac{k}{\mu} \cdot \frac{dp}{dr}$$

↑
 Darcy Velocity
 \neq
 Pore Velocity

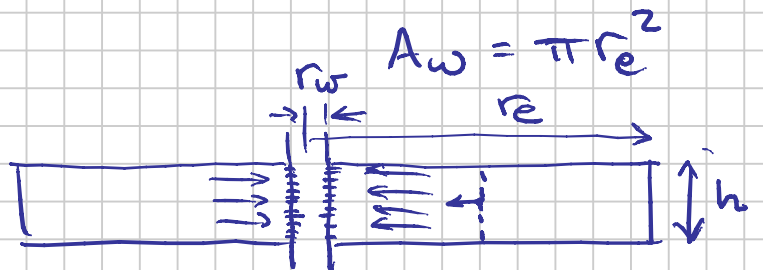
volumetric rate

$$q_{TR} \left[\frac{m^3}{s} \right] = v \cdot \underbrace{2\pi r h}_{A_z}$$

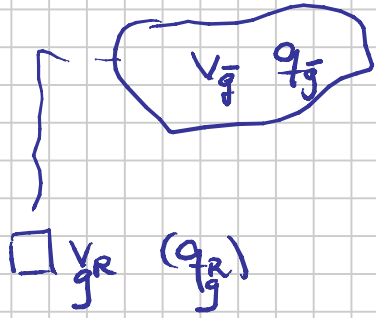
• p at r ("reservoir" rate)



Drainage Outer Area (Shape - don't worry)



Conversion from q_R to surface rate q_g (gas) in $\frac{\text{Sm}^3}{\text{s}}$



$$B_g \equiv \frac{V_{gR}}{V_g} = \frac{q_{gR}}{q_g}$$

$$q_g = q_{gR} \cdot B_g^{-1}; \quad B_g = \frac{p_{sc}}{p} \cdot \frac{Z_{sc}}{Z}$$

$$= v \cdot 2\pi r h B_g^{-1}$$

↑
Darcy's Law

$$q_g = \frac{k}{\mu_g} \cdot \frac{2\pi h}{B_g} \cdot r \frac{dp}{dr}$$

Constant Rate Assumption
(Steady-State)

p-dependant

r-dependant

μ_g
 B_g

r

" q_g " $\frac{\text{moles}}{\text{day}}$
= constant at ALL r

$$\int_{r_w}^{r_e} \frac{1}{r} \cdot dr = \left\{ \frac{2\pi k h}{q_g} \right\} \int_{p_{wf}}^{p_e} \frac{1}{\mu_g B_g} dp$$

$$\ln \frac{r_e}{r_w} = \frac{2\pi k h}{q_g} \int$$

$p(r_w) \equiv p_{wf}$
= wellbore flowing pressure
BHFP

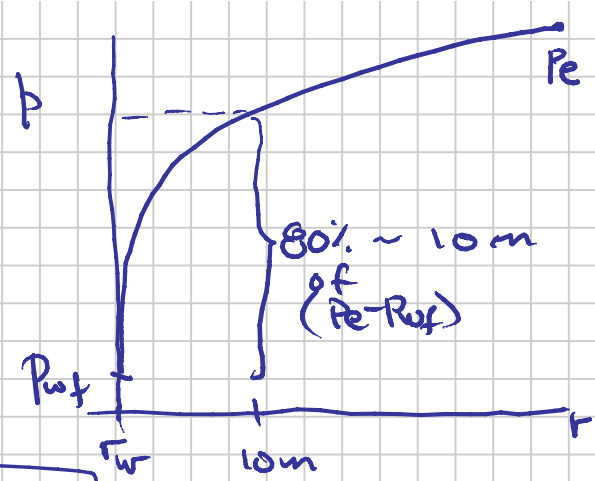
$$q_g = \frac{2\pi k h}{\ln \frac{r_e}{r_w}} \int_{p_{wf}}^{p_e} \frac{1}{\mu_g B_g} dp$$

↑
Can't measure

$\Rightarrow p = f(\ln r)$; plot p vs $\ln r \Rightarrow$ linear

$$\frac{\ln r^*/r_w}{\ln r_e/r_w} = 0.8$$

Solve for r^*



You (or me) or someone else

can show that $\bar{p}_R @ p(r=0.472 r_e)$

$$q_g = \frac{2\pi kh}{\ln \frac{0.472 r_e}{r_w}} \int_{p_{wf}}^{\bar{p}_R} \frac{1}{M_g B_g} dp$$

Reservoir
Steady state
Rate
Equation

Some folks write $\ln \frac{0.472 r_e}{r_w} = \ln \frac{r_e}{r_w} - \frac{3}{4}$

Pressure Integral

SPE

$$p_p (m(p)) \equiv \int_0^p \left(\frac{1}{M_g B_g} \right) dp = \text{"pseudopressure"}$$

"gas mobility term" λ_g

Sometimes: $B_g = \frac{P_{sc}}{T_{sc}} \frac{z_{TR}}{P}$

$$p_p \equiv \left(\frac{1}{2} \right) 2 \int_0^p \frac{P}{M_g z} dp$$

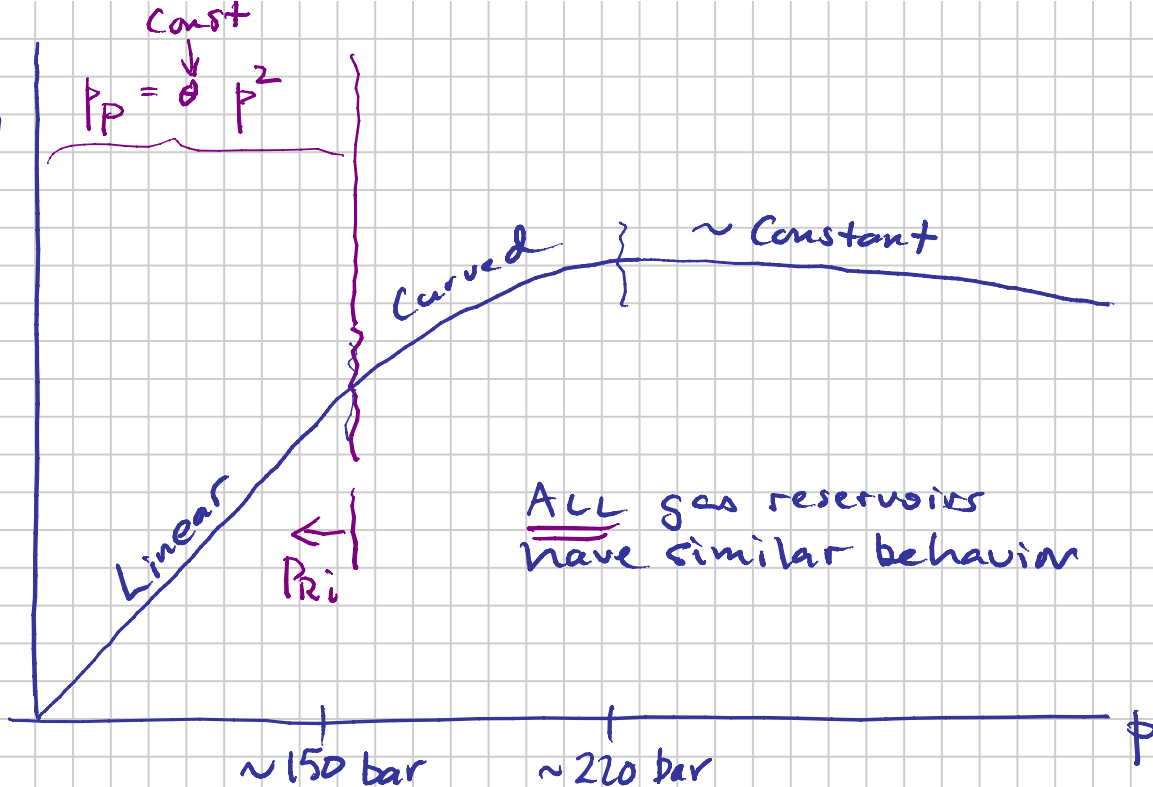
$$\frac{1}{2} \cdot \left(\frac{T_{sc}}{P_{sc} T_R} \right)$$

Original Form
(Al-Husseiny, Ramey,
Crawford)

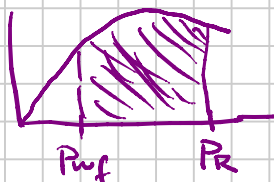
$$\lambda_g \equiv \frac{1}{\mu_g B_g}$$

(OR)

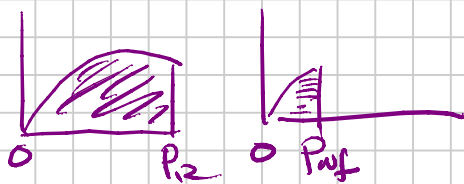
$$\frac{p}{\mu z}$$



Calculus
memory lane



$$\left[\int_{p_{wf}}^{p_R} \right] = \int_0^{p_R} - \int_0^{p_{wf}} = (p_{PR} - p_{pwf})$$



$$q_g = \frac{2\pi kh (p_{PR} - p_{pwf})}{\ln(r_e/r_w) - \frac{3}{4}}$$

$$p_R < 2500 \text{ psia (130 bar)} \Rightarrow p_P = p^2$$

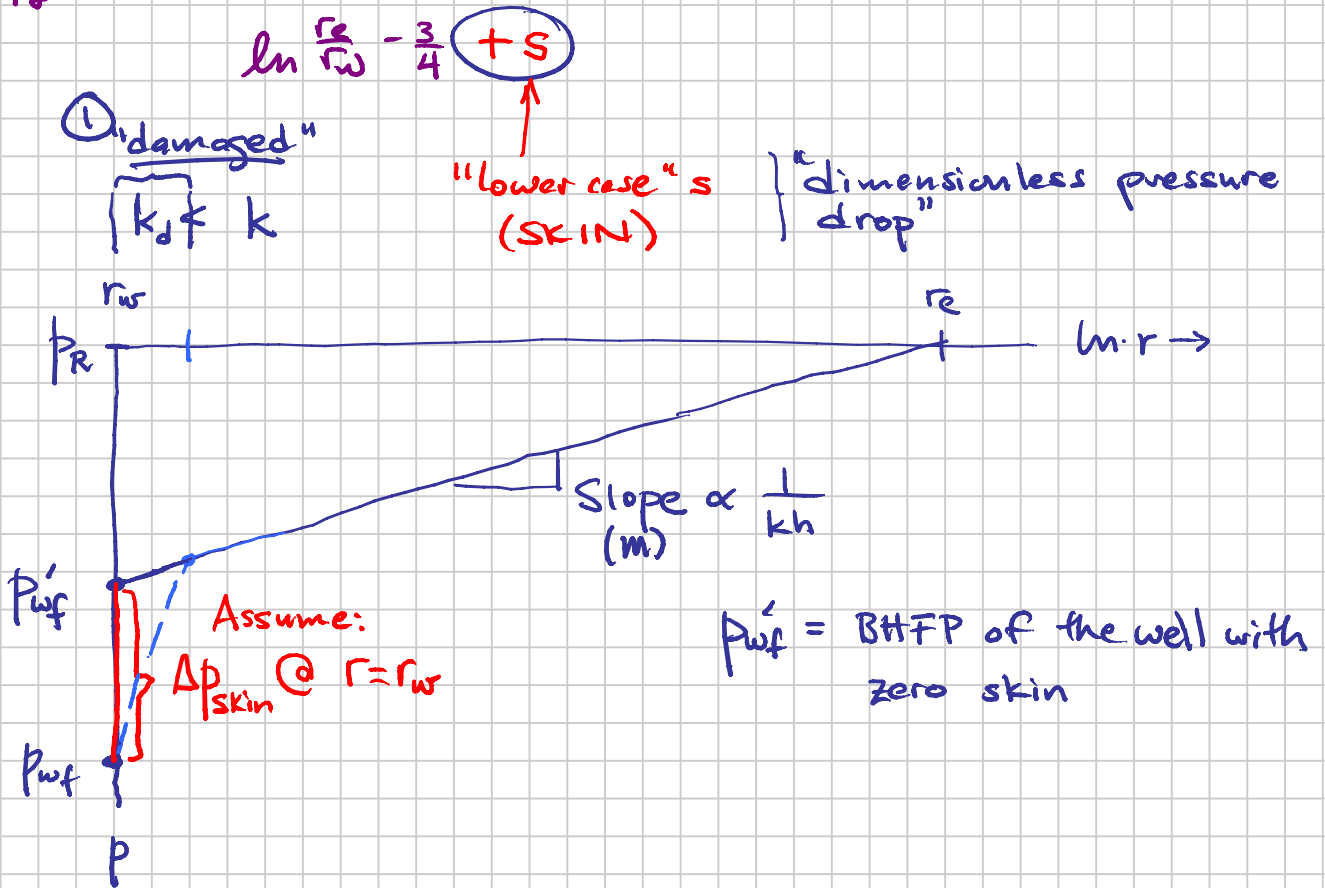
$$q_g \approx \frac{2\pi(\) kh (p_R^2 - p_{wf}^2)}{\ln \frac{r_e}{r_w} - \frac{3}{4} + S}$$

low-pressure
approximation

Non-Ideal Flow Conditions

(Concept: SKIN)

$$q_g = \frac{2\pi kh (P_{PR} - P_{pwf})}{\ln \frac{r_e}{r_w} - \frac{3}{4} + S}$$



$$\Delta p_t = \Delta p_R + \Delta p_{skin}$$

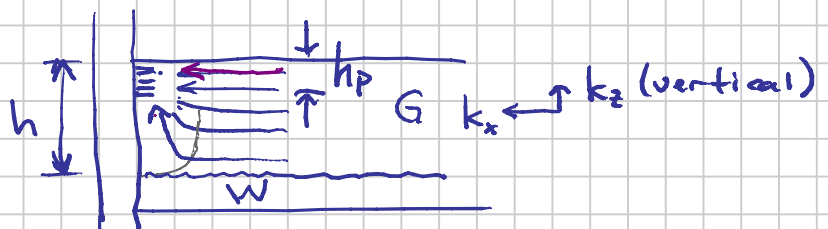
Solve rate eq.

$$\Delta p_{PR} = P_{PR} - P'_{pwf} = \frac{q_g}{2\pi kh} \cdot \underbrace{\ln \left(\frac{r_e}{r_w} \right) - \frac{3}{4}}_{\text{dimensionless}}$$

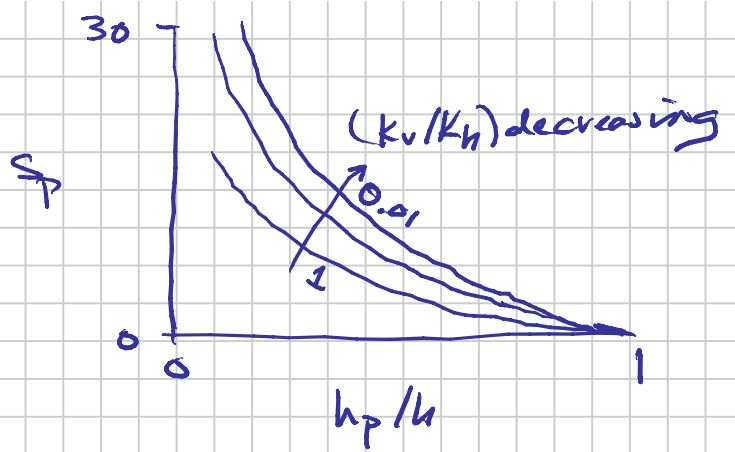
$$\Delta p_{P_{skin}} = P'_{pwf} - P_{pwf} = \underbrace{\left(\frac{q_g}{2\pi kh} \right)}_{\text{slope}} \cdot \underbrace{s}_{\text{dimensionless } \Delta p_{skin}}$$

② Partial Penetration

$$|S_p| > 0$$



$$\uparrow S_p \left(\underbrace{h_p/h}_\downarrow, \underbrace{k_v/k_x}_\downarrow \right)$$



③ ⑫ ⑮
Skin Effects

"High Velocity Flow"
"non-Darcy Flow"
"Turbulent"

Darcy's Law isn't good enough
"Laminar"
Like
Pore
Flow

Forcheimmer

$$\frac{dp}{dr} = \underbrace{\frac{\mu}{k} v}_{\text{Darcy}} + \underbrace{\beta \cdot \rho \cdot v^2}_{\text{PUT}}$$

Rock (like k)
↓ NEW

$\left. \begin{matrix} (kh) \\ s \\ D \\ R \end{matrix} \right\} q_g(P_{wf})$
"IPR"

you ...

$$q_g = \frac{2\pi kh (P_{PR} - P_{wf})}{\ln \frac{R}{r_w} - \frac{3}{4} + \left[\underset{\substack{\uparrow \\ \text{Damage, } P_D, \dots}}{s} + \{ D q_g \} \right]}$$

FINAL GENERAL
RESERVOIR
RATE
EQ.

Total Skin s_t

$$D = \frac{\beta}{z}$$

OR

• Correlations

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

• Well Tests (Special)

Rate-Dependent
Skin

$$s_t = s + D q_g$$

$$A q_g^2 + B q_g - (P_{PR} - P_{wf}) = 0$$

Quadratic
Equation

$$A = \frac{D}{2\pi kh}$$

$q_g (A_p)$

$$B = \frac{\ln \frac{R}{r_w} - \frac{3}{4} + s}{2\pi kh}$$

$$\left(\ln \frac{r_e}{r_w} + s\right) q_g + D q_g^2 - 2\pi kh \Delta p_p$$

$$\underbrace{\frac{D}{2\pi kh}}_{A \Rightarrow D} \cdot q_g^2 + \underbrace{\frac{\ln r_e/r_w + s}{2\pi kh}}_{B \Rightarrow s} \cdot q_g - \Delta p_p = 0$$

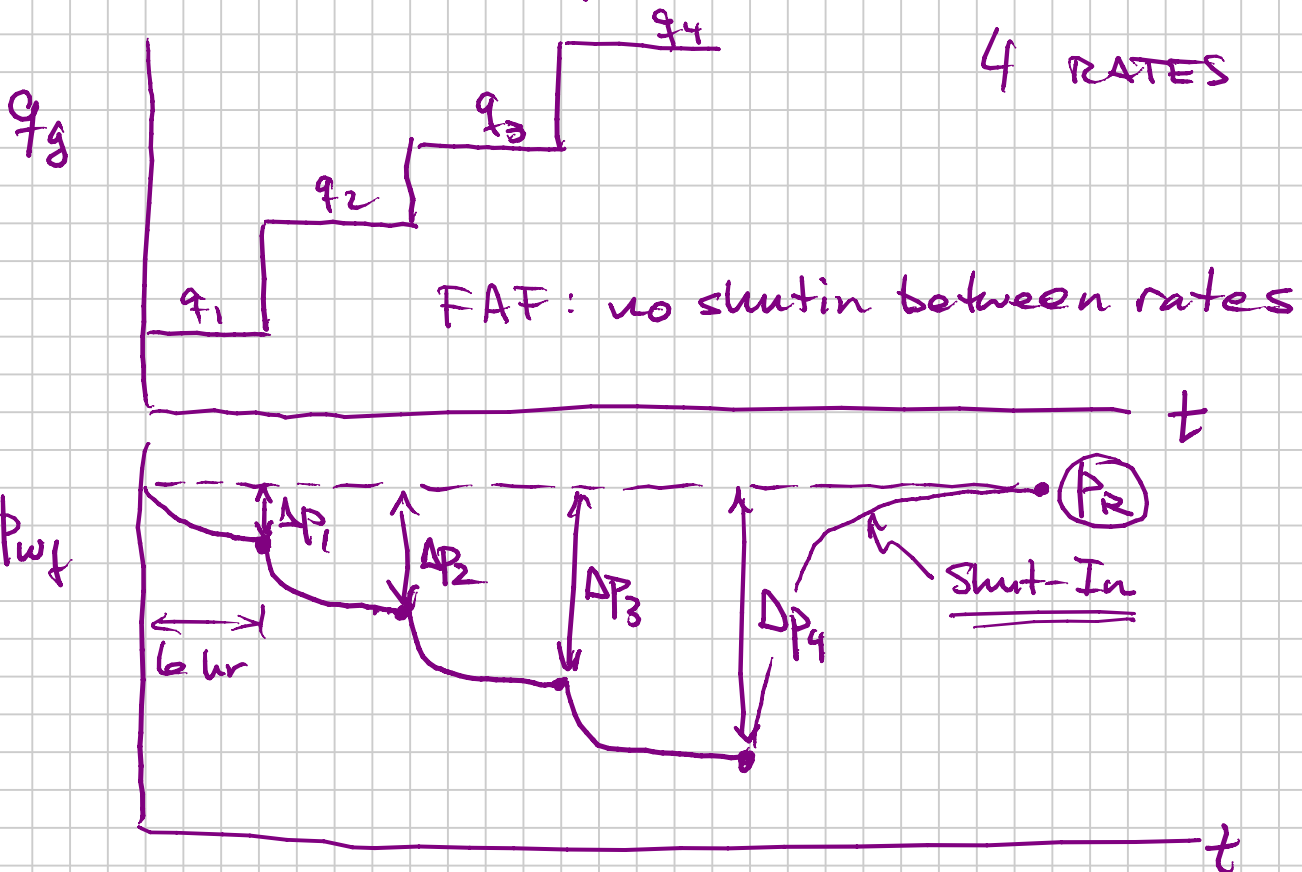
Normally you have an estimate of (kh) $\left\{ \begin{array}{l} \text{Core (Log)} \\ \text{PTA (Well Testing)} \end{array} \right.$

Special Well Tests $\Rightarrow \beta, D$

• SI between each rate

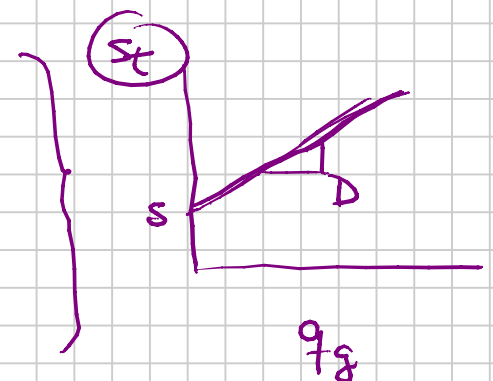
Multi-Rate Flow-After-Flow or Isochronal (FAF)

• Δp each rate



Best-Fit $\Rightarrow A, B$

$\left(\begin{array}{l} kh \\ s \end{array} \right), D(\beta)$



Multi-Rate Test

From Smit-In: $P_R = \boxed{\quad}$

2007.11.07

Rate #	q_g	P_{wf}^*	$\Rightarrow \int \Rightarrow$	P_{pwf}	$P_{PR} - P_{pwf}$
1					
2					
3					
4					

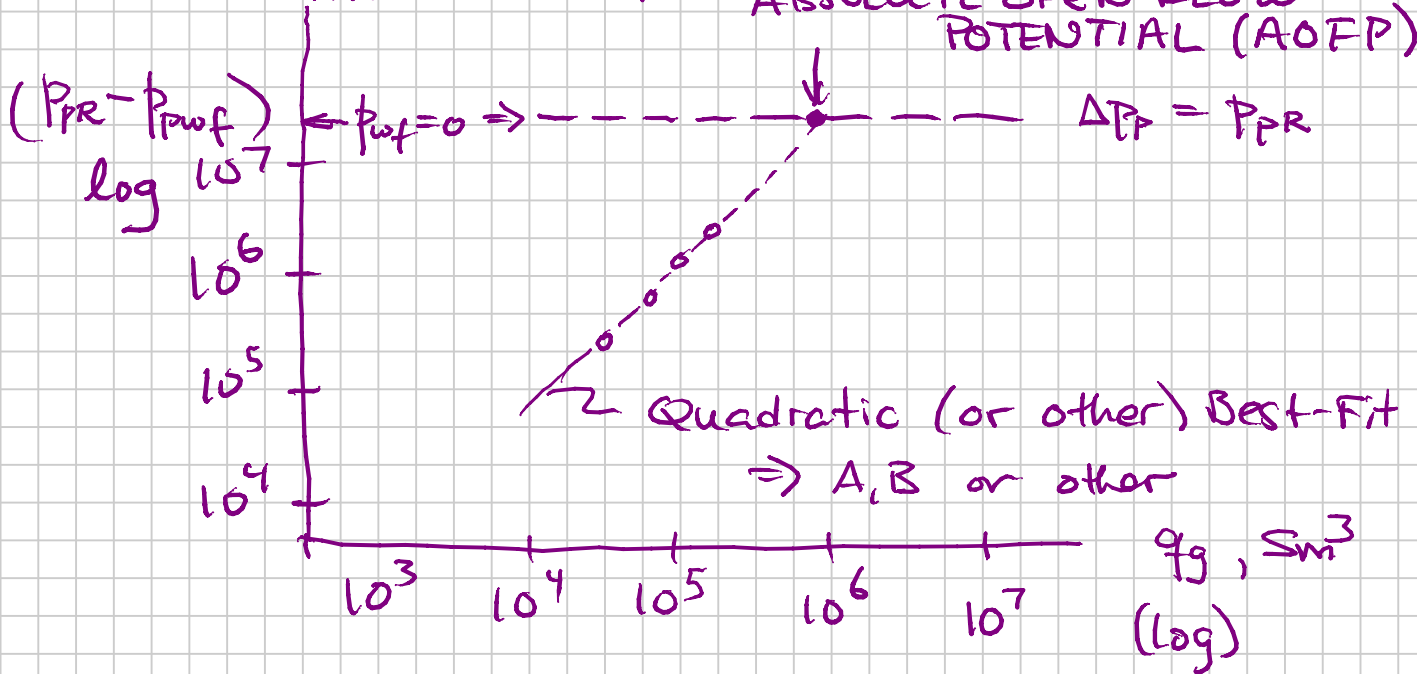
 Measured

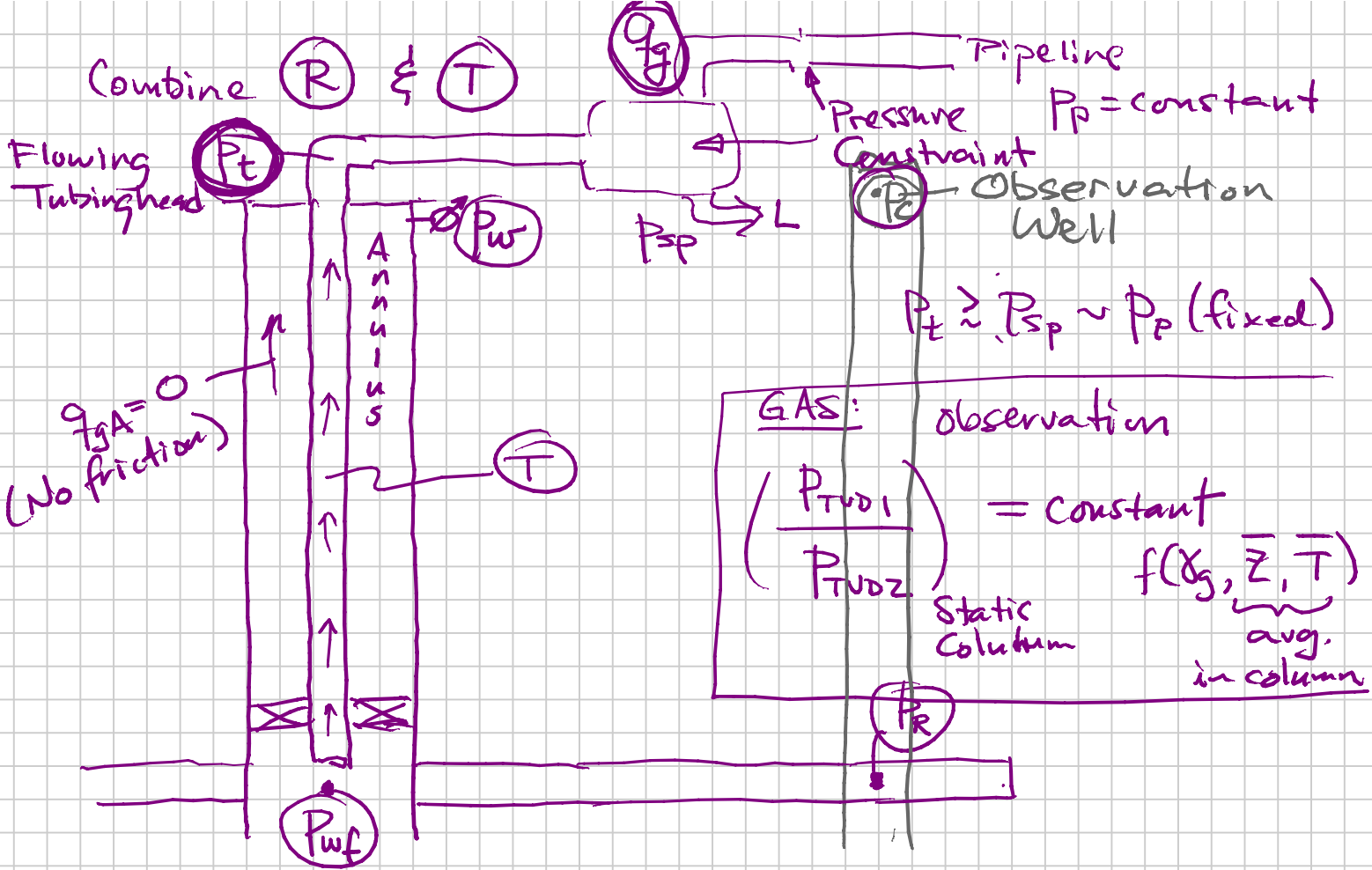
*^(a) Wireline-hung or permanent BHP pressure gauge

(b) Surface pressures \rightarrow Converted \rightarrow BHP's Accurately

Plot (tradition)
"BACKPRESSURE PLOT"

Theoretical
ABSOLUTE OPEN FLOW
POTENTIAL (AOFP)





Tubing Flows:

$$q_{Tg} = C_T (P_w^2 - P_t^2)^{0.5}$$

↑ ↑
Constant

$$\frac{dp}{dz} = \rho g$$

$$\rho = \frac{PM}{ZRT} \sim (\cdot) P$$

$C_T (d_t^{2.7}, L_t, \rho_g, TVD)$

↑ ↑ ↑ ↑
 Tubing Diameter Length of Tubing Gas Gravity True Vertical Depth

Bring \bar{R} pressures to a surface datum:

$$\frac{(p)_R}{(p)_s} = e^{S/2} = \text{constant} \sim 1.2 - 1.4$$

$S(\gamma_g, \bar{z}, \bar{T}, \text{TVD}) = \text{constant for all wells in a common } \bar{R}$

$$\left(\frac{p_R}{p_c}\right) = \left(\frac{p_{wf}}{p_w}\right) = e^{S/2} = \text{constant} \quad (1-32)$$

1.16
1.42

$$p_R = p_c e^{S/2}$$

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

$$A q^2 + B q = \underset{\uparrow}{p_c^2} \cdot e^S - \underset{\uparrow}{p_w^2} e^S$$

$$A' q^2 + B' q = p_c^2 - p_w^2 \quad \textcircled{R}$$

$$A' = A/e^S, \quad B' = B/e^S \quad +$$

$$\left(\frac{1}{C_T}\right)^2 q^2 = p_w^2 - p_c^2 \quad \textcircled{T}$$

$$\underbrace{\left(A' + \frac{1}{C_T^2}\right) q^2 + B' q}_{A''} = \underbrace{p_c^2 - p_w^2}_{\text{Surface-datum pressures}}$$

" p_R "

1st
order
account

Wellhead Backpressure Eq. (Fetkovich)

At a given time:

$$\downarrow P_R(Q_p)(t)$$

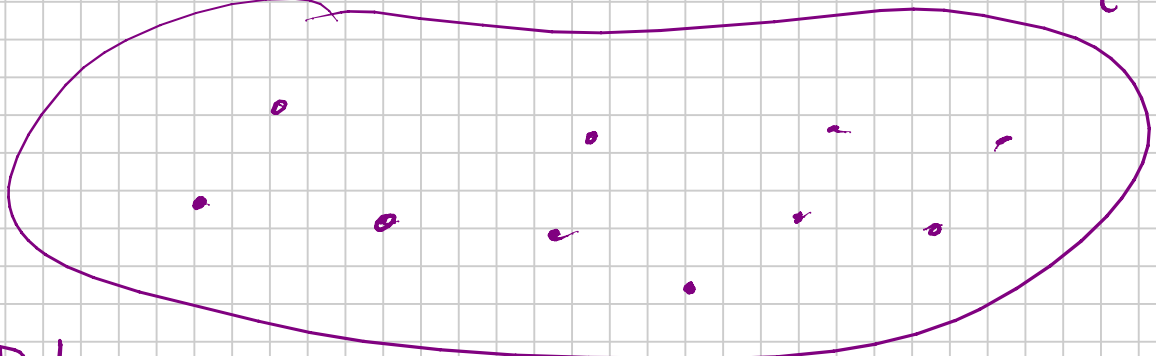
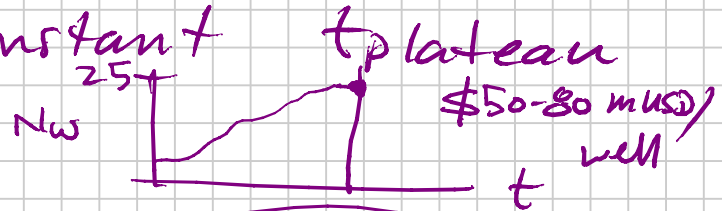
Material Balances

- Say let's set $P_R = \text{minimum (constraint)}$

$$\Rightarrow q_{g, \text{max, well}} \checkmark$$

$$\Rightarrow q_{g, \text{Field}} = \text{constant}$$

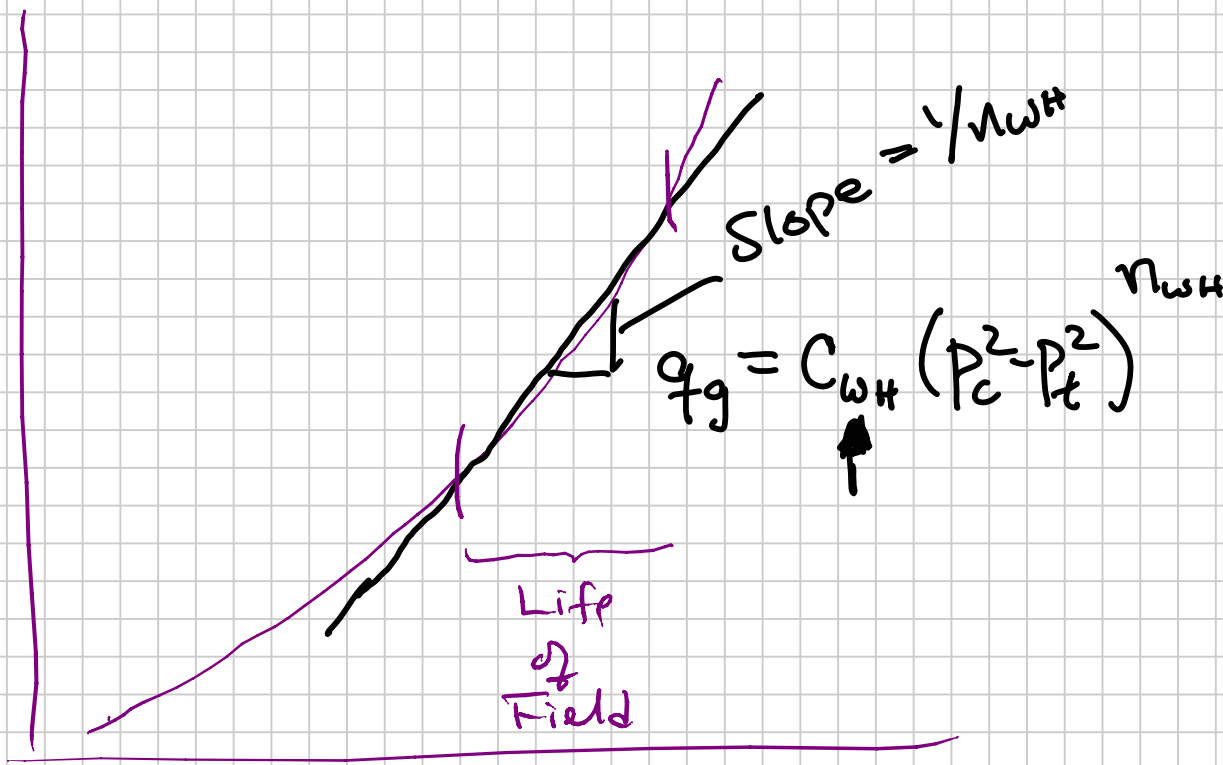
$$\underline{N_w(t)}$$



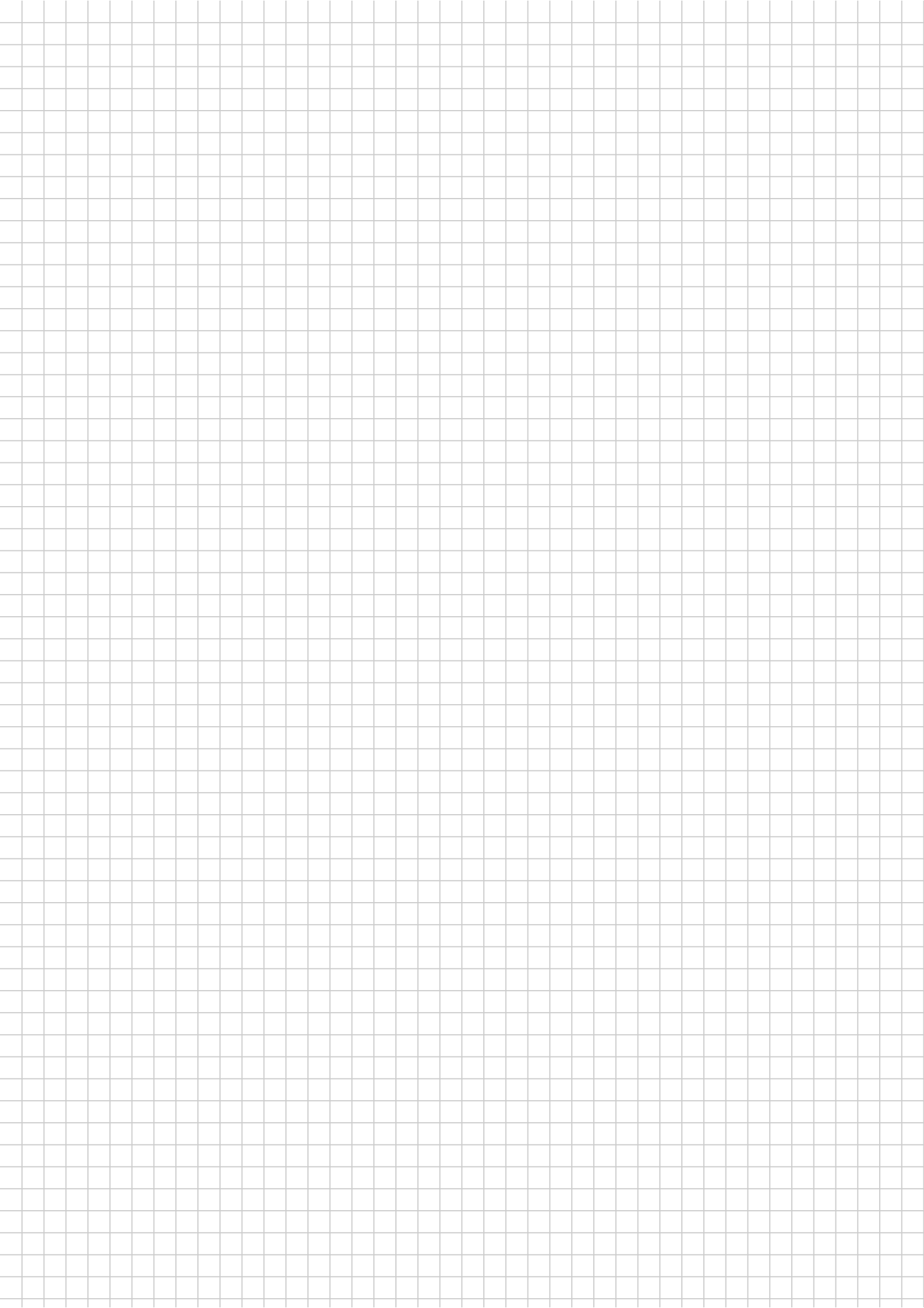
Key Data:

- IGIP (tank)
- All wells are identical \checkmark
- $q_{g, \text{Field}}$ / year

$P_c^2 - P_t^2$
(log)



q_g
(log)



GAS MATERIAL BALANCE

Note Title

11/13/2007

GAS PVTEQ. - REAL GAS LAW

$$pV = nRTZ$$

Assumptions:

$$V = HCPV = \text{constant} \otimes$$

$$Z = f(p, T)$$

$$T = T_R = \text{const.}$$

$$n_R = n_i - n_p$$

Introduce: Surface Gas Volumes

$$V_{gsc} = \frac{RT_{sc}}{p_{sc}} \cdot n$$

379 scf/lbmol
23.64 Sm³/kgmol

$$(G) \quad IGIP = n_i \cdot 379$$

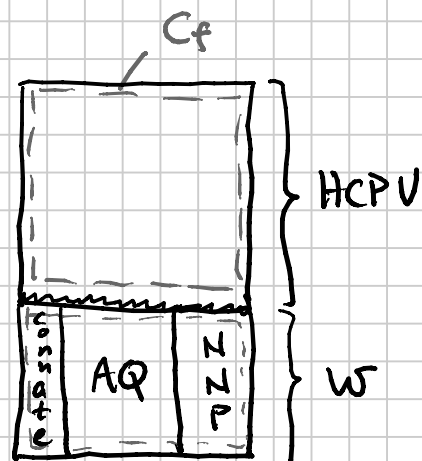
$$(G_p) \quad \text{Cum. Gas Prod.} = n_p \cdot 379$$

⇒ Straight-Line Gas. M.B

$$\left(\frac{p}{Z} \right) = \left(\frac{p}{Z} \right)_i \left(1 - \frac{G_p}{G} \right)$$

↑
RF

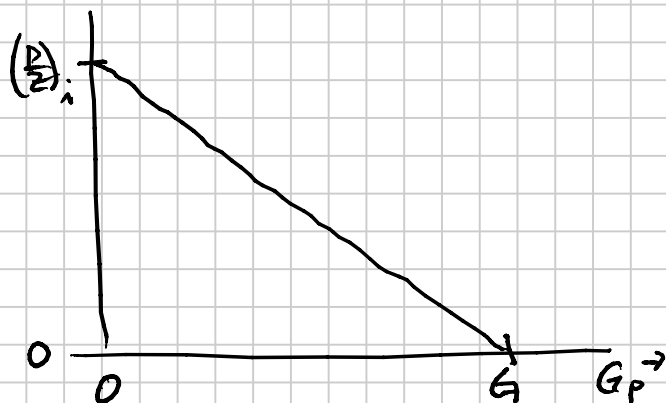
$$\frac{G_p}{G} = 1 - \frac{(p/Z)}{(p/Z)_i}$$



"Pot Aquifer"
Small AQ
High k

"s.c." 1 atm (14.7 psia)
60°F (15.56°C)

"POT AQ MODEL" -
 $\Delta P_g = \Delta P_w$
↑ instantaneously
By Production



Pot Aquifer Model

$$\frac{p}{z} \left[1 - \bar{c}_e (p_i - p) \right] = \left(\frac{p}{z} \right)_i \left(1 - \frac{G_p}{G} \right)$$

$$\bar{c}_e = \frac{c_f + c_w S_{wc} + \underbrace{M}_{(AQ+NHP)} (c_f + c_w)}{1 - S_{wc}}$$

$$S_{wc} \sim 0.25$$

$$c_f \sim c_w \sim 5 \cdot 10^{-6} \text{ psi}^{-1}$$

$$M \equiv \frac{V_{AR}}{V_{PR}} \sim 1-5 \text{ (Pot Ag.)}$$

Containing HC

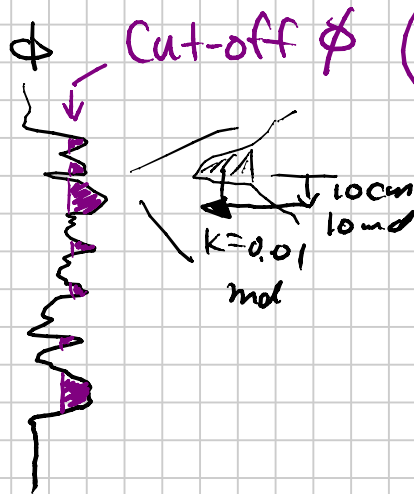
} $c_e =$

$$\frac{G_p}{G} = 1 - \frac{(p/z) \left[1 - \bar{c}_e (p_i - p) \right]}{(p/z)_i}$$

NMP: Non-Net Pay — Water-bearing "dirty" sand
 $\Delta z \sim 10-100 \text{ cm}$

- (1) Interbedded shales
- (2) "Low- ϕ " (low- k) 'sand'

Additional "interbedded" water

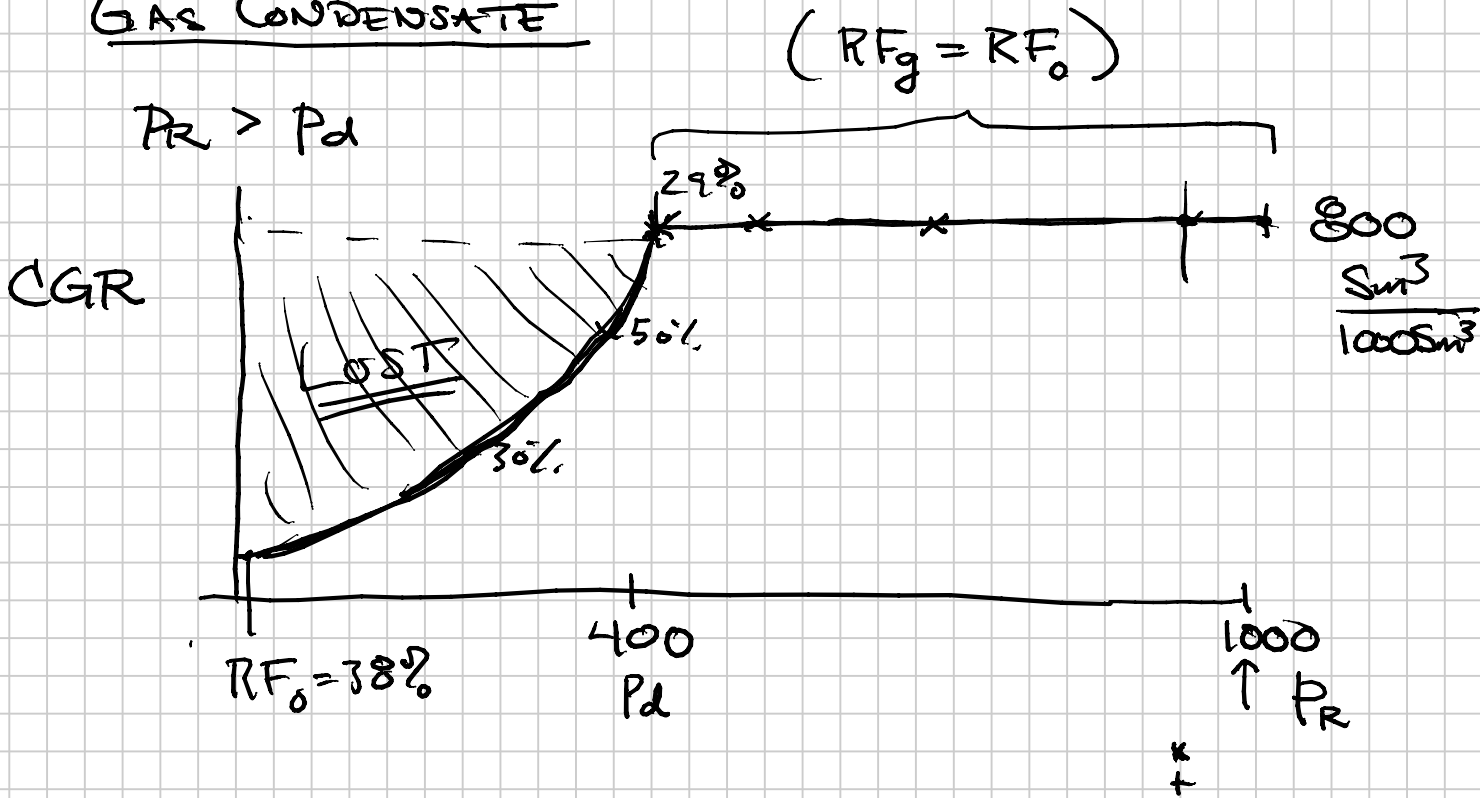


Cut-off ϕ (DON'T USE...)

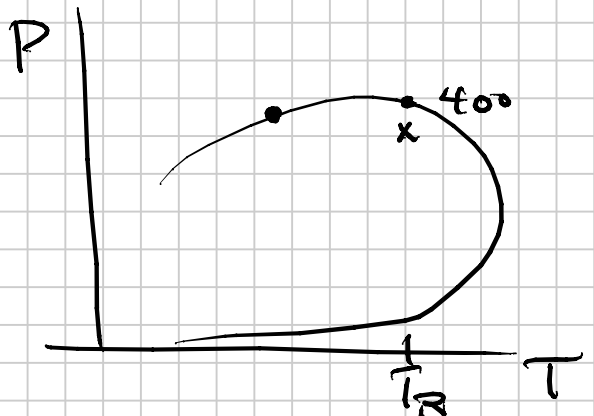
particularly for Gas Reservoirs

$$\underline{M} = \{ M_{AQ} + M_{NNP} \}$$

GAS CONDENSATE



~~PVT~~

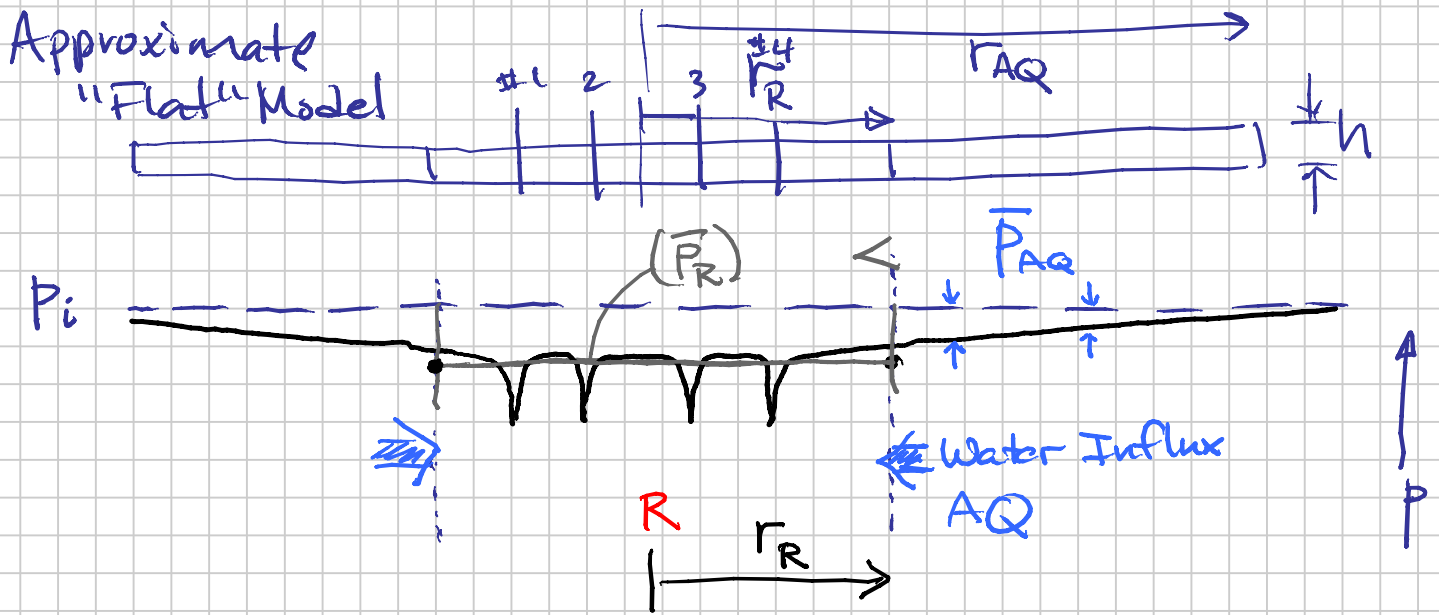
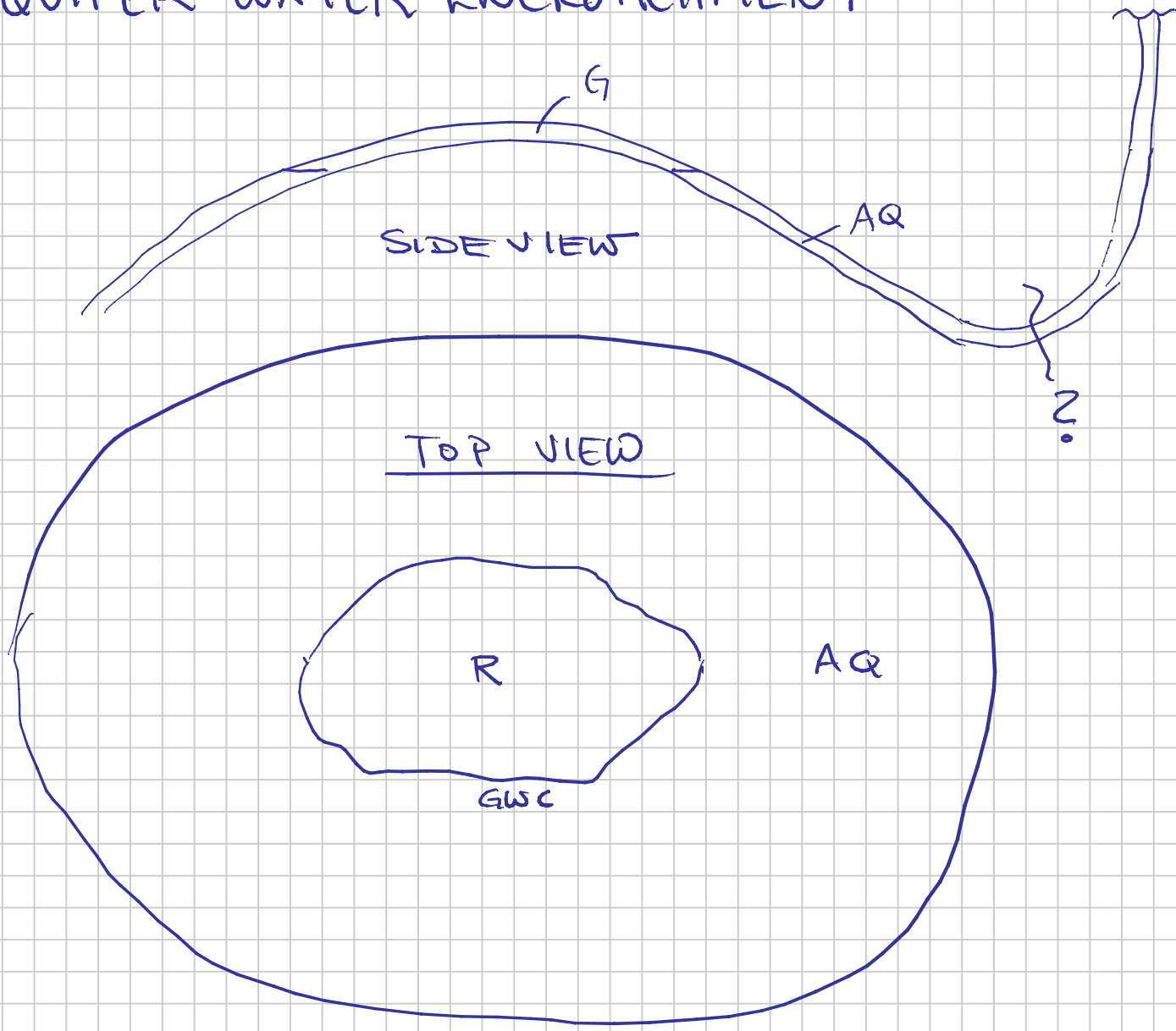


Limited pressure

bbl RB STB

5.615 ft^3

AQUIFER WATER ENCROACHMENT



$$q_g = \frac{2\pi kh (P_R - P_{wf})}{\ln r/r_w}$$

Mathematical Solution $(q_w)_{AQ \rightarrow R}$?

- $p_R = \text{const}$ $r < r_R$ @ t

(• p_{g-w} @ r_R changes in time)

(according to the rate of gas production)

Flow in the aquifer $r_R < r < r_{AQ}$
single-phase water flow

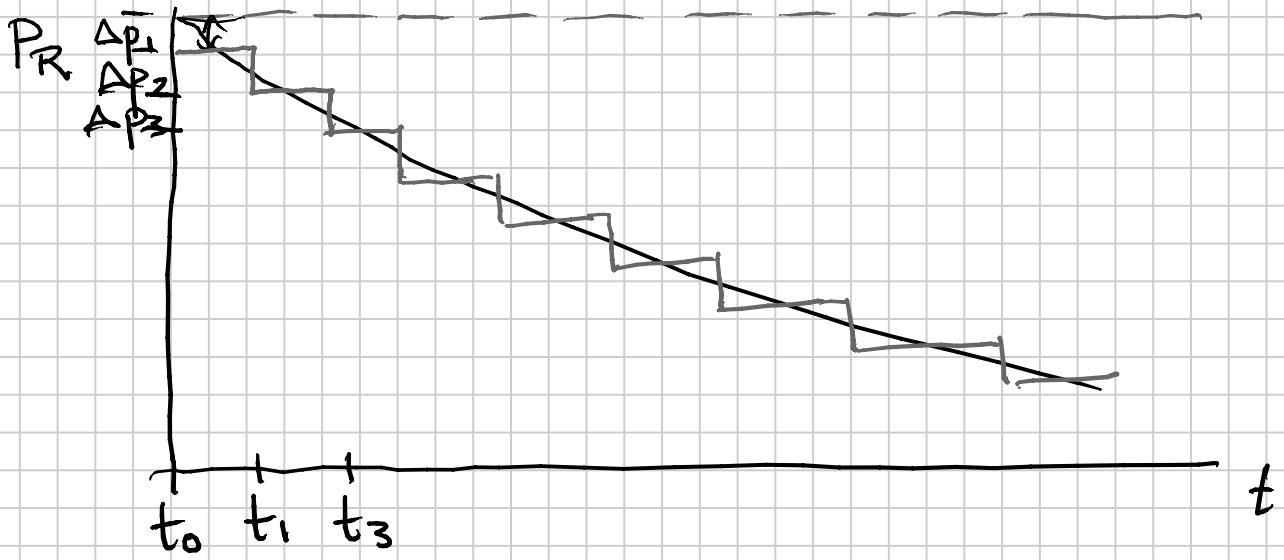
$p_R(t)$ boundary condition

Solution is to use superposition
to calculate $q_w(t)$

- van Everdingen-Hurst general solution

- Fetkovich PSS Approximation

$$q_w = q_{wi} \cdot e^{-Dt}$$



$$q_w(t) = \sum \Delta q_w (\Delta P_{\Delta t})$$

Δp_1 starts at $t_0 \rightarrow t$

Δp_2 starts at $t_1 \rightarrow t$

⋮

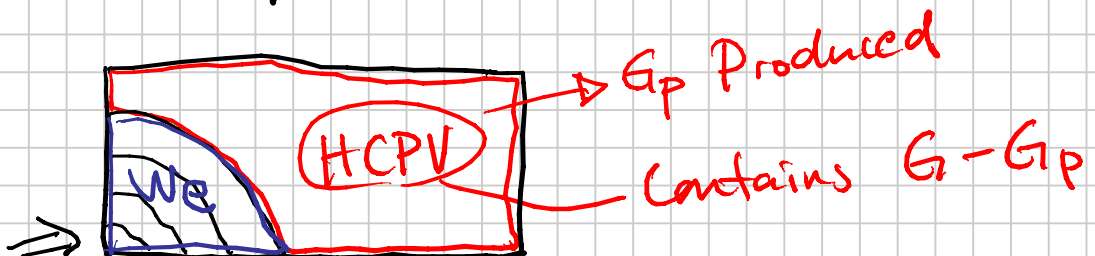
Cumulative Water Encroachment

$$W_e = \int_0^t q_w(t)$$



Filling the Gas R PV

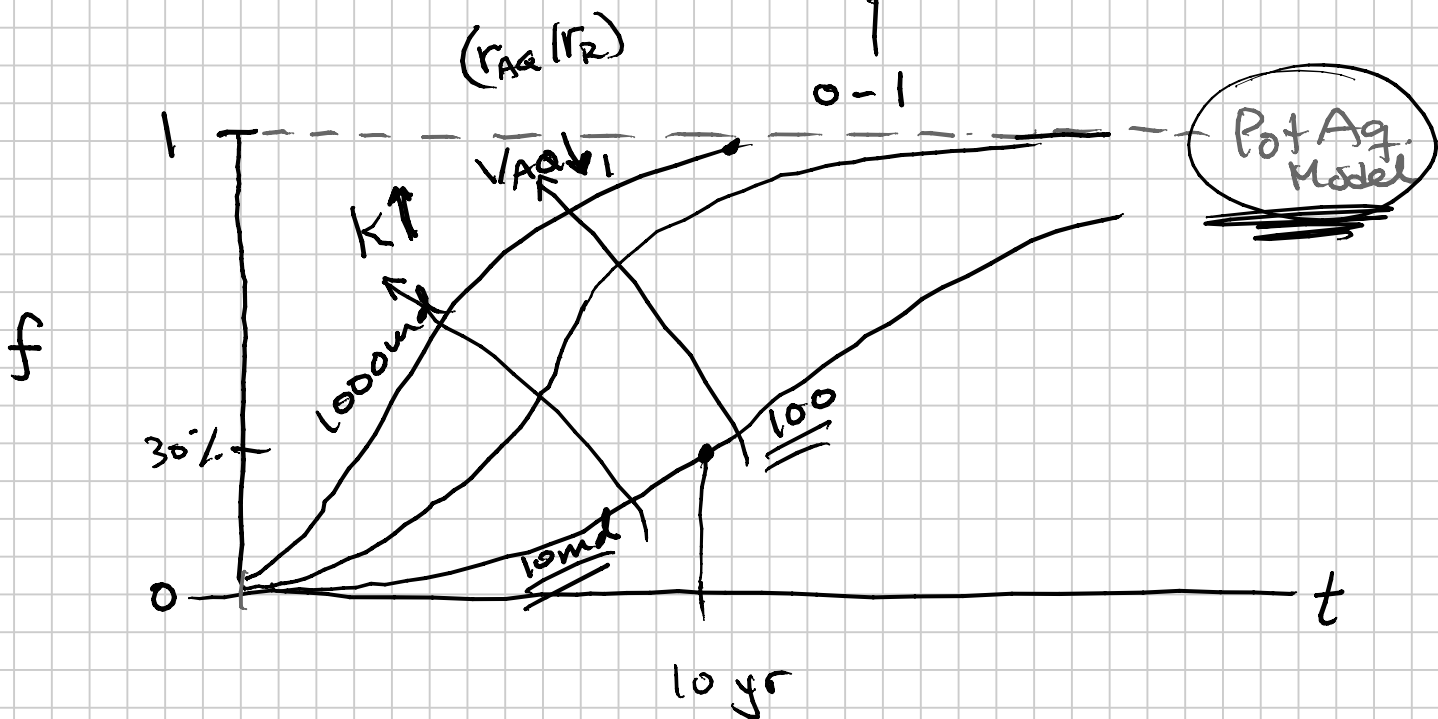
HCPV decreases



Pot Aq. Model gives the maximum encroachment

$$W_{\max} = V_{Aq} \cdot (c_w + c_f) \underbrace{(P_i - P_R)}_{\text{total } \Delta p}$$

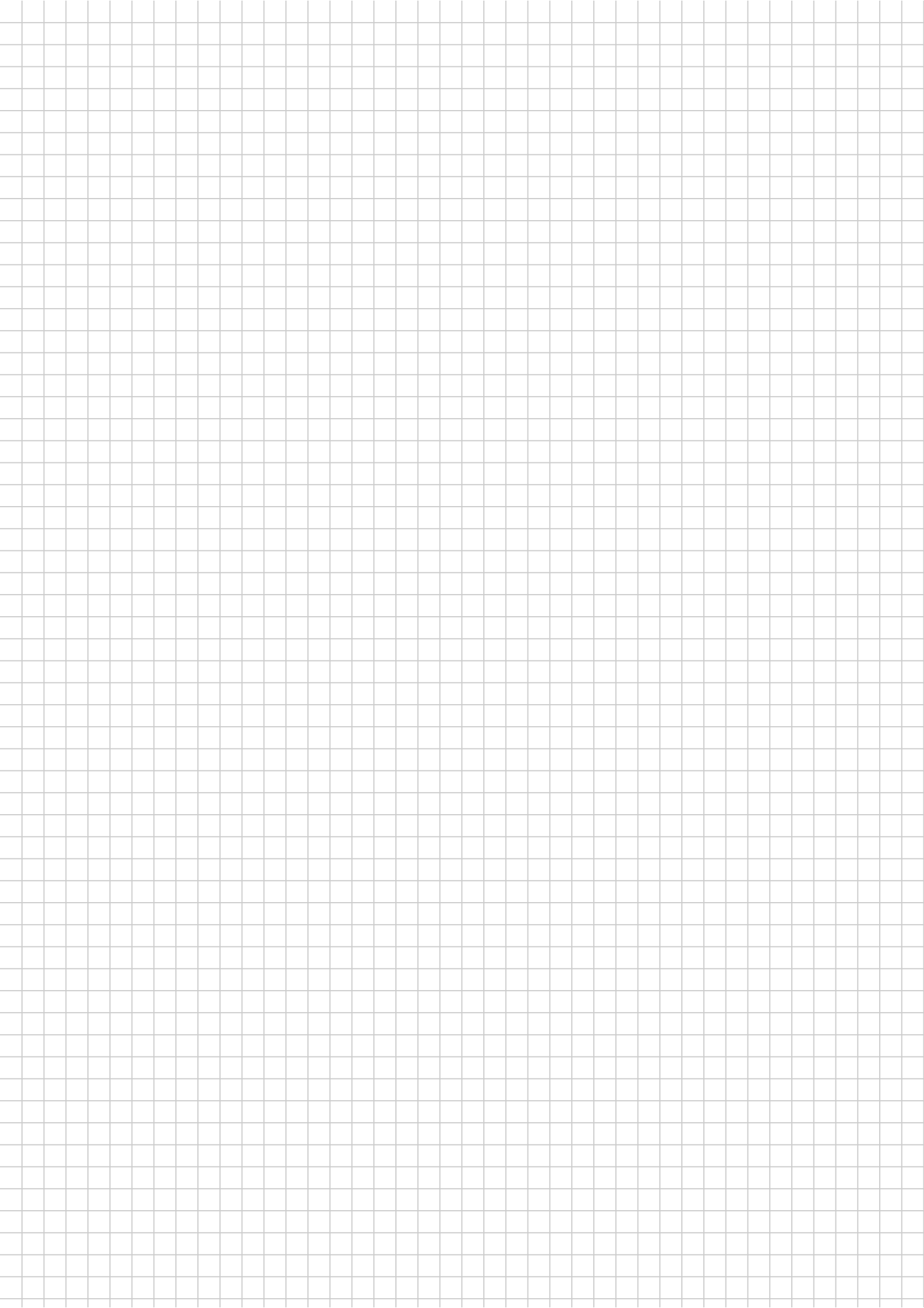
$$W_e(t) = W_{\max} \cdot \underbrace{f(t)}_{0-1}$$



$k \lesssim 1 \text{ md}$: little-no aquifer support in a normal 10-20 yr depletion life

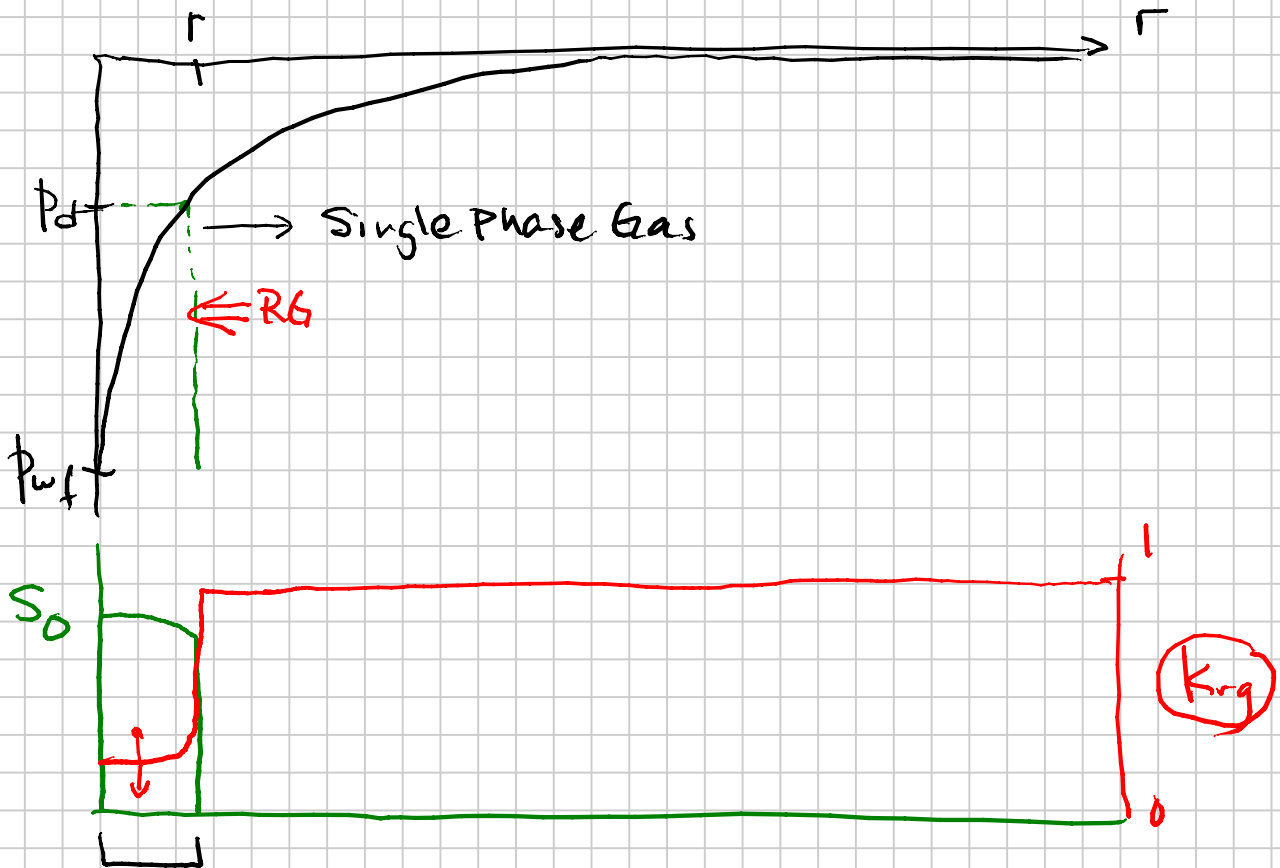
(P_{Ri}) (HP) reservoirs (> 500 bar)

even "small" water volumes can become important



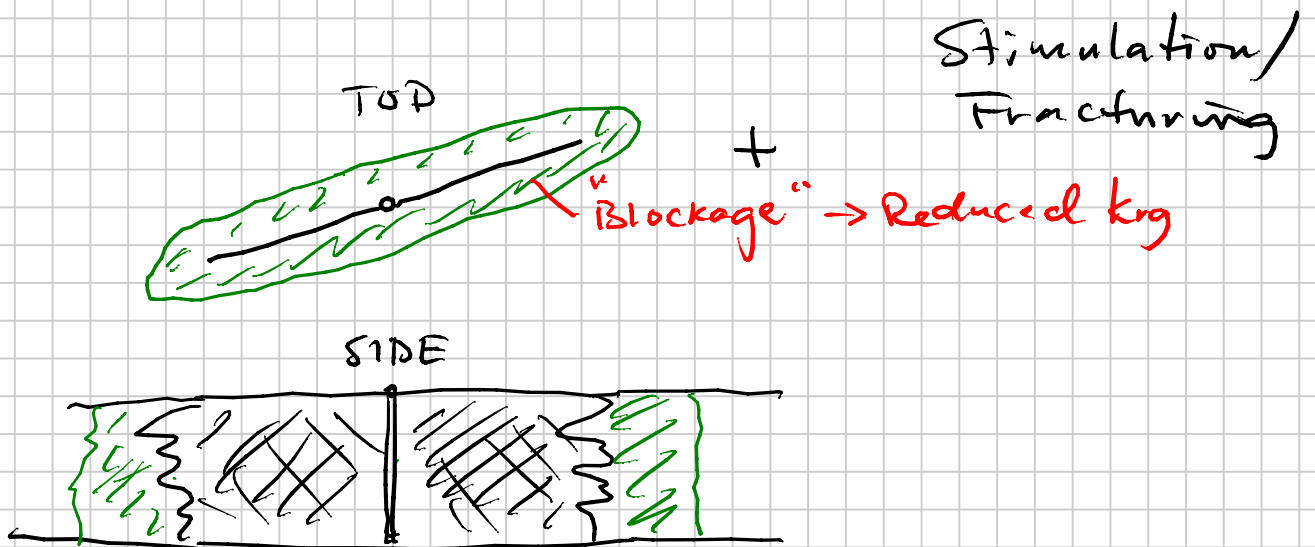
GAS CONDENSATE

$$p_{wf} \text{ (BHFP)} < \underline{\underline{p_d}}$$



Blockage Region \Rightarrow " S_D " \sim +5 \rightarrow +50

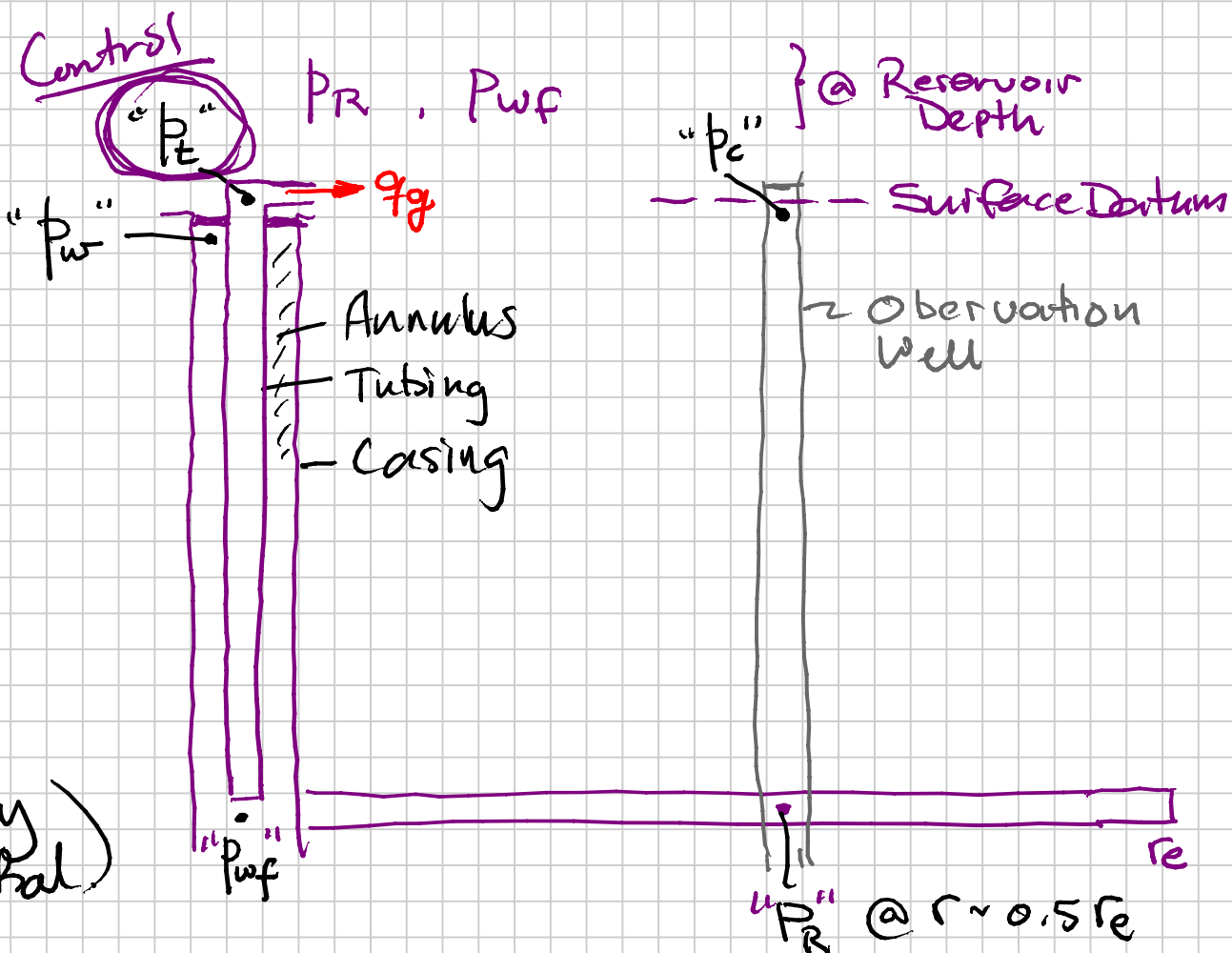
Radial, Vertical Well



Composite Effect Stim + Blockage

$$S_t \approx 0$$

Pressures P_c, P_w, P_t } @ Surface Datum



Static Gas Column

$$\frac{dp}{dz} = \rho g \Rightarrow \rho g = \underbrace{\left(\frac{M}{zTR} \right)}_{\sim \text{const}} \cdot P$$

$$\Rightarrow \left(\frac{P_{\text{Reservoir}}}{P_{\text{Surface}}} \right) = \text{const} = \underbrace{e^{S/2}}_{\sim 1.1 - 1.4}$$

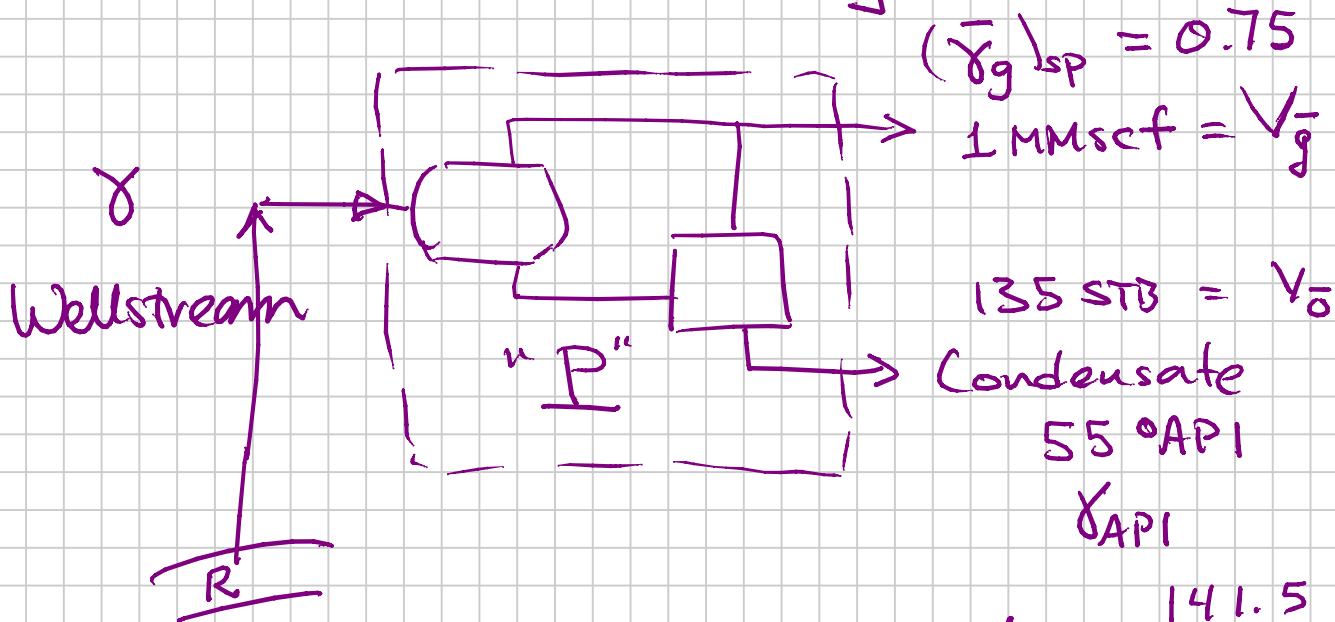
Static Gas Column

S ("static")

$$: \int_0^{\gamma_g} \frac{TVD}{TVD}, M_g, \bar{z}, \bar{T}$$

↑
K
OR

Wellstream Specific Gravity



$$CGR_i = \frac{135}{10^6} = 135 \frac{\text{STB}}{\text{MMscf}}$$

$$\gamma_o = \frac{141.5}{131.5 + \gamma_{API}}$$

Ch. 3:

$$\gamma_w = f(\bar{\gamma}_g, \gamma_{API}, CGR, M_o)$$

→ γ_o

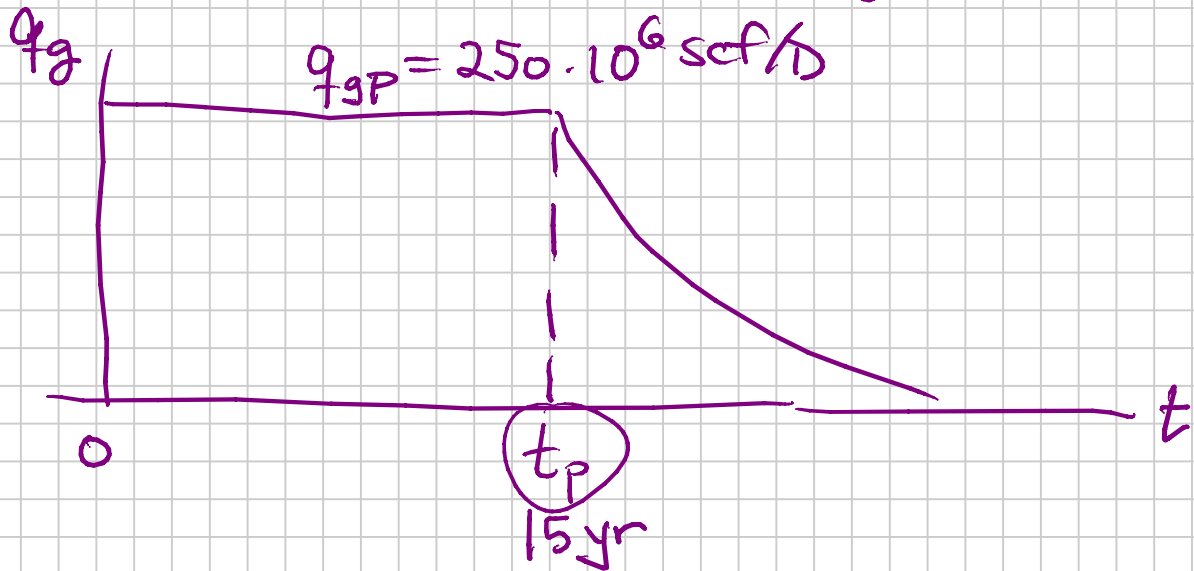
$$\gamma_w = \frac{1}{28.97} \cdot \frac{\left[10^6 \frac{\text{lbmol}}{\text{scf}} \cdot \frac{10}{379 \text{ scf}} \cdot 28.97(0.75) \right] + \left[135 \text{ bbl} \cdot (62.4) \cdot (0.759) \cdot \left(\frac{5.615 \text{ ft}^3}{\text{bbl}} \right) \right] m_o}{(10^6/379) + m_o/M_o}$$

$$C_{og} = \left(\frac{m_o}{M_o} \right) 379 \quad \underline{\underline{\text{per bbl}}}$$

$$= \frac{1 \text{ bbl} (62.4)(0.759)(5.615)}{124} \cdot 379$$

$$= \underbrace{(62.4)(5.615)(379)}_{\circ} \frac{\delta_o}{M_o}$$

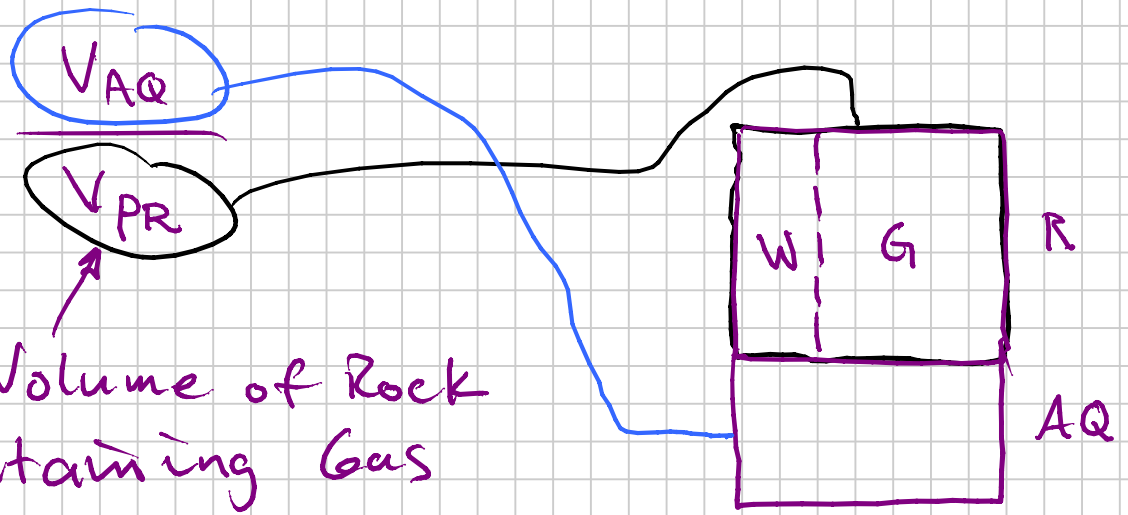
End Plateau Target Recovery



$$\left[\frac{(G_p)_{t_p}}{G} \right] \% = \frac{q_{gp} \cdot t_p}{\textcircled{G}} - 100$$

\uparrow
 $3 \cdot 10^{12} \text{ scf}$

$M \equiv$



Given $\frac{V_{AQ}}{HCPV} = 2 = \frac{V_{AQ}}{V_{PR} (1 - S_w)}$

$$\begin{aligned} M &= 2 \cdot (1 - S_w) \\ &= 2(1 - 0.3) \\ &= 1.4 \end{aligned}$$

Economics Issues in Project

① REVENUE (INCOME)

r - Rate q_g q_0 (Annual)

R - Cumulative $\int q dt$

- Price P_g P_0 (assuming no change in time)

$$r = q_g \cdot P_g + q_0 P_0$$

$P(t)$? Forecasting \pm

② COSTS

c = annual (OPEX - operating Expenses)

C = cumulative $\int c dt$

$$c = f(P)$$

$$c(t) = f(P(t))$$

Platform

Pipeline

Wells

{ Compression

{ Processing P

Taxes (Royalties)
Bank Interest

Control Variables

$\rightarrow d_T$

"V"

$\rightarrow P_{\text{min}}$

✓ Well type (U, S)

⊙(V) Complex



Model is often "empirical"

• may be part of "Platform" cost

③ Net Revenue (Profit)

$$P = R - C$$

Sell

$$p = r - \{c - tr\} \text{ annual}$$

④ Time value of money

Value 10^9 \$

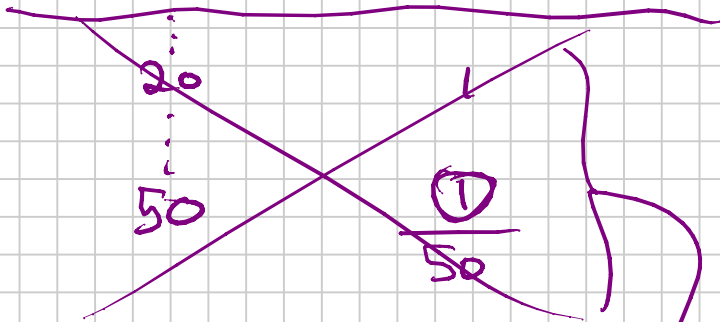
NPV

Discount Factor DF

Year	p (USD)	p "today"
→ 0	1	
1	1	$1/1.1 \quad P/(1+DF) \sim 0.9$
2	1	$P/(1+DF)/(1+DF) \sim 0.8$
3	1	⋮
4	1	⋮
5	1	⋮
⋮	⋮	⋮
10	1	$\frac{P(t)}{[1+DF]^t}$

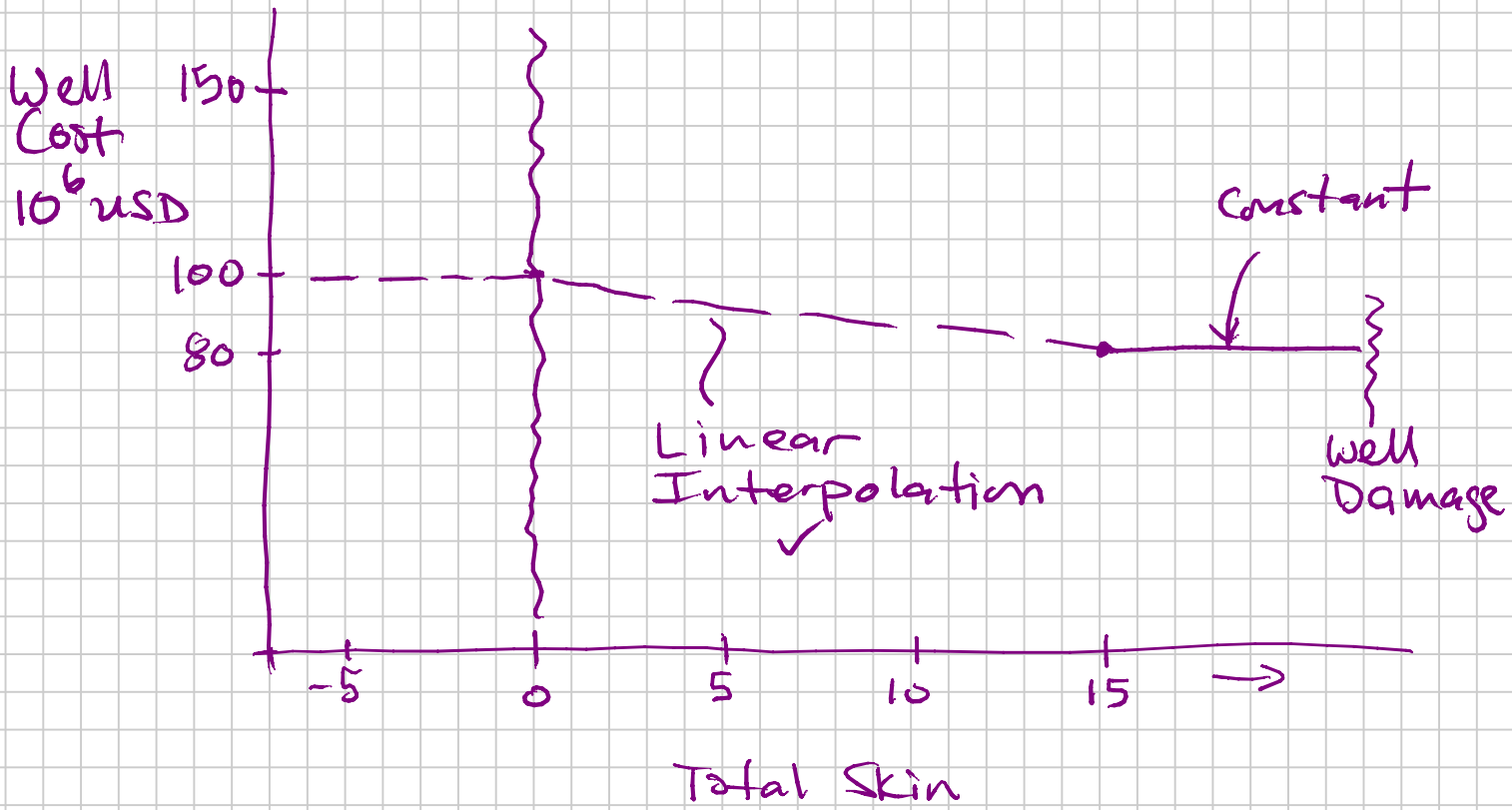
~ 0.1
(close to business interest for loans)

0.05-0.15



$$\frac{10^9 \text{ \$}}{(1.1)^{50}} \sim 10 \cdot 10^6 \text{ \$}$$

Curtis thinks it is BS



(Well Completion Efficiency)

Project:

Optimize the field development strategy

Maximize NPV

Without proper

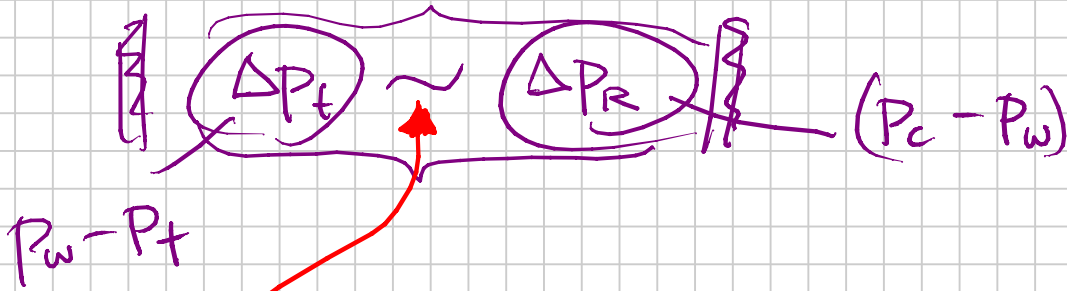
NPV (V)

d_T P_{tmin} skin

Engineering Approach

d_T selection

Minimize ΔP_t : $\{P_w - P_t\}$ friction



UPDATE in defining "optimal" Production Strategy:

$$\frac{P_w - P_t}{P_c - P_t} = 0.05$$

This condition "minimizes" to a realistic value (5%), the % of total well pressure drop ($P_c - P_t$) in the tubing ($P_w - P_t$).

For optimization with SOLVER, use this constraint at $t_{plateau} = 15 \text{ yr}$.

Also, assume maximum $d_t = 7"$ as this is the basis for the base well cost of $\$80 \cdot 10^6$.

$d_T = 12''$ for a reservoir
high (kh)

Work on a "new" well-cost
model

$d_T \sim 4''$ Lower kh

NIPV = 4.6 bUSD

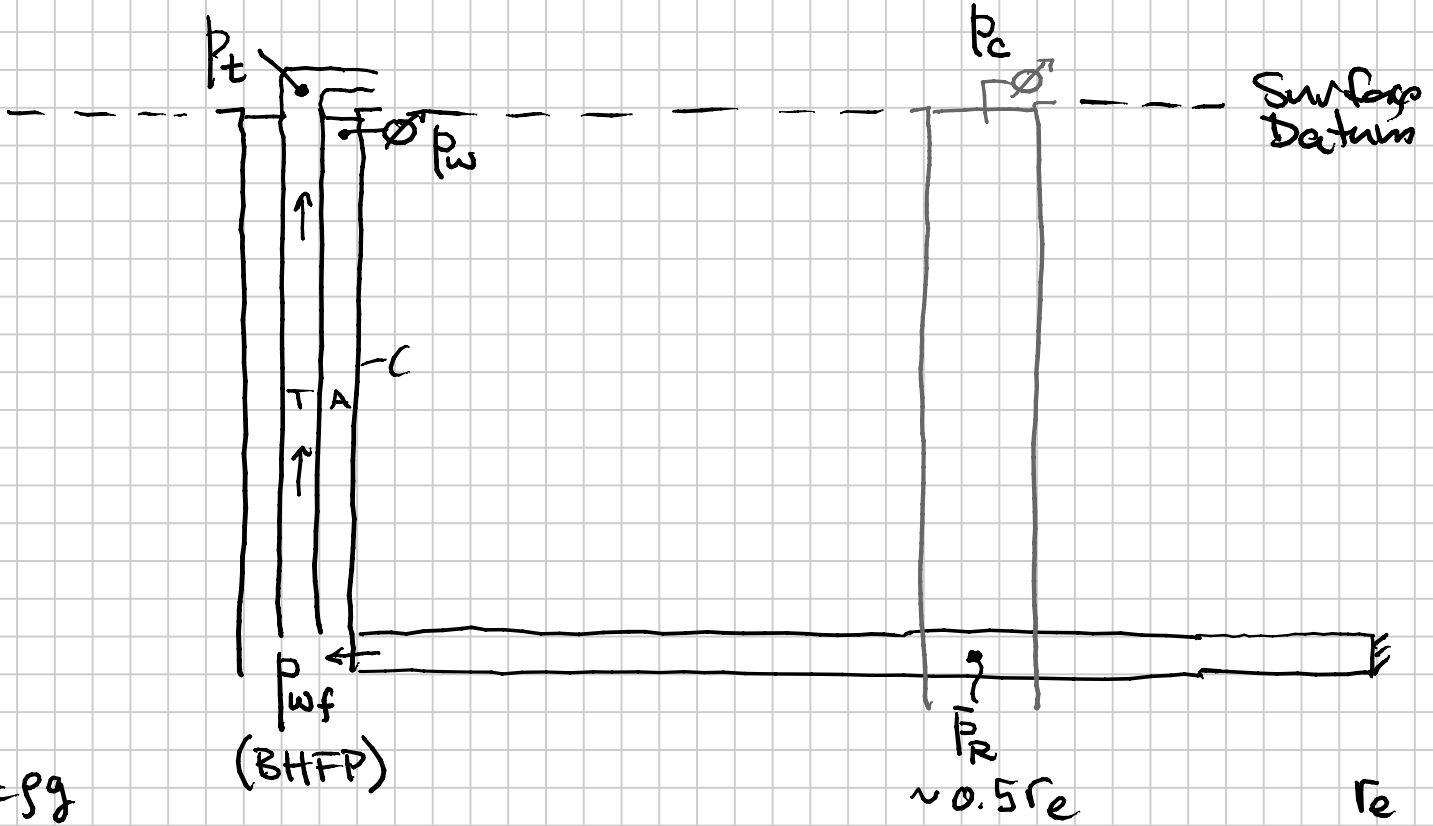
Q & A (Exam) TPG 4145

Note Title

5/2007

$$P_{wf} \rightarrow P_t = G, F \quad q_g = C_T \underbrace{(P_w^2 - P_t^2)}_{\text{"F"}}$$

Pressure Definitions



$$\frac{dp}{dz} = \rho g$$

$$\left(\frac{P_{wf}}{P_w} \right) = \text{constant}(TVD, \bar{\rho}_g) \approx \frac{P_R}{P_c} = e^{S/2}$$

Static Gas Column

$\gamma_g \text{ or } M_g$
 \bar{T}
 \bar{Z}
 TVD

Gas Mat. Bal.

$$\frac{P_R}{Z} = \left(\frac{P}{Z} \right)_i \left(1 - \frac{G_p}{G} \right)$$

No A_g
 No C_w
 No C_f } HCPV = const

$$\frac{e^{S/2}}{Z} \left[1 - C_e (P_i - P_R) \right] = \left(\frac{P}{Z} \right)_0 \left(1 - \frac{G_p}{G} \right)$$

A_g, C_w, C_f, S_wc t_0 (Previous Time Step)

@ R datum

$$c_e \checkmark$$

$$(P/Z)_i \checkmark$$

$$(G_p/G)^{n-1} \checkmark$$

solve for $\frac{P_R}{P_c}$; $Z(P_R)$

Hand Check P_c @ 1 year

$$P_c = 361.03 \text{ bara}$$

$$e^{S/2} = 1.5792$$

$$P_R = 570.14 \text{ bara} \quad \text{vs} \quad \text{Cell Q } 570.12 \checkmark$$

$$Z_R = 1.359 \quad \text{Cell T ; } \underline{\text{checked}} \text{ if you want}$$

(Tr, Pr) \Rightarrow Fig-Ch.3

$$(P/Z)_i = 423.68 \text{ bara}$$

$$P_i = 586.05 \text{ bara}$$

$$\nabla (G_p/G)_{1\text{yr}} = 0.01521$$

Column N

$$c_e = 3.40 \cdot 10^{-4} \text{ 1/bar ; } \underline{\text{check}}$$

$$\frac{570.14}{1.359} \left[1 - (3.40 \cdot 10^{-4})(586.05 - 570.14) \right] =$$

LHS

$$423.68 (1 - 0.01521) =$$

RHS



$$N_w = \begin{cases} \text{if } t < t_p \\ N_w = \min\left(\frac{q_{\text{Field}}}{q_{\text{AOF}}}, N_{\text{max}}\right) \\ \text{else} \\ N_w = N_w^{n-1} \end{cases}$$

Ch. 6 PVT Lab

Ch. 4

| vdw

ρ, M

$$\rho_{\text{H}_2\text{O}} = 992 \text{ kg/cm}^3$$

What is the molar volume

$$M_{\text{H}_2\text{O}} = 18$$

$$v = \frac{M}{\rho} = 0.05 \frac{\text{m}^3}{\text{kg-mole}}$$

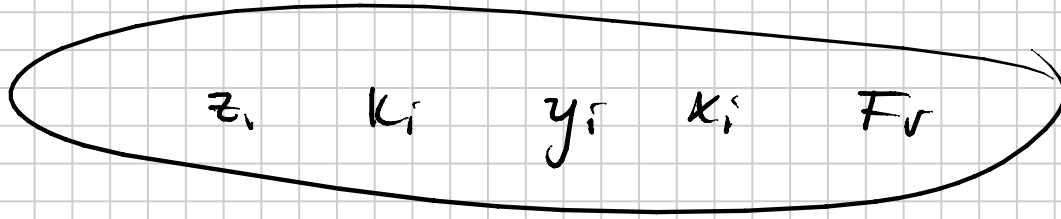
$$\left. \begin{matrix} a \\ b \end{matrix} \right\} \text{H}_2\text{O} = a =$$

$$p =$$

RR (Phase Split) Ch. 4

- Problems

- Lectured



$$h(F_v) = \Sigma$$



(G_p / G) end plateau

↓

P_R

↓

P_c

A B →

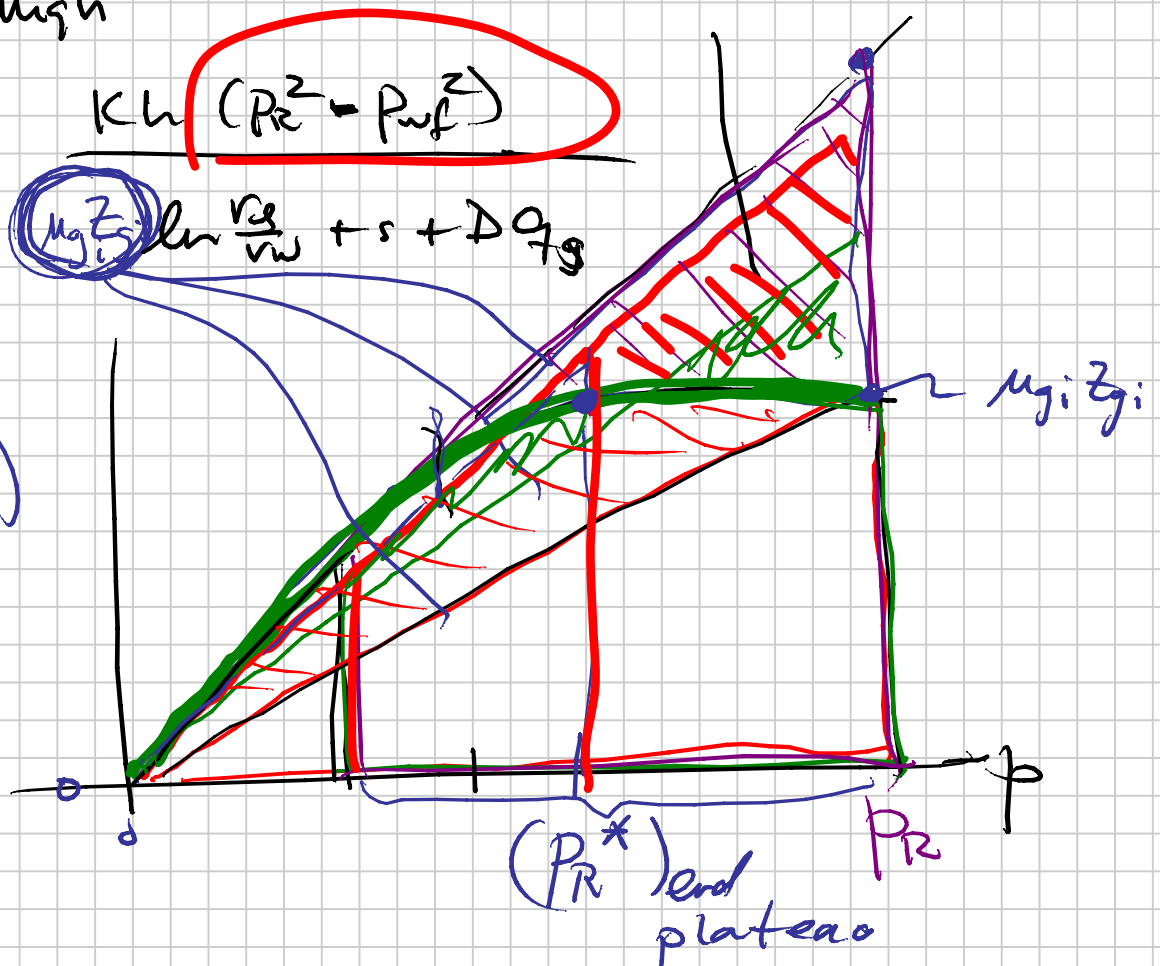
g_{max}

P_{Ri} high

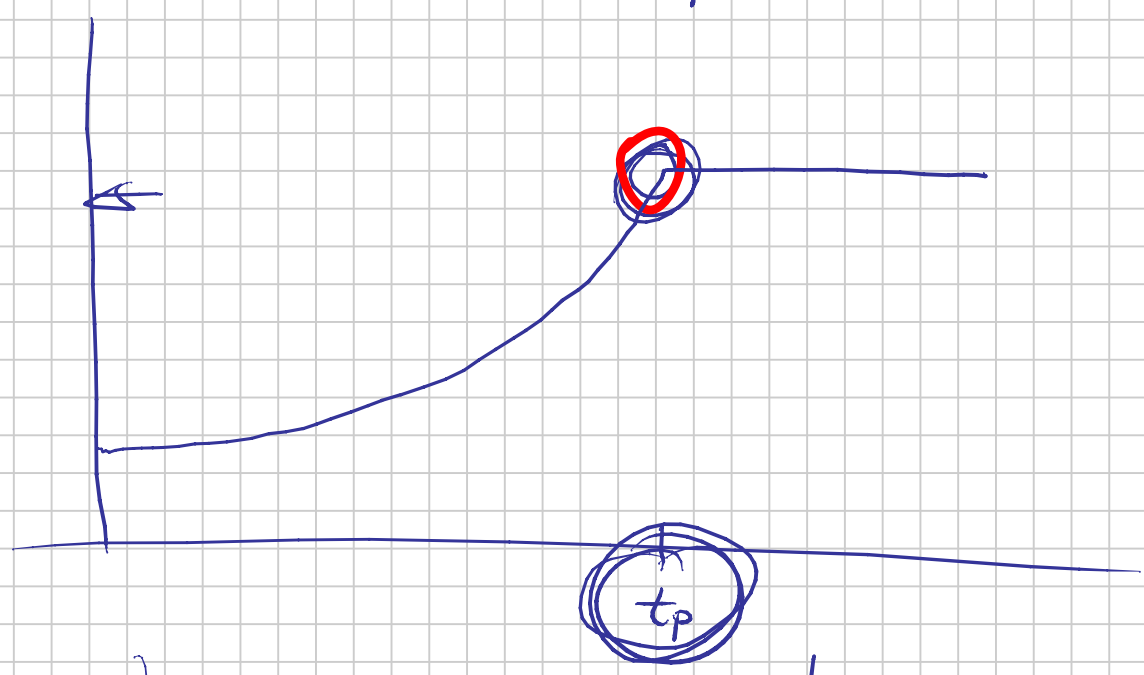
$$q_g = \frac{K h (P_R^2 - P_{wf}^2)}{\mu_g z_i}$$

$$\ln \frac{r_e}{r_w} + s + D q_g$$

$$\frac{1}{\mu_g B_g} \sim \left(\frac{P}{\mu z} \right)$$



N_w



q_{gF}

