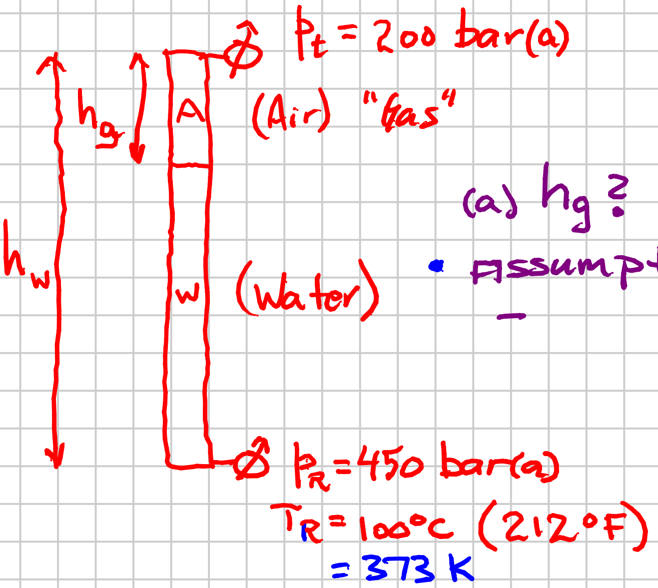
TPG 4145 PVT & FLOW — CURTIS H. WHITSON

Note Title — 2011-08-22



bara   barg

(a) h_g ? m

• Assumptions:

–

Pressure Units:

Absolute: p_A

Gauge: $p_g \equiv p_A - (p_A)_{s.c.}$

SI: Pa

kPa = 10^3 Pa

MPa = 10^6 Pa

(non-SI) bar = 10^5 Pa

common in Norway (Europe)

$h_w = 3000$ m

~10,000 ft

$\boxed{3.28 \text{ ft/m}}$

Old British (American)

p [psi]   psia   psig

$\text{lb}_f / \text{in}^2$

$\boxed{14.50377 \text{ psi/bar}}$

$T_{°F} = T_{°C} \cdot \frac{9}{5} + 32$; $T_K = T_{°C} + 273.15$

$T_R = T_{°F} + 459.67$

$T_R = 1.8 \cdot T_K$

Ideal Gas Law: $pV = nRT$

K, °R

abs. temp. units

@ 600 m under fjord:

$$p_b - p_t \simeq \underbrace{600\,\mathrm{m} \times 10\,\mathrm{m/s^2} \times 10^3\,\mathrm{kg/m^3}} = 6\cdot10^6 \underbrace{\frac{\mathrm{kg}}{\mathrm{m}\cdot \mathrm{s}^2}}$$

$$6\cdot10^6\ \cancel{\mathrm{Pa}} \times \underbrace{\left(\frac{\mathrm{bar}}{10^5\ \cancel{\mathrm{Pa}}}\right)}$$

$$= 60\ \mathrm{bar}$$

$$\boxed{\Delta p = h\cdot g\cdot \rho}$$

Static Pressure Difference

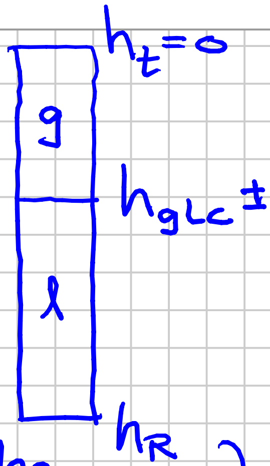
$p_t \sim 1$ bar

S.L.

$$P_B = P_t + hg\rho$$

$$= 1 + 60 = 61\ \mathrm{bar}$$

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



g : air

l : w

$$\int_{p_t}^{p_R} dp = g \int_{h_t}^{h_R} \rho \, dh$$

$$p_R - p_t = g \left\{ \int_{h_t}^{h_{glc}} \rho_g \, dh + \int_{h_{glc}}^{h_R} \rho_l \, dh \right\}$$

$$\rho \equiv \frac{m}{V}$$

$\rho(p, T, \text{composition})$: general

w: $\rho_l = \rho_w \simeq$ const

g: $\rho_g = \frac{m}{V}$

Ideal Gas Law: $pV = nRT$; $n = \frac{m}{M}$

$\rho_g \overset{\propto}{\sim} p$

$$pV = \frac{m}{M} RT$$

$$\boxed{\rho_g = \frac{pM}{RT}} = \frac{m}{V}$$

$M \left[\frac{g}{mol}\right]$, $\left[\frac{lb}{lb\text{-}mol}\right]$

g-mol

$\left[\frac{kg}{kg\text{-}mol}\right]$

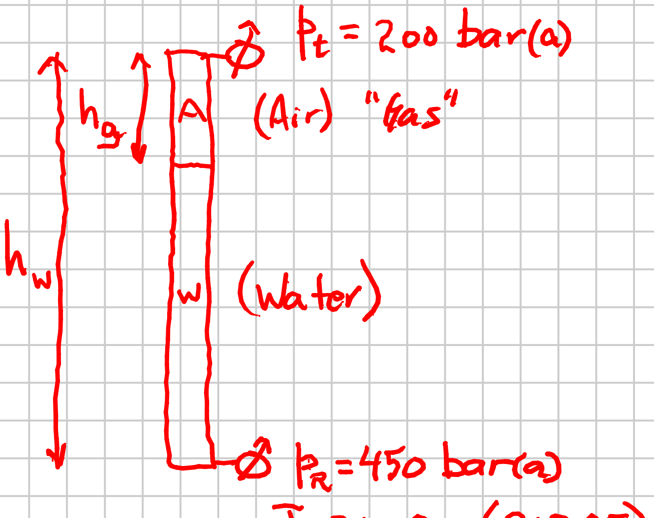
$M_G \equiv 16.04$

$M_{H_2O} = 18$

Reservoir/Petroleum:

Real Gas Law:

$pV = nRT \cdot Z_{(p, T,)}$ Correction Term / Deviation / "Z-factor" } $0.7 \rightarrow 2$



$$p_R - p_t = g\left\{\int_{h_t}^{h_{glc}} \rho_g \, dh + \int_{h_{glc}}^{h_R} \rho_\ell \, dh\right\}$$

$$p_R - p_t = g\bar{\rho}_g (h_{glc} - h_t) + g\bar{\rho}_\ell (h_R - h_{glc})$$

$$= h_{glc}\{(g\bar{\rho}_g - g\bar{\rho}_\ell)\} - \cancel{g\bar{\rho}_g \underset{0}{h_t}} + g\bar{\rho}_\ell h_R$$

$$\boxed{h_{glc} = \frac{(p_R - p_t) - \bar{\rho}_\ell g h_R}{g(\bar{\rho}_g - \bar{\rho}_\ell)}}$$

$\rightarrow$ $\bar{\rho}_\ell \simeq 1000 \text{ kg/m}^3$ fresh water

$g = 9.8 \text{ m/s}^2$

$h_R = 3000 \text{ m}$

$\bar{\rho}_g \cong \dfrac{pM}{RT}$ @ p_t, T_t

200 bar

$-15°C + 273 = 258 \text{ K}$

$= 270 \text{ kg/m}^3$

$R = 8.314$ $\qquad$ 10.7316

R depends on units for p, T, V, m

$\underbrace{[bar]\ [K]\ [m^3]\ [kg]}_{R = 0.08314}$

$M_{air} = 28.97$

$$\boxed{h_{glc} = \frac{(p_R - p_t) - (\bar{\rho}_l g h_R)}{g(\bar{\rho}_g - \bar{\rho}_l)}}$$

Consistent SI units

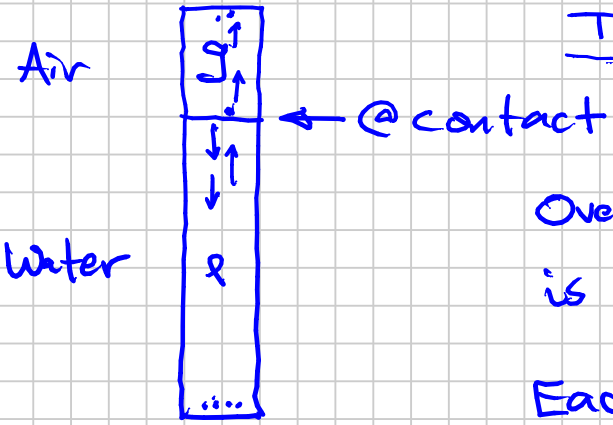
Units
Units
Units

$$\frac{10^5 \frac{Pa}{bar}(450-200) - 1000(9.8)(3000)}{(9.8)(270-1000)}$$

$h_{glc} = \underline{615}$ m below the surface

* Estimate the uncertainty in $h_{glc} \pm m$ due to gas density uncertainty:

$\left\{ \begin{array}{l} \text{- pressure dependence} \\ \text{- } T_t \text{ assumption (warm vs cold)} \\ \text{- Neglecte } Z \end{array} \right\} \begin{array}{l} \pm \\ \pm \\ \pm \end{array}$



Thermodynamic Equilibrium

(T = constant)

Overall or total Chemical Energy μ is at a minimum.

Each component in a mixture contribute to μ

"Fick" Molecular Diffusion

concentration

$$v_i = D_i \left(\frac{\Delta C}{\Delta h}\right)$$

$\frac{m}{s}$

$$\mu = \sum_{i=1}^{N} n_i \, \mu_i(T, P, \text{composition})$$

molar

components $i = 1, \ldots, N$

$\Delta \mu_i$ Air : $\{N_2, CO_2, O_2, CO, \ldots, H_2O\}$

Water : $\{H_2O, N_2, CO_2, O_2, CO, \ldots\}$

Molar Composition (u_i)

z_i = total system $= \dfrac{n_i}{\sum_{j=1}^{N_c} n_j} = \dfrac{n_i}{n}$

y_i = equilibrium gas (vapor) $= \dfrac{n_{iV}}{\sum_{j=1}^{N_c} n_{jV}} = \dfrac{n_{iV}}{n_V}$

x_i = equilibrium liquid $= \dfrac{n_{iL}}{\sum_{j=1}^{N_c} n_{jL}} = \dfrac{n_{iL}}{n_L}$

Single Phase

Total $\mu_{1\phi} = \sum n_i \mu_i (P, T, z_i)$

vs ? How

Two-Phase

Total $\left\{ \mu_{2\phi} = \sum n_{iL}\, \mu_{iL}(x_i, p, T) + \sum n_{iv}\, \mu_{iv}(y_i, p, T) \right.$ $\Bigg\}$ Many 10^{100} combinations of y_i x_i n_v

$$n_{Li} = n_L \cdot x_i$$
$$n_{vi} = n_v \cdot y_i$$

$\mu_i (p, T, x_i)$

When two-phase chemical equilibrium reached:

$\{ \mu_{iL} = \mu_{iv} \}$ all i

$$v_i = \tilde{D}_i \cdot \frac{\Delta \overbrace{\{ \mu_i(h) + M_i g \}}^{\text{Total Potential}}}{\Delta h}$$

As we approach total equilibrium:

$$\left\{ \frac{\Delta (\mu_i(h) + M_i g)}{\Delta h} = 0 \right.$$

$$\left\{ \frac{dp}{dh} = \rho(h) g \right.$$ Static Fluid Column

Equilibrium Calculations for Simple Binary CO_2 - Water System

Make Calculations μ_i

Need Component Properties
$\{M, T_c, p_c, \omega\}$

moles $\rightarrow$ mass

Ch. 4

$\boxed{\text{CUBIC EOS (Eq. of State)}}$

v^3

van der Waals (1873)

$$\left\{ p = \frac{RT}{v-b} - \frac{a \cdot \alpha}{v^2} \right\}$$

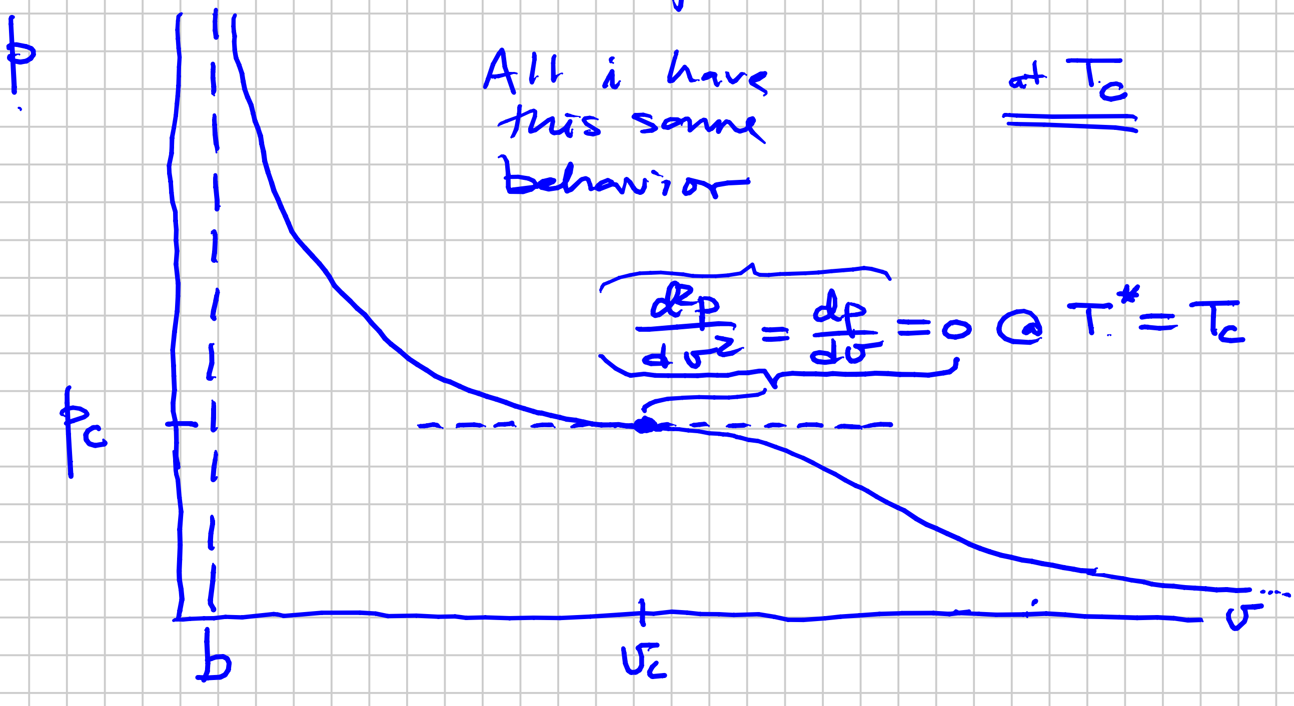
Two (empirical) constants (a, b)

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

μ_{vdW} :

- Ideal Gas $\quad p \to 0$ as $v \to \infty$ (compressible) $\Rightarrow p = \frac{RT}{v}$
- Real Gas
- Liquids $\quad v \to b \quad p \to \infty$ (near incompressible)

vdW : Theory of Corresponding States



All i have this same behavior at T_c

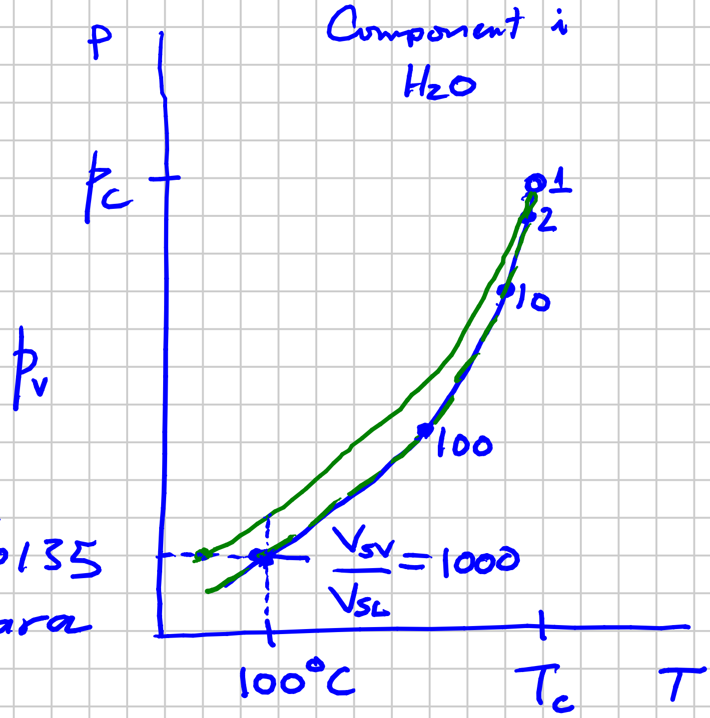
$$\frac{d^2p}{dv^2} = \frac{dp}{dv} = 0 \ @ \ T^* = T_c$$

a, b to satisfy this critical condition

Need $\{\underline{T_c}, \underline{P_c}, \underline{\omega}\}$ — Data

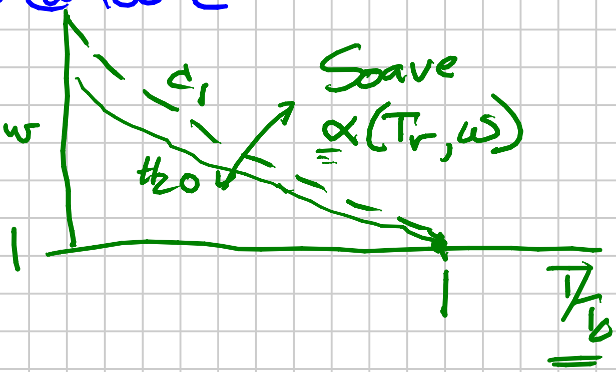
$$a = (\tilde{0.4}) \frac{R^2 T_c^2}{P_c}$$

$$b = (\tilde{0.1}) \frac{R T_c}{P_c}$$

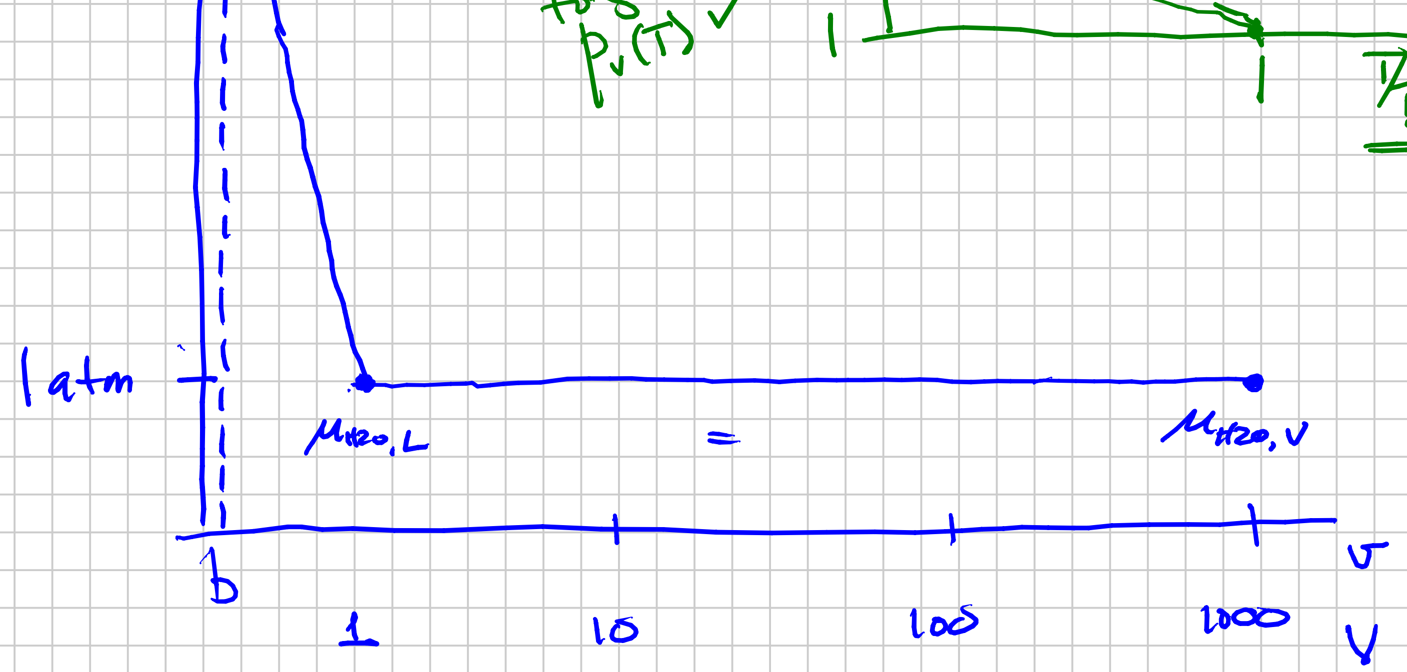


14.696 psia = 1 atm = 1.0135 bara

H_2O @ 100°C



Correction to vdw to get $P_v(T)$ ✓



1 L of boiling water

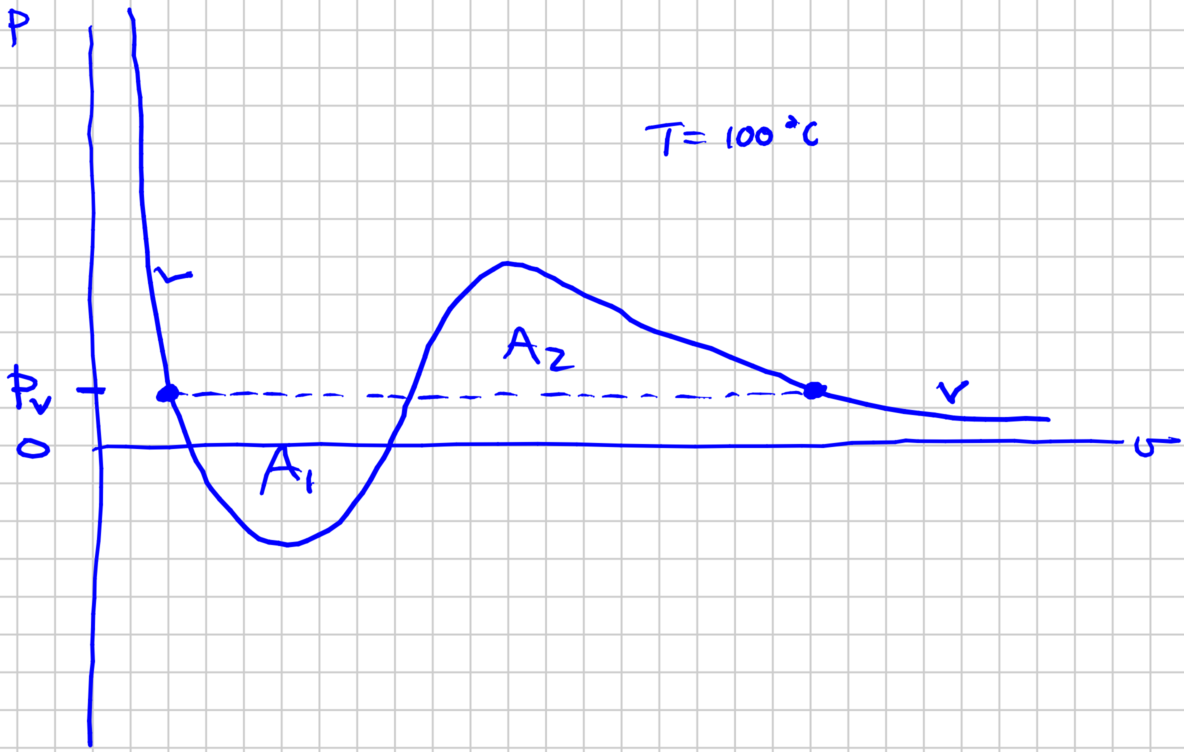
$\rho_L \sim 1000\ kg/m^3 \Rightarrow 1\ kg$

$\rho_{steam} \sim 1\ kg/m^3$

Download to PCs

www.zicktech.com

PhazeComp



Note Title 2011-08-29

PVT Calculations of H_2O & CO_2

1) Cubic EOS (Equation of State): Each Component M, T_c, p_c, ω

Peng-Robinson

"PhazeComp" program (free unlimited usage 1 mo, forever up to 5 comp)

www.zicktech.com

2) Good Excel Practices (Excel 2003)

- Tables
- Figures

PVT Calculations:

1. Vapor Pressure Curves of H_2O & CO_2
   - Critical Point (T_c, p_c)
   - Normal Boiling Point (T_b)

     @ p_{sc}

     "T_{sc}" 60°F
     15.56 °C
   - Saturated properties (ρ, μ)

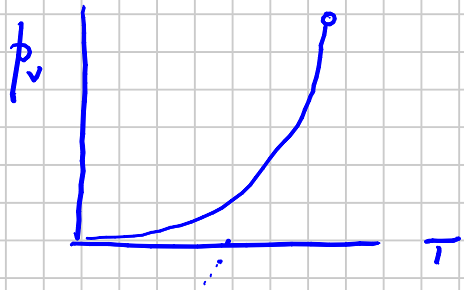
     phase is "saturated" with another phase

H_2O: boiling water & steam

2. $H_2O + CO_2$ mixture equilibrium

PhazeComp Calculations: Peng & Robinson

- Vapor pressure failed for $T = 10\,K$ for H_2O: ✓
- Added Volume Shift correction (VSHIFT) to improve liquid density predictions (Peneloux et al.)



Make Plots: $p_v(T)$, $\ln p_v(1/T)$

$p(V)$, $p(\rho)$

H_2O

$T = T_b$

TextPad: for Block Copy & Paste

Stuff in Ch. 2

Note Title 2011-09-01

Oil & Gas Compositions : Moles or Mass

$\{N_2 \quad CO_2 \quad H_2S \ \ldots\}$ (light) non-Hydrocarbons

$\{C_1 \quad C_2 \quad C_3 \quad iC_4 \quad nC_4 \quad iC_5 \quad nC_5\}$ Lighter HCs

"Surface Gas" Pseudo Component

$\{C_6 \quad C_7 \quad C_8 \ \cdots \ C_{20} \ \cdots \ C_{50} \ \cdots \ C_{100} \cdots\}$ Stock-tank Oil HCs "Surface Oil" Pseudo Component

Reservoir Gas $\lesssim$ 10–15 mol-% C_{6+}

Reservoir Oil $\gtrsim$ 12–15 mol-% C_{6+}

C_{7+} (C_{6+}) Characterization:

Paraffinic (less dense) — Aromatic (more dense)

UOP Watson Characterization Factor

12-14 $\quad \boxed{K_w} = \dfrac{T_b(°R)^{1/3}}{\gamma} \quad$ 8–10 $\quad$ Compounds

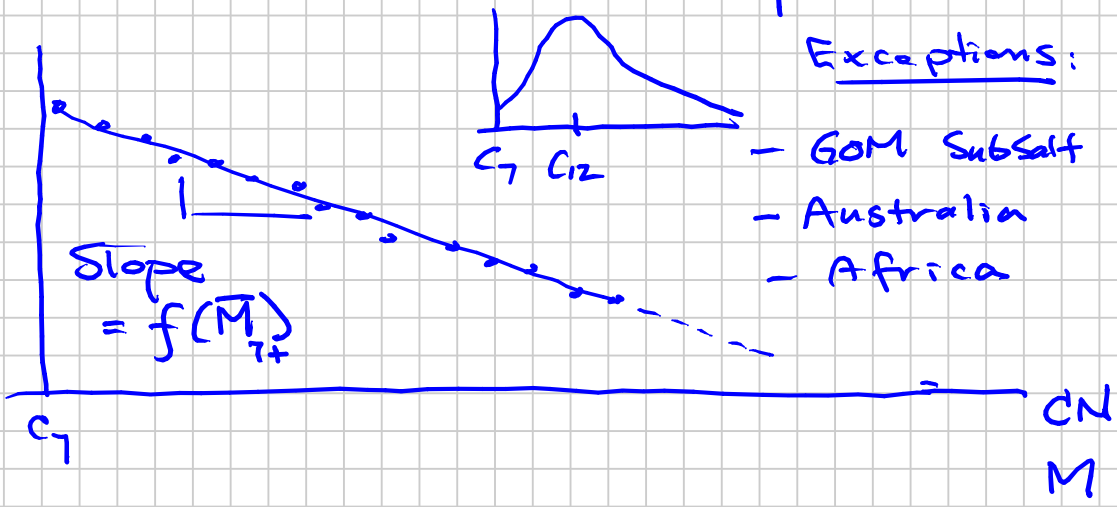
$$\gamma \equiv \frac{\rho_L(1\,atm, 60°F)}{\rho_w(\text{— " —})}$$

12.5 $\quad$ Oils (STO) $\quad$ 10

C_{6+}, STO: $K_w \simeq 4.5579\, \underline{\underline{M}}^{0.15178}\, \underline{\underline{\gamma}}^{-0.84573}$

e.g. N.S. 11–12.2

Exponential
C_{7+} Molar Distribution can be important



Exceptions:

- GoM Subsalt
- Australia
- Africa

C_{7+} Dist.

- Gas-based EOR
- Wax precipitation
- Continuous z_i variations with depth

$$M_i = 14 \cdot i + h$$

P: $h = +2$

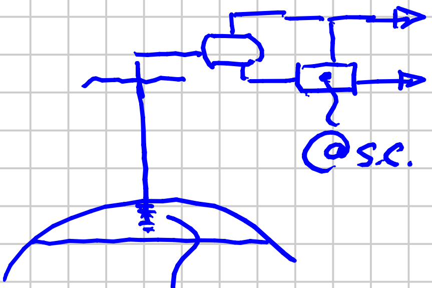
A: $h = -6$

TABLE 2.1—COMPOSITION AND PROPERTIES OF SEVERAL RESERVOIR FLUIDS

Composition (mol%)						
Component	Dry Gas	Wet Gas	Gas Condensate	Near-Critical Oil	Volatile Oil	Black Oil
CO_2	0.10	1.41	2.37	1.30	0.93	0.02
N_2	2.07	0.25	0.31	0.56	0.21	0.34
C_1	86.12	92.46	73.19	69.44	58.77	34.62
C_2	5.91	3.18	7.80	7.88	7.57	4.11
C_3	3.58	1.01	3.55	4.26	4.09	1.01
i-C_4	1.72	0.28	0.71	0.89	0.91	0.76
n-C_4		0.24	1.45	2.14	2.09	0.49
i-C_5	0.50	0.13	0.64	0.90	0.77	0.43
n-C_5		0.08	0.68	1.13	1.15	0.21
$C_{6(s)}$		0.14	1.09	1.46	1.75	1.61
C_{7+}		0.82	8.21	10.04	21.76	56.40
Properties						
$M_{C_{7+}}$		130	184	219	228	274
$\gamma_{C_{7+}}$		0.763	0.816	0.839	0.858	0.920
K_{wC_7}		12.00	11.95	11.98	11.83	11.47
GOR, scf/STB	∞	105,000	5,450	3,650	1,490	300
OGR, STB/MMscf	0	10	180	275		

GOR = Gas-Oil Ratio, R

OGR = Oil-Gas Ratio, r



Surface Gas $\bar{g}$ (SG) $\sim C_{5-}$

Surface Oil $\bar{o}$ (SO) $\sim C_{6+}$

$\left\{ \begin{array}{l} \text{Reservoir} \\ \text{Fluid } z_i \end{array} \right\} \rightarrow$ $\underline{R, GOR} = \dfrac{V_{\bar{g}}}{V_{\bar{o}}} \left[\dfrac{Sm^3}{Sm^3}\right] \left[\dfrac{scf}{STB}\right]$

Reservoir Gases : $r, OGR = \dfrac{V_{\bar{o}}}{V_{\bar{g}}} \left[\dfrac{Sm^3}{10^6 Sm^3}\right] \left[\dfrac{STB}{MMscf}\right]$

Mscf = 10^3 scf ft^3 @ s.c.

MMscf = 10^6 scf

bcf = 10^9 scf

Tcf = 10^{12} scf

$3-5 / Mscf   ($4/Mscf)

$100 / STB

6 Mscf ~ 1 STB

$25 $100

Estimate the % of Value from SG ($\bar{g}$) & SO ($\bar{o}$) for the gas condensate fluid

SG $\sim C_{5-}$ 90.70

SO $\sim C_{6+}$ 8.21 + 1.09 = $\underline{9.30 \text{ mol-\%}}$ 9.30 kg-mole

$M_{6+} \sim M_{7+} = 175$ kg/kg-mole

$\rho_{6+} \sim \rho_{7+} = 800$ kg/m^3

$$V_{\bar{o}} \sim V_{6+} = \underset{\cancel{\text{Kgmole}}}{n_{6+}} \cdot \underset{\frac{\cancel{\text{kg}}}{\cancel{\text{Kgmole}}}}{M_{6+}} \cdot \underset{\frac{\text{S m}^3}{\cancel{\text{kg}}}}{\frac{1}{\rho_{6+}}} = 9.30(175)/800 = 2.03 \text{ Sm}^3$$

$$= 12.75 \text{ STB}$$

$$V_{\bar{g}} \sim V_{5-} = 90.7\,(23.68) = 2147 \text{ Sm}^3 = 75.8 \text{ Mscf}$$

~ Ideal Gas Law @ s.c.

$$\frac{\text{m}^3}{\text{kg}} \quad \frac{V_{\bar{g}}}{n} = \frac{R\,T_{sc}}{P_{sc}} = (0.08314)\frac{(273.15+15.56)}{1.0135} = \underbrace{\qquad}_{\boxed{23.68 \ \frac{\text{Sm}^3}{\text{Kg-mole}}}}$$

K, bar

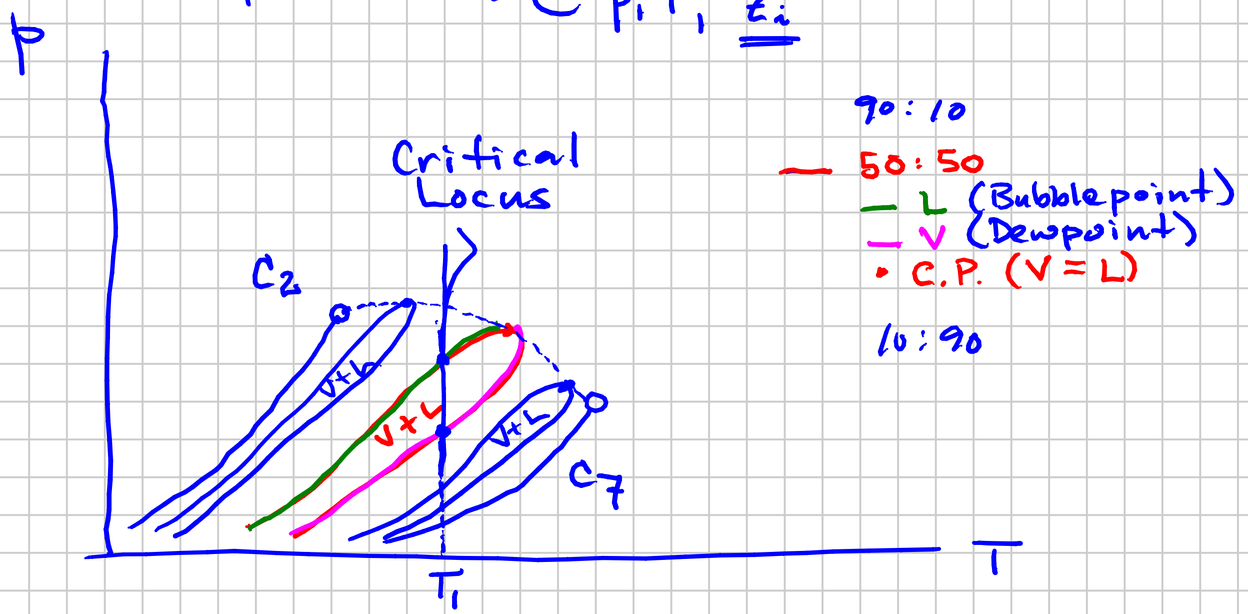
6.28 bbl / Sm^3
35.31 scf / Sm^3 } App. A

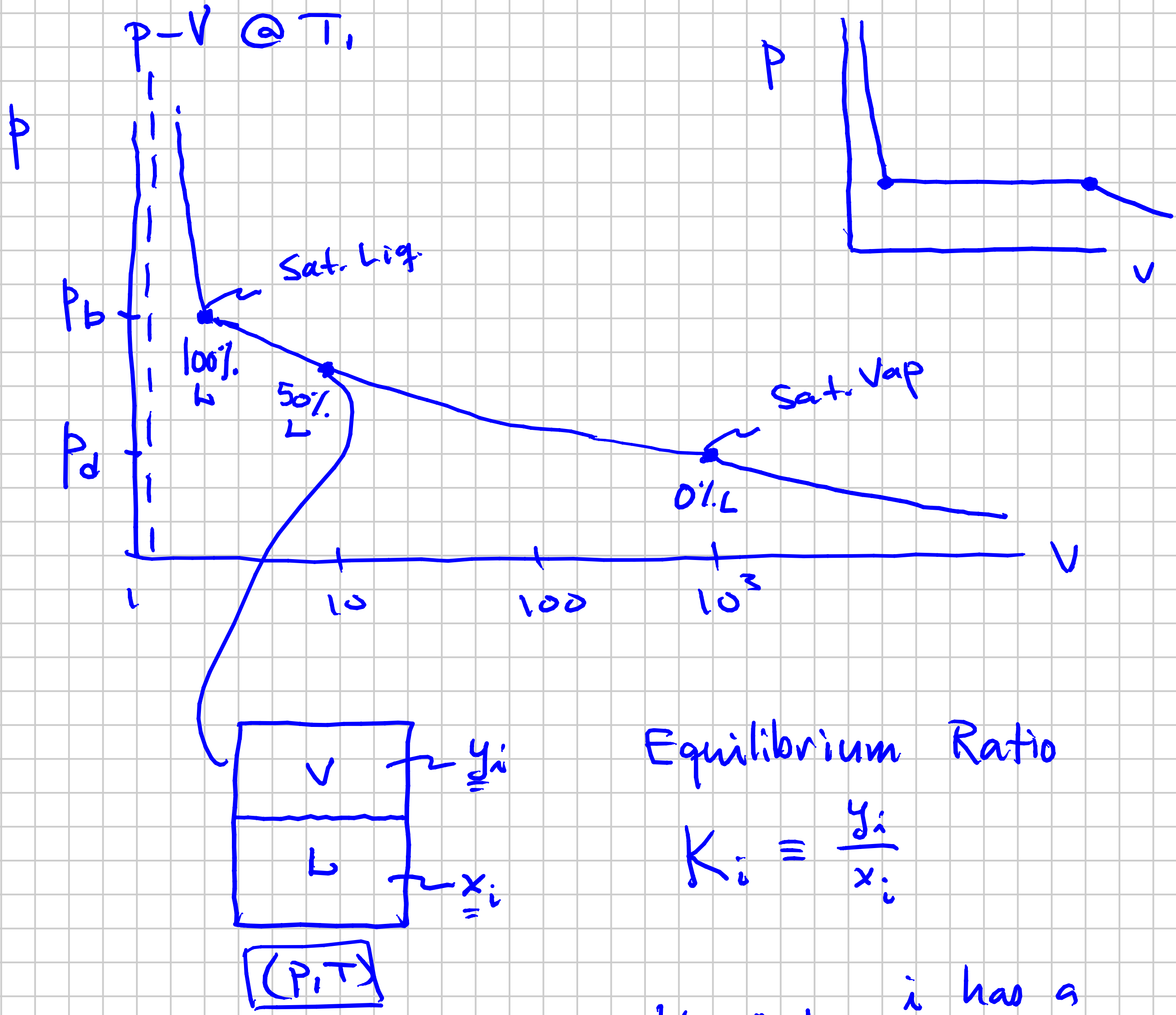
0.03531 Mscf / Sm^3

12.75 STB × \$100/STB = \$ 1275 [81%]
75.8 Msct × \$4/Mscf = \$ 303
1578

Two-Component Phase Behavior : Example $C_2 - C_7$

Vapor (Gas)
Liquid } How much of each phase @ p_1, T_1, z_i





Equilibrium Ratio

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

$K_i > 1$: i has a preference to be in the V phase

$K_i < 1$: i has a preference to be in the L phase

$$\boxed{K_i\,(p, T) \; : \; \text{not} = f(z)}$$

3+ components

$$K_i\,(p, T, z)$$

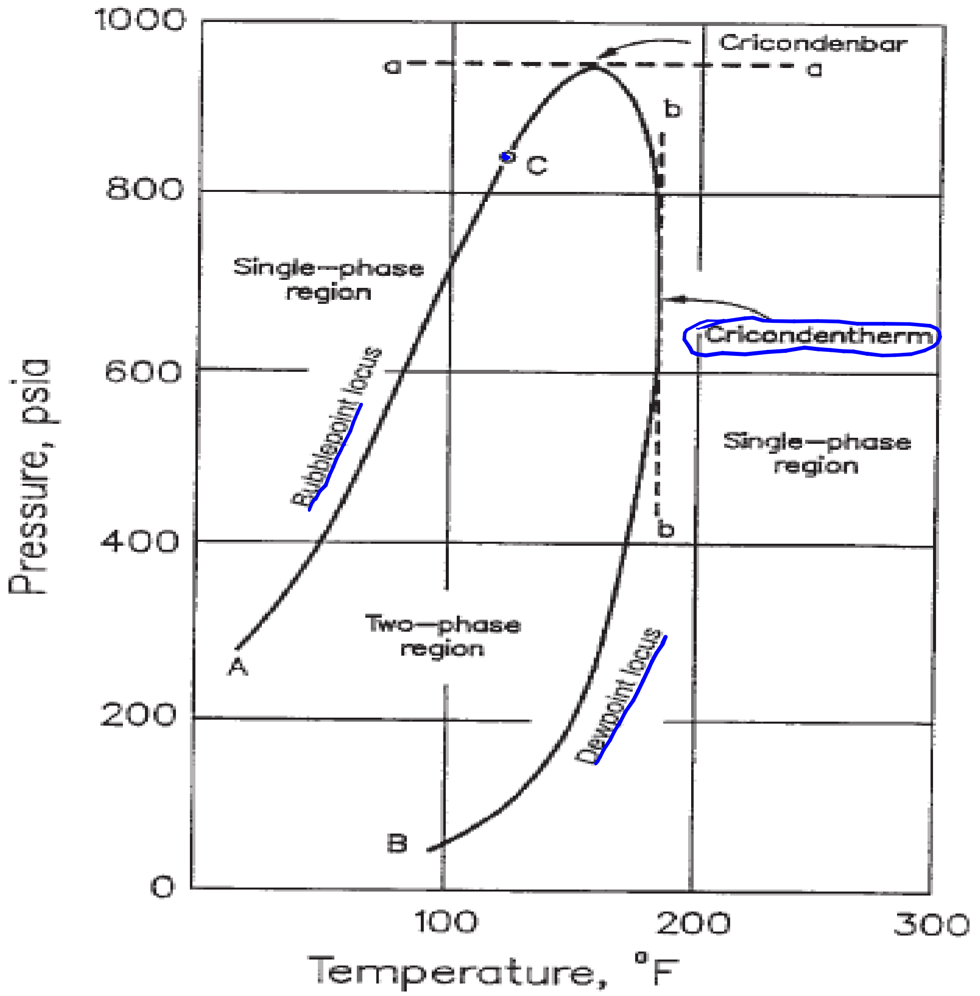


Fig. 2.9—p-T diagram for a C_2/n-C_7 mixture with 96.83 mol% ethane (from Standing[26]).

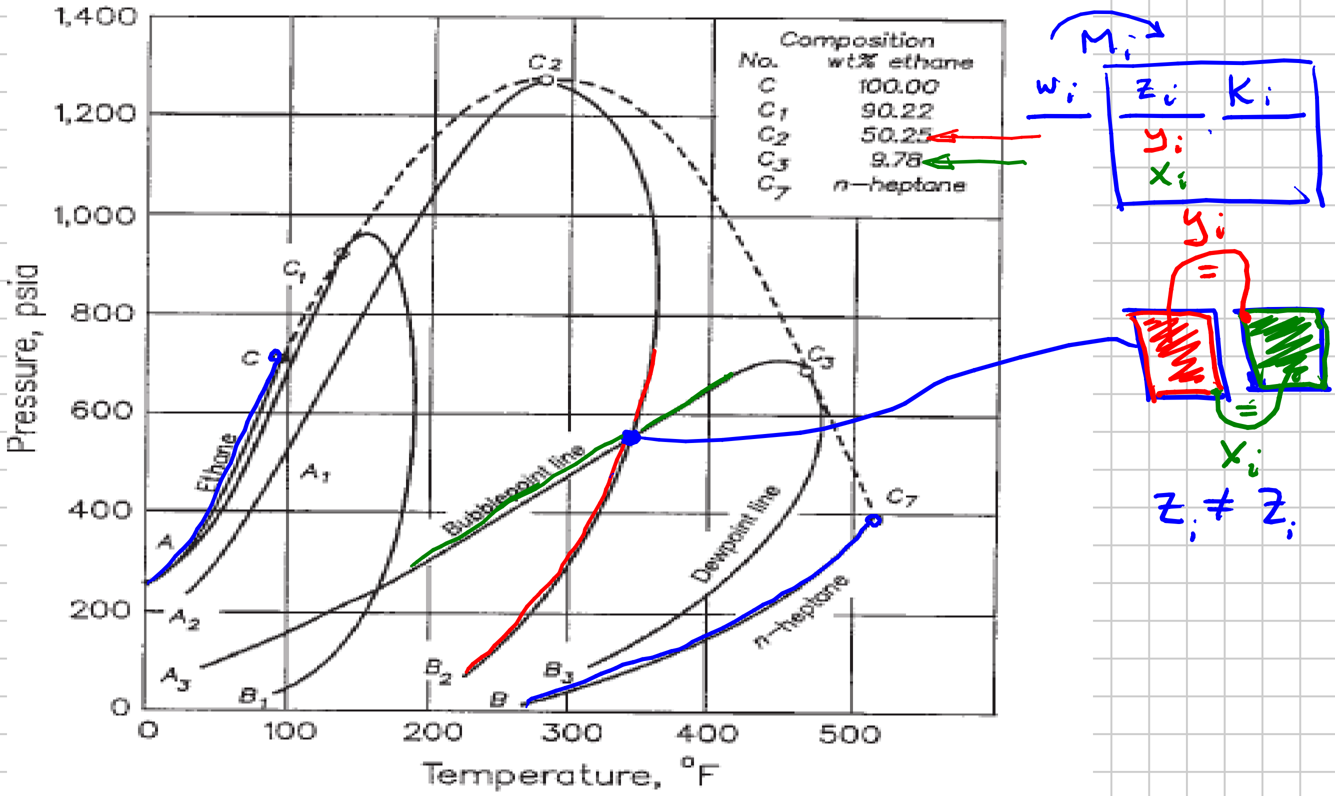
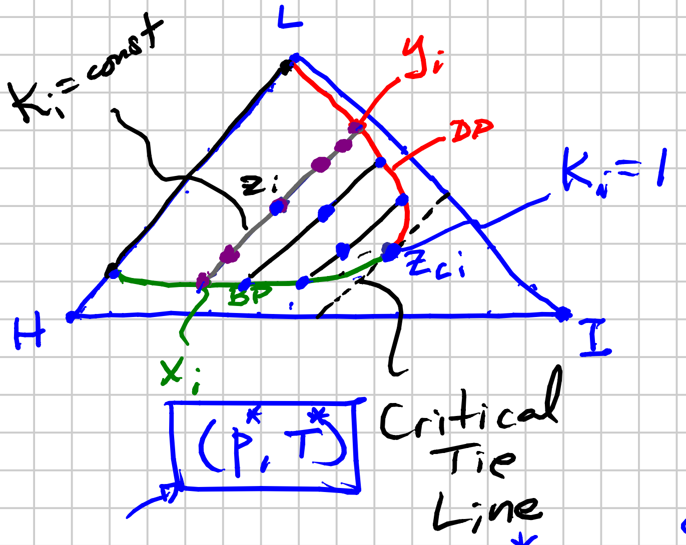


Fig. 2.10—p-T diagram for the C_2/n-C_7 system at various concentrations of C_2 (after Kay[30]).

3-Component Phase Behavior

Ternary Diagram (Used for Conceptual understanding / confusion in EOR using gas injection)

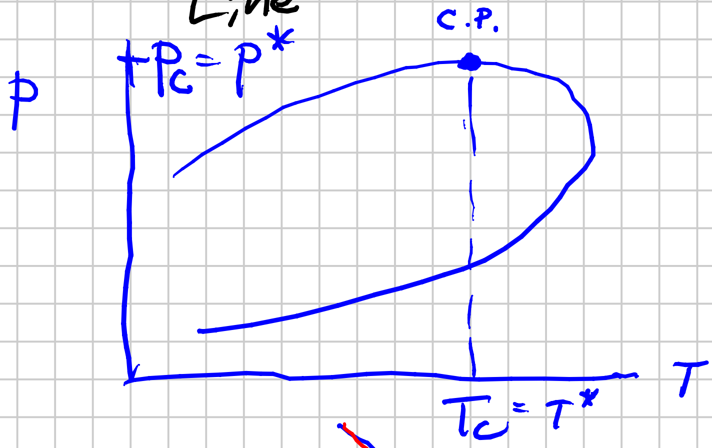


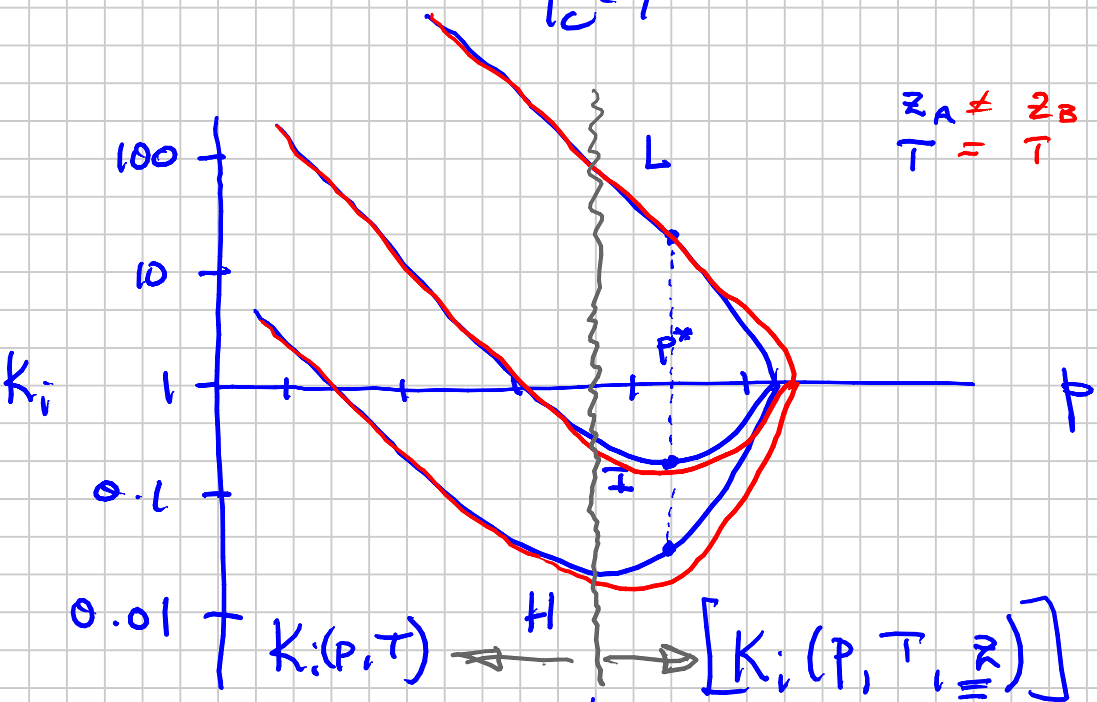
$z_L = 0.3$ (30%)

$z_I = 0.3$ (30%)

$z_H = 0.4$ (40%)

$\overline{1.0}$





y_i
x_i
n_v
n_L

"Low Pressure" ← | → Reservoir Conditions

$p \lesssim 50$ bar
↓
80 bar

$\underbrace{\phantom{p \lesssim 50\text{ bar}}}_{\text{Surface Processing}}$

Note Title 2011-09-05

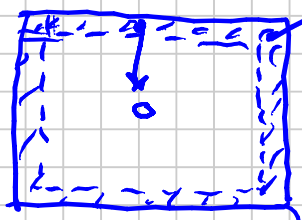
Multicomponent Phase Behavior

www.npd.no

(p-T, p-V)

Used to define a "Reservoir Fluid" as "Gas" or "Oil"

Section



$p \sim p_{Ri}$

1 mile ~ 1.6 km

10-20% of the area

1 mi

$t_{final} \sim$ "20-50" yr (25)

$$\boxed{\left(\left(\frac{k}{\mu \phi c}\right)\right)}$$

Diffusivity constant:

~ "Spacing" A/well

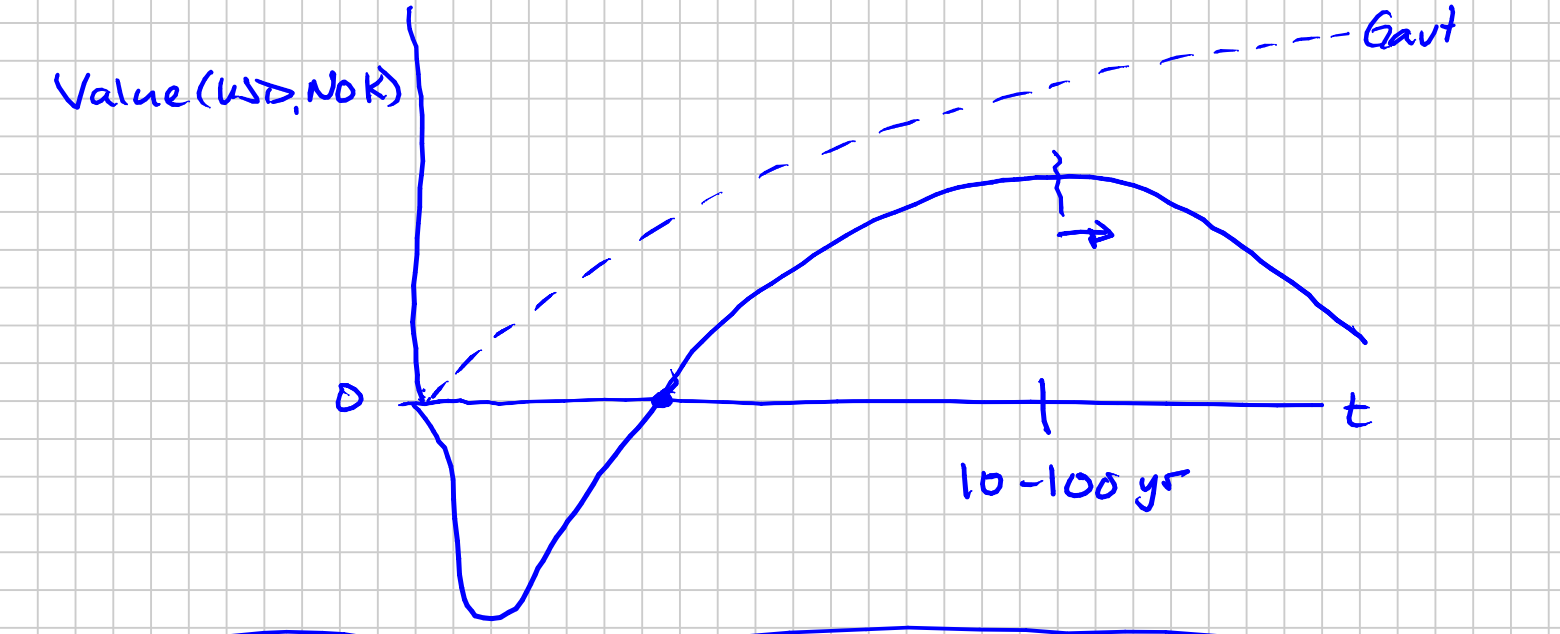
How long it takes to drain a given area

μ (cp)	k
0.01	$\boxed{10^{-6} \text{ md}}$
μ_g (0.02)	
0.1	
1	
10^4	$\boxed{10^{4} \text{ md}}$

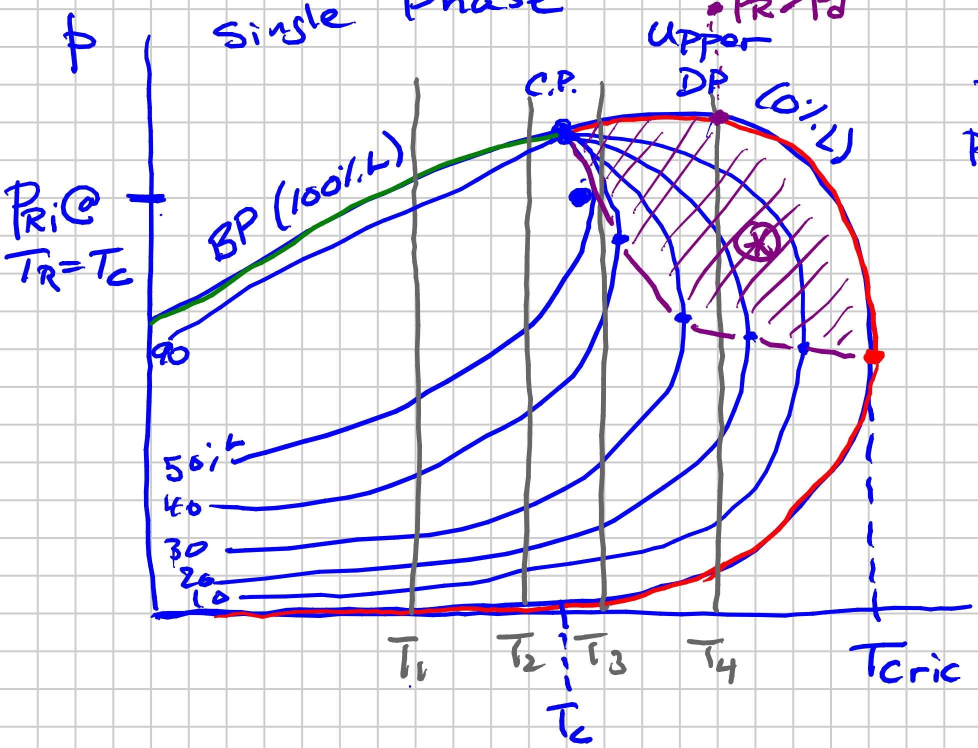
Gases ↑

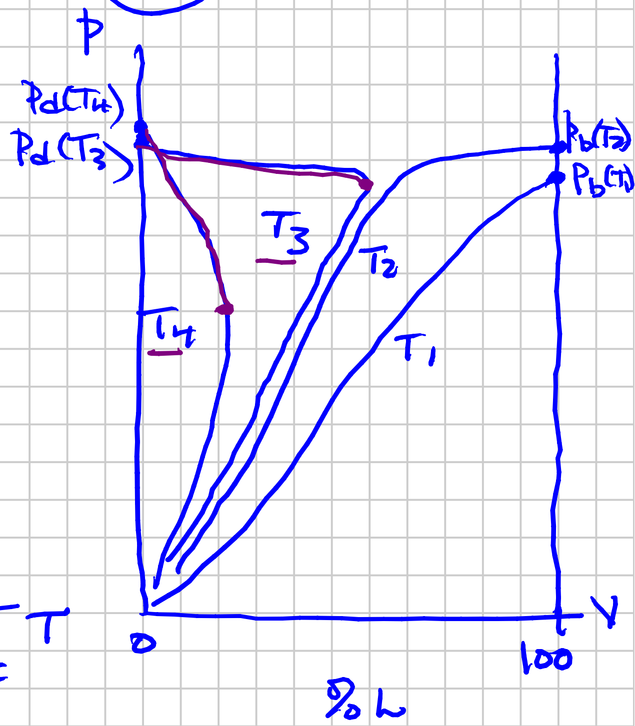
Oils ↓

life expectancy gets longer



For a Reservoir Fluid - Composition z_{Ri}



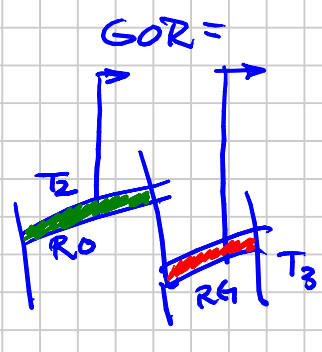


* Increasing L% as pressure decreases:
"Retrograde Condensation"

Reservoir Fluid Types

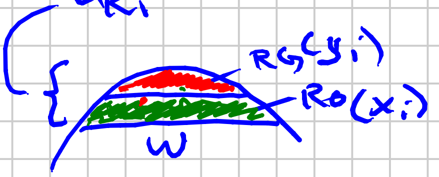
GOR [Sm^3/Sm^3]

GOR	OGR	"z_{R6+}" mol-%	"OIL" ($T_R < T_c$)
~0		>90%	Heavy Oil
			Dead Oil
			Black Oil
200			Volatile Oil
500		≳ 12-15	Near-Critical Oil

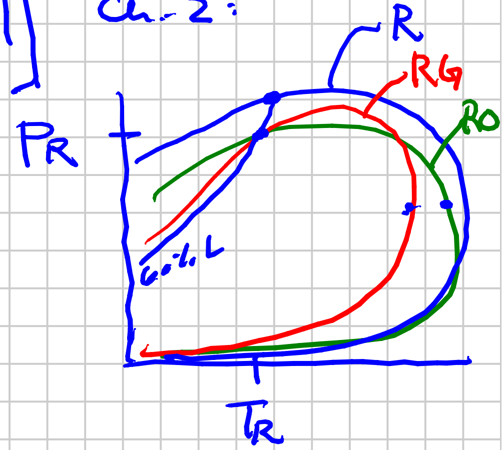


>500-700	≤ 12	GAS ($T_R > T_c$)
		G.C. { Near-Critical Gas Cond
		Rich Gas Condensate
20 000		Lean Gas Condensate
>20 000	<1	Wet Gas
∞	0	Dry Gas

Z_{R_i} = Total R



Ch. 2:



Dead
Black
Volatile
N.C
} Oils

N.C.
Rich
Lean
} Gas Cond

Wet
Dry
} Gas

Decreasing "Size" of Envelope

Decreasing Tcricondentherm

Decreasing T_c

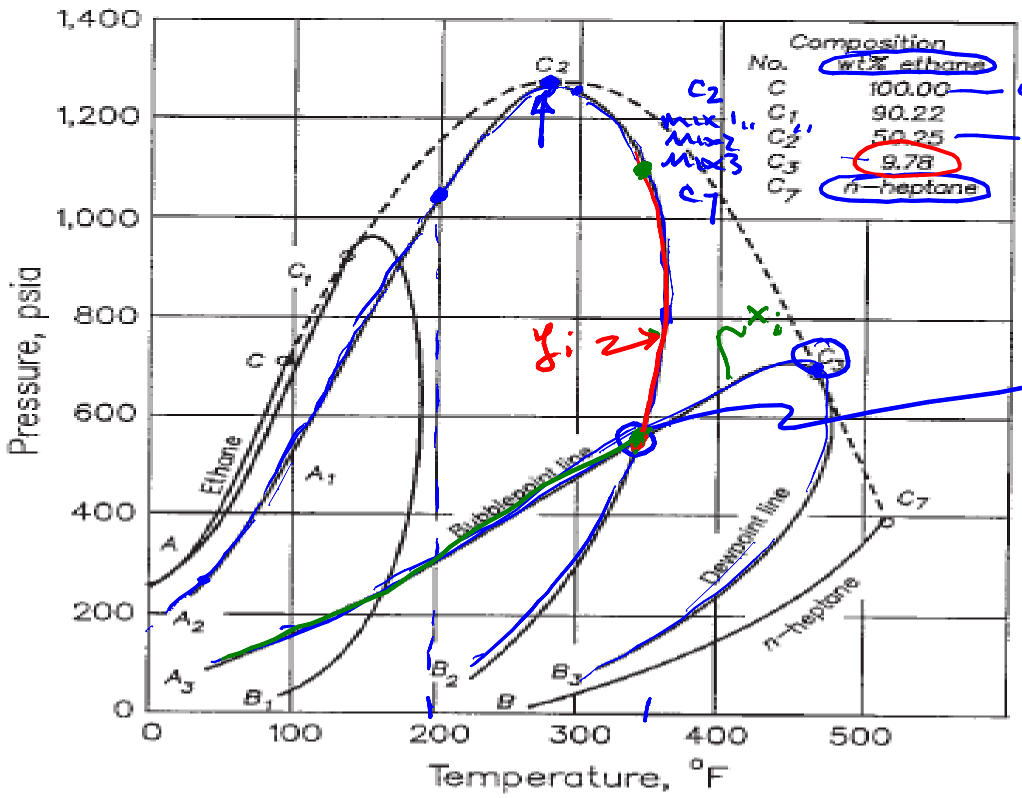
Decreasing Surface Oil Opaqueness

PhazeComp Calculations

- C_2-C_7 Binary : Model Verification ✓
- Table 2.1

(Dry Gas, Wet Gas, Gas Condensate)

1. P-T Mix 2 Good
   - T_c slightly high
- x_i @ 330 F, 550 psia good



C_2 : 100% wt

C_2 : 50 wt-%

C_2 : 0 wt-%

Lower D.P.

@ 330 F, 550 psia

Equilibrium Liquid with

x_i: C_2 wt-% ~10

9.78

Fig. 2.10—*p-T* diagram for the C_2/*n*-C_7 system at various concentrations of C_2 (after Kay[30]).

$$M_i^{n\text{-}P} = 14 \cdot i + 2$$

C_2 : $M_{C2} = 30$

n-C_7 : $M_{C7} = 100$

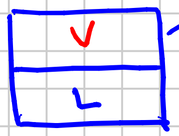
wt-% ⟷ mol-%

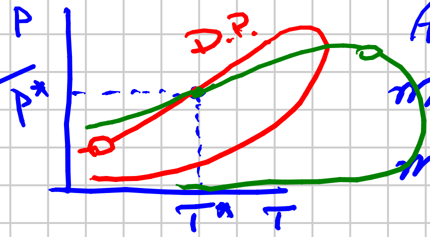
w_i z_i

m_i n_i

Mix : 50 wt-% C_2

$$z_{C2} = \frac{n_{C2}}{n} = \frac{(m_{C2}/M_{C2})}{(m_{C2}/M_{C2} + m_{C7}/M_{C7})}$$

y_i  x_i



@ p^*, T^*

Assume $m = 100$ g

$m_{C_2} = 50$ g

$m_{C_7} = 50$ g

$$y_i = \frac{n_{vi}}{n_v}$$

$$x_i = \frac{n_{Li}}{n_L}$$

$$z_{C_2} = \frac{50/30}{(50/30) + (50/100)} \times 100$$

$$= 76.92 \text{ mol-\%}$$

$$z_{C_7} = 23.08 \text{ mol-\%}$$

DRY GAS SYSTEM

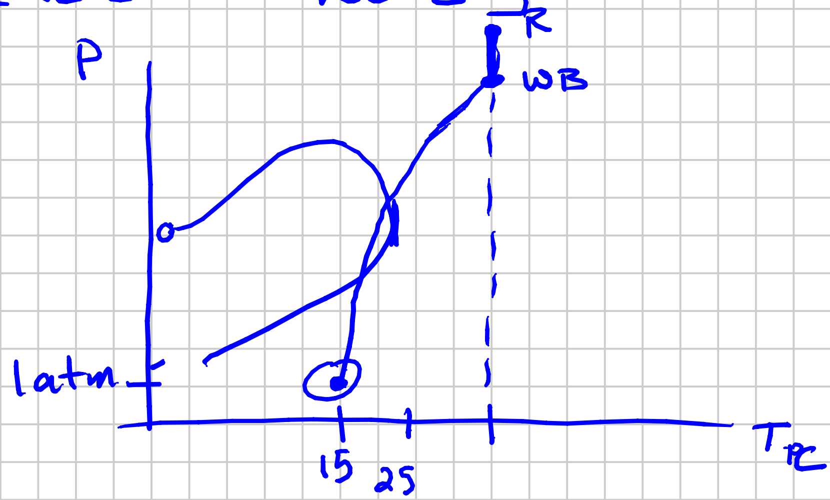
$T_{cric} < 0°C$

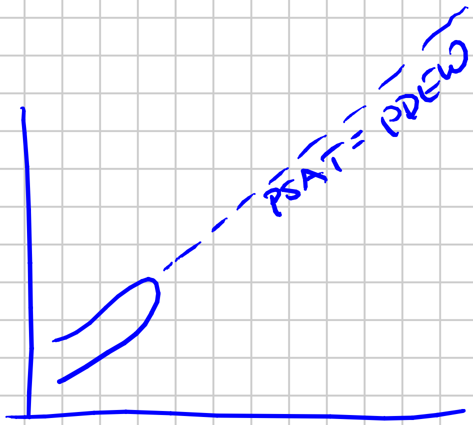
Realistic Reservoir Temperatures

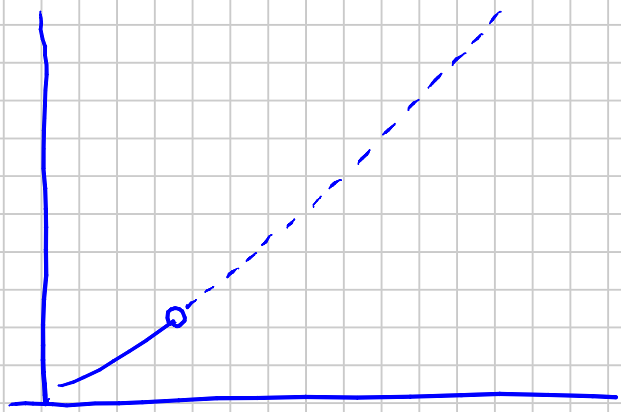
$$\left[\begin{array}{ccc} 80 < & T_R & < 300°F \\ 25°C & & 150°C \end{array} \right]$$

✓

Component	Dry Gas
CO_2	0.10
N_2	2.07
C_1	86.12
C_2	5.91
C_3	3.58
i-C_4	1.72
n-C_4	
i-C_5	0.50
n-C_5	
$C_{6(s)}$	
C_{7+}	

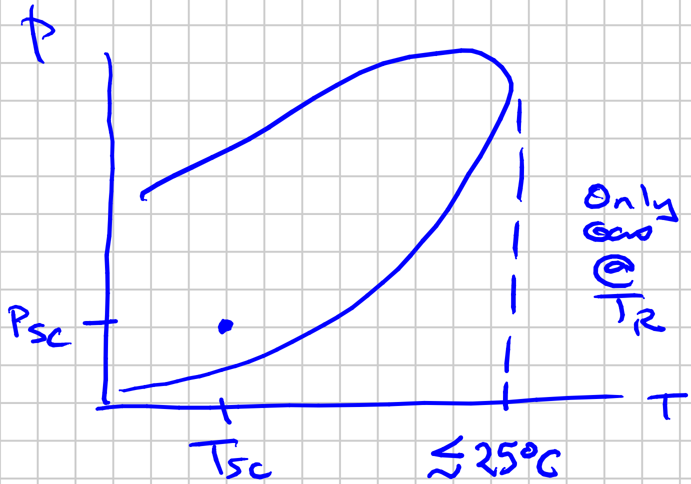






Component	Dry Gas	Wet Gas
CO_2	0.10	1.41
N_2	2.07	0.25
C_1	86.12	92.46
C_2	5.91	3.18
C_3	3.58	1.01
$i\text{-}C_4$	1.72	0.28
$n\text{-}C_4$		0.24
$i\text{-}C_5$	0.50	0.13
$n\text{-}C_5$		0.08
$C_{6(s)}$		0.14
C_{7+}		0.82

C_7
C_8
C_9
⋮
C_N



$T_{cric} \sim 100°C$

$T_R \gtrsim 100°C \Rightarrow$ Wet Gas

$T_R \le 100°C \Rightarrow$ Gas Cond.

$T_c \le T_R \le T_{cric}$

Component	Dry Gas	Wet Gas	Gas Condensate
CO_2	0.10	1.41	2.37
N_2	2.07	0.25	0.31
C_1	86.12	92.46	73.19
C_2	5.91	3.18	7.80
C_3	3.58	1.01	3.55
$i\text{-}C_4$	1.72	0.28	0.71
$n\text{-}C_4$		0.24	1.45
$i\text{-}C_5$	0.50	0.13	0.64
$n\text{-}C_5$		0.08	0.68
$C_{6(s)}$		0.14	1.09
C_{7+}		0.82	8.21
			Properties
$M_{C_{7+}}$		130	184 ← SPLIT
$\gamma_{C_{7+}}$		0.763	0.816

TABLE 2.1—COMPOSITION AND PROPERTIES OF SEVERAL RESERVOIR FLUIDS

Component	Dry Gas	Wet Gas	Gas Condensate	Near-Critical Oil	Volatile Oil	Black Oil
			Composition (mol%)			
CO_2	0.10	1.41	2.37	1.30	0.93	0.02
N_2	2.07	0.25	0.31	0.56	0.21	0.34
C_1	86.12	92.46	73.19	69.44	58.77	34.62
C_2	5.91	3.18	7.80	7.88	7.57	4.11
C_3	3.58	1.01	3.55	4.26	4.09	1.01
i-C_4	1.72	0.28	0.71	0.89	0.91	0.76
n-C_4		0.24	1.45	2.14	2.09	0.49
i-C_5	0.50	0.13	0.64	0.90	0.77	0.43
n-C_5		0.08	0.68	1.13	1.15	0.21
$C_{6(s)}$		0.14	1.09	1.46	1.75	1.61
C_{7+}		0.82	8.21	10.04	21.76	56.40
			Properties			
$M_{C_{7+}}$		130	184	219	228	274
$\gamma_{C_{7+}}$		0.763	0.816	0.839	0.858	0.920
K_{wC_7}		12.00	11.95	11.98	11.83	11.47
GOR, scf/STB	∞	105,000	$\boxed{5,450}$	3,650	1,490	300
OGR, STB/MMscf	0	10	180	275		
γ_{API}		57	49	45	38	24
γ_g		0.61	0.70	0.71	0.70	0.63
p_{sat}, psia		3,430	6.560	7,015	5,420	2,810
B_{sat}, ft³/scf or bbl/STB		0.0051	0.0039	2.78	1.73	1.16
ρ_{sat}, lbm/ft³		9.61	26.7	30.7	38.2	51.4

Girls: $\bar{o} = C_{5+}$

Boys: $\bar{o} = C_{6+}$

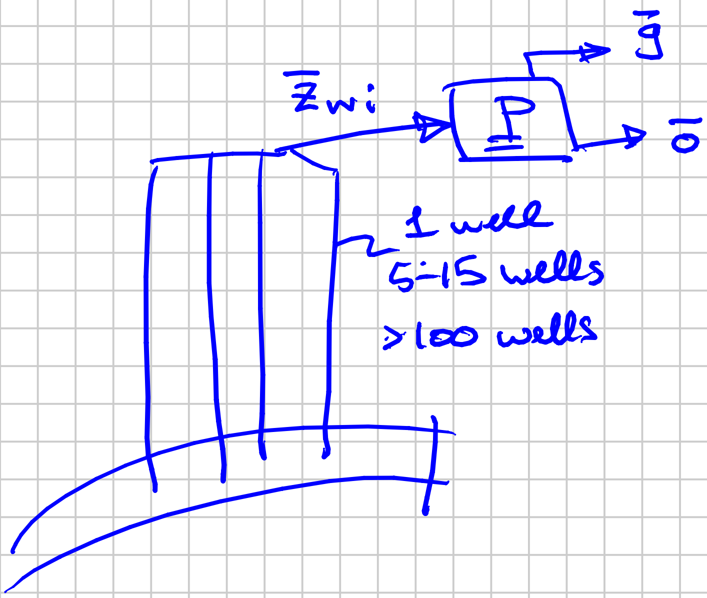
$$\boxed{\frac{\rho_{\bar{o}}}{M_{\bar{o}}} \sim \frac{816}{184} \sim 4.5}$$

$$\frac{5450}{5.615} \Rightarrow Sm^3/Sm^3$$

Molar Composition z_{Ri} ($\leftrightarrow$ $\updownarrow$) spatial variation

$\downarrow$ $\boxed{P}$

Sales Surface Products

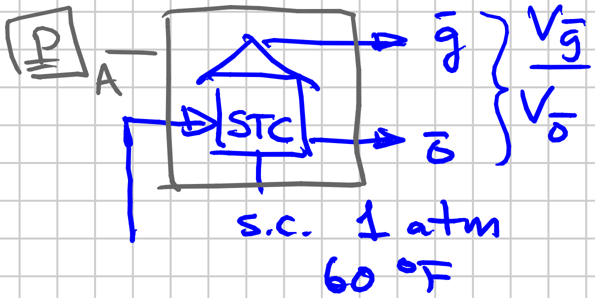


$3-4/Mscf

$115/bbl

$\boxed{P}$

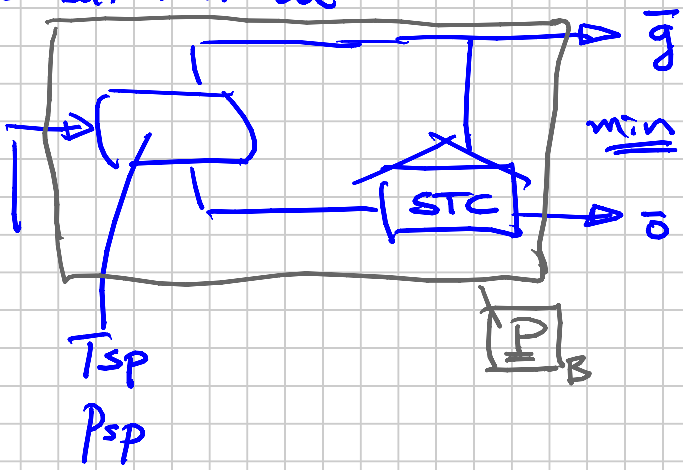
Simple (Single Well Testing in Podunck OK)



Inefficient Process

High $GOR = V_{\bar{g}}/V_{\bar{o}}$

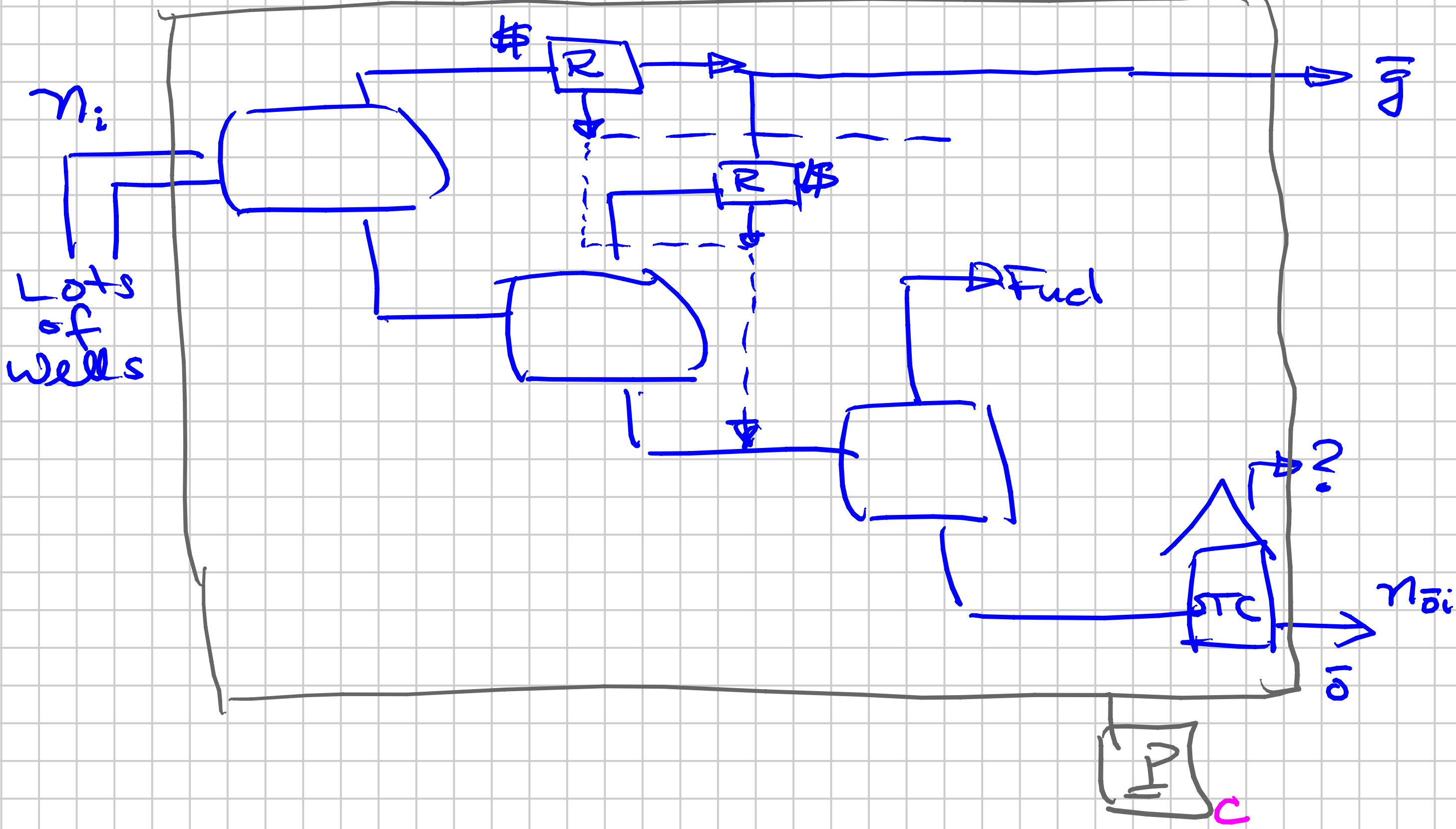
Simple-But-Normal



$\underline{\text{min}}$ $GOR(P_{sp}, T_{sp})$

$\Rightarrow$ max Value \$

Offshore/Larger Projects



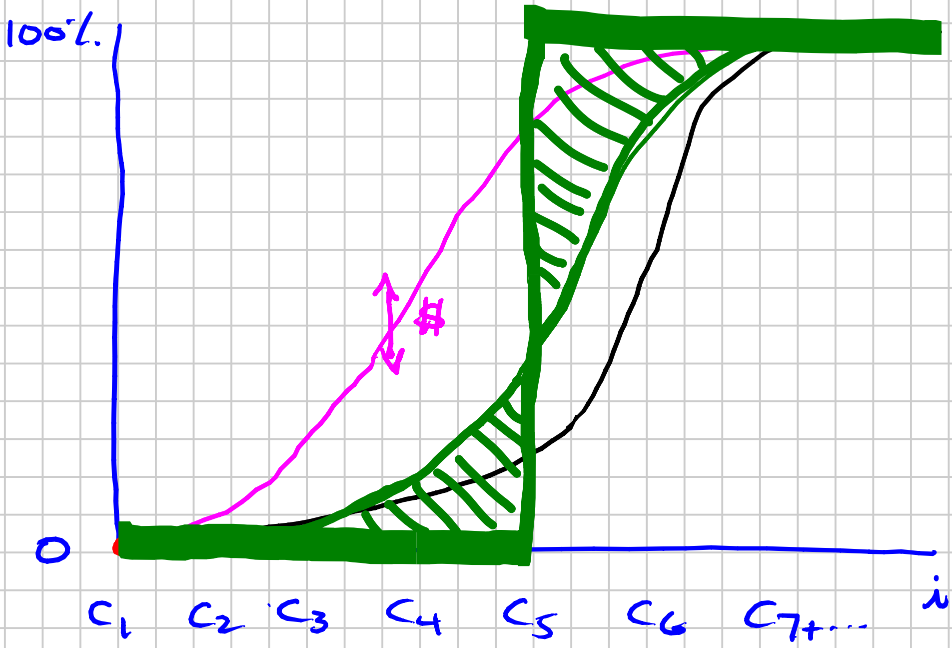
$$E_i \equiv \frac{n_{\bar{o}i}}{n_i}$$

$RF_{\bar{o}i}$

$\boxed{P}_A$

$\boxed{P}_B$ * "Default" Pet Eng

$\boxed{P}_C$



± 5-15%

$\approx$ $\bar{g} \sim C_{5-} \longrightarrow C_{4-}$

$\bar{o} \sim C_{6+} \longrightarrow C_{5+}$

Given $z_i \propto n_i$ $\qquad$ $23.6\ Sm^3/kg\text{-mole}$

$$\text{Est. } GOR = \frac{V_{\bar{g}}}{V_{\bar{o}}} = \frac{n_{\bar{g}} \cdot \left(\frac{RT_{sc}}{p_{sc}}\right)}{n_{\bar{o}} \left(M_{\bar{o}}/\rho_{\bar{o}}\right)}$$

$$n_{\bar{g}} = 1 - z_{C5+}$$

$$n_{\bar{o}} = z_{C5+}$$

$$\boxed{GOR \left[\frac{Sm^3}{Sm^3}\right] = \frac{23.68(1 - z_{C5+})}{z_{C5+}} \left[\underbrace{\left(\rho_{5+}/M_{5+}\right)}_{A\ >\ P}\right]}$$

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

$M \quad \rho \quad (\rho/M)$

Table 5.2 : C_7, C_8, C_9, (C_{13}) $\qquad$ $\sim$ const

Cragoe : $M_{\bar{o}} \simeq \dfrac{6084}{\gamma_{API} - 5.9}$

$\gamma_{\bar{o}}$ $\rho_{\bar{o}}$ $\hat{M}_{\bar{o}}$ $(\rho_{\bar{o}}/M_{\bar{o}})$

$\uparrow$ °API

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

PhazeComp 2-stage GOR [50 bar, 50°C] sep.cond.
= 808 Sm^3/Sm^3 [Note: $(\rho_{\bar{o}}/M_{\bar{o}}) = 4$]

Book GOR = $\dfrac{5450}{5.615}$ = 970 Sm^3/Sm^3

C_{5+} (Girls) GOR = 961 Sm^3/Sm^3 $z_{5+} = 9.98$ mol-%

C_{6+} (Boys) GOR = 1024 Sm^3/Sm^3 $z_{6+} = 9.3$ mol-%

PhazeComp 2-stage GOR [50 bar, 50°C] sep. cond.

$= 808 \ Sm^3/Sm^3$ [Note: $(\rho_o/M_o) = 4$]

Book GOR $= \frac{5450}{5.615} = 970 \ Sm^3/Sm^3$

C_{5+} (Girls) GOR $= 961 \ Sm^3/Sm^3$ $z_{5+} = 9.98$ mol-%

C_{6+} (Boys) GOR $= 1024 \ Sm^3/Sm^3$ $z_{6+} = 9.3$ mol-%

$$\boxed{\frac{\rho_o}{M_o} \sim \frac{816}{184} \sim 4.5}$$

C_{7+} $\left(\frac{\rho}{M}\right)_{C6+} \sim \left(\frac{\rho}{M}\right)_{C7+}$

$$GOR_{C6+} = \frac{1-z_{C6+}}{z_{C6+}} \frac{23.68}{(M/\rho)_{C6+}} = \frac{(1-0.093)(23.68)}{(0.093)/(4.5)}$$

$$= 1039 \ Sm^3/Sm^3$$

Phase Equilibrium Calculations:

- Saturation Pressure
  - Know z_i, T
  - Want p_s, incipient phase composition
  - (BP, DP) (y_i, x_i)
- Isothermal "Flash"

Equilibrium Ratios K_i

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

$K_i(p, T, \text{"}z\text{"})$

Known: z_i (n)

Want: $\left(\frac{n_V}{n}, \frac{n_L}{n}\right)$

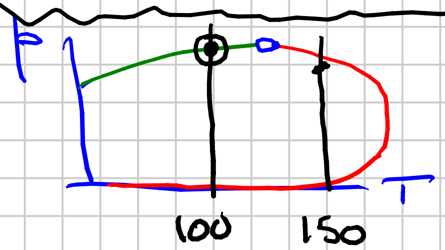
f_V : $f_L = 1 - f_V$

Mechanics: $\{\underline{\underline{z_i}}, K_i(p)\}$ $\rightarrow$ p_{sat}

$\{z_i, K_i\}$ @ (p,T) $\rightarrow$ Flash

e.g. $\boxed{z_i}$ Gas Cond, $T = 100°C$

$p_{sat} = 400$ bara $\boxed{(y_i)}$ bubble



Flash @ $T = 100°C$, $p = 400$ bara

$f_v = 0$ ✓ (ϵ)

$y_i = (y_i)_{BP}$

$(1-f_v)x_i = z_i \cdot 1 - f_v y_i$ Molar Component Balance

$x_i = z_i$

$p_s = p_d = 418$ bar

Flash @ p_s

$f_v = 1$

$y_i = z_i$

$x_i = (x_i)_{DP}$ "droplet"

p_{sat} Calc

=

Flash Calc

w/ Constraint: by Changing p

$f_v = 0$ ✓

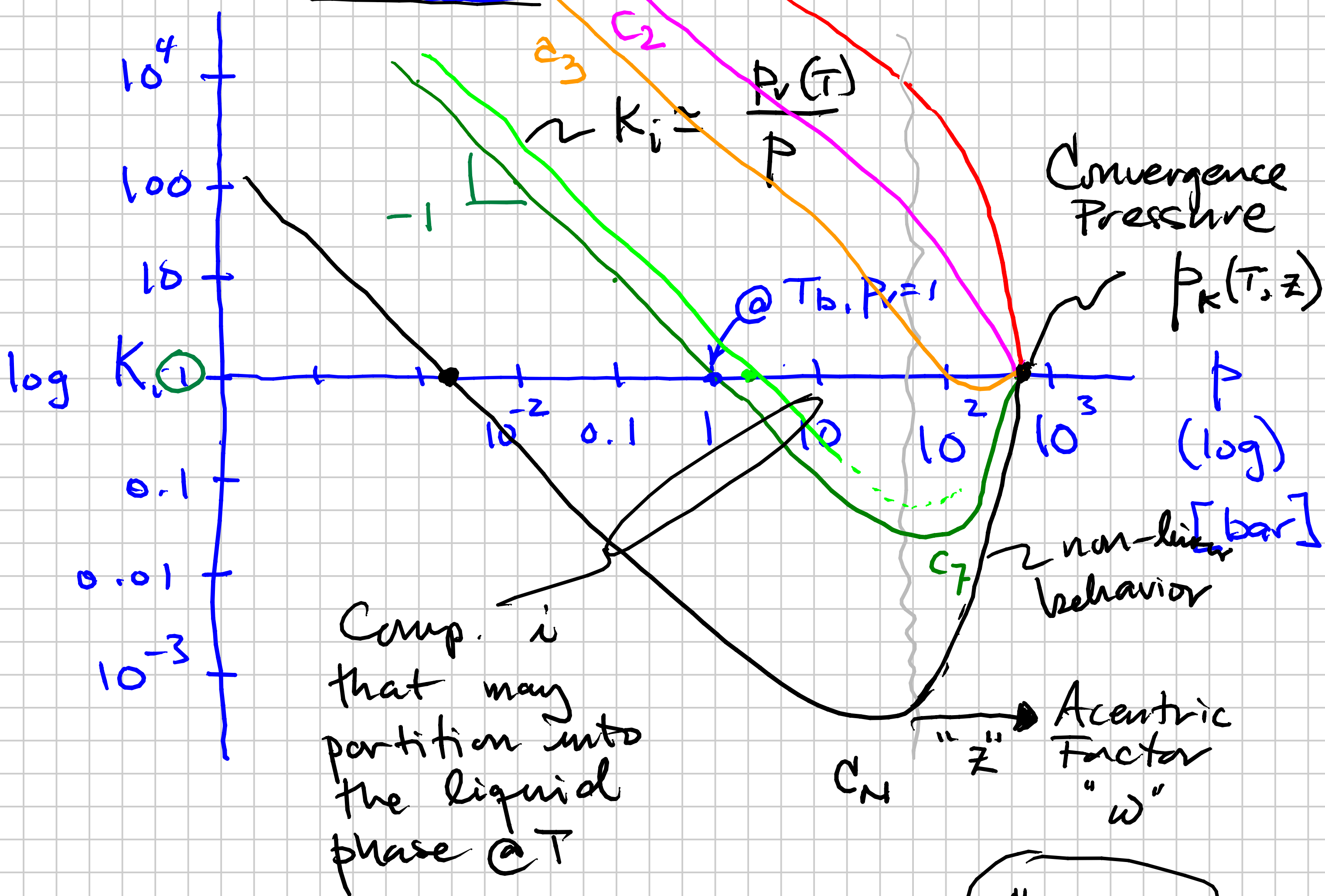
or

$f_v = 1$ ✓

C_1

Equilibrium Calculations: $K_i(P, T, z) \equiv \dfrac{y_i}{x_i}$

$T = 100°C$ (150°C)

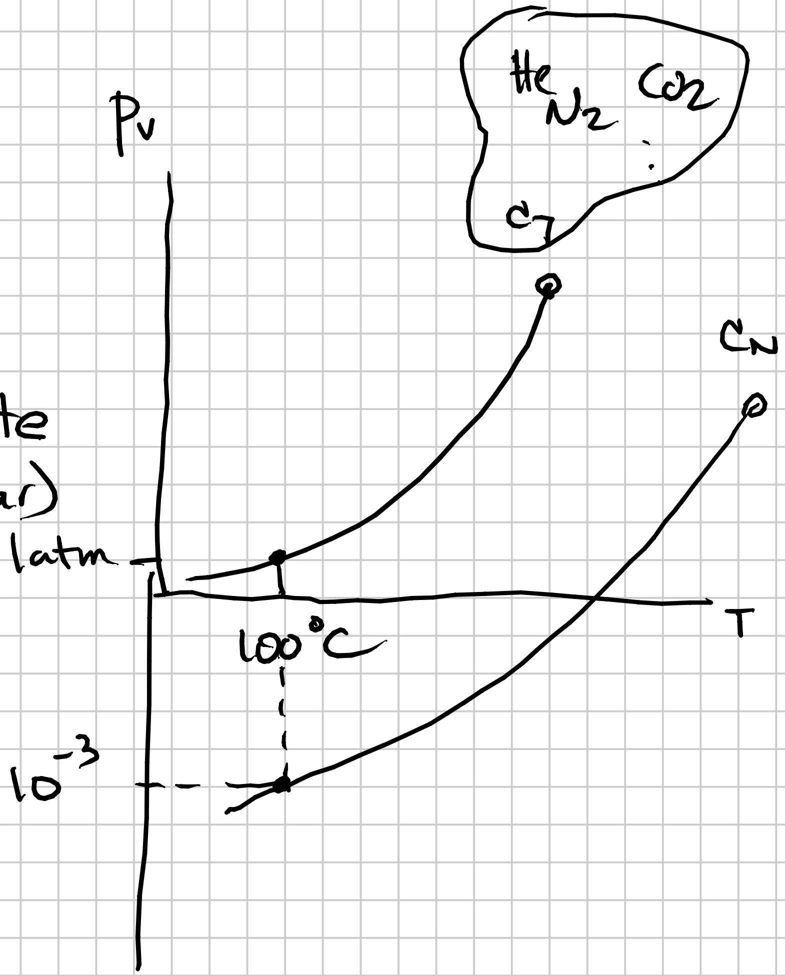


Getting (by Correlation
by EOS
by Charts)

$p_{v_i}(T) \Rightarrow$ Accurate

"low-P" (<50 bar)

$K_i(P, T)$



Simpler Equilibrium Calculations

(not EOS)

Modified Wilson Eq. Ch. 3

$T_{ri} = \frac{T}{T_{ci}}$

p_{ci} Acentric Factor

$$K_i = \left(\frac{p_{ci}}{p_K}\right)^{A_1 - 1} \frac{\exp\left[5.37\, A_1 (1 + \omega_i)\left(1 - T_{ri}^{-1}\right)\right]}{p_{ri}}, \qquad (3.159)$$

Different for each Reservoir

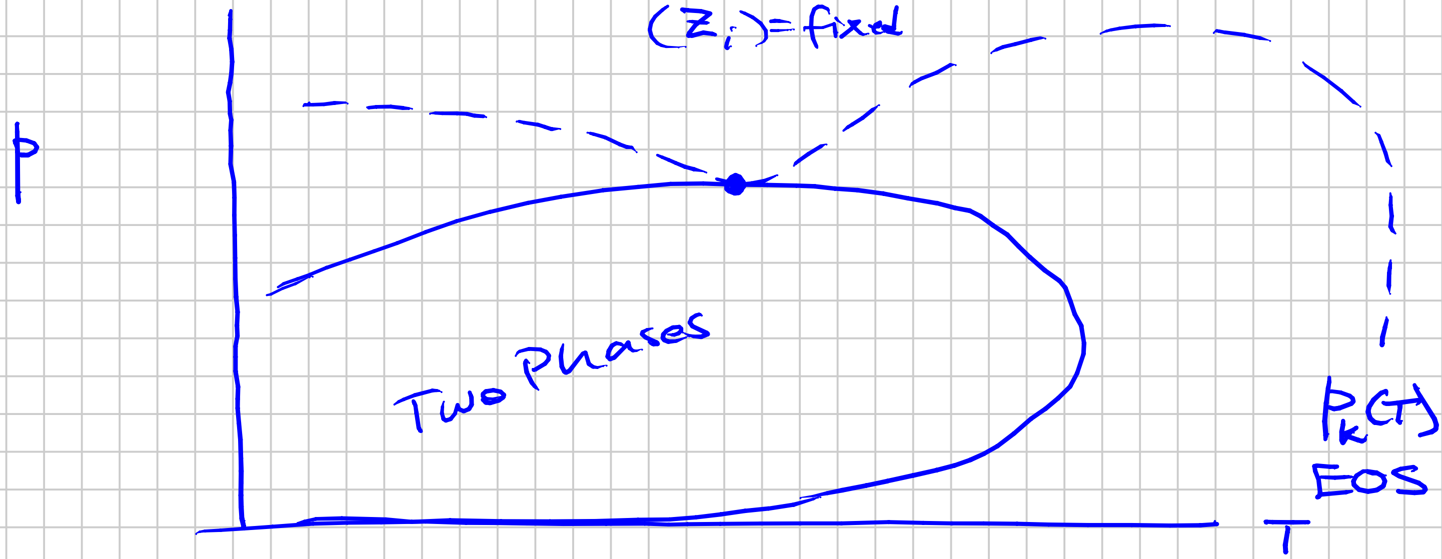
$p_{ri} = p/p_{ci}$

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

$$A_1 = 1 - (p/p_K)^{A_2}, \qquad (3.160)$$

where A_2 ranges from 0.5 to 0.8 and pressures p and p_K are given

0.7



(z_i) = fixed
P
Two Phases
$P_k(T)$
EOS
T

EQUILIBRIUM CALCULATIONS

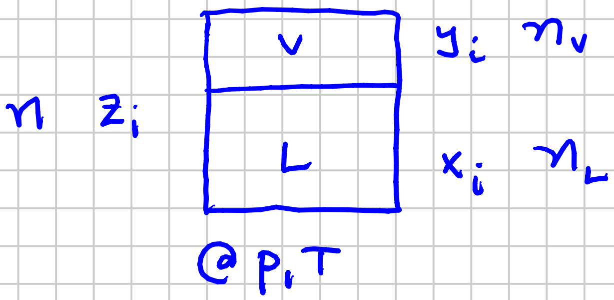
Note Title 2011-09-15

(1) Isothermal Flash

(2) Saturation Pressure

$\Big\}$ Know $\underline{K_i(p,T)}$

(1) Isothermal Flash



Known: z_i

$K_i(p,T)$

Component Material Balance:

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

$$n_i = n_{iv} + n_{iL}$$

Def. $f_v \equiv \dfrac{n_v}{n}$

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

Def. $\left\{ K_i \equiv \dfrac{y_i}{x_i} \right\}$ Known values $y_i = K_i x_i$

$$\left\{ \begin{aligned} \sum y_i &= 1 \\ \sum x_i &= 1 \end{aligned} \right\}$$

$y_i \equiv \dfrac{n_{iv}}{n_v}$

$x_i \equiv \dfrac{n_{iL}}{n_L}$

✓ $\sum z_i = 1$

1949 : Muskat & McDowell

Solve f_v, y_i, x_i : $h(f_v) = \sum y_i - \sum x_i = 0$

$= \sum y_i - x_i = 0$

$$h(f_v) = \sum y_i - x_i = 0$$

$$y_i = K_i x_i$$

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

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

Find f_v $\Rightarrow$ calc x_i

$$y_i = K_i x_i$$

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

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

"Rachford Rice" (195x)

$$h(\underline{\underline{f_v}}) = \sum \left(\frac{z_i}{f_v + c_i} \right) = \sum t_i = 0 ; \quad t_i = 0 \text{ if } K_i = 1$$

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

Muskat-McDowell

of the N-1 solutions $f_v \Rightarrow \Sigma = 0$

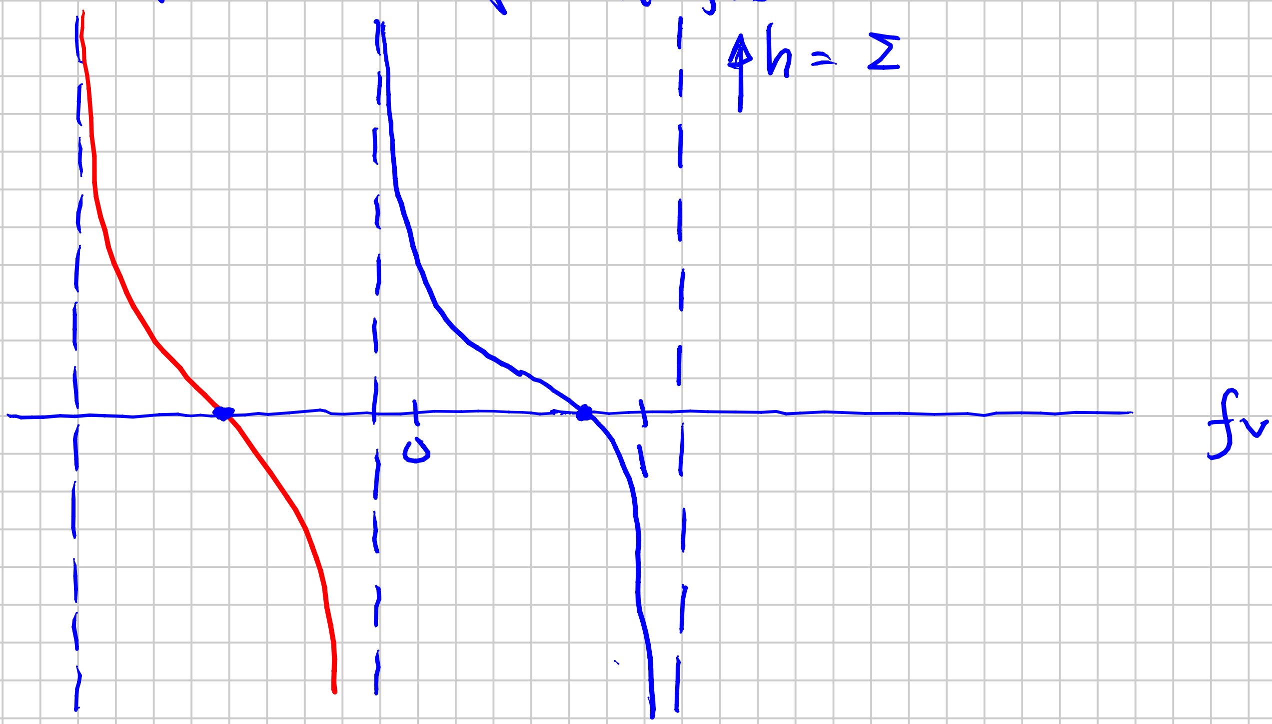
only one of interest: $\left\{ \begin{matrix} y_i > 0 \\ x_i > 0 \end{matrix} \right\}$

$$\frac{1}{1-K_{max}} = \underset{\substack{\vee \\ 0 \le}}{f_v^{min}} \le f_v \le \underset{\substack{\vee \\ \le 1}}{f_v^{max}} = \frac{1}{1-K_{min}}$$

Required to get 2-phases, at least one
$K > 1$ at least one $K < 1$

$h(f_v)$ monotonic $\left\{ \begin{array}{l} \text{can be HIGHLY non-linear} \\ \text{can be prone to} \\ \text{numerical roundoff} \end{array} \right.$

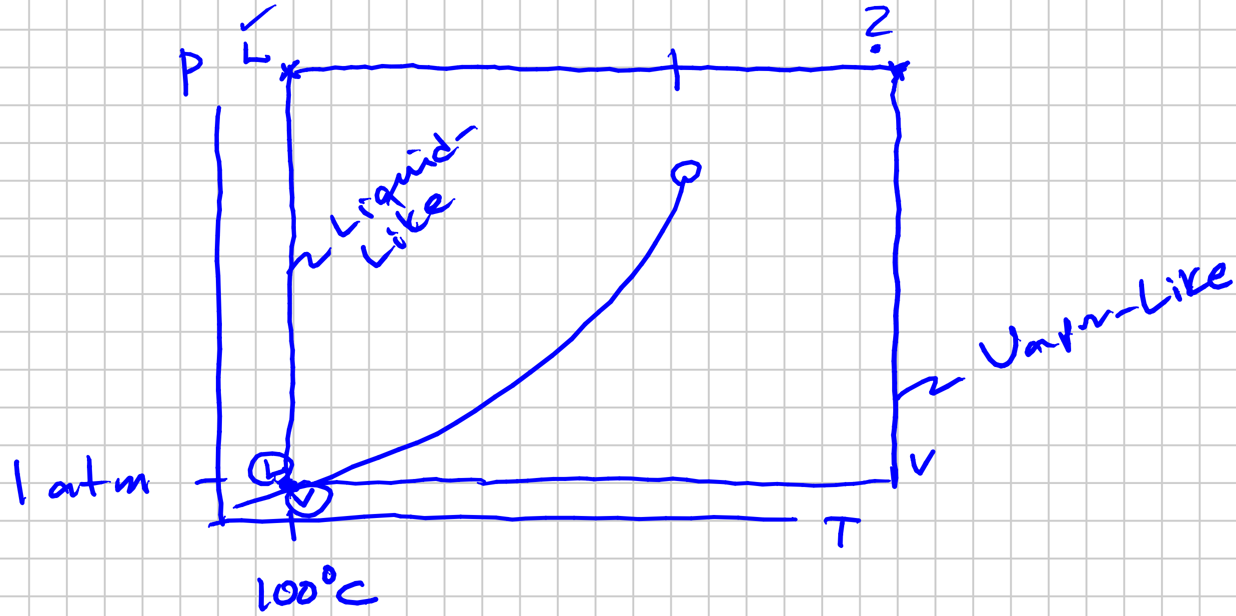
$\Rightarrow$ Newton-Raphson good, efficient method to solve for $h(f_v)$



Valid solution : $f_{v\,min} < f_v < f_{v\,max}$

Valid 2-phase solution: $0 \le f \le 1$

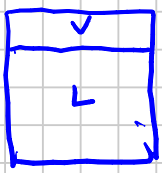
Single phase solution : $f_v > 1$: "gas"
$f_v < 0$: "liquid"



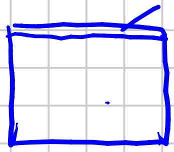
Ch. 4

Saturation Pressure Calculation

T = const



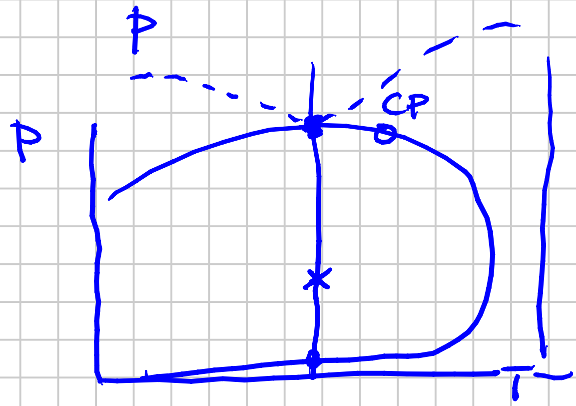
$f_v = 0.1$



$f_v = 0.01$

$f_v \to 0$
$(f_v \to 1)$

P_1? P_2 ....



* Flash $(P, T) \Rightarrow f_v$

$K_i(P)$ $K_i = 1$ @ P_c, T_c
@ P_K, T

$f_v(P) - 1 = 0$: Dewpoint

or

$f_v(P) = 0$: Bubblepoint

$$\left\{ \underbrace{[f_v(P) - 1]}_{\cdot} \times [\underline{\underline{f_v(P)}}] \right\} = 0$$

Find either solution (BP or DP)

Alternative:

BP: $F_b(p) \equiv 1 - \sum y_i = \boxed{1 - \sum z_i K_i(p) = 0}$

Know: $x_i = z_i$ All oil

$K_i = y_i / x_i$

$y_i = K_i x_i = K_i z_i$

?

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

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

$y_i = z_i$ All gas

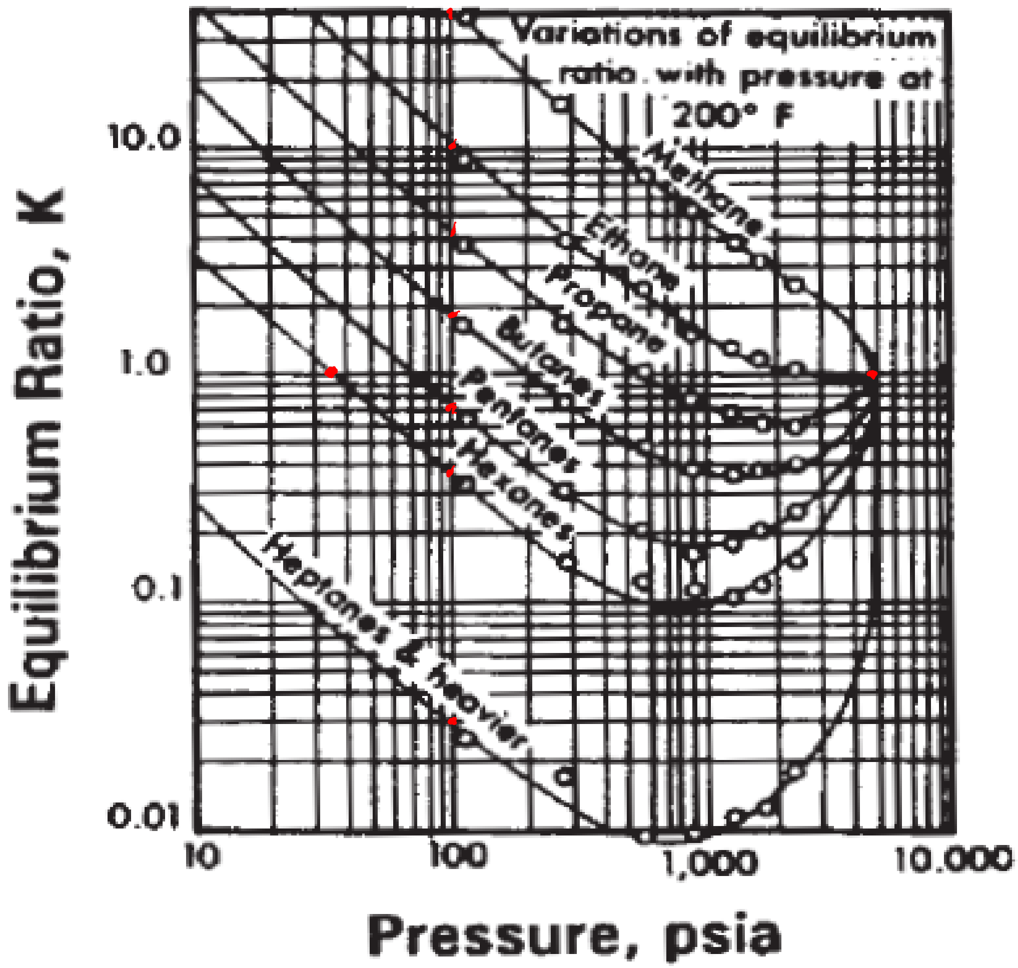
$x_i = y_i / K_i = z_i / K_i$

SAT PRESSURE: Solve one function

$$\boxed{F_s(p) = \underbrace{F_b(p) \cdot F_d(p)}_{@\,P_{sat}} = 0}$$

Ask was $F_b = 0$
or
$F_d = 0$

$$F_s = \left(1 - \sum z_i K_i\right)\left(1 - \sum z_i / K_i\right)$$



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

App. A or $\left\{ \begin{matrix} p_{ci} \\ T_{ci} \\ \omega_i \end{matrix} \right\} \Rightarrow T_{ri} \equiv T / T_{ci}$

$A_1 = 1 - \left(\frac{p}{p_K}\right)^{A_2 = 0.7}$

p_K ?

$p_{ri} \equiv \frac{p}{p_{ci}}$

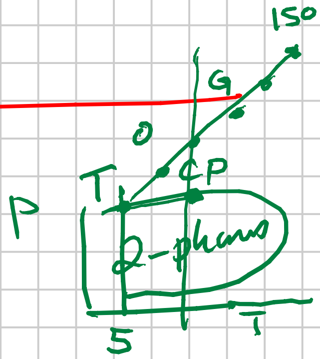
Pitzer

$$\omega \equiv -1 - \log_{10}\left\{\frac{p_v(0.7T_c)}{p_c}\right\}$$

0.01,
0.1

~1
-2

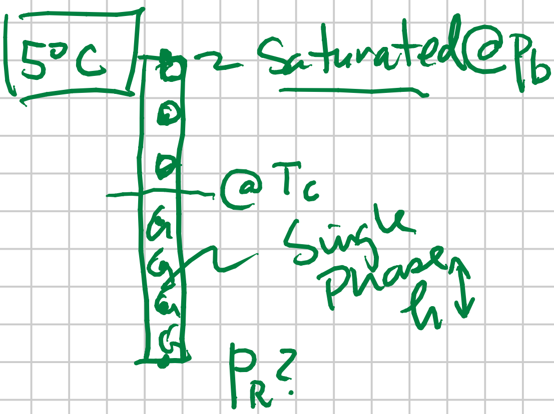
0
+1

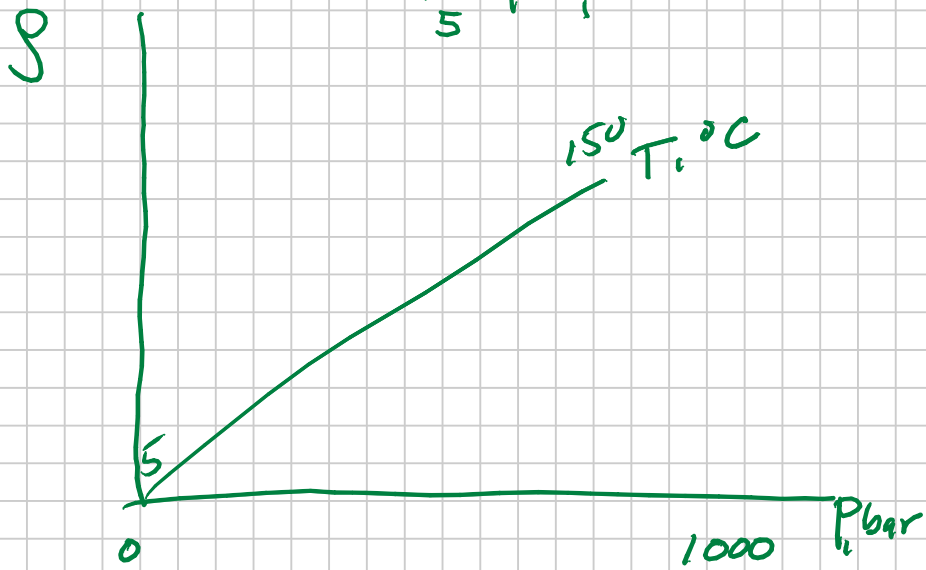


$h \downarrow$

$$\boxed{\frac{dp}{dh} = \rho g}$$

constant



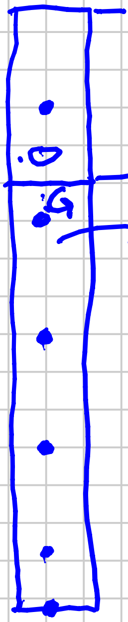


Note Title 2011-09-26

Depth (m)

0

"0,1"



$T = 5°C$

$p_t = 285.6$ bara (sat. cond.) ✓ $\Big\}\ \rho = 484\ kg/m^3$

$T(D) = T_c$

$\rho(D) =$ constant

$$D_R = \frac{\overbrace{P_R - P_t}^{961-286}}{\rho g}$$

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

$$\Rightarrow \int_{P_t}^{P_R} dp = \rho g \int_0^{D_R} dD = \rho g D_R$$

$$= P_R - P_t$$

"Gas" 150°C

961 bara = P_R? $\Big\}\ \rho = 484\ kg/m^3$

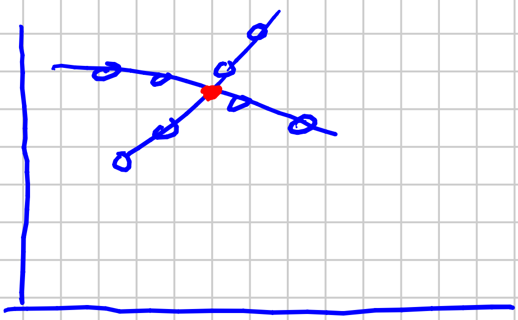
Know T(D)

$\rho g \simeq 0.0484\ \frac{bar}{m}$

$\frac{psi}{ft}$

$D_R = 14240$ m

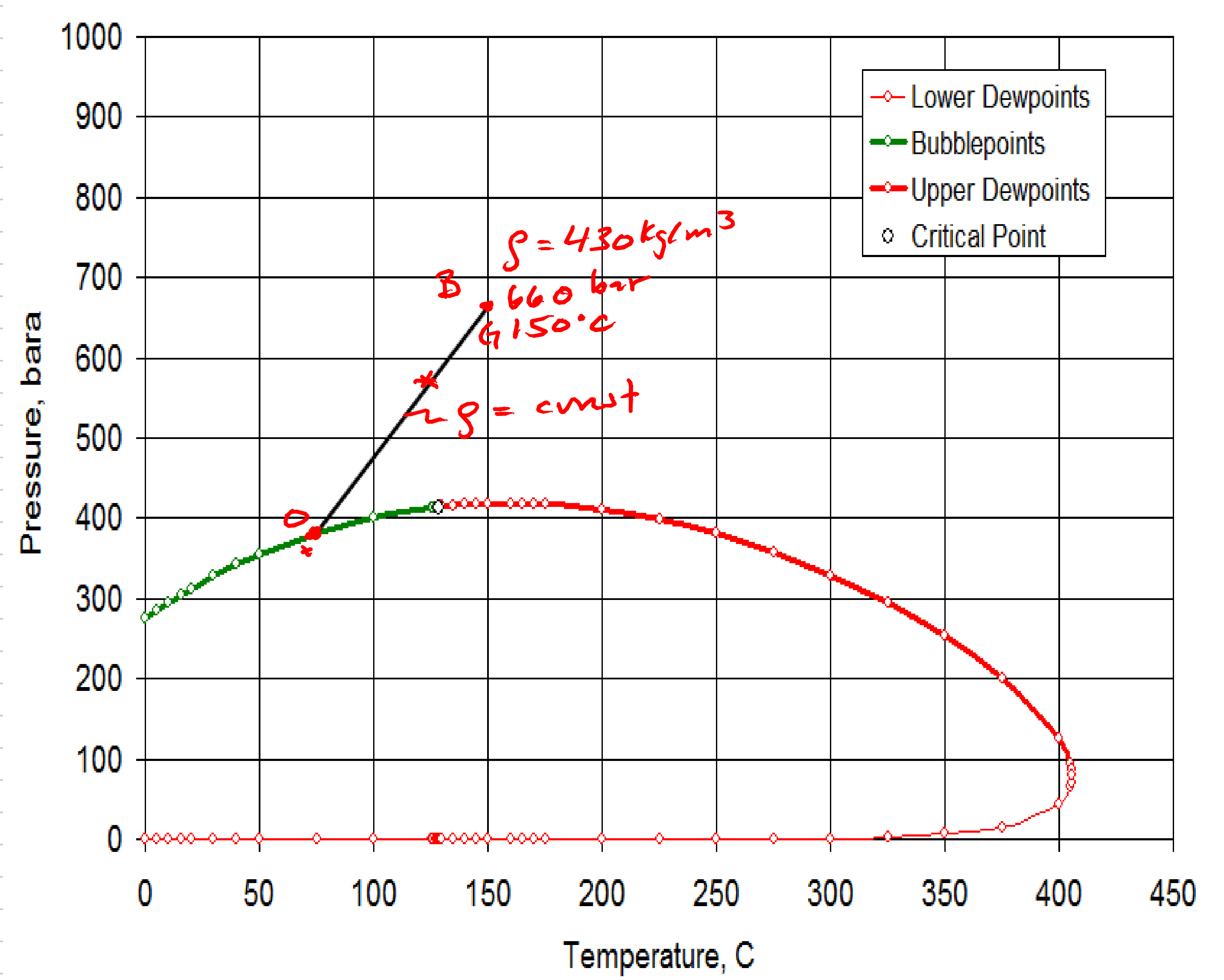
(Yes - not realistic)



$\rho_{660\ \text{bar},\ 150\,°\text{C}} = 431\ \text{kg/m}^3$

$p(D) = 660 - 0.0431\,(D_R - D(T))$

Down-to-Up



$$\frac{dp}{dD} = \rho g = \rho(D)\, g$$

$$\int_{p^*}^{p_t} dp = g \int_{7665}^{0} \rho(D(p,T))$$

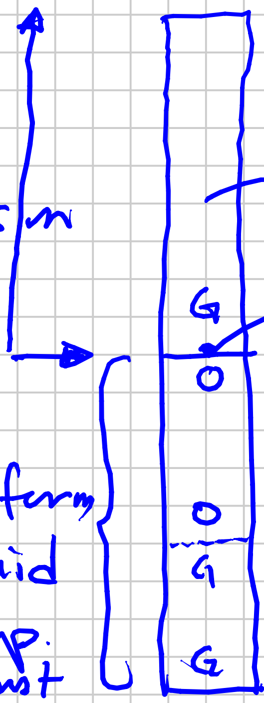
$\rho_g \sim 100\ \text{kg/m}^3$

$$p_t = \overset{382}{p^*} - 7665(0.0375) = \underset{5\,°\text{C}}{94^+}\ \text{bara}$$

p_t /

7665 m

p^*



Gas

Uniform Fluid Comp. $\rho \doteq$ const

$$\rho_g = \frac{pM}{ZRT_{(0)}}$$

Sat Gas: $\rho_{gs} = \underline{375\ kg/m^3}$

$T \approx 75°C \quad p = p_s = p_b = 382$ bara

$T_c = 128°C$

$T = 150°C$

$p_R = 660$ bar

$$\Delta D = \frac{660 - 382}{0.0431}$$

$$= 6575 \quad m$$

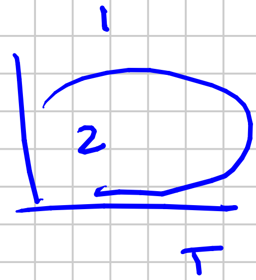
$$D = 14240 - 6575$$

$$= 7665 \quad m$$

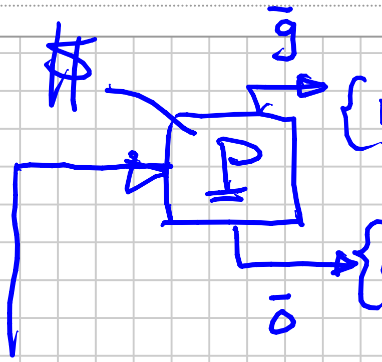
$$\left[\frac{dp}{dD} = \rho g \right]$$

+

Basic (Ch. 2) Phase Behavior



+ Gravity Segregation in Two-Phase



$\bar{g}$: $\{N_2 \ CO_2 \ C_1 \ C_2 \ C_3\}$ Surface Gas $\quad n_{\bar g} = 1 - z_{4+}$

$\bar{o}$: $\{\underline{\underline{C_4}} \ C_5 \ C_6 \ C_{7+}\}$ Surface Oil $\quad n_{\bar o} = z_{4+}$

Wellstream z_i

$n = 1$ kg-mole

$$C_{4+}: RF_{\bar o i} = \frac{n_{\bar o i}}{n_i} = 100\%$$

$$= OGR = \frac{\left\{ z_{4+} \cdot \left(\frac{M_{4+}}{\rho_{4+,Lsc}} \right) \right\} Sm^3}{(1-z_{4+}) \underbrace{\frac{RT_{sc}}{p_{sc}}}_{23.68} \cancel{Sm^3}} \cdot \frac{10^6 \cancel{Sm^3}}{[10^6 Sm^3]}$$

$$M_{4+} = \frac{\sum_{4+} m_i}{\sum_{4+} n_i} = \frac{\sum_{C_{4+}} z_i M_i}{\sum_{i \in C_{4+}} z_i} =$$

$$\begin{array}{cccc} i \\ \downarrow \\ \underbrace{C_4 \quad C_5 \quad C_6}_{M_i = 14 \cdot i + 2} & & & C_{7+} \text{ (Table 2.1)} \\ 58 \quad 72 \quad 86 & & & 184 \end{array}$$

$$\rho_{4+} \approx \frac{\sum_{4+} z_i M_i}{\sum \frac{z_i M_i}{\rho_{Lsc i}}} =$$

Assume Ideal Liquid Volume Mixing

$$V_{Lsc\,i} \simeq \frac{m_i}{\rho_{Lsc\,i}}$$

$$\left(\frac{M_{4+}}{\rho_{4+}}\right) = \frac{\sum \frac{z_i M_i}{\rho_{Li\,r}}}{\sum z_i}$$

ρ_{7+} (Table 2.1) = 816 kg/m^3

North Field (Qatar)

$$\text{IGIP} \sim 900 \cdot 10^{12} \text{ scf} = 900 \text{ Tcf}$$

$$= 900 \cdot 10^{6} \text{ MMscf}$$

$$\overline{OGR}_i \simeq 40 \quad \text{STB/MMscf}$$

$$\Rightarrow \text{IOIP} = 36 \underbrace{\text{billion}}_{10^9} \text{ bbl}$$

Lotta Gas & oil

$$\underbrace{\left(\frac{6.28 \text{ STB}}{\cancel{\text{Sm}^3}}\right) \frac{\cancel{\text{Sm}^3}}{10^6 \cancel{\text{Sm}^3}}}_{(1/5.6146)} \times \frac{\cancel{\text{Sm}^3}}{35.31 \text{ scf}} \longrightarrow \frac{\text{STB}}{10^6 \text{ scf}} = \frac{\text{STB}}{\text{MMscf}}$$

$$\frac{\text{Sm}^3}{10^6 \text{ Sm}^3}$$

(5) C_1

$$n_{\bar{o}} = 0.10xxx$$

$$x_{C_1} = 0.0029$$

$$(n_{C_1})_i = n \cdot z_{C_1} = 1(0.7319)$$

$$RF_{\bar{o}C_1} = \frac{(0.1)(0.0029)}{0.7319} = 0.0004$$

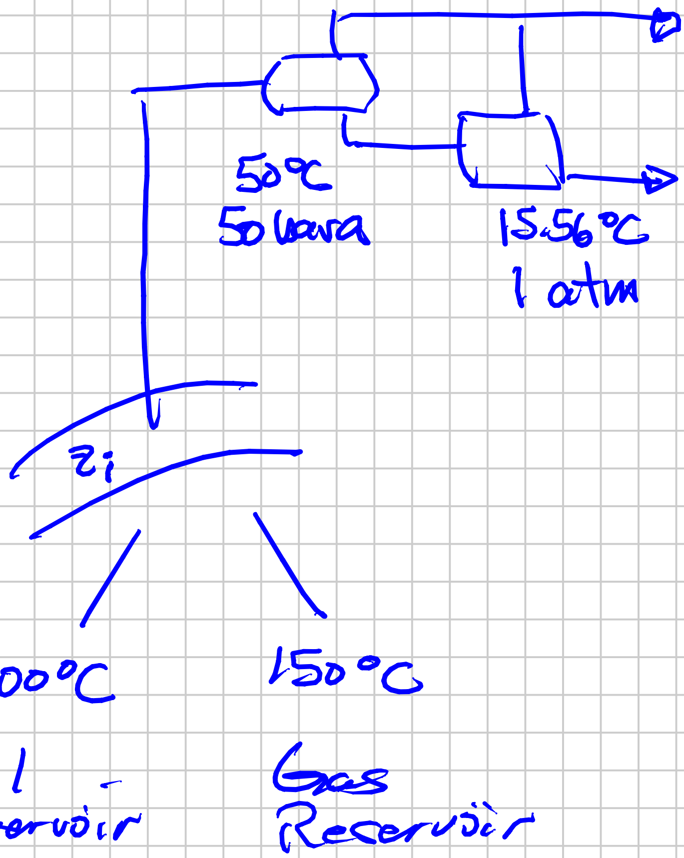
0.04 %

Kg-mole $\quad 21.22\,Sm^3$

$$V_{\bar{g}} = (1-0.10384)(23.68) =$$

$$\sim 1000 \frac{Sm^3}{10^6 Sm^3} = OGR = \frac{V_{\bar{o}}}{V_{\bar{g}}}$$

$$V_{\bar{o}} = 0.020384\ Sm^3$$



$$GOR = \frac{21.22}{0.020384} = 1041 \frac{Sm^3}{Sm^3}$$

(6) $\$115/STB \times (1-0.8) = \$23/STB$

$\$3.50/Mscf \times (1-0.3) = \$2.45/Mscf$

$$V_{\bar{g}} = 21.22\,\cancel{Sm^3} \times 35.31 \frac{\cancel{scf}}{\cancel{Sm^3}} \cdot \frac{Mscf}{1000\,\cancel{scf}}$$

$$= 0.75\ Mscf \times 2.45\ \$/Mscf$$

$$= \$1.80$$

$$V_o = 0.020384\ Sm^3 \times 6.28 \frac{STB}{Sm^3}$$

$$= 0.128\ STB \times \$23/STB$$

$$= \$2.94$$

$$\%\ oil\ Value = \frac{2.94}{2.94 + 1.80} = 62\ \%$$

$$K_{C_{7+}} = \frac{\sum_{C_{7+}} y_i}{\sum_{C_{7+}} x_i}$$

PVT LAB EXPERIMENTS (Ch. 6 & App. D)

Note Title 2011-10-03

* SAMPLING & COMPOSITIONAL ANALYSIS

* MULTI-STAGE SEPARATOR FLASH

~

* DEPLETION TESTS

  - CCE (Constant Composition Exp.)
  - DLE (Differential Liberation Exp.)
  - CVD (Constant Volume Depletion)

~ (not covered in TPG 4145 – Ch. 8)

* GAS-BASED EOR TESTS

  - Swelling
  - Special Swelling (Miscible processes)
  - Slimtube
  - Multi-Contact Vaporization

SAMPLING

① Separator Samples
- During production testing

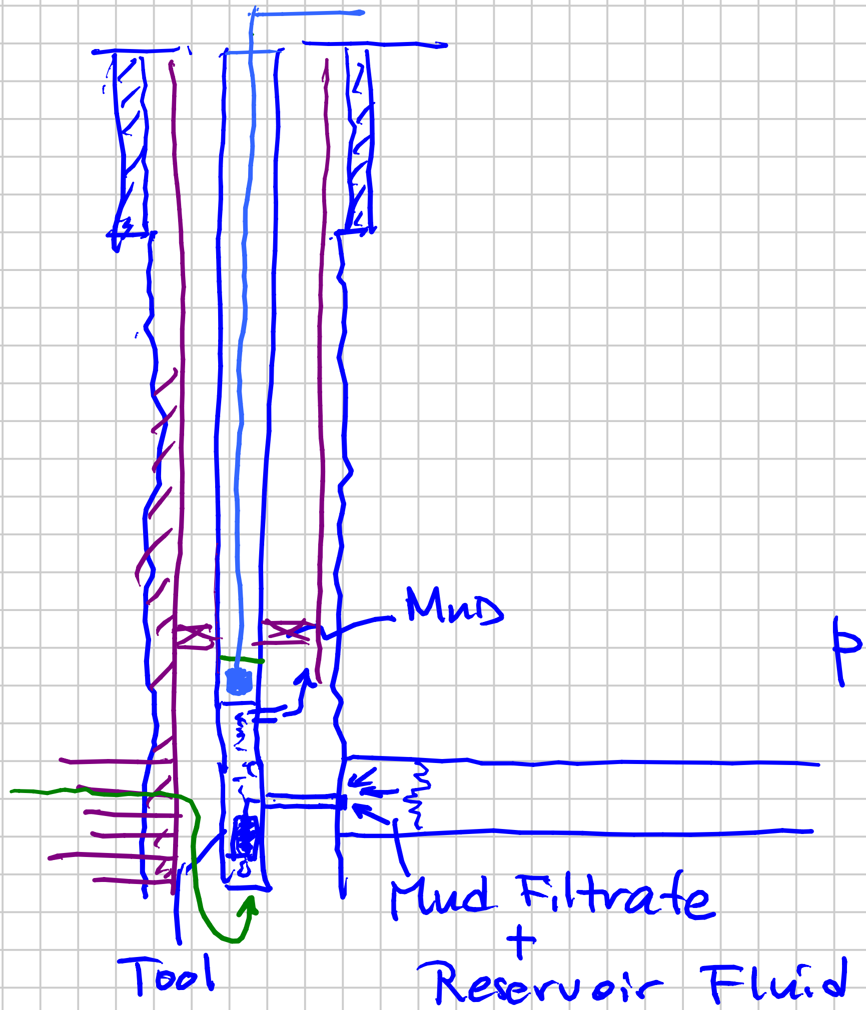
} Gas Condensates & Oils

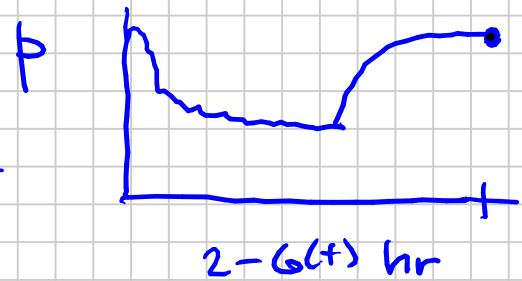
"Old School"
② (Cased-Hole Wireline) Bottomhole Samples (BHS)

③ Open-Hole Formation Tester Samples
- MDT (SLB)
- RCI

} Mini Production Test at a SPECIFIC Depth

⇒ $p_R(D)$ & sample



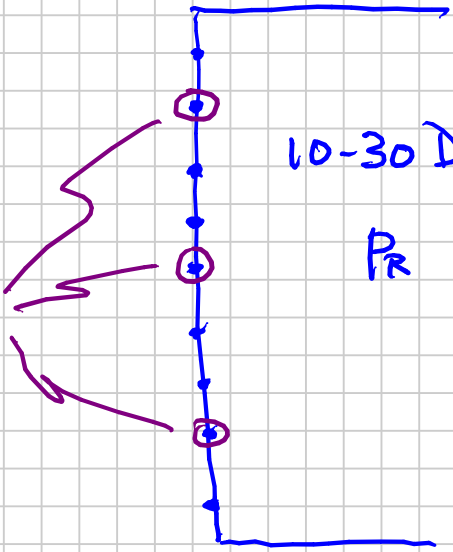


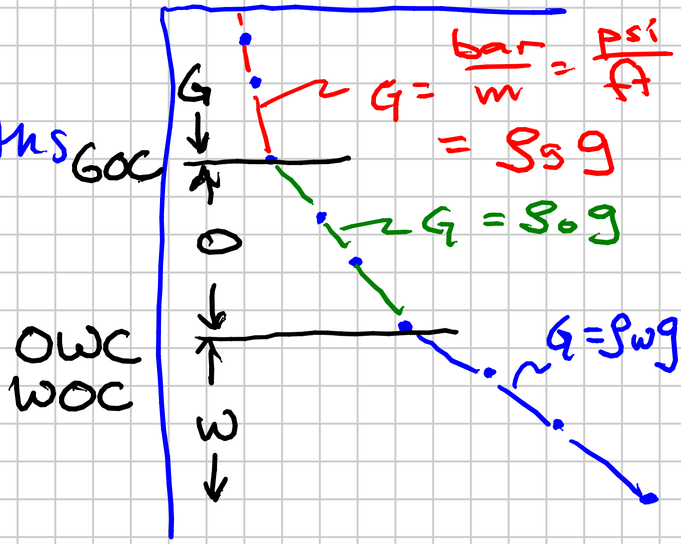
$$\boxed{\frac{dp}{dD} = \rho g}$$

Take Samples

(HP ~ small)

< 100 cc's

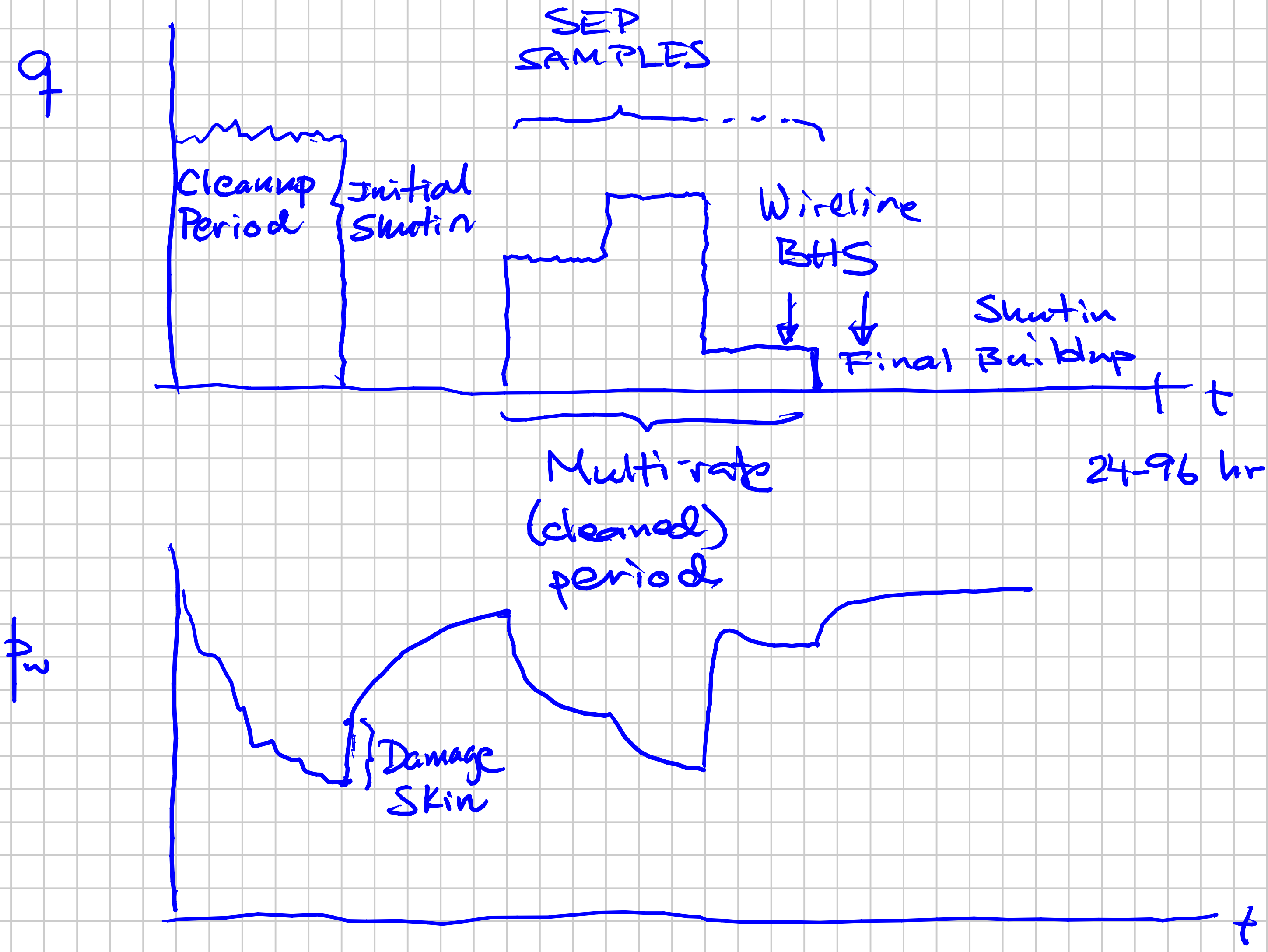




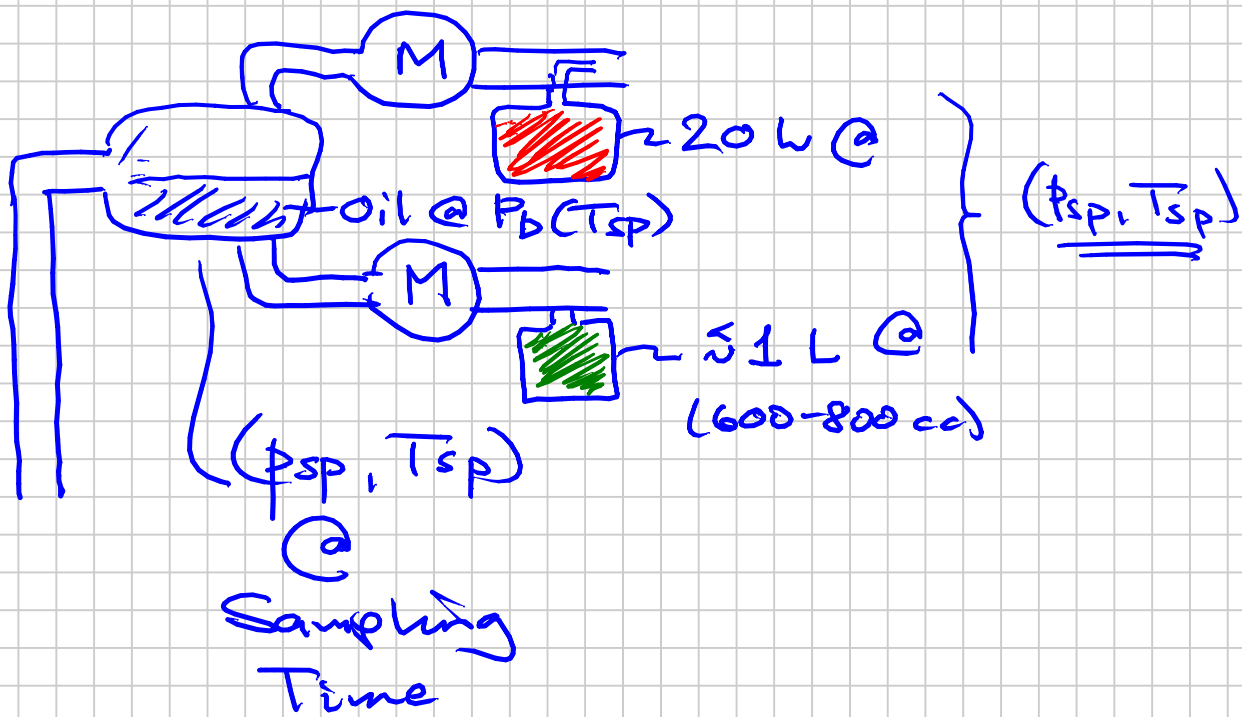
Quality of $p(D) \rightarrow$ GOC, WOC

$\propto k \uparrow$

PRODUCTION TEST SEQUENCE



SEP. SAMPLES



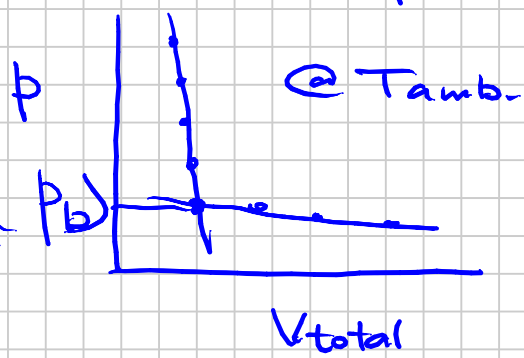
What we do with the samples

① QC Check for "leakage" from the bottles

- BHS
(- MDT ?)

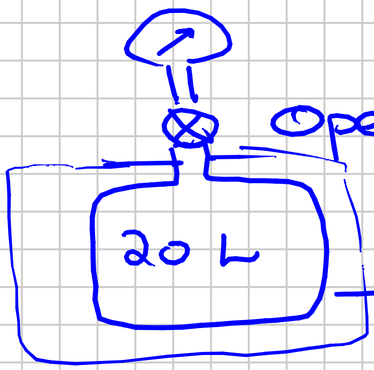
OHS:
Measure in the field
~ bubblepoint p_b ($T_{ambient}$)

Lab $p_b(T_{amb})$ ⟷ Field (p_b)



② Sep. Gas

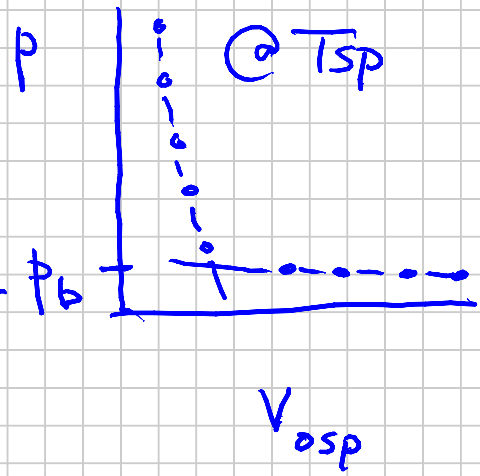
QC by



Open: $p_{opening} \simeq p_{sp}$ ± 1-2 bar

③ Sep Oil

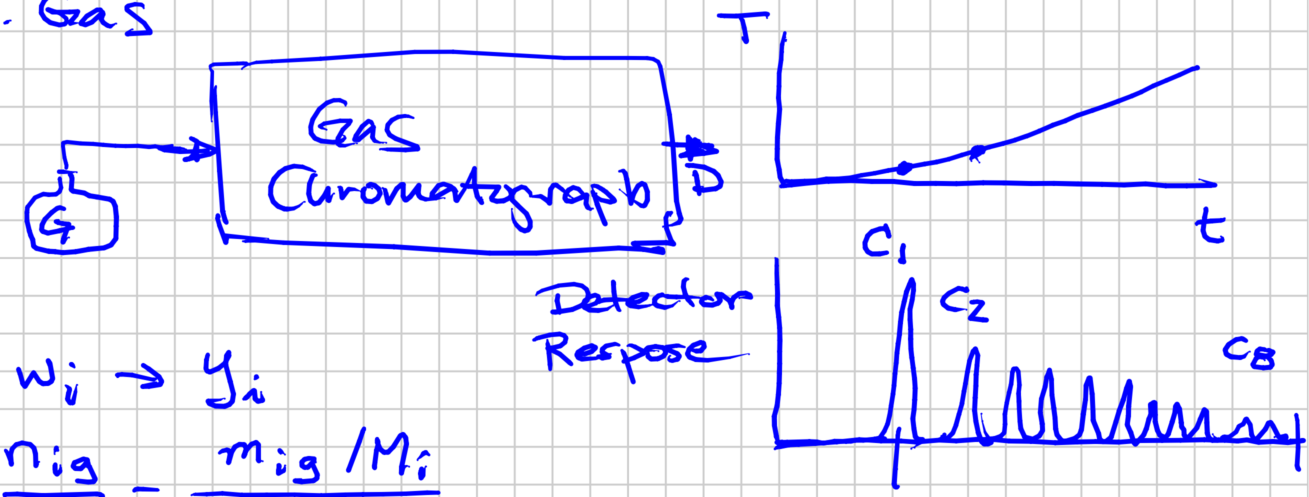
QC by Lab $p_b(T_{sp})$



Measure Composition

$\Rightarrow m_i$ or $\overset{\downarrow}{w_i} = \dfrac{m_{ig}}{m_g}$

① Sep. Gas



From $w_i \to y_i$

$$y_i = \frac{n_{ig}}{n_g} = \frac{m_{ig}/M_i}{\sum_j m_j/M_j}$$

Area $\propto$ Mass $A_i \propto m_i$ $\sum A_i \propto m$

Total Area = Total Mass

② All other Samples (pressurized, form two phase g + o at ~ P_{sc})

* Sep. Oil
* BHS
* MDT (RCI)

"Flash / GC" Analysis

$\downarrow$

Equilibrate @ $\underline{\underline{P_{sc}}}$, T

Measurements

Flash $\to$ $\bar{g}$: $V_{\bar{g}}$ $m_{\bar{g}}$

Flash $\to$ $\bar{o}$: $V_{\bar{o}}$ $m_{\bar{o}}$ $\underline{\underline{M_{\bar{o}}}}$ $\underline{\underline{\rho_{\bar{o}}}}$

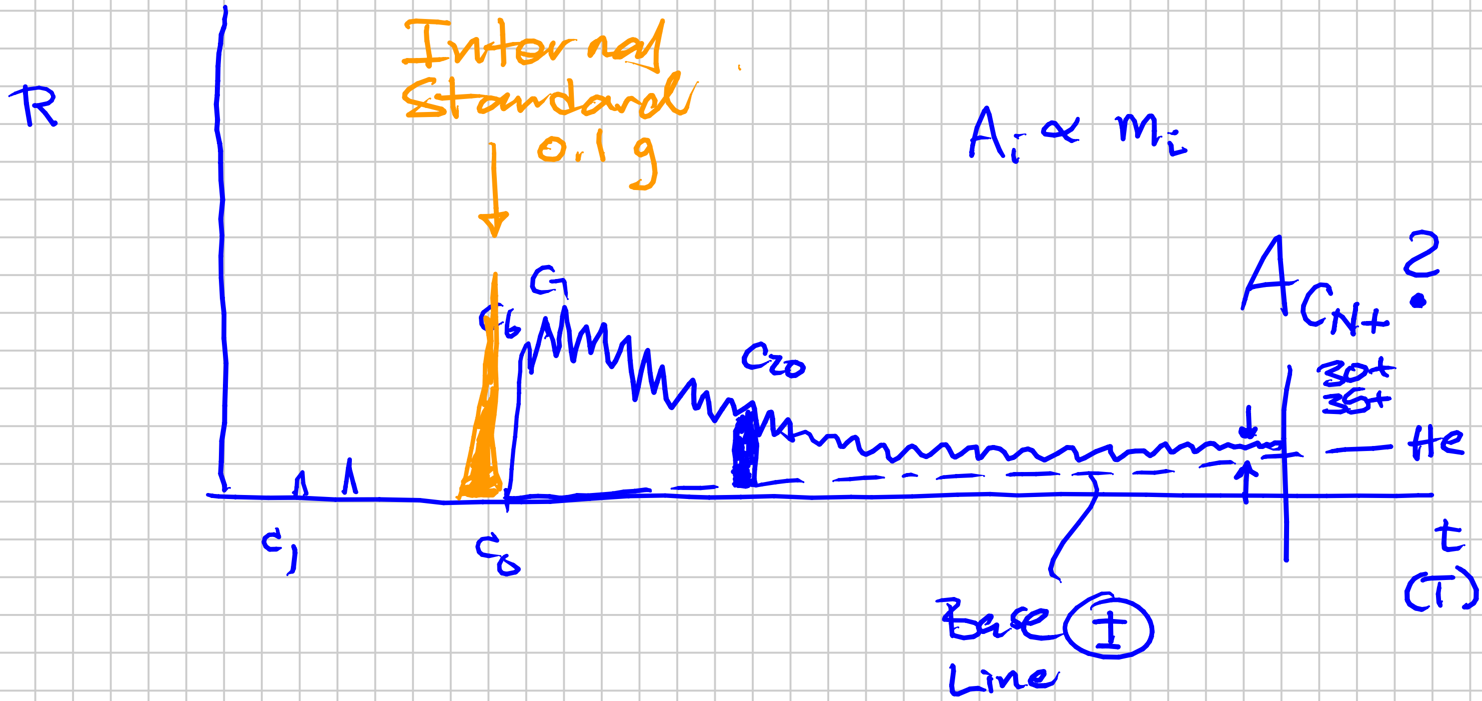
Comp. Analysis

(a) $\bar{g} \to \boxed{GC} \to w_{i\bar{g}}$ ✓ $(y_{i\bar{g}})$

(b) $\bar{o} \rightarrow \boxed{GC} \rightarrow w_{i\bar{o}}$ ±

$\downarrow$

mole fractions



$A_i \propto m_i$

M_{N+} ±

$\downarrow$

$\boxed{C_{25+}}$

$W_{i\bar{o}} \rightarrow x_{i\bar{o}}$ ±

M_i ± Use Table 5.2 for $i \ldots N-1$ (24)

Lab

$$M_{\bar{o}} = \frac{\sum_{i=1}^{N+} w_i}{\left(\sum_{i=1}^{N-1} \frac{w_i}{M_i}\right) + \frac{w_{N+}}{M_{N+}\,?}}$$

±5%

Back-Calculated

(c) Recombination of $\bar{g}$ & $\bar{o}$

PVT LAB TESTS

Note Title 2011-10-06

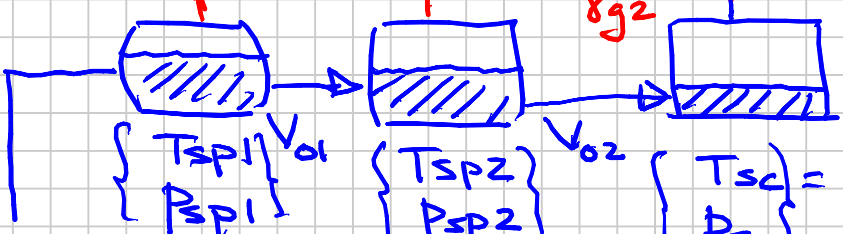
MULTI-STAGE SEPARATOR

* Reservoir Fluid < BHS (MDT) / Separator Recombined

Purpose: Est. Sellable Surface Products
- Stock-Tank Oil
- Separator Gases → Est. NGLs "L_i"

How: Use 2-3 stage sep. process

γ_{g1}, y_{1i} $\quad V_{\bar{g}1}$ $\quad V_{\bar{g}2}\ y_{2i}\ \gamma_{g2}$ $\quad V_{\bar{g}3}\ y_{3i}\ \gamma_{g3} \equiv \dfrac{M_{g3}}{M_{air}}$



STO $\quad V_{\bar{o}} = V_{o3}$

V_{o1}: $\begin{Bmatrix} T_{sp1} \\ P_{sp1} \end{Bmatrix}$ $\quad V_{o2}$: $\begin{Bmatrix} T_{sp2} \\ P_{sp2} \end{Bmatrix}$ $\quad \begin{Bmatrix} T_{sc} \\ P_{sc} \end{Bmatrix}$ $T_{sc} = 15.56\,°C$ (60F) ± ; $P_{sc} \sim 1$ atm

Reservoir Fluid

$V_s (P_s, T_R)$

$\{z_i\}$ known

$\rho_{\bar{o}} \Rightarrow \gamma_{API}$

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

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

* On Oils

On "Richer" Gas Condensates $\left(OGR \gtrsim 100\ \dfrac{STB}{MMscf}\right.$ $= 560\ \dfrac{Sm^3}{10^6\,Sm^3}$

FVF

Oil / Gas Formation Volume Factors (B) @ P_R, T_R

Oil sample:

$$B_{ob} = B_{ob} \equiv \frac{V_{ob}}{V_{\bar{o}}} \sim 1.2 - 2.0$$

@ P_b, T_R 80%

$$GOR = \frac{\Sigma V_{\bar{g}}}{V_{\bar{o}}} = \text{Solution Gas-Oil Ratio } (R_s)$$

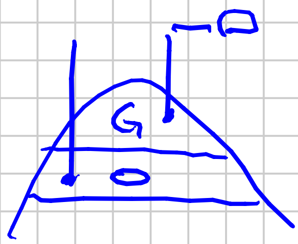
Gas Sample:

$$B_{gd} = \frac{V_{gd}}{V_{\bar{g}}} \sim \frac{1}{P_{atm}} \sim \underbrace{\frac{P_{sc}}{P}}_{\frac{1}{P_{atm}}} \cdot \underbrace{\left(\frac{T_R}{T_{sc}}\right)}_{1.2-1.4}$$

$$OGR = \boxed{\frac{V_{\bar{o}}}{\Sigma V_{\bar{g}}}} = \text{Solution Oil-Gas Ratio } (r_s) \quad R_v$$

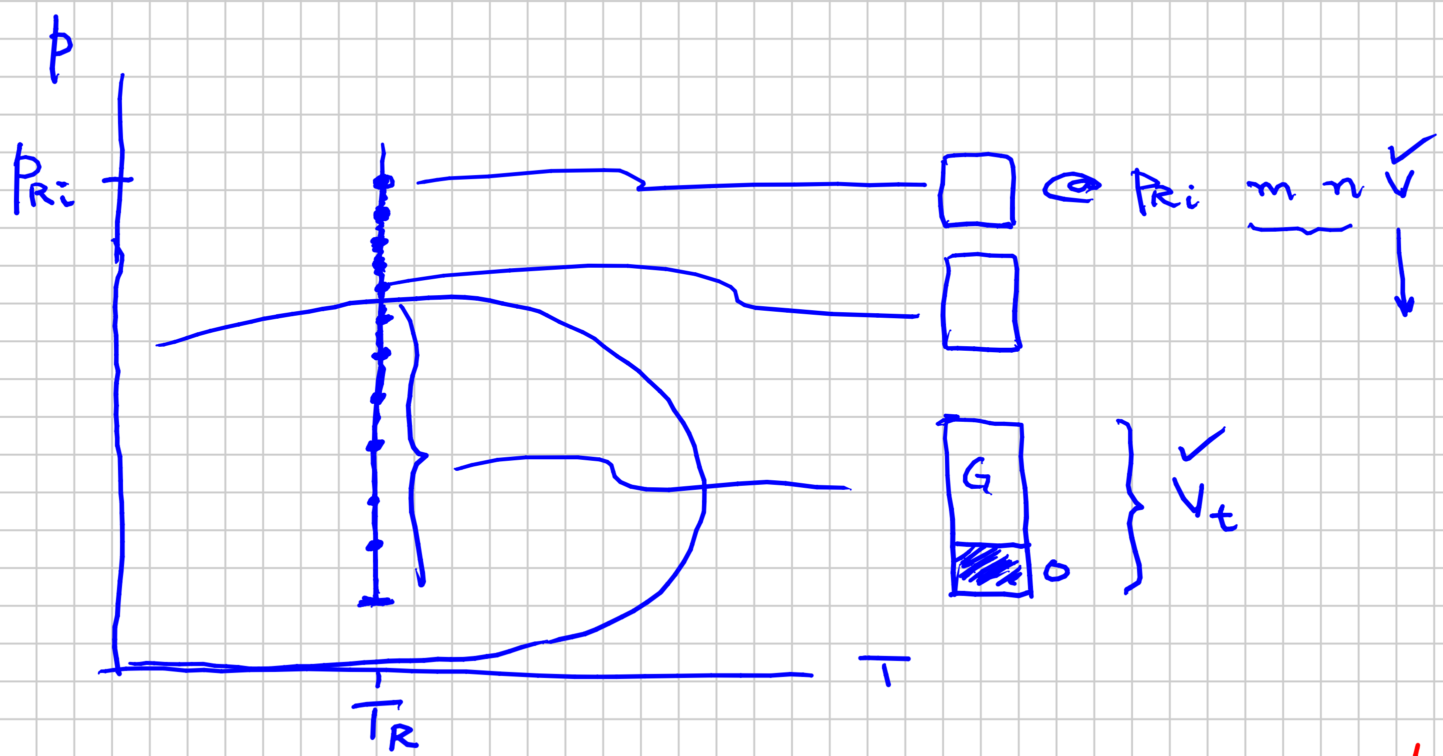
$$\ddot{C} \left[\frac{r_s^{(P)}}{B_{gd}^{(P)}}\right] \frac{\left(\frac{V_{\bar{o}}}{V_{\bar{g}}}\right)}{\left(\frac{V_g(P_R)}{V_{\bar{g}}}\right)} = \frac{V_{\bar{o}}}{V_g(P_R)}$$

$1 \, m^3$



CONSTANT COMPOSITION EXP. (CCE) (MASS)

@ $T = const = T_R$

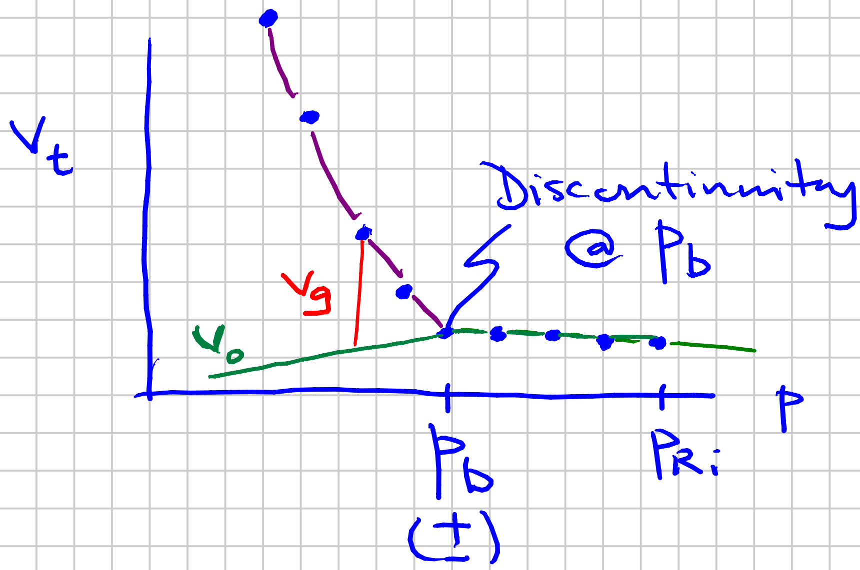


- Measure p_s @ T_R (BP or DP)
- $\rho(p, T_R)$ $p \geq p_s$; Z_g @ $p \geq p_d$ $\rho_g = \frac{pM}{ZRT}$
- Two-phase Volume behavior @ $p < p_s$
  $V_o + V_g$

Two PVT Cells:

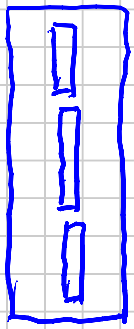
- Blind Cell
  (no window)

  OILS only



- Windowed PVT Cell

High-GOR Oils & Gas Condensates

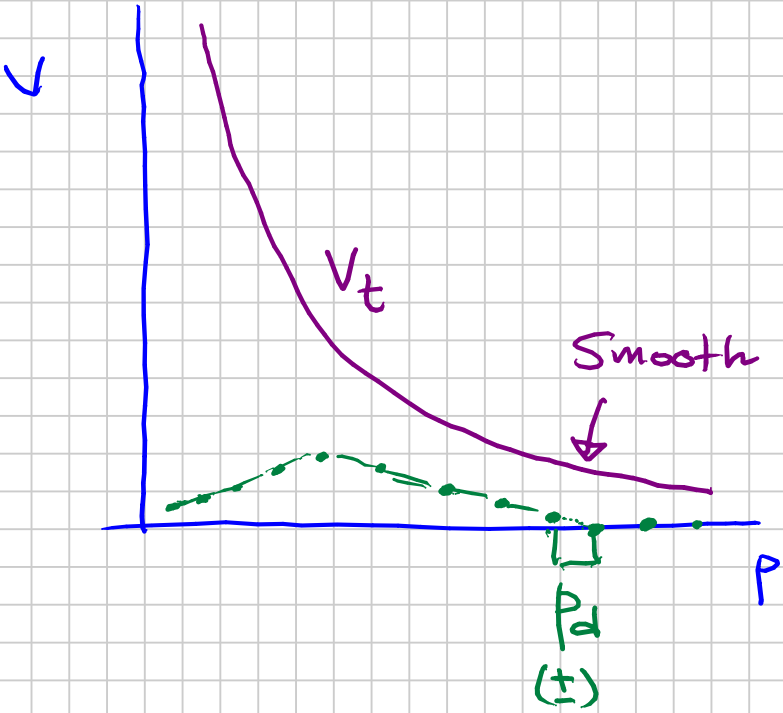


Ruska

p	V_t	V_o	$V_g = V_t - V_o$

$\gtrsim 250 \; Sm^3/Sm^3$

300



$\left(\frac{V_o}{V_d}\right)$ $\frac{V_o(p)}{V_t(p)} = V_{ro}$

CCE

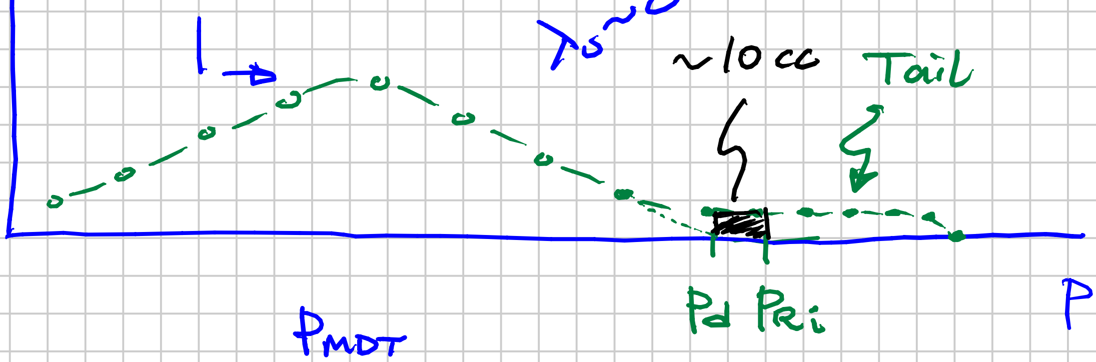
max oil $\frac{V_o}{V_d} \sim 35\% - 40\% = \frac{S_o}{1-S_w}$

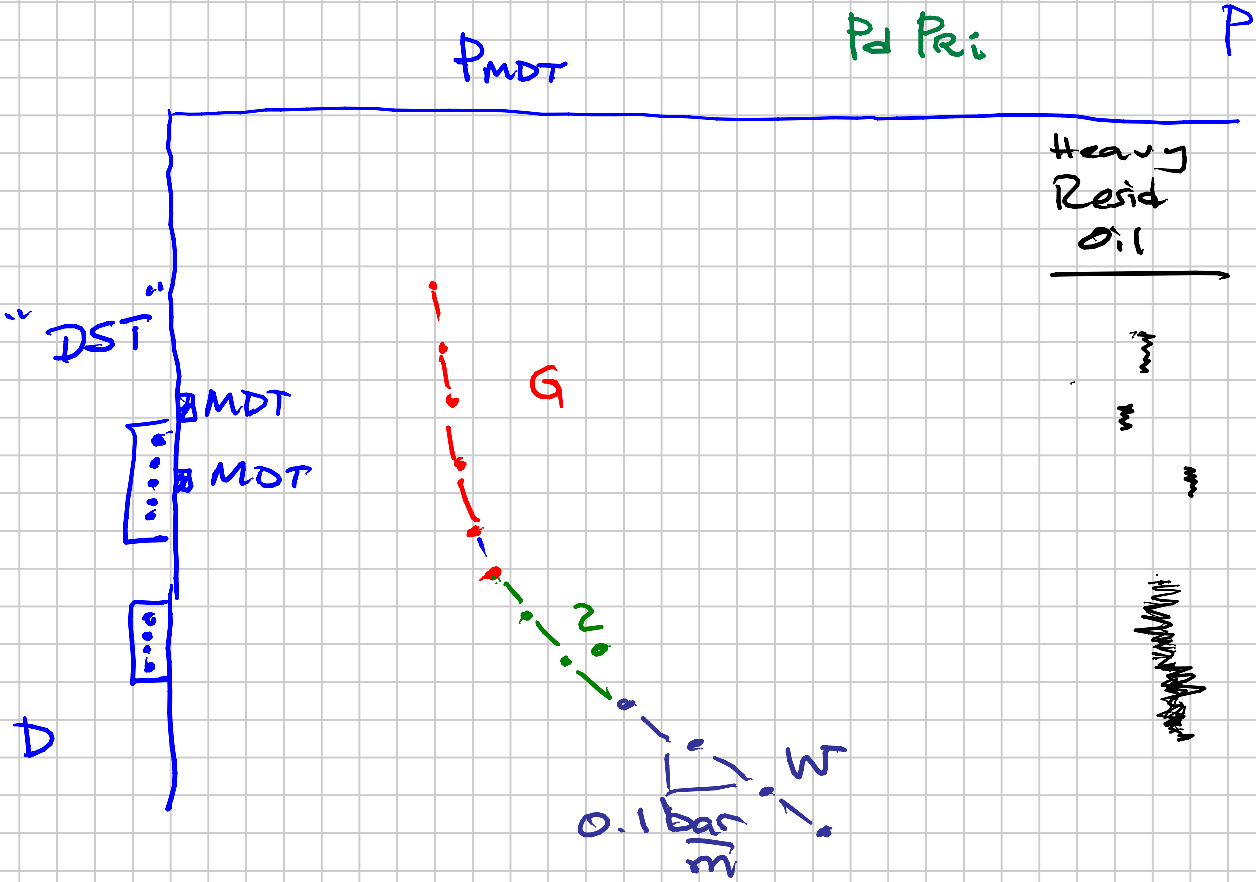
G.C: $S_{omax} \sim 40(80) = 32\%$

$K_{ro} \sim 0.08\times$

$0.0\times$

Liquid





DEPLETION TESTS

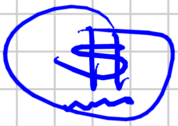
OILS: Differential Liberation Test
(DLE)

GAS CONDENSATES & VERY-HIGH GOR OILS:
Constant Volume Depletion Test
(CVD)

$V_g \propto \frac{1}{p}$

$$\lambda_g^{(p)} = \frac{k_{rg}\left(S_g = V_g^{(p)}/V_p\right)}{\mu_g^{(p)}}$$ ↑ Depletion

$$\lambda_o^{(p)} = \frac{k_{ro}\left(S_o = V_o^{(p)}/V_p\right)}{\mu_o(p)}$$ ↓ Depletion



↓ Depletion

"ST Condensate" Carrying capacity of Gas $\left\{ \left(\frac{r_s}{B_g}\right)(p) \right.$ ↓ Depletion

Gas Condensate Reservoir:

$\lambda_o \sim 0$

OIL TEST : DLE

✓ μ_o

✓ $V_o(p)$

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

$\Delta R_s = R_{si} - R_s(p)$

$\left\{ \begin{array}{l} \text{Solution} \\ \text{Gas} \end{array} \right.$ liberates from the oil $\}$ ✓

$\Rightarrow \left\{ \begin{array}{l} \text{Solution} \\ \text{Gas} \end{array} \right.$ remains in solution $\}$ $R_s(p)$

GAS CONDENSATE : CVD

$\lambda_o \sim 0$ (Ignore $\mu_o(p)$)

$k_{rg}(S_g) \sim 1 \rightarrow 0.5$ as retrograde condensation in R

$V_g, V_o(p)$

$\left(\frac{r_s}{B_{gd}}\right) \propto y_{\bar{o}} \sim$ "y_{C6+}"(p)

CVD

y_{H_2O}

0% H	0
100% H	0.00x

OIL DEPLETION PVT TESTS (App. D & Ch. 6)

Note Title 2011-10-10

DLE – Differential Liberation "Depletion"
&
SEP – Multi-Stage Separator Test "Flash"

↓

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

Combined together to provide "black-oil" PVT properties

Oil Phase
- $B_o(p)$ – Undersaturated ($p > p_b$); Saturated ($p \le p_b$) — Same (p) "shape"
- $R_s(p)$ – Saturated ($p \le p_b$)
- $\mu_o(p)$ – $p > p_b$; $p \le p_b$

$B_o = f(R_s)$ "Linear" (all oils)

Gas Phase
- $B_{gd}(p)$ – $p > p_d$; $p \le p_d$
- (✓) (t) $r_s(p)$ – $p \le p_d$ (sat)
- $\mu_g(p)$ – $p > p_d$; $p \le p_d$

@ "R" (p_R, T_R)

$$\rho_o = f(B_o, R_s, \rho_{\bar{o}}, \rho_{\bar{g}}) = \frac{\rho_{\bar{o}} + \rho_{\bar{g}} R_s(p)}{B_o(p)}$$

@ "R"

$$\rho_g = f(B_{gd}, r_s, \rho_{\bar{o}}, \rho_{\bar{g}}) = \frac{\rho_{\bar{g}} + \rho_{\bar{o}} r_s(p)}{B_{gd}(p)}$$

if $r_s = 0$

$B_{gd} = B_g$ (trad.)

Oil Material Balance (Depletion)

"Solution Gas Drive" $(P_R \leq P_b)$

Expansion Drive $(P_R > P_b)$

$$\pm \; N = \frac{\overset{\checkmark}{N_p}\left[B_t + (\overset{\checkmark}{R_p} - R_{si})\,B_g\right]}{B_t - B_{ti}}$$

(IOIP)
(ISTOIP)
(STOIP)
(OOIP)

$$B_t \equiv B_o + (R_{si} - R_s)\,B_g$$

R_p = cumulative "average" producing gas-oil ratio

$= \dfrac{G_p}{N_p}$

N_p = cum. surf. oil prod. ✓✓✓

G_p = cum surf gas prod. ✓

	Production Data			(Lab Test) PVT Data				
time	P_R	N_p	G_p	$B_o(P_R)$	$R_s(P_R)$	$B_g(P_R)$	B_t (calc)	$\underline{\underline{N}}$

DLE+SEP ⇒

NEVER use B_{od} & R_{sd} directly for ANY engineering calc.

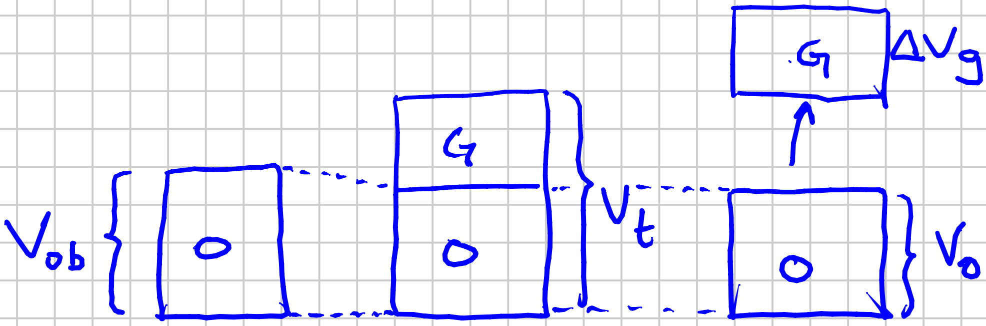
DLE Test

$T_R = \text{const}$ (Blind PVT Cell)

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

ΔV_g $(\Delta m_g \ \Delta n_g) \leftrightarrow M_g$

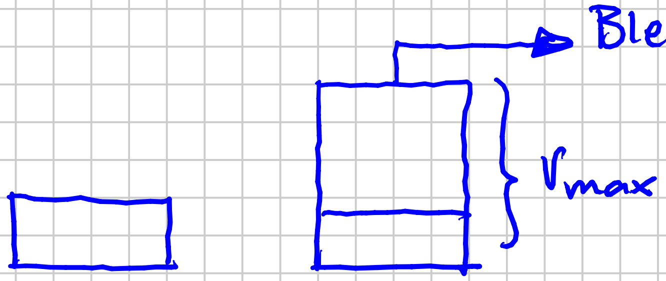
$\{y_i\} \to \Delta \bar{V}_g$ scf Sm^3



@ $p_b = p_1$ $\quad p_2 < p_b$ --- p_2

Repeat with the remaining oil

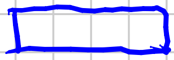
p_3 ... p_4 ... $p_{(6-10)}$ $\qquad N_{DLE} \sim 6-10$



p_{N-1} $\qquad p_{N-1} > p > 1\text{ atm}$

$\sim$ 100 – 250 psi

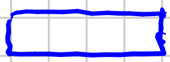
$\sim$ 10 bar $\qquad v_g \propto \frac{1}{p}$



1 atm $\quad V_{or}(T_R)$

T_R

Cool Residual Oil to T_{sc}



(T_{sc}, p_{sc})

Lab Reports:

✓ $$B_{od}^{(p)} \equiv \frac{V_o(p, T_R)}{V_{\bar{o}r}(p_{sc}, T_{sc})}$$

Total Gas Released = Total Gas in Solution

$$R_{sd,b} = \sum_{k=1}^{N} \Delta R_{sd,k}$$

✓ $$\Delta R_{sd}^{(p)} \equiv \frac{\Delta V_{\bar{g}}(p_{sc}, T_{sc})}{V_{\bar{o}r}(p_{sc}, T_{sc})}$$ $\Rightarrow$ ✓ $$\underbrace{R_{sd,k} = R_{sd,b} - \sum_{j=2}^{k} \Delta R_{sd,j}}_{\text{remaing gas in Solution}}$$

✗ $$B_g^{(p)} = \frac{\Delta V_g}{\Delta V_{\bar{g}}} = \frac{p_{sc}}{T_{sc}} \frac{Z_g T_R}{p}$$

✓ $\gamma_{\bar{o}r}$ or $\rho_{\bar{o}r}$ @ T_{sc}, p_{sc} (°API)

✓ $$\gamma_g = \frac{M_g}{M_{air}}$$

✓ Z_g

✓ $\rho_o(p)$: Calculated by a material balance

$$\rho_{ok} = \frac{\rho_{\bar{o}r} + \sum_{j=N}^{k} \Delta R_{sd,j} \cdot \gamma_{g_j} \cdot \rho_{air,sc}}{B_{od,k}}$$

Gravity of residual oil = 42.2°API at 60°F.

UNDERSTANDING LABORATORY OIL PVT REPORTS

			Differential Liberation at 258°F		
			Gas/Oil Ratio		
Gauge Pressure (psi)	Pressure/Volume Relation at 258 °F Relative Volume of Oil and Gas V/V_{ob}	Viscosity* of Oil at 258 °F (cp)	ΔR_{sd} Liberated/bbl Residual Oil	R_{sd} In Solution/bbl Residual Oil	B_{od} Relative Oil Volume V_o/V_{or}
6,000	0.9387	0.119			1.948
5,500	0.9471				1.965
5,300		0.113			
5,000	0.9562				1.984
4,590		0.107			
4,500	0.9666				2.006
4,100		0.102			
4,000	0.9781				2.030
3,800	0.9833				2.040
3,720		0.099			
3,600	0.9888				2.052
3,500	0.9918				2.058
3,400	0.9948				2.064
3,390		0.096			
3,300	0.9979				2.071
P_b $\boxed{3,236}$ P_1	1.0000	0.093	0	1,518	2.075
3,200	1.0047				
3,141	1.0128				
3,110		0.095			
3,094	1.0192				
3,039	1.0273				
2,969	1.0387				
$\boxed{2,938}$ P_2			$\boxed{183}$	$\boxed{1,335}$	1.970
2,882	1.0534				
2,800		0.104			

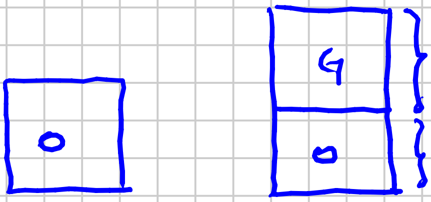
shrinkage of oil

Supplementary Differential-Liberation Data

Pressure (psig)	γ_g Gas Gravity	ρ_o Oil Density (g/cm³)	Deviation Factor Z_g
3,236		0.5773	
2,938	0.870	0.5905	0.886
2,607	0.846	0.6055	0.879
2,301	0.833	0.6179	0.878
1,903	0.830	0.6326	0.884
1,505	0.835	0.6455	0.897
0	1.532	0.7340	

SEP & DLE

Test procedure is the same



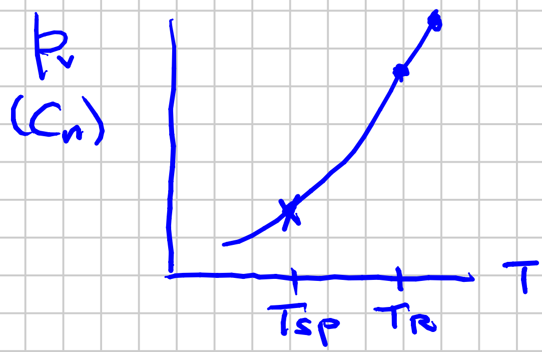
→ Remove All Gas

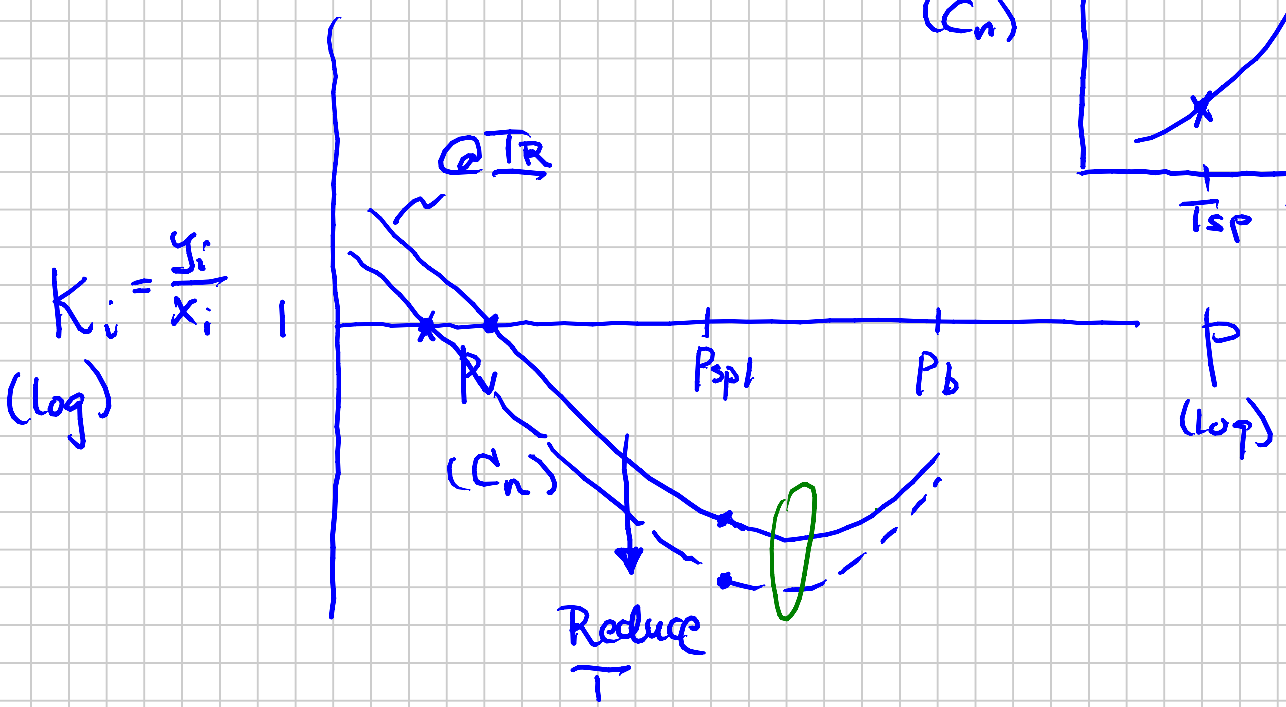
→ Conduct a New Flash @ a lower pressure

$P_b > P_2$

T_R { DLE T_R = const
SEP Change T each stage } ... (P_{sc}, T_{sc})

Differential Process is "less efficient" (smaller $V_{\bar{o}}$) than the Separator Test.





$\Rightarrow R_{sd,b} > R_{sb}$

(DLE) (SEP)

$B_{od,b} > B_{ob}$

$\frac{STB}{RB} = \frac{1}{B_o}$

Traditional

DLE → SEP Correction

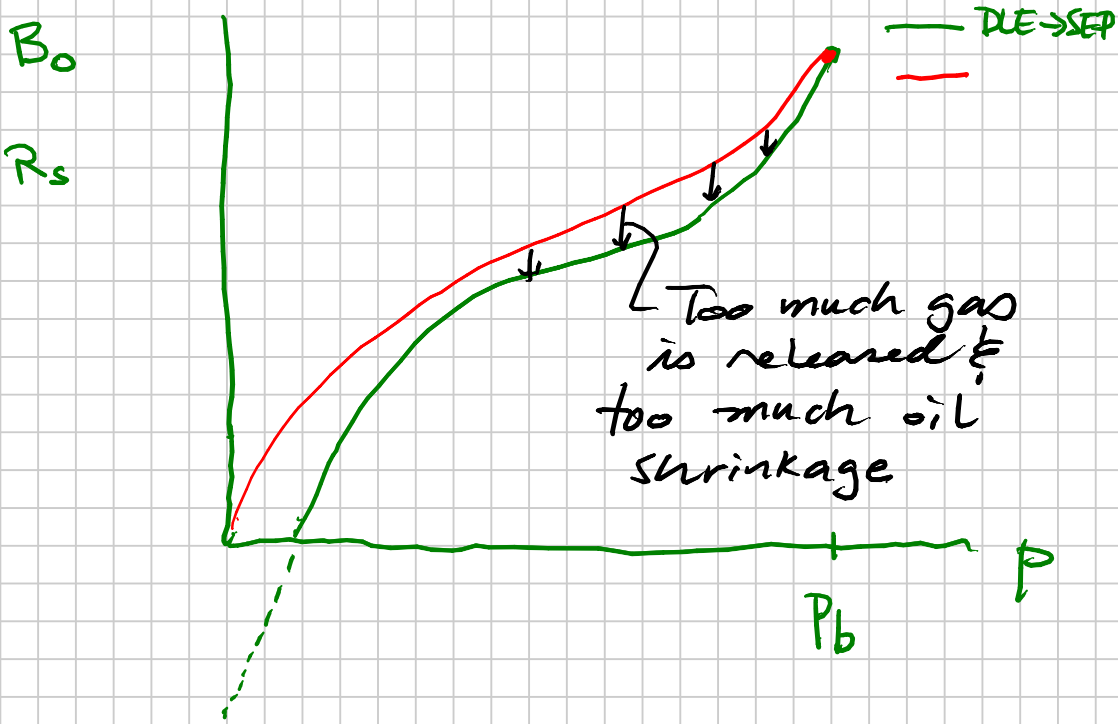
$$\left\{\begin{matrix} B_{od}(p) \\ R_{sd}(p) \end{matrix}\right\} \rightarrow \left\{\begin{matrix} B_o(p) \\ R_s(p) \end{matrix}\right\}$$

All engineering calculation

Never use directly

Not be used if $R_{sb} \gtrsim 350\ Sm^3/Sm^3$ (300)

Why? Too pessimistic (RF_o too low 1...5 RF-%) for depletion strategy



$$\left(\frac{\lambda_g}{\lambda_o}\right) = \frac{k_{rg}(S_o)/\mu_g}{k_{ro}(S_o)/\mu_o} \sim$$

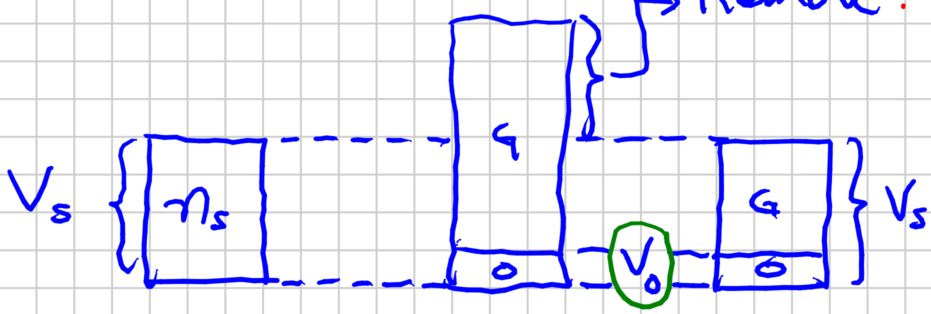
$$k_{ro} \sim S_o^{\,n} \qquad n \sim 2\text{-}4$$

Constant Volume Depletion Test
("CVD")

- Gas Condensates
- High GOR (R_{sb}) Oils $\gtrsim 400\text{-}500\ Sm^3/Sm^3$
- T_R = constant
- Some gas removal
- 6–10 steps
- Windowed PVT Cell

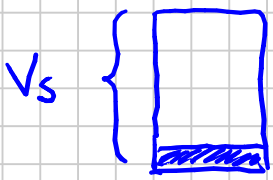
Remove: $\Delta V_g(p,T)$; Δn_g ; Δm_g → $\Delta V_{\bar{g}}$

Z_g ; y_i



T_R $\quad \underline{p_s} > p_2 \quad \cdots \quad p_{N-1}$ (10-20 bar)

Reported Data:



... $V_{cell,max}$ Final bleed off gas → p_{sc} x_i

$\left\{V_{ro} = \frac{V_o}{V_s}\right\}$; $\left(\frac{\Delta n_g}{n_s}\right.$ or $\left.\frac{\Delta V_{\bar{g}}}{(V_{\bar{g}})_{initial}}\right)$ % x.xxx %

Z_g ✓ y_i (mol-%) ✓

TABLE 6.12—CVD DATA FOR GOOD OIL CO. WELL 7 GAS-CONDENSATE SAMPLE 2*

Wellstream z_{wi} ~ y_i

	Reservoir Pressure, psig							
Component, mol%	5,713**	4,000†	3,500	2,900	2,100	1,300	605	0‡
CO_2	0.18	0.18	0.18	0.18	0.18	0.19	0.21	
N_2	0.13	0.13	0.13	0.14	0.15	0.15	0.14	
C_1	61.72	61.72	63.10	65.21	69.79	70.77	66.59	
C_2	14.10	14.10	14.27	14.10	14.12	14.63	16.06	
C_3	8.37	8.37	8.26	8.10	7.57	7.73	9.11	
i-C_4	0.98	0.98	0.91	0.95	0.81	0.79	1.01	
n-C_4	3.45	3.45	3.40	3.16	2.71	2.59	3.31	
i-C_5	0.91	0.91	0.86	0.84	0.67	0.55	0.68	
n-C_5	1.52	1.52	1.40	1.39	0.97	0.81	1.02	
C_6	1.79	1.79	1.60	1.52	1.03	0.73	0.80	
C_{7+}	6.85	6.85	5.90	4.41	2.00	1.06	1.07	
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	
Properties								
C_{7+} molecular weight	143	143	138	128	116	111	110	
C_{7+} specific gravity	0.795	0.795	0.790	0.780	0.767	0.762	0.761	
Equilibrium gas deviation factor, Z_g	1.107	0.867	0.799	0.748	0.762	0.819	0.902	
Two-phase deviation factor, Z	1.107	0.867	0.802	0.744	0.704	0.671	0.576	
Wellstream produced, cumulative % of initial $\sum_{k=1}\left(\frac{\Delta n_g}{n_d}\right)$		0.000	5.374	15.438	35.096	57.695	76.787	93.515

$r_s \cong \left(\frac{y_{6+}}{1-y_{6+}}\right)\left(\frac{M}{\rho}\right)_{6+} \cdot \frac{10^6}{23.68} \cdot \left[\frac{Sm^3}{10^6 Sm^3}\right]$

Form Surface Condensate "Oil"

Est.

2±

$\left(\frac{\Delta n_g}{n_d}\right)$

$\bar{S}_o \simeq V_{ro}^{CVD}(1-\bar{S}_w)$

25% (1 − 0.2) = 20% $k_{ro} \sim 0$

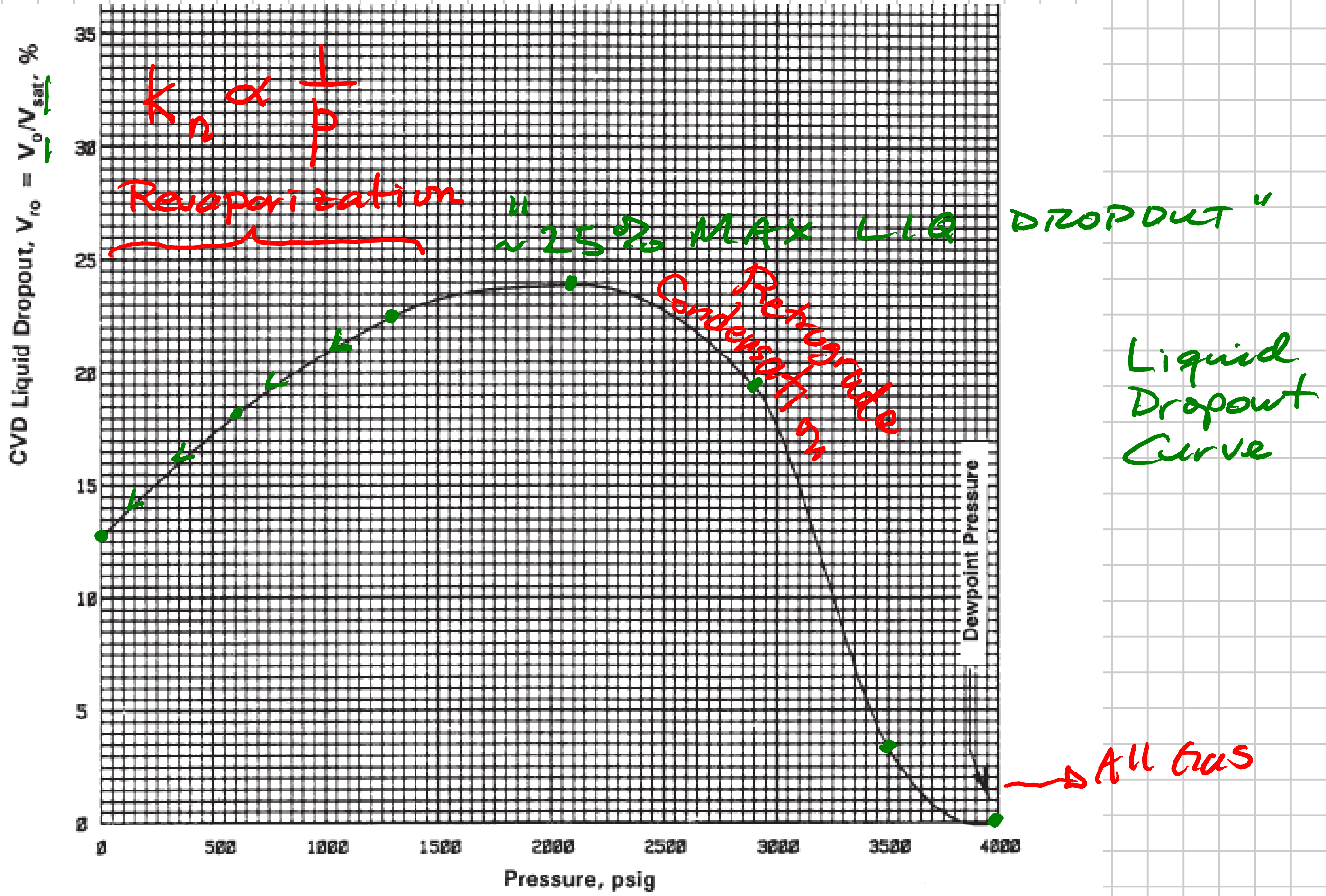


Fig. 6.9A—CVD data for gas-condensate sample from Good Oil Co. Well 7; liquid-dropout curve, V_{ro}.

Component Material Balance "QC" of CVD

— Forward M.B.

· Calc. $x_i(p)$ ... x_{iN} vs Lab x_{iN}

QC

— Backward M.B.

Start Lab x_{iN} + $\{\sum \Delta n_g\, y_i\}$ → $(z_i)_d$ vs Lab $(z_i)_d$

Ask

"C_{6+} mol-%"

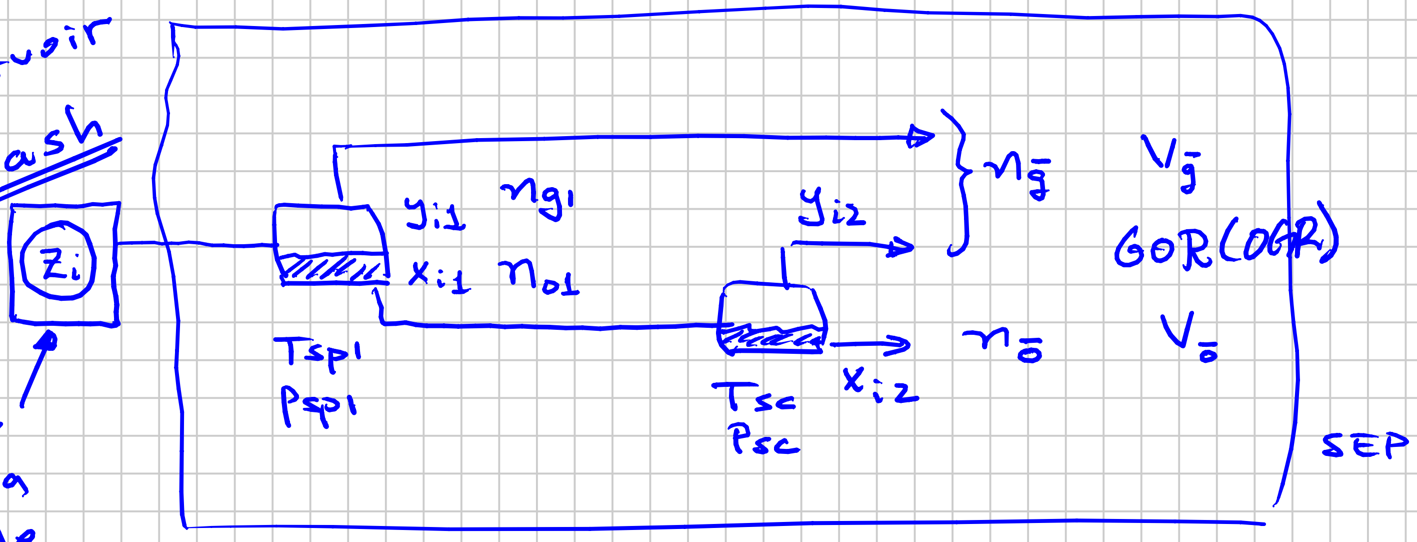
QC

Problem 3 —

Flash Calculation

Multi-Stage Separator Test

Reservoir Flash



Get By a Single Depletion Calculation @TR, p<Ps

$\boxed{P}$

$$\bar{M} = \frac{\sum x_i M_i}{\sum x_i} \quad \begin{matrix} \text{mass} \\ \text{moles} \end{matrix}$$

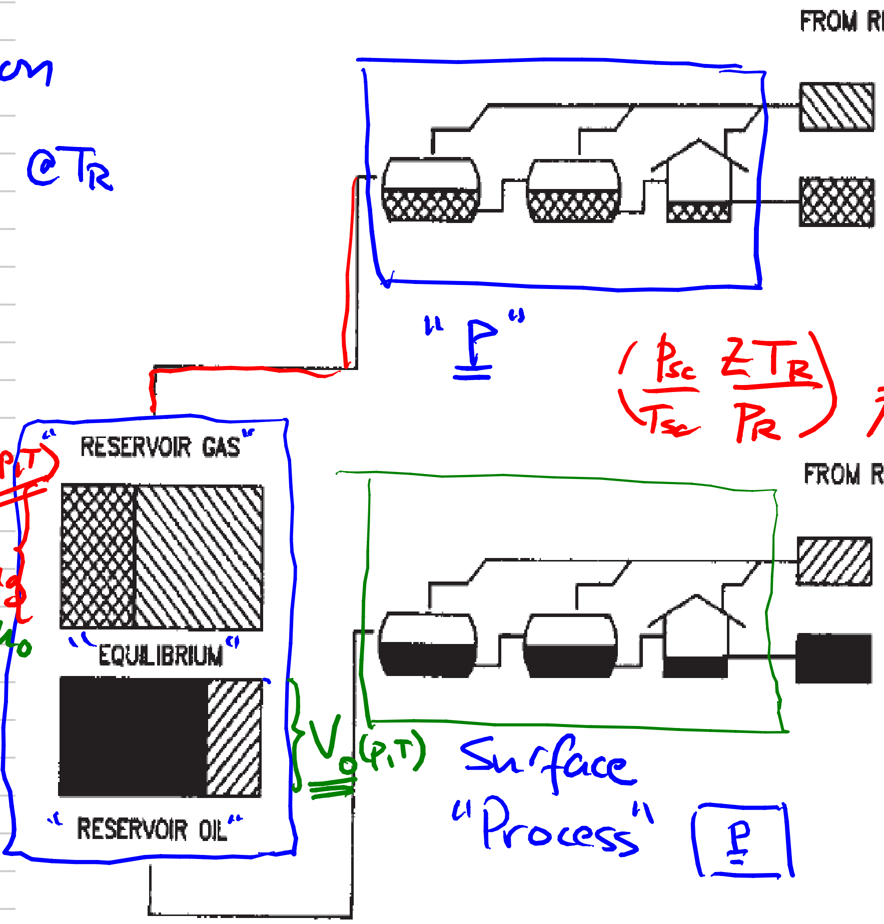
BLACK-OIL PVT PROPERTIES (Ch. 7)

Note Title 2011-10-17

PVT Depletion Test

$\left\{ \begin{array}{l} \text{CCE} \\ \text{CVD} \end{array} \right\}$ @ T_R

(DLE)



$V_g(p,T)$, μ_g, μ_o

(p, T)

(p_R, T_R)

"$\underline{p}$"

SURFACE GAS $(\bar{g})$ $V_{\bar{g}g}$

SURFACE OIL $(\bar{o})$ $V_{\bar{o}g}$

$$r_s \equiv \frac{V_{\bar{o}g}}{V_{\bar{g}g}} \quad \text{OGR}$$

$$\left(\frac{p_{sc}}{T_{sc}} \frac{Z T_R}{p_R}\right) \neq B_{gd} = \frac{V_g(p,T)}{V_{\bar{g}g}}$$

SURFACE GAS $(\bar{g})$ $V_{\bar{g}o}$

SURFACE OIL $(\bar{o})$ $V_{\bar{o}o}$

$V_o(p,T)$

Surface "Process" $\boxed{\underline{p}}$

$$B_o \equiv \frac{V_o(p,T)}{V_{\bar{o}o}}$$

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

BO PVT : Compositional Model with Two Components $\{\bar{g}, \bar{o}\}$

Oil Phase : $B_o(p)$

$R_s(p)$

✓ $\mu_o(p)$

Gas Phase : $B_{gd}(p)$

$r_s(p)$

✓ $\mu_g(p)$

Tables

p	B_o	R_s	μ_o	B_{gd} or $\frac{1}{p}$	r_s	μ_g

SATURATED

UNDERSATURATED $p > p_s$

Surface Gas Density $\rho_{\bar{g}}$ (assumed) constant

Surface Oil Density $\rho_{\bar{o}}$ (assumed) constant

Usage:
Flowing (Darcy)
Remaining (Material Balance)

1. Relate $\boxed{\text{reservoir volumes}}$ of the R gas phase and R oil phase To $\boxed{\text{surface "product" volumes}}$

$3.50/Mscf └ Surface Gas $\bar{g}$

d'Arcy

$114/bbl └ Surface Oil (STO) $\bar{o}$

(2.) Reservoir phase densities $\rho_o(p)$ $\rho_g(p)$

- Vertical Flow (high k)
- Initial estimate S_o(depth) $P_{cow}^{(S_o)} = \left\{ \left[\left(\frac{\rho_w^{\alpha}}{1000} - \rho_o \right) \right] g \right\}$

(3.) Known "Composition" $(V_{\bar{g}}, V_{\bar{o}}) \Rightarrow \frac{V_{\bar{g}}}{V_{\bar{o}}} \equiv R$

gas-oil ratio

R $\{R_s, B_o, r_s, B_{gd}\}$ @ p

"z_i" "K_i"

$\Rightarrow$

- One Phase
  - Gas (V_g)
  - Oil (V_o)

  $\Rightarrow p_s = p$

- Two Phases
  - V_g, V_o

  $\Rightarrow$ "Saturated"

$p = p_s$ Sat. or Underat. $p > p_s$

$$B_{gd} = \frac{p_{sc}}{T_{sc}} \frac{z_g T_R}{p_R} \cdot \frac{1}{f_v}$$

f_v = mole fraction of RG wellstream becoming $\bar{g}$

$\sim 1 - y_{c6+}$ ← Reservoir Gas composition

0.01 – 0.15

Surface Gas Density $\rho_{\bar{g}}$ (assumed) constant

Surface Oil Density $\rho_{\bar{o}}$ (assumed) constant

$\rho_{\bar{o}o} \neq \rho_{\bar{o}g}$ Physically

$\rho_{\bar{g}o} \neq \rho_{\bar{g}g}$ — " —

ECL100, PROSPER, MBAL, OLGA ....

$\rho_{\bar{o}}$ = const

$\rho_{\bar{g}}$ = const

Calculate Reservoir Phase Densities:

Data
EOS
"Actual"

$$\rho_o(p) = \frac{\rho_{\bar{o}} + \rho_{\bar{g}} R_s(p)}{B_o(p)} \quad \underline{vs} \quad \rho_o(p)$$

$$\rho_g(p) = \frac{\rho_{\bar{g}} + \rho_{\bar{o}} r_s(p)}{B_{gd}(p)} \quad \underline{vs} \quad \rho_g(p)$$

You will "get" or "steal" $\rho_{\bar{o}}$ $\rho_{\bar{g}}$

Minimize difference in $\rho_o^{BO}(p)$ & $\rho_o^{\substack{Lab\\EOS}}(p)$

— " — & $\rho_g^{BO}(p)$ & $\rho_g^{EOS}(p)$

$\boxed{\rho_{\bar{g}} \mid \rho_{\bar{o}}}$

SSQ
min

$$\sum_{n=1}^{10} \left[\frac{\rho_o^{BO}(p_n) - \rho_o^{EOS}(p_n)}{\max\{\rho_o^{EOS}\}} \right]^2 w_o + \left[\frac{\rho_g^{BO}(p_n) - \rho_g^{EOS}(p_n)}{\max\{\rho_g^{EOS}\}} \right]^2 w_g$$

10 p's in depletion test

$\boxed{\rho_{\bar{o}}}$ $\boxed{\rho_{\bar{g}}}$

min $\boxed{}$ SSQ_{total}

p	B_o	R_s	B_{gd}	r_s	ρ_o^{BO}	ρ_g^{BO}	ρ_o^{EOS}	ρ_g^{EOS}	SSQ
									–
									–
									–
									–
									–
									–
									–

PROBLEM 3 SOLUTION TECHNIQUE

Note Title 2011-10-20

- Rachford-Rice Flash (p, T, z_i) ✓
  - Multiple times to solve different
- Two-stage separator test
  - Several times (4)

  $\Big\}$ $8 = 4 \times 2$
- Black-Oil PVT Properties

  $\underbrace{B_o \quad R_s}$ μ_o $\underbrace{B_{gd} \quad r_s}$ μ_g — Plot from .out PhazeComp Calcs.

(a) ✓2 oils @ p_R, T_R ✓2 gases @ p_R, T_R

Using Flash Calculation $\Big\}$ Teach the mechanics of calculation

(b) Complete table from .out file
- Basic calculations
- Plotting

$\Big\}$ ✓

$B_o(p)$

$R_s(p)$

$B_o(R_s)$

$\mu_o(p)$

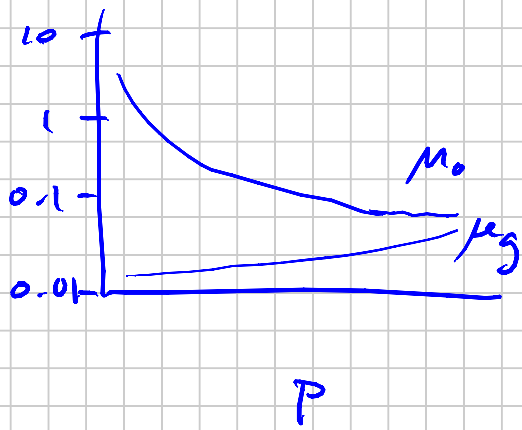
log $\mu(p)$

$B_{gd}(p)$ — log $B_{gd}(p)$

$\frac{1}{B_{gd}} \equiv b_{gd}(p)$

$\mu_g(p)$

$r_s(p)$



"BO PVT"

Depletion Test @ T_R $\quad p_s < p < p_{low} \sim p_{sp}$

$\left\{ \begin{array}{l} \text{CCE} \\ \text{CVD} \end{array} \right\}$

DLE

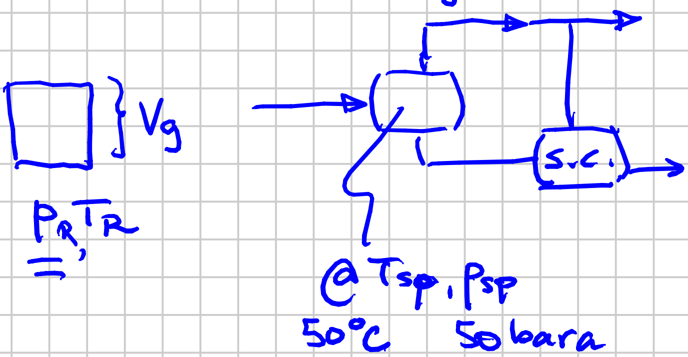
Gas $\quad y_i(p)$

Oil $\quad x_i(p)$

$\}$ Equilibrium reservoir phases

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

Gas : $\quad y_i$



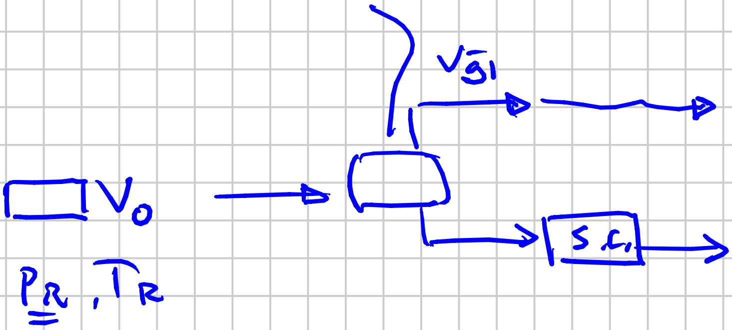
$V_{\bar{o}}$

$B_{gd}(p)$

$r_s(p)$

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

Oil : $\quad x_i$



$V_{\bar{o}}$

$B_o(p)$

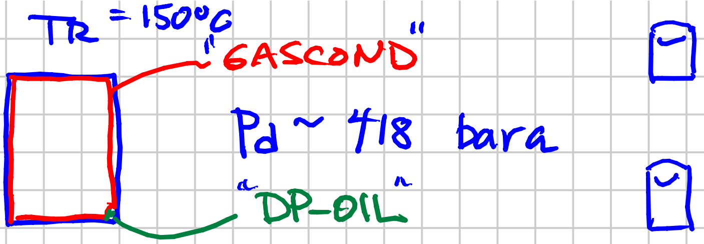
$R_s(p)$

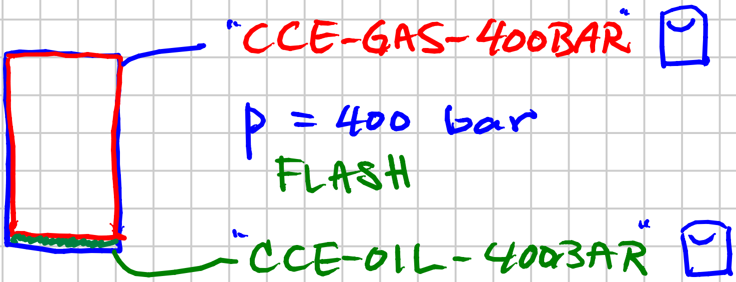
Problem 3 Data

- "Gas Condensate" fluid used in Problem 2.
- $T_R = 150\,°C$ $\quad (p_d \sim 418$ bara$)$ $\quad p_{Ri} = 600$ bara
- $T_{sp1} = 50\,°C$

  $p_{sp1} = 50$ bara
- CCE depletion test $\Rightarrow$ $y_i(p)$ ✓ $\quad x_i(p)$ ✓ $\quad$ @ $T_R = 150\,°C$

  $\underset{\text{bara}}{75} < p \leq p_d$





:

350

300

250

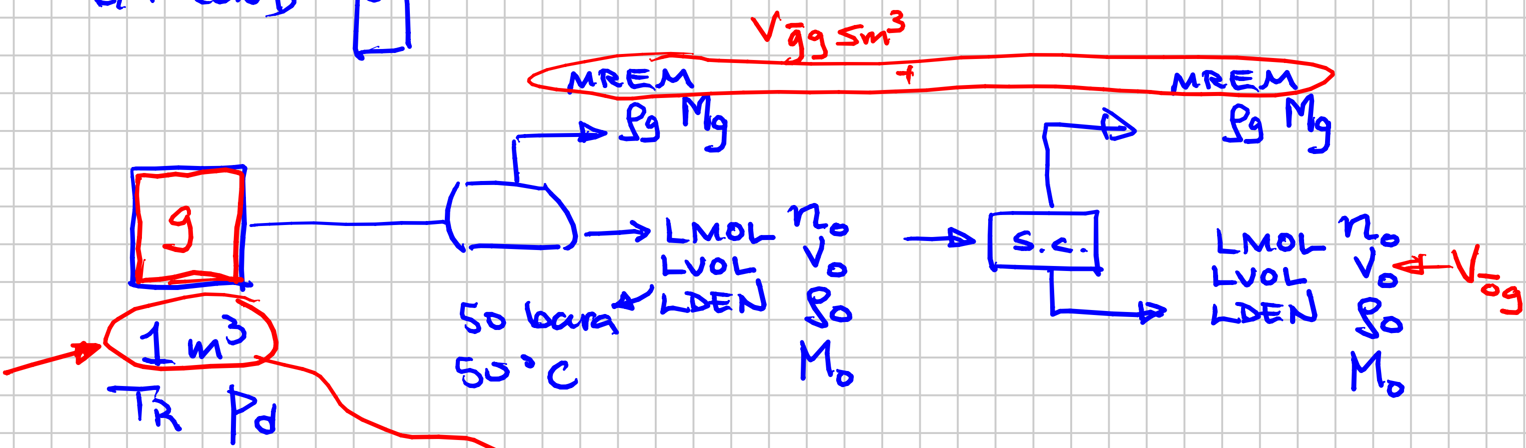
200

150

100

75

GASCOND



"dry" surface gas

$$B_{gd} = \frac{V_g(p_d, T_R)}{V_{\bar{g}g}}$$

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

$$V_{\bar{g}g} = 223.3 \text{ Sm}^3$$

$$V_{\bar{o}g} = 0.2144 \text{ Sm}^3$$

$$r_s = \frac{0.2144}{223.3}$$

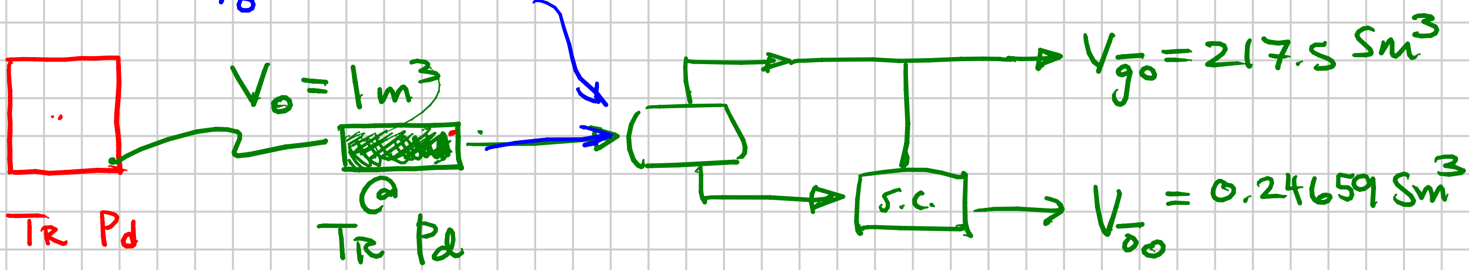
$$B_{gd} = \frac{1 \text{ m}^3}{223.3 \text{ Sm}^3} = 0.00447 \frac{\text{m}^3}{\text{Sm}^3}$$

$$= 9.60 \cdot 10^{-4} \text{ Sm}^3/\text{Sm}^3$$

$$= 960 \text{ Sm}^3 / 10^6 \text{ Sm}^3$$

$$\rho_{\bar{o}g} = 803 \text{ kg/m}^3$$

$V_o = 0.8818\,m^3$



μ_o

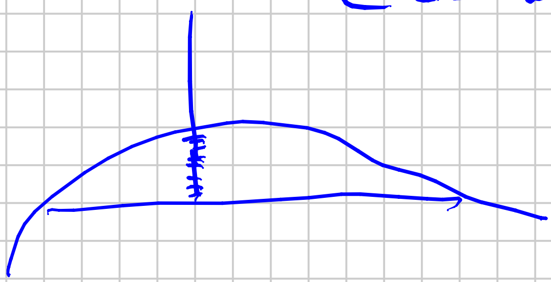
μ_g

Saturated $B_o = \dfrac{V_o}{V_{\bar{o}o}} = \dfrac{1}{0.24659} = 4.055\ \dfrac{m^3}{Sm^3}$

$$R_s = \frac{V_{\bar{g}o}}{V_{\bar{o}o}} = \frac{217.5}{0.24659} = 882\ \frac{Sm^3}{Sm^3}$$

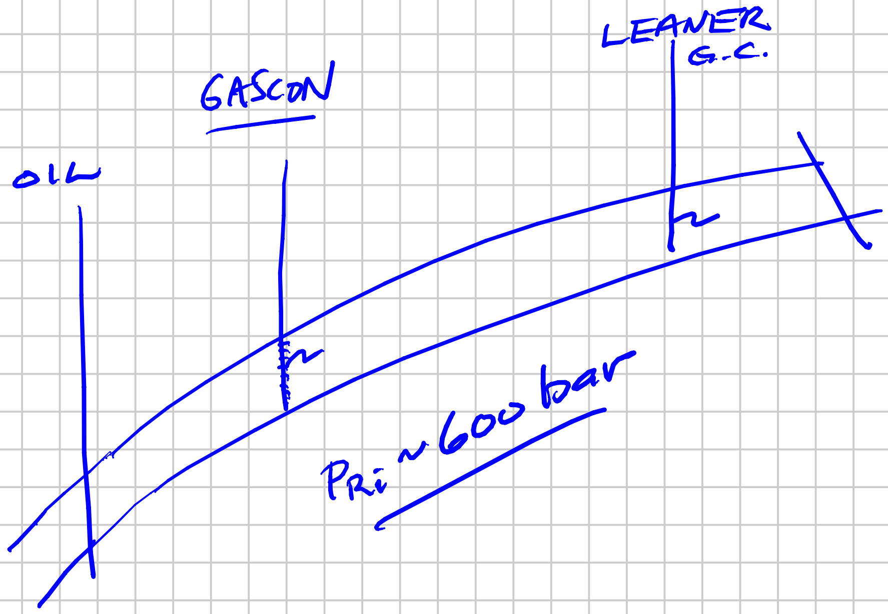
Undersated B_o @ 600 bara $= \dfrac{V_{oi}(600\,bar, T_R)}{V_{\bar{o}o}} = \dfrac{0.8818\ m^3}{0.24659\ Sm^3}$

$$B_{oi} = 3.576\ \frac{m^3}{Sm^3}$$



$V_{oR_i} = V_{p\,est} \times (1-\bar{S}_w)$

$$IOIP = N = \frac{V_{oRi}}{B_{oi}}$$


OIL
GASCON
LEANER G.C.
Pr i ~ 600 bar

GAS WELL & RESERVOIR PERFORMANCE

Note Title 2011-11-14

$600 \le \rho_{\bar{o}} \le \rho_w = 1000$

$\gamma_{API} = \dfrac{141.5}{\gamma_{\bar{o}}} - 131.5$

$0.5 \le \rho_{\bar{g}} \le 2.5$ kg/m^3

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

$\rho_{\bar{g}min} = \rho_{air} \cdot \gamma_{\bar{g}min}$

C_r 1.22 kg/m^3 0.55

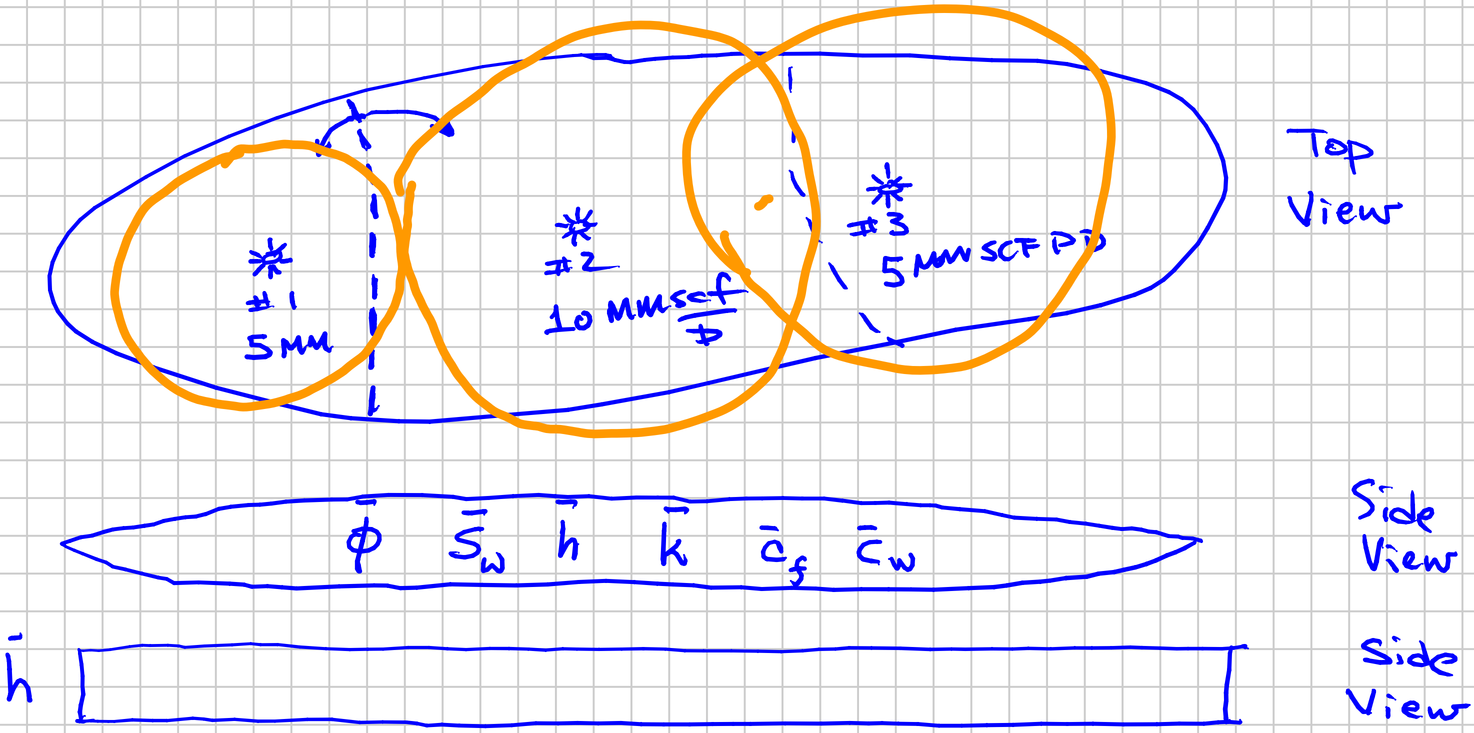
$\rho_{\bar{g}max} = \rho_{air} \cdot \gamma_{\bar{g}max}$

2

$10 \le \gamma_{API} \le 100$

$\gamma = 1$ $\rho = 1000$ kg/m^3

$\rho \sim 600$ kg/m^3



Assume:

- Uniform rock, water, gas properties Spatially
- k is sufficiently high ($\gtrsim 1$ md) to guarantee "pseudosteady state" (PSS) flow conditions ~within a month

$$\frac{A_w(t)}{A_F} \sim \frac{q_w(t)}{q_F(t)}$$

- Without any significant error you can assume a RADIAL drainage geometry

Actual A_w = πr_e^2

Exact by introducing a small "geometric skin" term $s_G \lesssim 1$

- Average pressure in each well's drainage area (volume) is always the same

$\bar{p}_R$: Volumetric average

Well Performance

Reservoir Performance

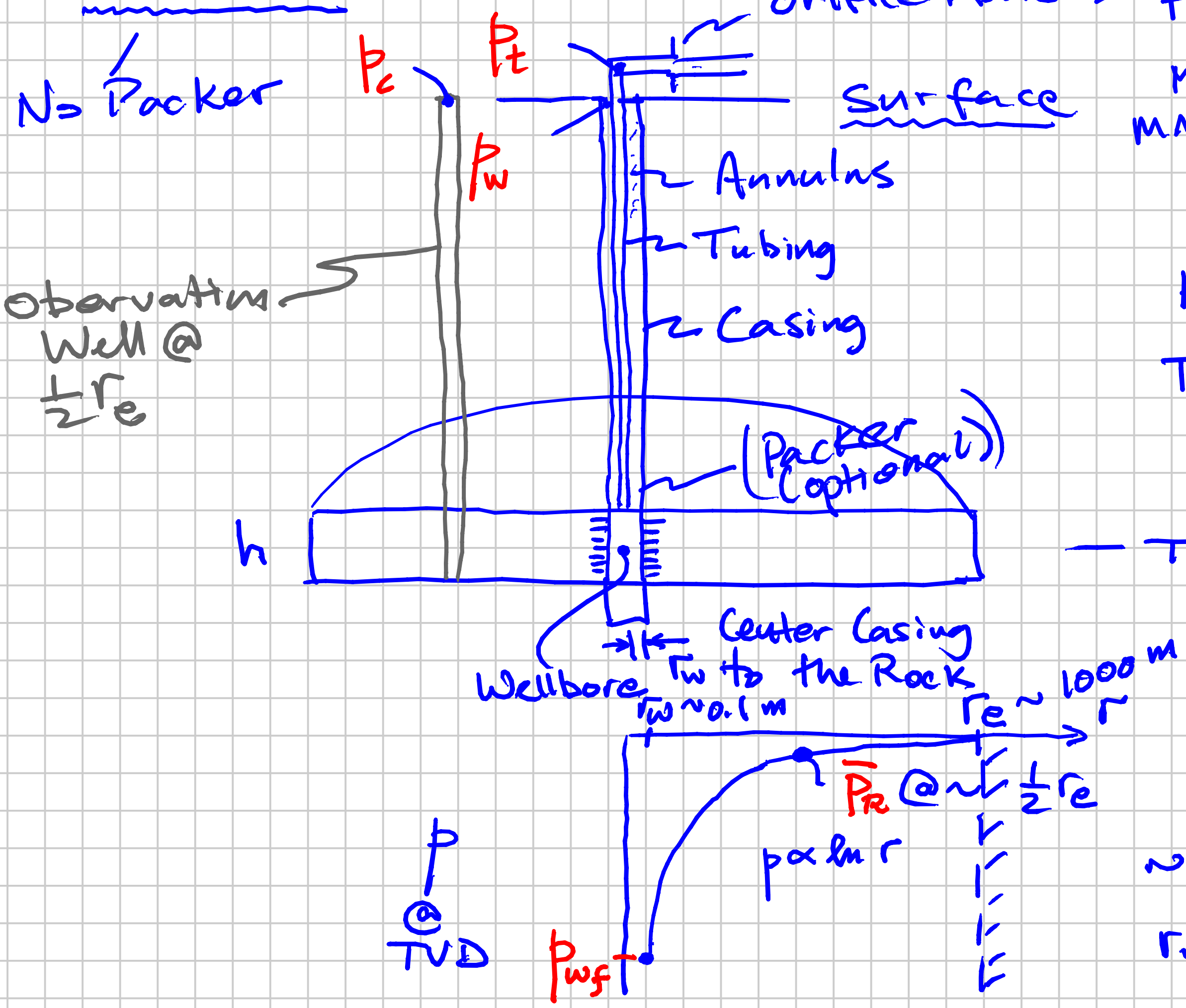
- q_g = Well Gas Rate Sm^3/d or scf/D

- G_p = cumulative gas produced (Field ; or Well)

- G = initial gas in place

- $RF_g \equiv \frac{G_p}{G}$

- Pressures in a Well



Sm^3/d

scf/D

Mscf/D = $10^3 \frac{scf}{D}$

MMscf/D = $10^6 \frac{scf}{D}$

bcf = 10^9 scf

Tcf = 10^{12} scf

— TVD (SSL)

Relative to S.L.

$\sim 90\% \, (p_e - p_{wf})$

$r_w \to 10$ m

p_{wf} = BHFP = bottomhole (wellbore) flowing p

$\bar{p}_R$ = BHSIP = volumetric average p

p_t = FTP = flowing tubing p

p_w = FCP = flowing annulus p

p_c = shutin pressure of observation well @ surface = shutin of p_t, p_w

$(p_t)_{SI} = (p_w)_{SI} = p_c$

Note Title 2011-11-17

GAS RESERVOIR & WELL PERFORMANCE

@Res H | @Surface

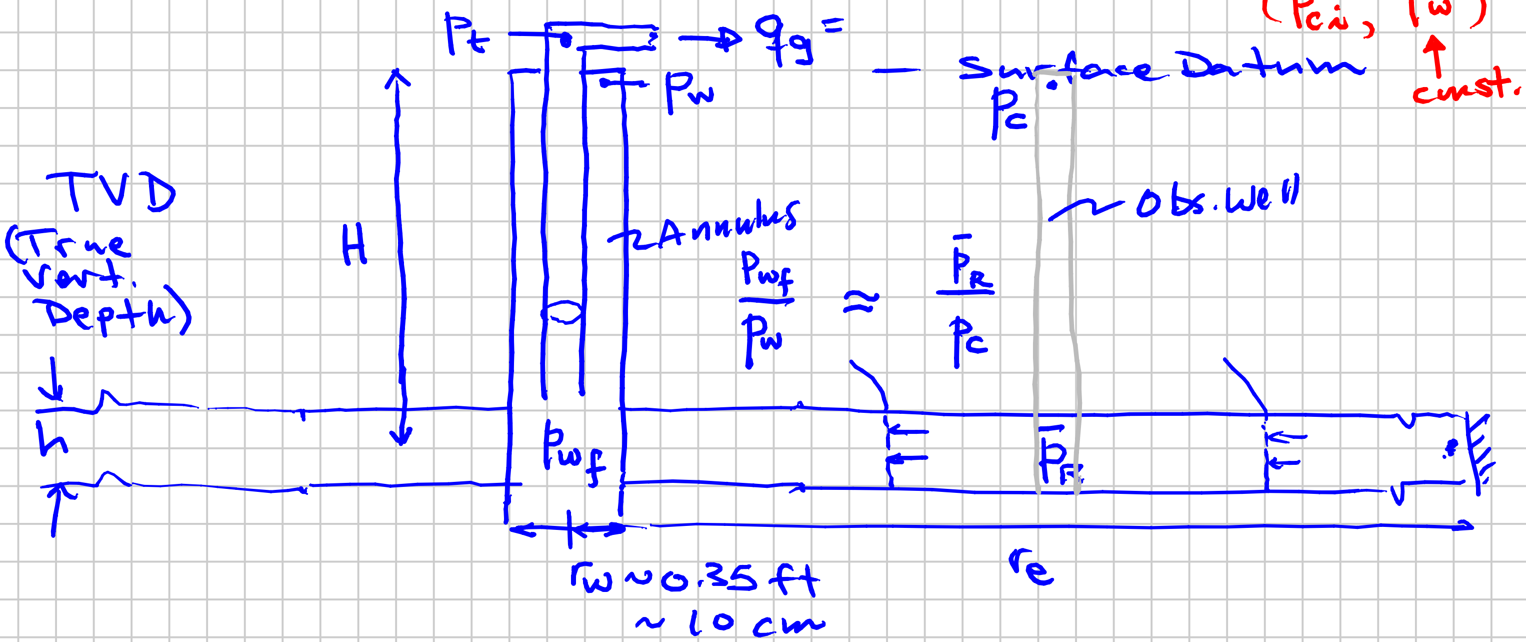
1. GAS Reservoir Material Balance $\bar{p}_R$ (p_c)

2. Gas Reservoir Rate Equation(s) $(\bar{p}_R, p_{wf})$ (p_c, p_w)

3. Gas Tubing Rate Equation (p_{wf}) (p_w, p_t)

4. "Composite" Wellhead (R+T) Backpressure Rate Eq. (p_c, p_t)

5. Gas (Pseudosteady State) Decline Curve Analysis (p_{ci}, p_w)



Everywhere in the System: Steady State Flow

Production + Reservoir (+ Process) Engineering Team:

Forecasting $q_g(t)$

- Well
- Σ Well = Field

Gas M.B.

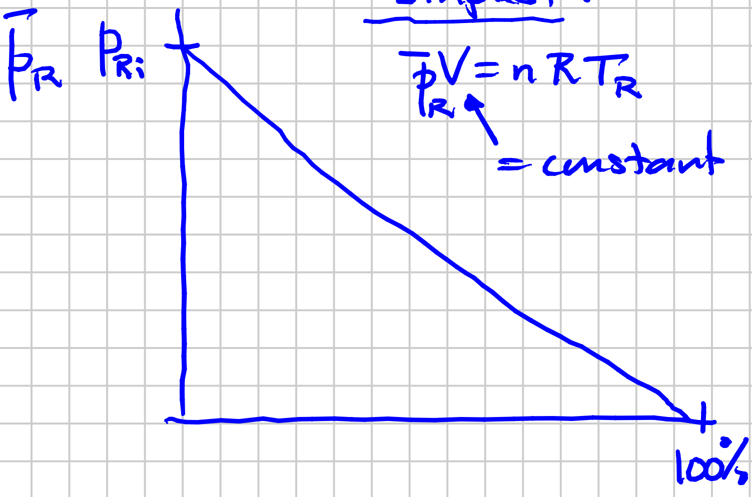
$$\bar{p}_R = f\left(\frac{G_p}{G}\right)$$

$\frac{G_p}{G}$ ← Recovery Factor of Gas

Simplest:

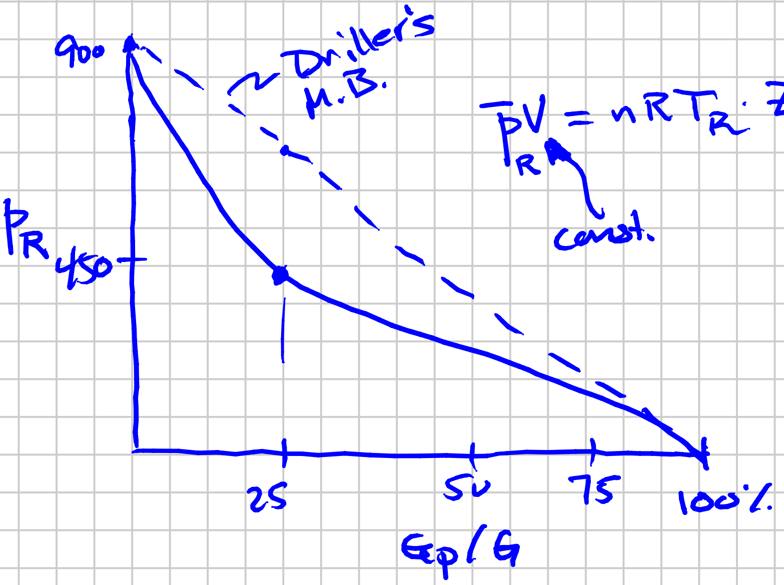
$\bar{p}_R V = nRT_R$

$\bar{p}_R$ = constant



$\bar{p}_R V = nRT_R \cdot Z_g(p)$

$\bar{p}_R$ const.



Realistic Gas Mat. Bal.

(a) $\underline{V_g}$ = HCPV = hydrocarbon (Gas) Pore Volume = const.

$c_f = (c_p) \sim 0$

$c_w \sim 0$

$p_R \cdot \overset{\checkmark}{V_g} = n_R \cdot \overset{\checkmark}{R}\overset{\checkmark}{T_R}\, Z(p_R)$ @ any pressure

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

n_{gi} ← $G/23.68$ $\qquad$ n_{gp} ← $\underline{G_p}/23.68$ $\qquad$ $23.68 = \frac{R\,T_{sc}}{p_{sc}}$

$$\frac{p_R}{Z_R(p_R)} = \left(\frac{G - G_p}{23.68}\right) RT_R / V_g$$

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

Straight-Line Gas. Mat. Bal.

(b) "Pot Aquifer" Model

$V_{gi} = V_{pR}(1 - S_{wc})$

– HCPV = $V_g(p_R)$

- Pore volume reduction $c_f(p_{Ri} - \bar{p}_R) \cdot V_{pRi}$

$S_{wc} \sim \bar{S}_w$ (In the V_{pR})

- Connate Water expands $c_w(p_{Ri} - \bar{p}_R)V_{pRi} \cdot S_{wc}$

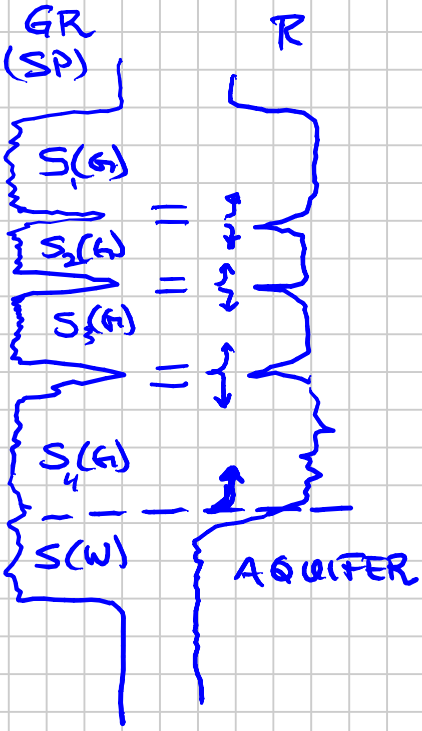
  Water sharing the pores with the reservoir gas

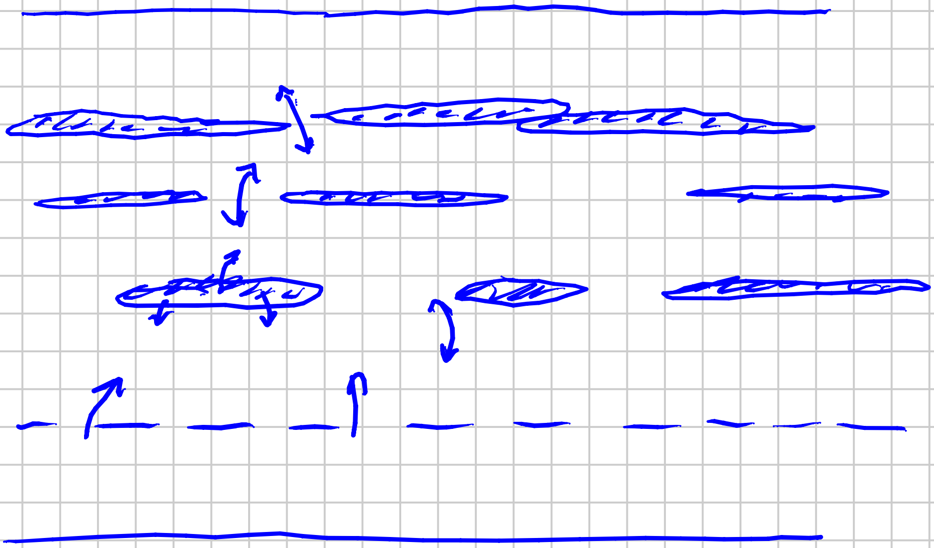
- External Water Encroachment

  Outside "V_{pR}"

  – Aquifer

  – Non-Net (Dirty sand/shale) interbedded layers





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

$$\bar{c}_e = \frac{c_f + c_w S_{wc} + M\left(c_f + c_w\right)}{1-S_{wc}}$$

$$M = \frac{V_{NNP} + V_{AQ}}{V_{PR}} \sim \underline{0.5-5}\ (10) \quad ?\pm$$

$c_f \sim 3-6 \cdot 10^{-6}$ 1/psi $\frac{vol}{vol}\cdot\frac{1}{psi}$

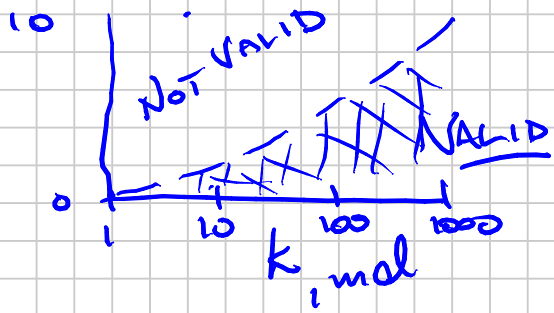
$c_w \sim 3-6 \cdot 10^{-6}$ 1/psi

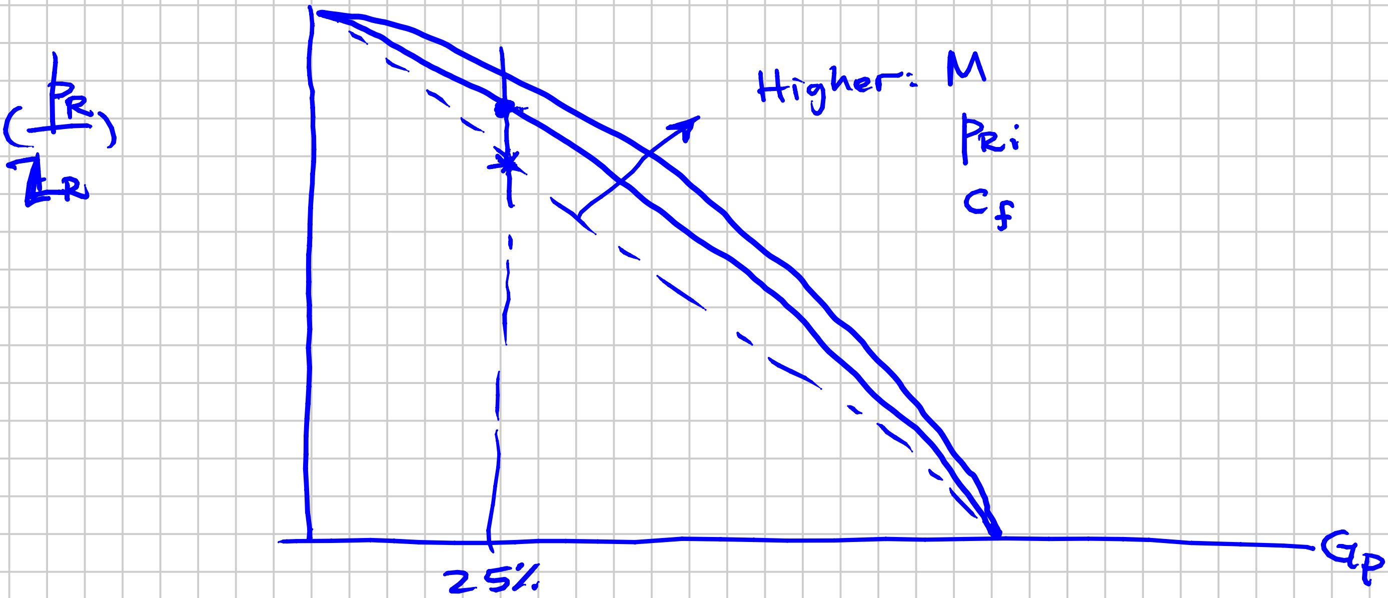
$S_{wc} \sim 0.05-0.4$

<u>VALID</u>:

- High $k > 10$ md
- Lower V_{AQ}

  $M_{AQ} = V_{AQ}/V_{PR}$
- $\Delta p_{Rg} \sim 10$ psi/mo $\Delta p_{AQ,NNP} \sim 9$ psi/mo



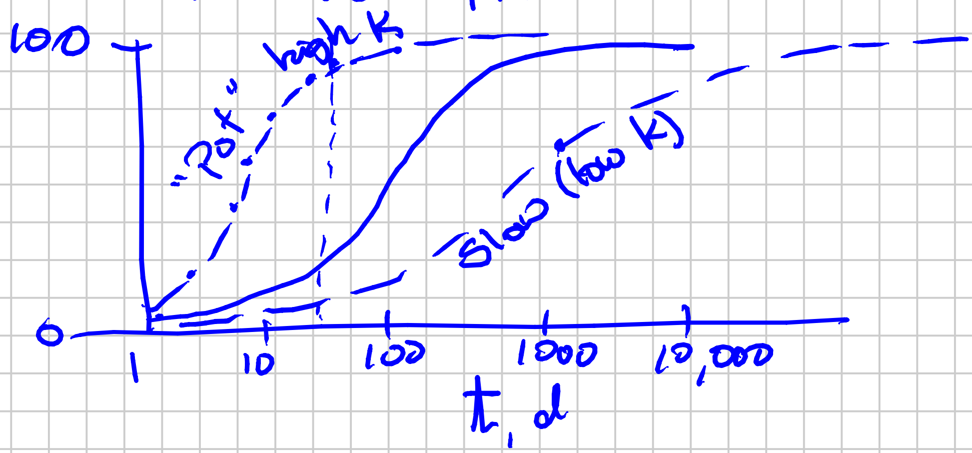


NOT VALID:

- Transient Aquifer Model
  - PSS Fetkovich
  - van Everdingen-Hurst (Infinite-Acting + PSS)
  -

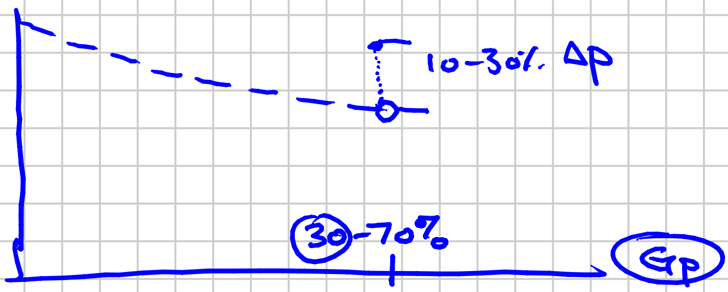
W_e = volume of water encroaching into the V_{pR}

$$\frac{\left(\frac{\Delta W_e}{\Delta t}\right)}{\left(\frac{\Delta W_e}{\Delta t}\right)_{Pot\ Model}} \%$$



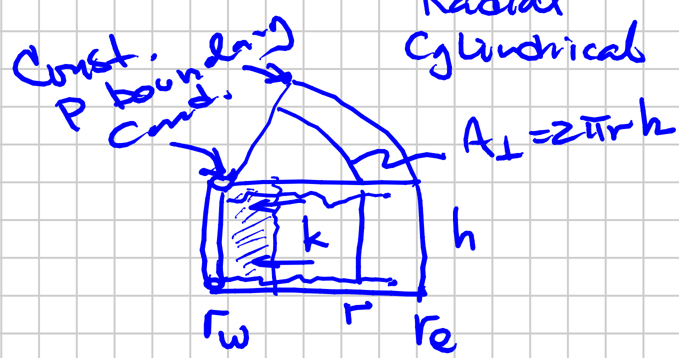
Extreme Aquifers: $k > 500$ md $\rightarrow$ 5000 md +

Large $\underline{\underline{M}}$ $\quad \frac{p_R}{z_R}$



GAS RATE EQ (RESERVOIR)

Radial Cylindrical



Darcy's Law

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

"Laminar-like flow"

Forcheimmer Law

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

Rock property: β

"Laminar" "Turbulent"

HVF

Darcy Eq.

$m^3/s \quad m/s \quad m^2$

$$q_{gR} = v \cdot A_\perp = 2\pi r h v \qquad @ \; p, T_R \qquad p_e \to p_{wf}$$

"Darcy" velocity

$$\left\{ v_{true} = v/\phi \right\}$$

Steady State Flow: q_m = const everywhere

$$\rho_g = \frac{p M_g}{R T_R Z}$$

$$q_{gm} = q_{gR} \cdot \rho_g(p(r)) = \text{const}$$

$$= \frac{k}{\mu} \cdot \frac{dp}{dr} \cdot 2\pi r h \cdot \frac{p M}{R T_R Z}$$

Surface Gas Rate q_g @ T_{sc}, P_{sc} =

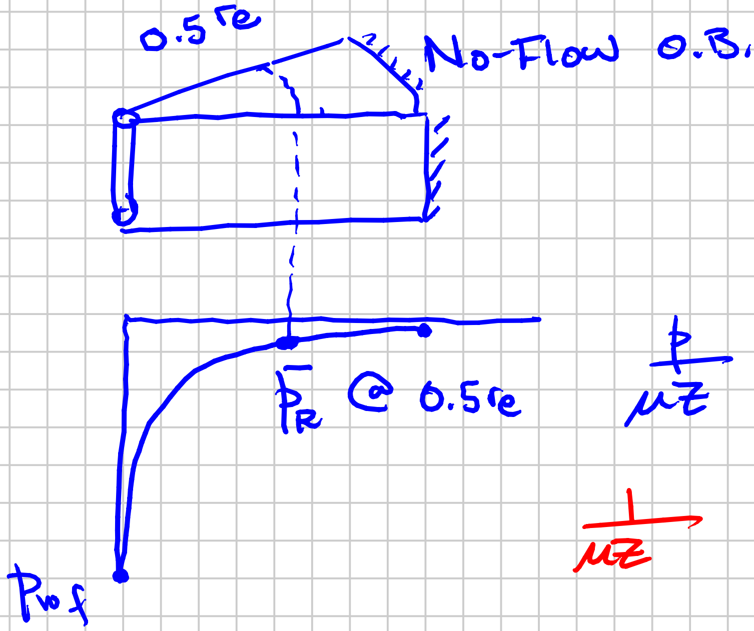
$$q_g = \underbrace{q_{gm}}_{q_{gmolar}} \cdot \frac{1}{M_g} \cdot \underbrace{\frac{R\,T_{sc}}{P_{sc}}}_{23.68}$$

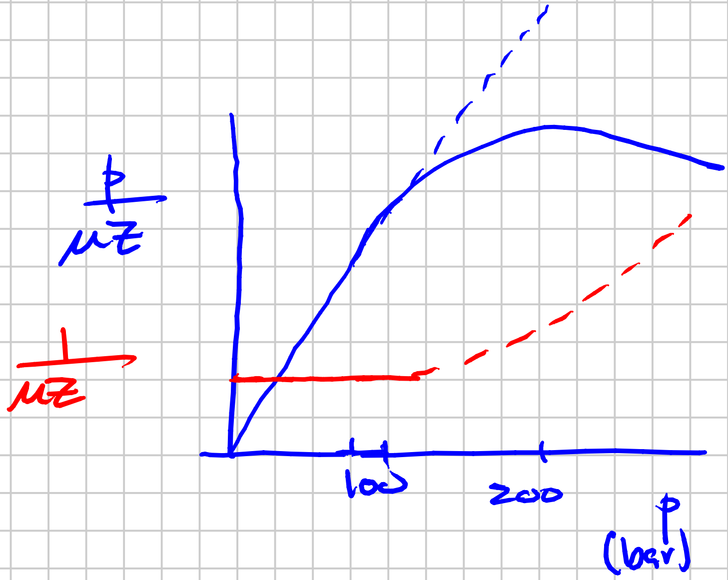
$$q_g = \left\{ \frac{k}{\mu} \frac{dp}{dr} \cdot 2\pi r h \frac{pM}{RT_R Z} \right\} \cdot \frac{1}{M} \cdot \frac{R\,T_{sc}}{p_{sc}}$$

$$q_g = 2\pi \left(\frac{T_{sc}}{p_{sc}}\right) \cdot \frac{kh}{T_R} \cdot \frac{p \cdot r}{\mu Z} \frac{dp}{dr}$$

$$q_g \cdot \underbrace{\int_{r_w}^{r_e} \frac{1}{r} dr}_{\ln r_e/r_w} = 2\pi \left(\frac{T_{sc}}{p_{sc}}\right) \frac{kh}{T_R} \int_{P_{wf}}^{P_e} \frac{p}{\mu Z} dp$$

$$q_g = \frac{2\pi (T_{sc}/P_{sc})\, kh}{T_R \cdot \ln r_e/r_w} \cdot \int_{P_{wf}}^{p_e} \frac{p}{\mu Z} dp$$





No Flow O.B.

$$q_g = \frac{2\pi (T_{sc}/p_{sc})\, kh}{T_R\left[\ln \frac{r_e}{r_w} - \frac{3}{4}\right]} \cdot \int_{p_{wf}}^{\bar{p}_R} \frac{p}{\mu Z}\, dp$$

Low Pressures:

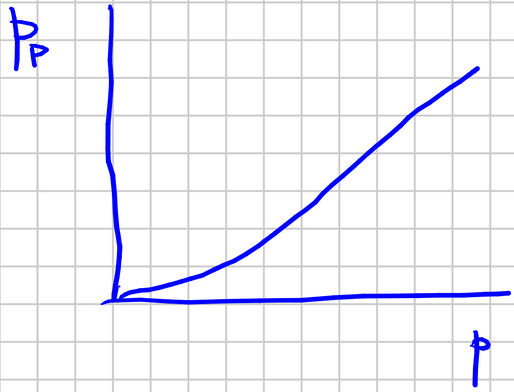
$$\int \frac{p}{\mu Z}\, dp \sim \int_{p}^{\bar{p}_R} \alpha p\, dp \rightarrow \underbrace{\frac{1}{(\mu Z)^*} \frac{1}{2}(\bar{p}_R^2 - p_{wf}^2)}_{} \qquad \boxed{\ln \frac{1}{2}\frac{r_e}{r_w} = \ln \frac{r_e}{r_w} - \frac{3}{4}}$$

Low-Pressure ($p \lesssim 2000$ psia)

$$\boxed{q_g = \frac{\{\pi (T_{sc}/p_{sc})\}\, kh\, (\bar{p}_R^2 - p_{wf}^2)}{T_R (\mu Z)^* \left[\ln \frac{r_e}{r_w} - \frac{3}{4}\right]}}$$

Introduce: Hussainy & Ramey & Crawford
Gas Pseudopressure Function

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



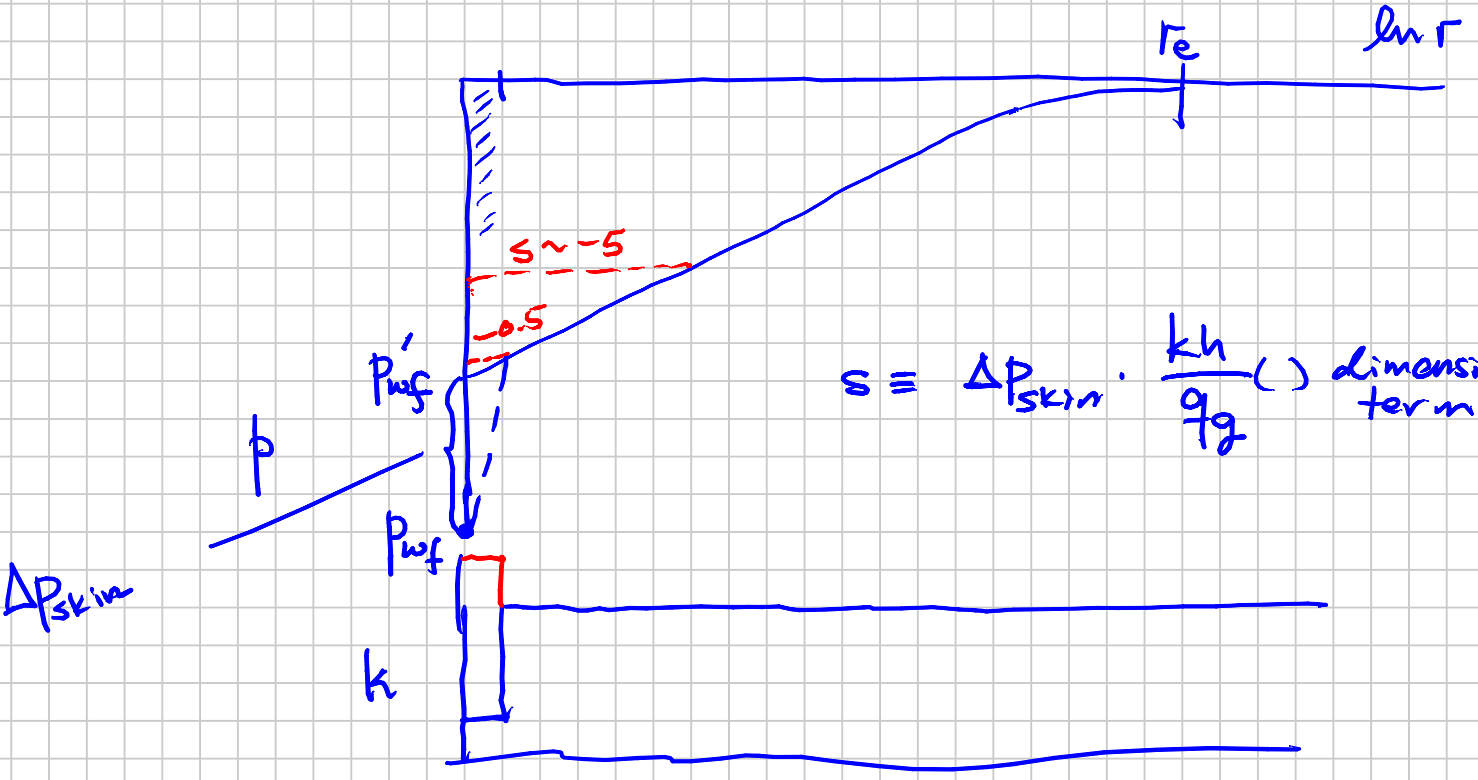
$$\int_{p_{wf}}^{p_R} = \int_0^{p_R} - \int_0^{p_{wf}}$$

$$= p_{pR} - p_{pwf}$$

$$\boxed{q_g = \frac{\{\pi (T_{sc}/p_{sc})\}\, kh\, (p_{pR} - p_{pwf})}{T_R \left[\ln \frac{r_e}{r_w} - \frac{3}{4}\right]}}$$

Quan	Numerical Constant	Units	Numerical Constant	
q_g		scf/D		Sm^3
k		md		md
h	0.703	ft	7.7	m
p		psia		bar
T_R		°R		K
μ		cp		cp

Concept of Skin (Hawkins, Craft)



$$s \equiv \Delta p_{skin} \cdot \frac{kh}{q_g} (\ ) \text{ dimensionless term}$$

$+1 \rightarrow +100$

$-0.5 \rightarrow -5$

$s > 0: \quad k(r_w \rightarrow r_{altered}) < k$

$s < 0: \quad k(\text{— '' —}) > k$

$$\boxed{q_g = \frac{7.7\ kh\ (P_{PR} - P_{pwf})}{T_R \left[\ln \frac{r_e}{r_w} - \frac{3}{4} + s\right]}}.$$

Forcheimmer

$$s = s^* + D\, q_g \quad ; \quad D \propto \beta$$

Steady State Constant

Constant

$$B\, q_g^2 + \underbrace{A\, q_g - (P_{PR} - P_{pwf})}_{\text{Darcy}} = 0$$

$$A = \frac{T_R \left[\ln \frac{r_e}{r_w} - \frac{3}{4} + s^*\right]}{7.7 \cdot kh}$$

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

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

GAS RATE EQUATIONS

Note Title 2011-11-21

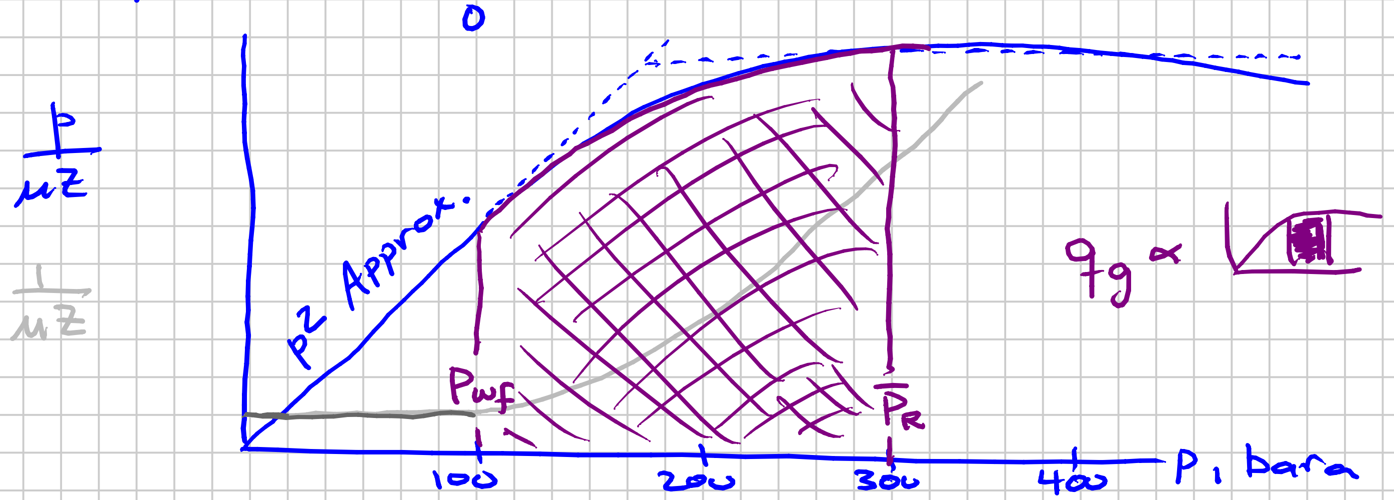
Summary Reservoir Rate Eqs.:

$$q_g = \frac{\alpha \, kh}{T_R \left[\ln \frac{r_e}{r_w} - \frac{3}{4} + s_t \right]} \cdot 2 \int_{p_{wf}}^{\bar{p}_R} \frac{p}{\mu Z} \, dp$$

SI-Like Units		Field Units	Fetkovich
7.7	α	0.703	$\frac{1}{\alpha} = \frac{1000}{0.703} = 1424$
(std m³/d) Sm³/d	q_g	scf/D	Mscf/D
md	k	md	md
m	h	ft	ft
bara	p	psia	psia
cp	μ	cp	cp
K	T_R	°R	°R
–	Z	–	dimensionless
–	r_e/r_w	–	dimensionless
–	s_t	–	dimensionless

Gas Pseudopressure Function p_p : $m(p)$

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



Low-Pressure ("Pressure-Squared Approx.)

$$q_g = \frac{\alpha\, kh \cdot (p_R^2 - p_{wf}^2)}{T_R\, (\mu z)^* \left[\ln \frac{r_e}{r_w} - \frac{3}{4} + s_t\right]}$$

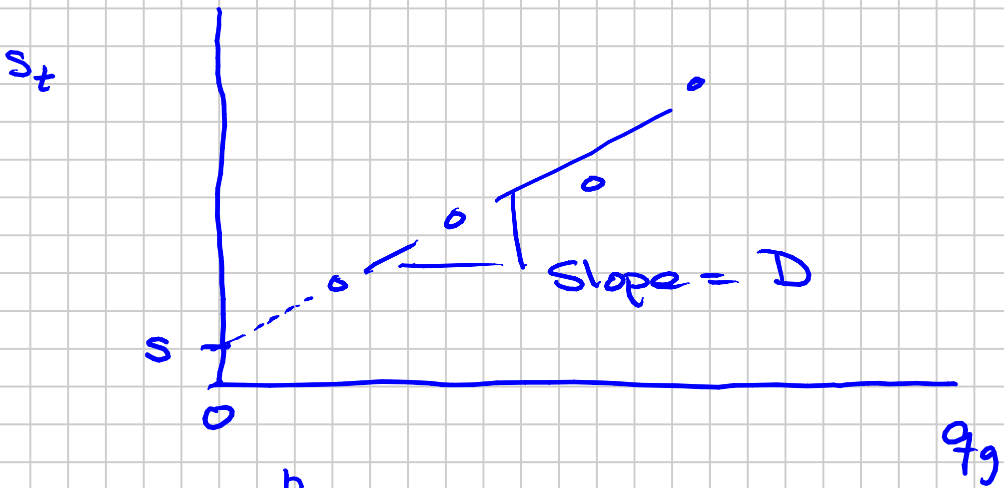
~

Forcheimmer (non-Darcy)

$$s_t = \underset{\text{const.}}{s} + \underset{\substack{\text{rate-dependent} \\ \text{skin constant}}}{D\, q_g}$$

$D \propto \beta$ [rock prop]

[$1/\text{Sm}^3/\text{d}$, $1/\text{scf/D}$]



$p_{R,est}$

Test	q_g	p_{wf}	s_t (PTA)
1			
2			
3			
4			

$\Rightarrow$ Multi-Point Test

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

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

$$A = \left\{ \frac{\alpha\, kh}{T_R \left[\ln \frac{r_e}{r_w} - \frac{3}{4} + s\right]} \right\}^{-1}, \quad B = \frac{T_R}{\alpha\, kh} D$$

Tubing Rate Equation

$$\boxed{q_{tg} = C_T \left(p_w^2 - p_t^2 \right)^{0.5}}$$

Inflow Outflow

$$\frac{q^2}{C_T^2} - \left(P_w^2 - P_t^2\right) = 0$$

Friction Loss Equation

$$C_T = f\left(S,\ d_T,\ \bar{Z},\ \bar{T}\right) = \left[\frac{31.62\, e^{S/2}}{\left(e^S - 1\right) F_r\, \bar{T}\, \bar{Z}}\right]$$

Mscf/D + Field

Static Gas Column term

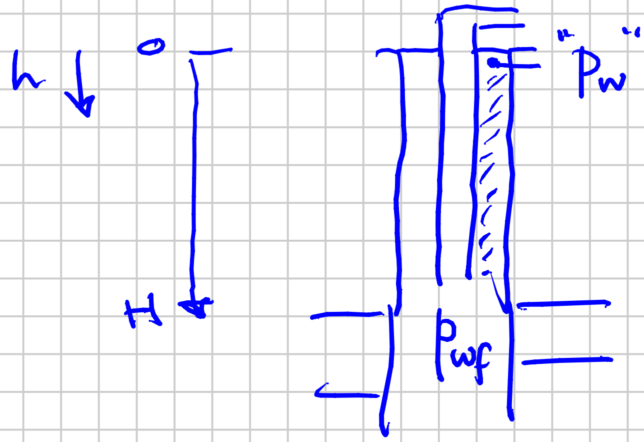
$$F_r \sim \frac{0.1}{d_{T[in]}^{2.612}}$$

$$\frac{dp}{dh} = \rho_g g \qquad \rho_g \cong \frac{M}{R \bar{T} \bar{Z}} \cdot p$$

h : true vertical depth

$$\frac{dp}{dh} = \frac{Mg}{R\bar{T}\bar{Z}}\, p$$

$$\int_{P_w}^{P_{wf}} \frac{1}{p}\, dp = \left(\frac{Mg}{R\bar{T}\bar{Z}}\right) \int_0^H dh$$



$$\ln \frac{P_{wf}}{P_w} = \left(\frac{Mg\,H}{R\bar{T}\bar{Z}}\right) \equiv \frac{S}{2} \Rightarrow \boxed{S \equiv 2 \cdot \frac{Mg\,H}{R\bar{T}\bar{Z}}}$$

Consistent Metric Units

$$\underbrace{(\bar{T}\bar{Z})_{\text{Annulus}} \sim (\bar{T}\bar{Z})_{\text{observation Well @ } \frac{1}{2} r_e}}_{\sim \text{ same } S}$$

$$\frac{P_{wf}}{P_w} = e^{S/2} = \frac{p_c}{P_R} \quad ; \quad e^{S/2} \sim 1.1 - 1.4$$

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

"G"

Fetkovich Eq $\quad S = \dfrac{0.0375\, \gamma_g H}{T Z}$

$H[ft]$

$T[°R]$

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

where S = 0.0375 GH/T_a Z_a (This S should not be confused with skin)

and e = natural log

G = gas gravity

H = vertical depth, ft

T_a = average temperature, °R

Z_a = gas deviation factor at average pressure

$p_c^2 = p_R^2/e^s$

$p_w^2 = p_{wf}/e^s$

Q = Mscfd

COMBINE RESERVOIR & TUBING RATE EQS →

"WELLHEAD DELIVERABILITY EQ"

Assume: p^2 Approx in R

R: $\quad \tilde{B} q^2 + \tilde{A} q - (p_R^2 - p_{wf}^2) = 0$

$$B' q^2 + A' q - \left[\left(\frac{p_R}{e^{S/2}}\right)^2 - \left(\frac{p_{wf}}{e^{S/2}}\right)^2\right] = 0$$

Divide by e^S

$B' = \tilde{B} \cdot e^{-S}$

R: $\quad B' q^2 + A' q - (p_c^2 - p_w^2) = 0$

$A' = \tilde{A} \cdot e^{-S}$

T: $\quad \dfrac{1}{C_T^2} q^2 - (p_w^2 - p_t^2) = 0$

$p_c = \left(\dfrac{p_R}{e^{S/2}}\right)$

$$\underbrace{\left(B' + \frac{1}{C_T^2}\right)}_{\text{constant}} q^2 + A' q - (p_c^2 - p_t^2)$$

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

"R" "T" "R"

└ Eliminated an intermediate pressure "node" p_w @ wellbore

$$\boxed{B_{wH}\, q_t^2 + A'_{wH}\, q_t - (p_c^2 - p_t^2) = 0}$$

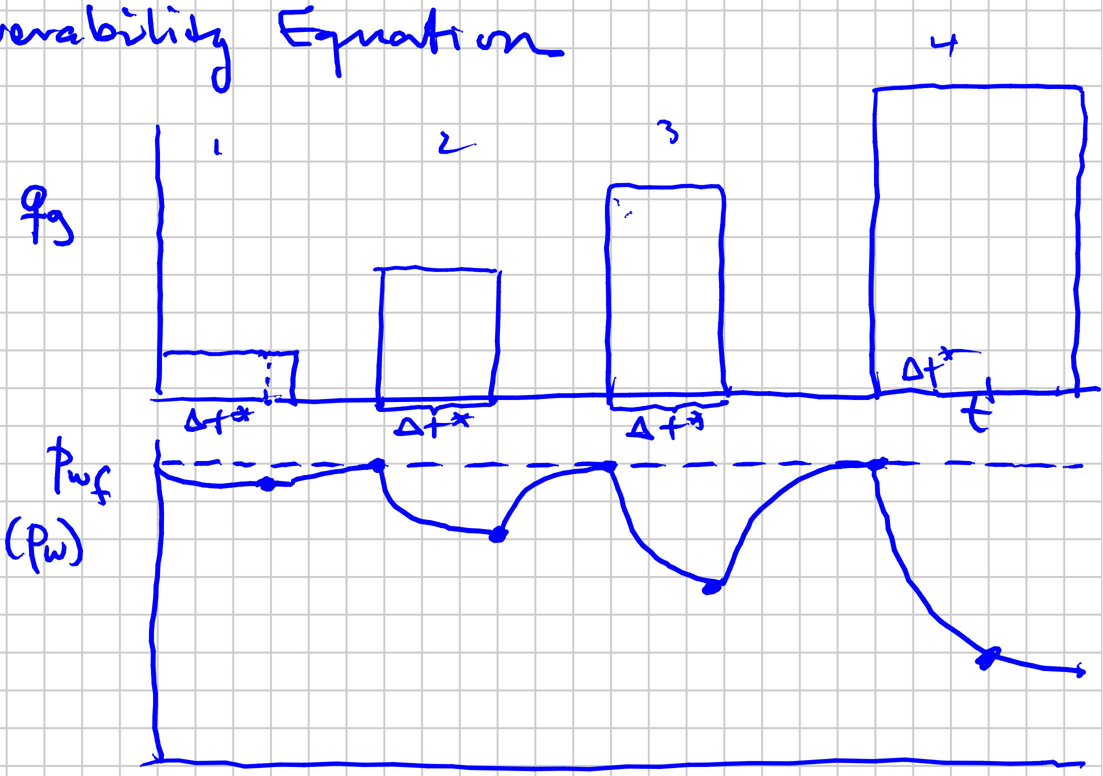
Wellhead Deliverability Equation

Initial Test:

$p_c = p_{ci}$

Isochronal Test

"p_{wf}" @ $\boxed{\Delta t^*}$



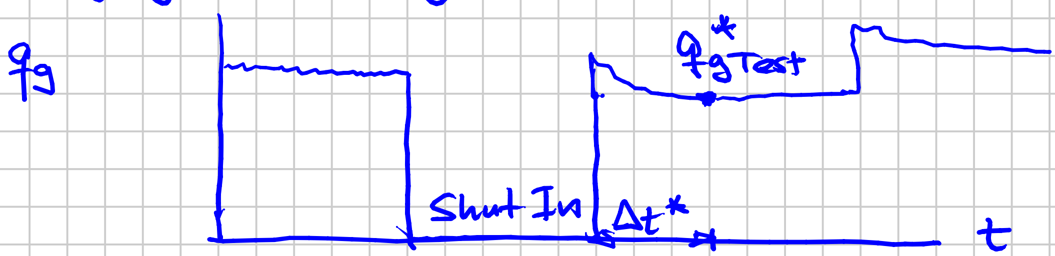
#	q	p_{ci} (Const)	p_t	$p_{ci}^2 - p_t^2$
1				
2				
3				
4				

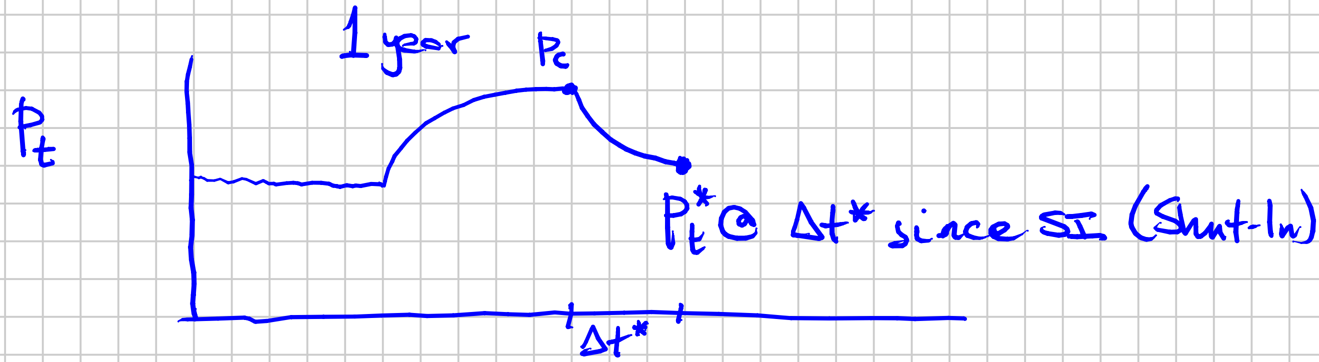
$$\underbrace{Bq^2 + Aq} - \Delta p^2 = 0$$

$\Downarrow$

A, B : Expect A & B to remain constant "forever" — i.e. unless "C_T" or "A_R" or "B_R" change.

Every Year: Single Rate Test

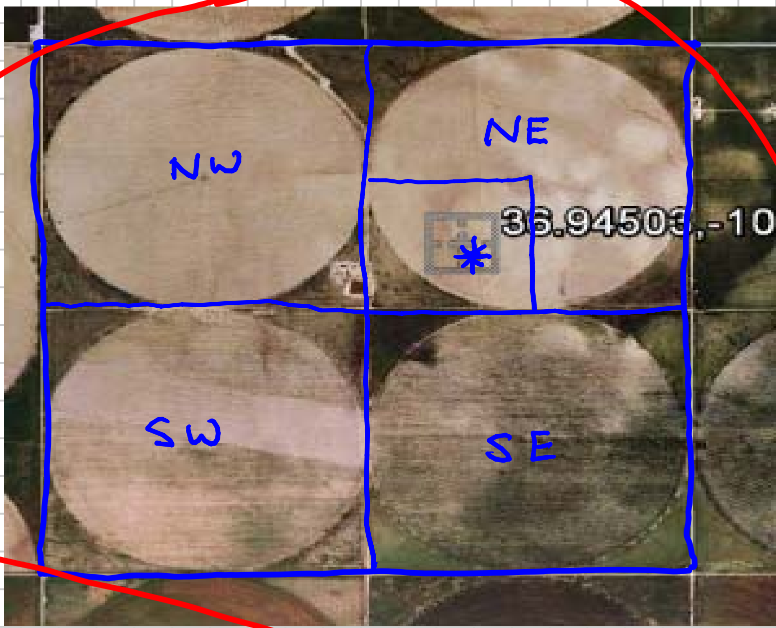




$q_{g_{Test}}$: $(p_c^2 - p_t^2)_{Test}$ vs ORIGINAL wtt Backpressure Equation

Note Title 2011-11-24

State (Operator: Beta)

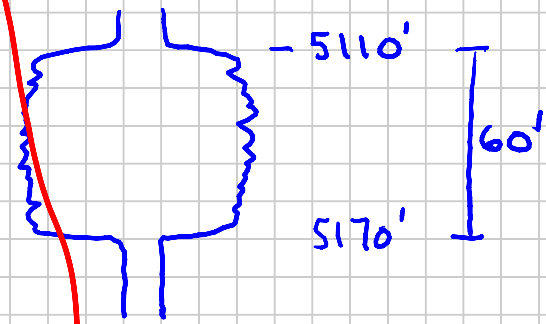


1 mi

1 mi

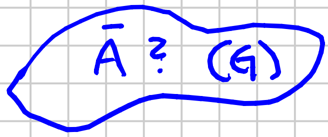
Section: 1 mi × 1 mi

S 36 T6N R11E



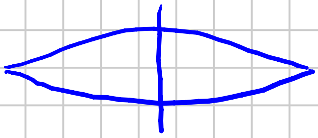
Morrow Sand Channel

$$\bar{G} = \underbrace{\underbrace{\underbrace{\bar{h}\, A}_{V_b} \cdot \bar{\phi}}_{V_p} \cdot (1-\bar{S}_w)}_{V_{pg}\ \ \text{HCPV}} \Big/ B_{gi}$$



Top

$\bar{h} \sim 60'$ I
Res.


Side

PVT: T_R, $P_R \rightarrow$ 1 atm $\quad \gamma_g = 0.78$ (IHS)

Z, μ_g ?

$G_{p\ 2011\text{-}09} = 26.813$ bcf $= 26.813\ 10^9$ scf

$G_{est} \sim 27.5 \cdot 10^9$ scf

$P_{Ri} \sim 1350$ psia ±

$T_R \sim 158$ °F ±

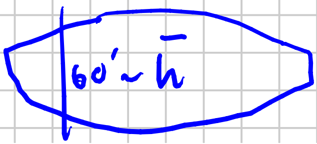
$z_i \sim 0.84$

$$B_{gi} = \frac{14.7}{520}\,\frac{(158+460)}{1350} = 0.0106\ \frac{ft^3}{scf}$$

$\bar{\phi} = 0.15$

$\bar{S}_w = 0.25$

$\bar{h} = 60$ ft



$$A = \frac{G_{est}\ B_{gi}}{\bar{h}\,\bar{\phi}\,(1-\bar{S}_w)} = \frac{8637 \cdot 10^6}{43.18 \cdot 10^6}\ ft = 1982\ acre\quad 991\ acres$$

$$= \frac{(27.5 \cdot 10^9)(0.0106)}{(60)(0.15)(1-0.25)}$$

$$\frac{43560\ ft^2}{acre}$$

640 acres/section

Check Governments' conversion

from "p_c" → "p_R"
Field

Fetkovich:

$$\left(\frac{p_R}{p_c}\right) = e^{s'/2}$$

$$s' = \frac{0.0375\ \gamma_g\ H}{\bar{T}\ \bar{z}}$$

$$= \frac{0.0375(0.78)(5110)}{(580)(0.92)}$$

$$= 0.280$$

$$e^{s/2} = 1.15\ ✓$$

$\gamma_g = 0.78$

$H = 5110\ ft$

$$\bar{T} = \left\{\frac{(160+80)}{2} + 460\right\}$$

$\bar{z} = 0.92$ @ $\bar{T}$, $\bar{p}_c$

120°F, 500 psia

Analysis: Annual Test Data

q_g $\quad p_c \quad p_t$

$$B_{WH}\, q_g^2 + A_{WH}\, q_g - (p_c^2 - p_t^2) = 0$$

$$\left[\ q_g \simeq C_{WH}\,(p_c^2 - p_t^2)^{n_{WH}}\ \right]$$ Backpressure Equation

If $B_{WH}\, q^2$ is neglible vs $A_{WH}\, q$

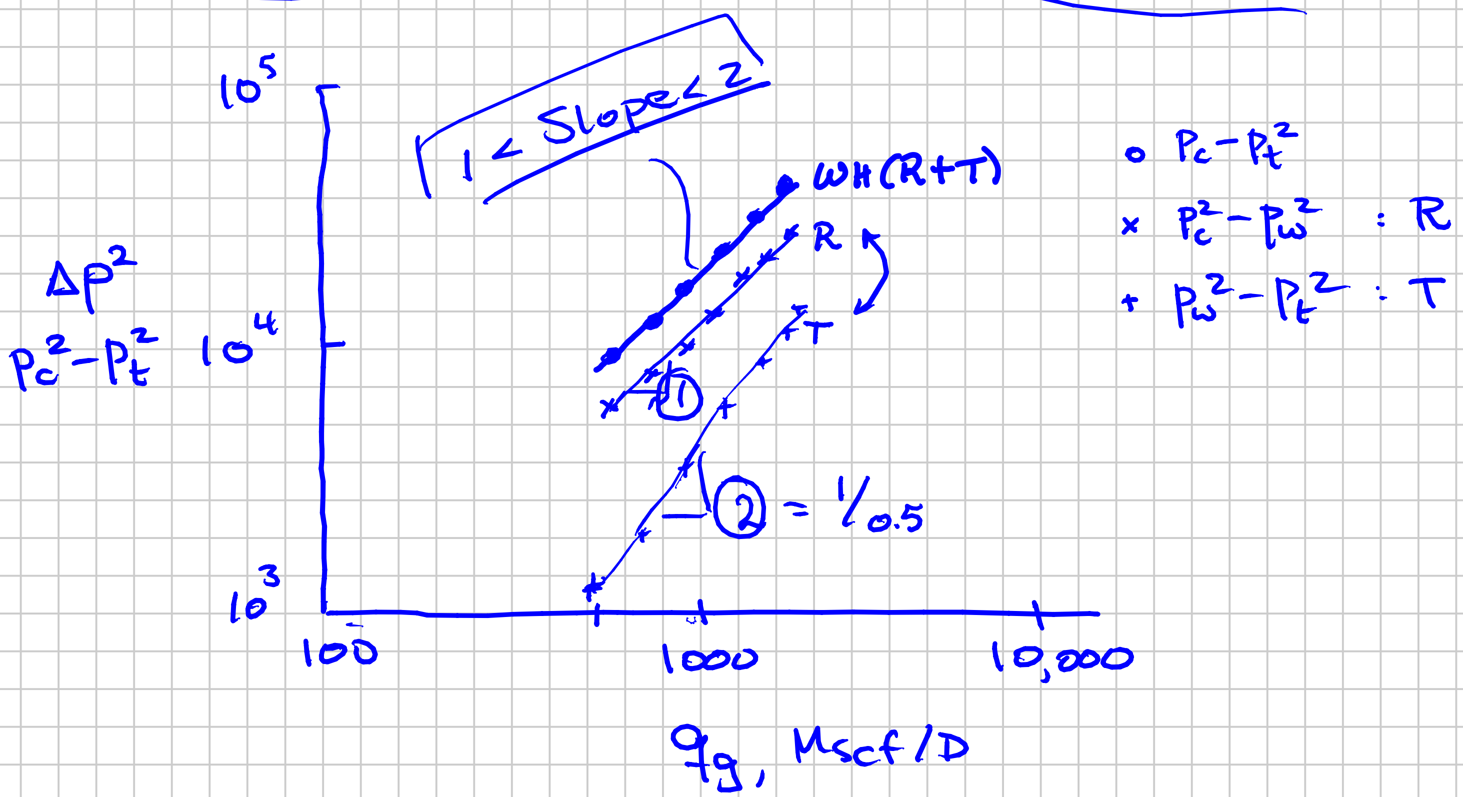
$\Rightarrow$ Darcy Flow
Little Δp in Tubing $\Big\}$ $n_{WH} = 1$

If $B_{WH}\, q^2 \gg A_{WH}\, q$: "Tubing Limited" Well

$$\boxed{n_{WH} \Rightarrow 0.5}$$

$$0.5 < n_{WH} < 1$$

R + T

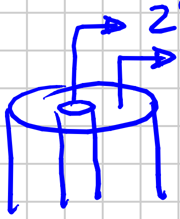


$$C_T(d_T) = C_T(2'') \cdot \left(\frac{d_T}{2}\right)^{2.7}$$

$$q_g = C_T\, (p_w^2 - p_t^2)^{0.5}$$

$$\Delta p^2 = \left(\frac{q}{C_T}\right)^2$$

Casing size: 7.5" OD ~ 7" I.D.



$\left.\begin{array}{l}\text{2" Tubing} \\ (d_c - d_T) \text{ Annulus}\end{array}\right\}$ Both

No Tubing

$$(d_{Te})_{Annulus} = \left[\frac{\pi\left(\frac{d_c^2}{4} - \frac{d_t^2}{4}\right)}{\pi}\right]^{1/2}$$

$$\left(\frac{7^2 - 2.375^2}{4}\right)^{1/2} = 3.3"$$

Q & A

Monday Dec. 5 Kl. 9-12 P1

Tues Dec. 6 Kl. 9-12 (my office)