PVT & FLOW (TPG 4145)

CURTIS HAYS WHITSON

PETROLEUM NOMENCLATURE

QUANTITIES	SYMBOL	UNITS		
		SI	(Metric)	Field
Pressure	p	Pa kPa MPa	bar = 10^5 Pa	psi pounds per square inch lb_f

Blaise Pascal

Two types of pressure:

Absolute (p^A) Gauge (p^g)

$$p^A - p^A_{sc} = p^G$$

standard conditions

$p^g = 0$

$p^G_{10m} = (2-1)\,10^5$ Pa $(30-15)$ psi

$\sim 1 \cdot 10^5$ Pa 15 psi

~ 1 bar

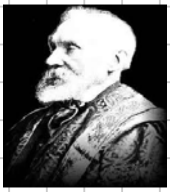
MPa abs	bara	psia
MPa guage	barg	psig

Pressure Units Conversion (App. A SPEPBM)

$\underline{14.5037 \text{ psi} = 1 \text{ bar} = 10^5 \text{ Pa}}$

14.697 psi = 1 atm

$$\frac{1\ \text{atm}}{1\ \text{bar}} = \frac{14.697}{14.5037} = 1.01325$$


Lord Kelvin

$$1\ \text{atm} = 1.01325 \cdot 10^5\ \text{Pa}$$

Use in PVT (EOS)

Absolute Temp

TEMPERATURE T K °C °R °F

Not Absolute Temp


Rankine (Bill)

Kata Celcius

$$T_K = T_{°C} + 273.15$$

$$T_{°R} = T_{°F} + 459.6$$

$$T_{°R} = 1.8 \cdot T_K$$

$$T_{°F} = 1.8\, T_{°C} + 32$$

Many PE correlations (equations) use °F

Water
Boils @ 100°C (1 atm) 212°F
Freeze @ 0°C (1 atm) 32°F

VOLUME V m³ (cm³ or cc)

$$cm^3 = (10^{-2}\ m)^3$$
$$10^{-6}\ m^3$$

prefix:

m	milli	10^{-3}
c	centi	10^{-2}
d	deci	10^{-1}
D	deca	10
k	kilo	10^{3}
M	mega	10^{6}
G	giga	10^{9}

ft^3 in^3

bbl (STB)

barrels (liquid: o+w)

Gas @
1 atm &
60°F
1.0135 bara
14.696 psia
"scf"
standard cubic

T   tera 10^{12} feet

STB : stock tank barrel = "sc"

1 atm
60 °F

Latin 1000

$$\text{Mscf} = 10^3 \text{ scf}$$

$$\underbrace{\text{MM}}_{10^3 \cdot 10^3}\text{scf} = 10^6 \text{ scf}$$

Sm^3 = std m^3

standard condition

$$\text{bcf} = 10^9 \text{ scf}$$

$$\text{Tcf} = 10^{12} \text{ scf}$$

approaching a "giant" (large) gas field

Conversions : $35.31 \text{ ft}^3 = 1 \text{ m}^3$
$6.28 \text{ bbl} = 1 \text{ m}^3$ } $5.615 \text{ ft}^3 = 1 \text{ bbl}$

Mass   m   kg   (g) lb_m oz

Conversion : $2.2046 \text{ lb}_m = 1 \text{ kg}$
$1000 \text{ g} = 1 \text{ kg}$
$16 \text{ oz} = 1 \text{ lb}_m$

Length   m   (cm)   ft, in, mi

3.28 ft = 1 m   5280 ft = 1 mi

Area   A m^2 (cm^2) ft^2

$\sim 10 \text{ ft}^2 = 1 \text{ m}^2$ Acre = 43560 ft^2

⇒ Section: 1mi x 1mi
→ 640 Acres/section

Time   t   s   (s)   D, hr, yr

Permeability (Area) m^2 (md)   md, D

$p \quad V \quad T$

$1\ \mu m^2 = 1\ D$

$10^{-12}\ m^2 = 1\ D$

8.314

Ideal Gas Law

$$pV = nRT$$

abs. pressure

moles of the gas

Universal gas constant

abs. temp.

SI Units : p [Pa]
V [m^3]
T [K]
n [kgmole]

Pure SI

$R_{SI} = 8314.3$

$$M_{\substack{C_1\\CH_4}} = 16.04\ \frac{g}{gmole} = 16.04\ \frac{kg}{kg\cdot mole} = 16.04\ \frac{lb_m}{lbmole}$$

$$= 16.04\ \frac{oz}{ozmole}$$

$$pV = nRT$$

Convert : T[°R]   1.8 K = 1 °R

Find R_{Field} p[psia]   14.5037 psia = 1 bara

V [ft^3]   35.31 ft^3 = 1 m^3

n [lb-mol]   2.204 lb = 1 kg

$$\overset{\downarrow}{p} \quad V \quad = \quad n \quad R \quad T$$

$$[\text{Pa}] \quad [\text{m}^3] \quad [\text{kg}] \quad R_{SI} \quad [\text{K}]$$

Input using:

$$p\,[\text{psia}] \qquad V\,[\text{ft}^3] \qquad n\,[\text{lb}] \qquad T\,[^{\circ}\text{R}]$$

$$p\,[\text{Pa}] = \left\{ p\,[\text{psia}] \cdot \frac{\text{bara}}{14.50377\ \text{psia}} \cdot \frac{10^5\ \text{Pa}}{\text{bara}} \right\}$$

$$V\,[\text{m}^3] = \left\{ V\,[\text{ft}^3] \cdot \frac{\text{m}^3}{35.31\ \text{ft}^3} \right\}$$

$$n\,[\text{kg}] = \left\{ n\,[\text{lb}] \cdot \frac{\text{kg}}{2.204\ \text{lb}} \right\}$$

$$T\,[\text{K}] = \left\{ T\,[^{\circ}\text{R}] \cdot \frac{\text{K}}{1.8\ ^{\circ}\text{R}} \right\}$$

$$\left\{ p[\text{psia}] \cdot \frac{10^5}{14.5} \right\} \left\{ V[\text{ft}^3] \cdot \frac{1}{35.31} \right\} =$$

$$\left\{ n[\text{lb}] \cdot \frac{1}{2.2} \right\} \cdot \left\{ T[^{\circ}\text{R}] \cdot \frac{1}{1.8} \right\} \cdot \underset{8314}{R_{SI}}$$

$$p[\text{psia}] \cdot V[\text{ft}^3] = n[\text{lb-mole}]\, T[^{\circ}\text{R}] \cdot \underbrace{\left\{ 8314 \cdot \frac{1}{2.2} \cdot \frac{1}{1.8} \cdot \frac{14.5}{10^5} \cdot 35.31 \right\}}_{R_{Field}}$$

$$R_{Field} = 10.73146$$

IDEAL GAS LAW

Note Title 2012-08-24

$$p\,V = n\,R\,T$$

Depends on Units

Absolute Units
[Pa, bara, psia]

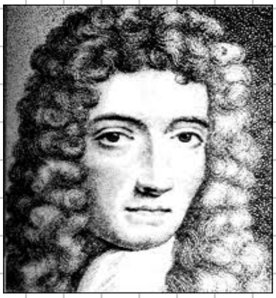
Always associated with a mass unit
[g-mole, kg-mole, lb-mole]
"mol"

Absolute Units
[K, °R]

Assumption:
"Low Pressure"
"High Temperature"

ANY
Compound or Mixture

Boyle : $pV = \text{constant}$ @ "Low" pressures



Charles Law : $V \propto T$

Other Quantities used in this equation

"Equation of State"
(EOS)

v = molar volume
$\equiv V/n$

Z = deviation factor $\boxed{p-V-T-n}$

$\uparrow$

from ideal gas behavior

$$Z \equiv \frac{pv}{RT} = \frac{pV}{nRT} = 1$$

$pV = nRT$

Ideal Gas Molar Volume

$$v_{\bar g} \; @ \; p_{sc}, T_{sc} \equiv \boxed{v_{\bar g} = \frac{V_{\bar g}}{n} = \frac{RT_{sc}}{p_{sc}}} \qquad V_{\bar g} \leftrightarrow n$$

1 atm
14.696 psia
1.0135 bara

60°F + 459.67 = 520°R
15.56°C + 273.15 = 520/1.8 = K

s.c. STC

$\bar g$, $\bar o$, $\bar w$: bar implies @ p_{sc}, T_{sc}

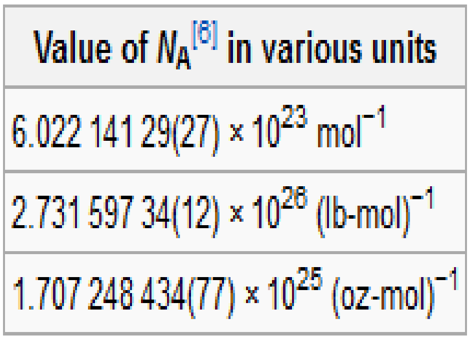
SI: $v_{\bar g}$ = 23.6x Sm³/kg-mole std m³/kg-mole

Field: v_g = 379.1x scf/lb-mole

Avogadro's Law:

Ideal Gases:

$$\frac{V}{n} = \text{constant}$$



Value of N_A[6] in various units
6.022 141 29(27) × 10^{23} mol^{-1}
2.731 597 34(12) × 10^{26} $(lb\text{-}mol)^{-1}$
1.707 248 434(77) × 10^{25} $(oz\text{-}mol)^{-1}$

Avogadro's Number $N_A = \frac{N}{n}$

gmol

6.022×10^{26} $kg\text{-}mol^{-1}$

CLASS EXERCISES:

1. Calculate Ideal Gas Molar Volumes $v_{\bar{g}}$ for

(a) SI : m^3 , kg-mole

(b) Field : scf , lb-mole
(standard condition ft^3)

$$v_{\bar{g}} = \frac{R\,T_{sc}}{p_{sc}}$$

	SI	Field
p_{sc}	1.0135 bara ✓	14.696 psia ✓
T_{sc}	15.56 °C → K $+273.15 = 288.71$ K ✓	60 °F → °R $+459.67 = 519.67$ °R ✓
R	✓ 8314.3	10.7315 ✓
$v_{\bar{g}}$	23.68 $\frac{\text{std } m^3}{\text{kg-mole}}$	379.5 $\frac{\text{scf}}{\text{lb-mole}}$

2. TROLL GAS RESERVOIR

SPE symbol

$$V_{\bar{g}i} = \text{IGIP} = \text{OGIP} \quad (G) \quad = 45 \text{ Tcf}$$

$$= \underline{45 \cdot 10^{12} \text{ scf}}$$

sc gas

(a) → n_g [lb-mole] $= 45.10^{12}\ \cancel{\text{scf}} \times \frac{\text{lb-mole}}{379\ \cancel{\text{scf}}} = 11.87 \cdot 10^{10}$ lb-mole

(b) → n_g [Kg-mole] $= 11.87 \cdot 10^{10}\ \cancel{\text{lb-moles}} \cdot \frac{\text{kg-mole}}{2.204\ \cancel{\text{lb-mole}}} = 5.39 \cdot 10^{10}$

(c) → $V_{\bar{g}i}$ (G) [std m3] $= 5.39 \cdot 10^{10}\ \cancel{\text{kg-mole}} \cdot 23.68\ \text{Sm}^3/\cancel{\text{Kg-mole}}$

$= 127.\underline{6} \cdot 10^{10}\ \text{Sm}^3$

NOK/Sm^3

(d) Check (c) using 35.31 scf/Sm^3

$= 45.10^{12}$ scf $\times \frac{\text{Sm}^3}{35.31 \text{ scf}} = 127.\underline{4} \cdot 10^{10}\ \text{Sm}^3$

$\cancel{\$5/\text{Mscf}} \times 6\ \underbrace{\frac{\text{NOK}}{\cancel{\$}}}_{1} \times \underbrace{\frac{\cancel{\text{Mscf}}}{1000\ \cancel{\text{scf}}}}_{1} \times \underbrace{\frac{35.31\ \cancel{\text{scf}}}{\text{Sm}^3}}_{1} = 1.05\ \frac{\text{NOK}}{\text{Sm}^3}$

6 NOK/USD

$$0.2 \cdot 10^{10}\ \mathrm{Sm}^3 \times 1\ \frac{\mathrm{NOK}}{\mathrm{Sm}^3} = 2 \cdot 10^{9}\ \mathrm{NOK}$$

~ 100 Life-Salaries

Life-Salary Unit ~ $700{,}000\ \mathrm{NOK/yr} \times 30\ \mathrm{yr} = 21 \cdot 10^{6}\ \mathrm{NOK}$

EXCEL Etiquette for Engineers

- * Title
  Name
  Date

- * Tables

  - Pre-Header Information

Text Descriptor A, e.g. Radius	1.234	cm
Text Descriptor B, e.g. Diameter	2.468	cm

	Must	Optional
- Headers row	Centered	bold
- Units row	Centered	italic (psia) [psia]

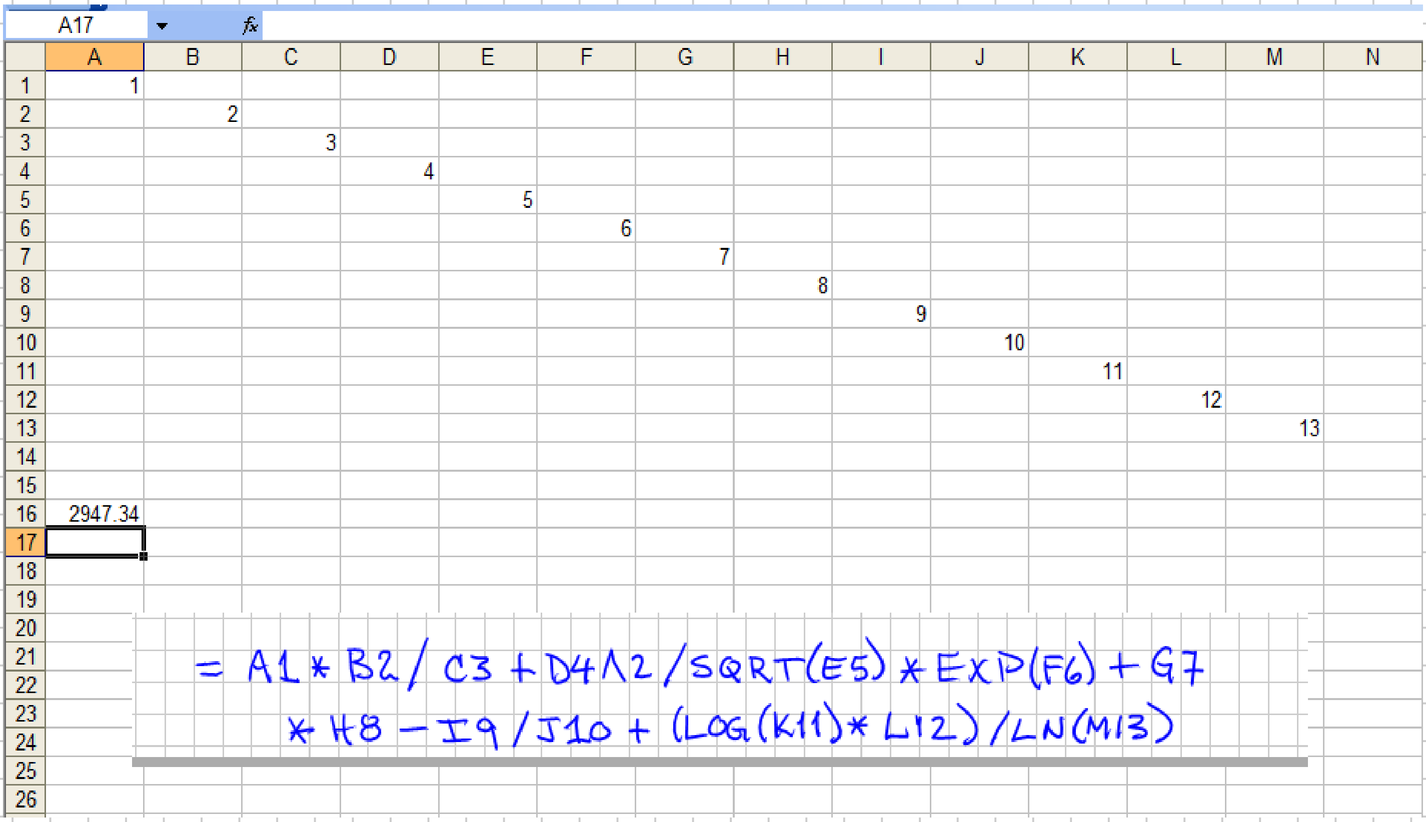
  - Digits
    - 3-4 significant digits usually OK (eye-comprehendable)
    - Machine "knows" 15-16 digits
    - Sometimes E format 1.23E-4
    - Setup immediately! (to avoid forgetting)

- * Equations
  - Cell Referencing
    - A1 : relative
    - $A1 : fixed column A
    - A$1 : fixed row 1
    - A1 : fixed cell (column & row)

```
= A1*B2/C3+D4^2/SQRT(E5)*EXP(F6)+G7
    *H8-I9/J10+(LOG(K11)*L12)/LN(M13)
```

	A	B	C	D
1	1			
2		2		
3			3	
4				4

Result = 2947.34 or 2947 (proper etiquette!)



A17 fx

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	1													
2		2												
3			3											
4				4										
5					5									
6						6								
7							7							
8								8						
9									9					
10										10				
11											11			
12												12		
13													13	
14														
15														
16	2947.34													
17														
18														
19														
20														
21														
22														
23														
24														
25														
26														

= A1 * B2 / C3 + D4^2 / SQRT(E5) * EXP(F6) + G7 * H8 − I9 / J10 + (LOG(K11) * L12) / LN(M13)

* Charts (Figures)

- Always on a separate sheet (tab)
- White background (not default gray)
- Black lines
- 16 or 18 pt font - all text (except legends: 12-14 pt)
- Symbols:

  ○ △ □ ◇ x + *

  white "inside"

  ● ▲ ■ ◆

  4-8 pt usually

  many data ↗ ↑ fewer data

- Lines: solid, thickest (never thinnest)
- Colors: OK

  Black, Red, Blue, Green, Pink

- Grid Lines
  - Show major
  - Only minor ticks (inside)
- Min/Max x- and y- selection
  - Use "nice" round values

  0 50 100 150 200 NOT 0 48 96 ...

- 2nd (Right) y-axis
  - Try to use same major ticks/lines
- Log axes: 1 10 100 ... use "General" number format (often)

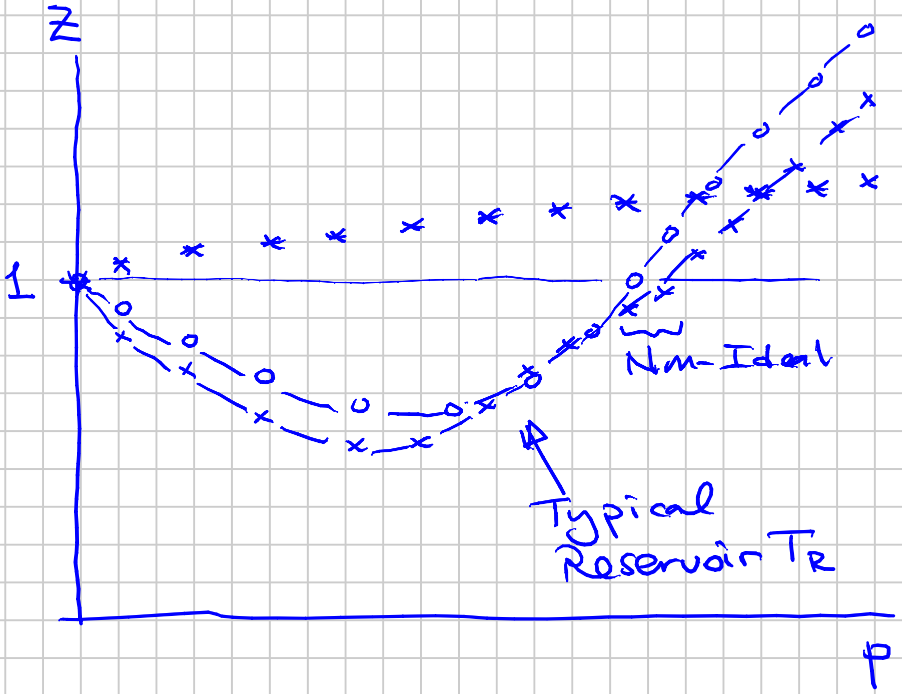
REAL GAS LAW

Deviation of p-V-T behavior of real systems (gas)
from "Ideal Gas Law" behavior $(Z = 1)$

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

Measurements: Fixed n, Fixed Component (C_1)

	T(°C)	P(bara)	V(m³)	=>	Z
	200	1			
o		⋮			
		100			
x	100	1			
		⋮			
		100			
*	400				



$$\underbrace{C_1 \quad N_2 \quad CO_2 \quad H_2S \quad C_2}_{\text{Reservoir Gases Consist of "Large" quantities}}$$

van der Waals (187x): p-V-T gases & liquids & dunno
"Theory of Corresponding States"

Reduced Variables:

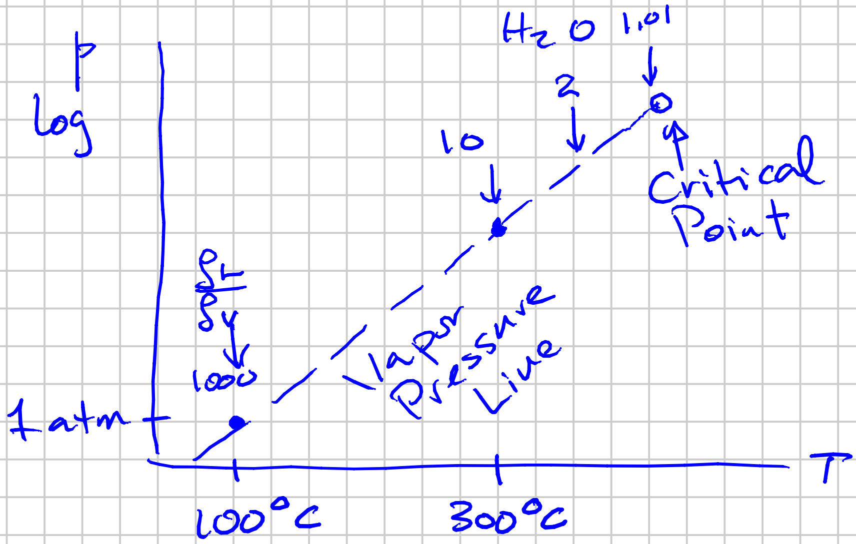
$$p_r \equiv \frac{p}{p_c}$$

$$T_r \equiv \frac{T}{T_c}$$

$$V_r \equiv \frac{V}{V_c}$$

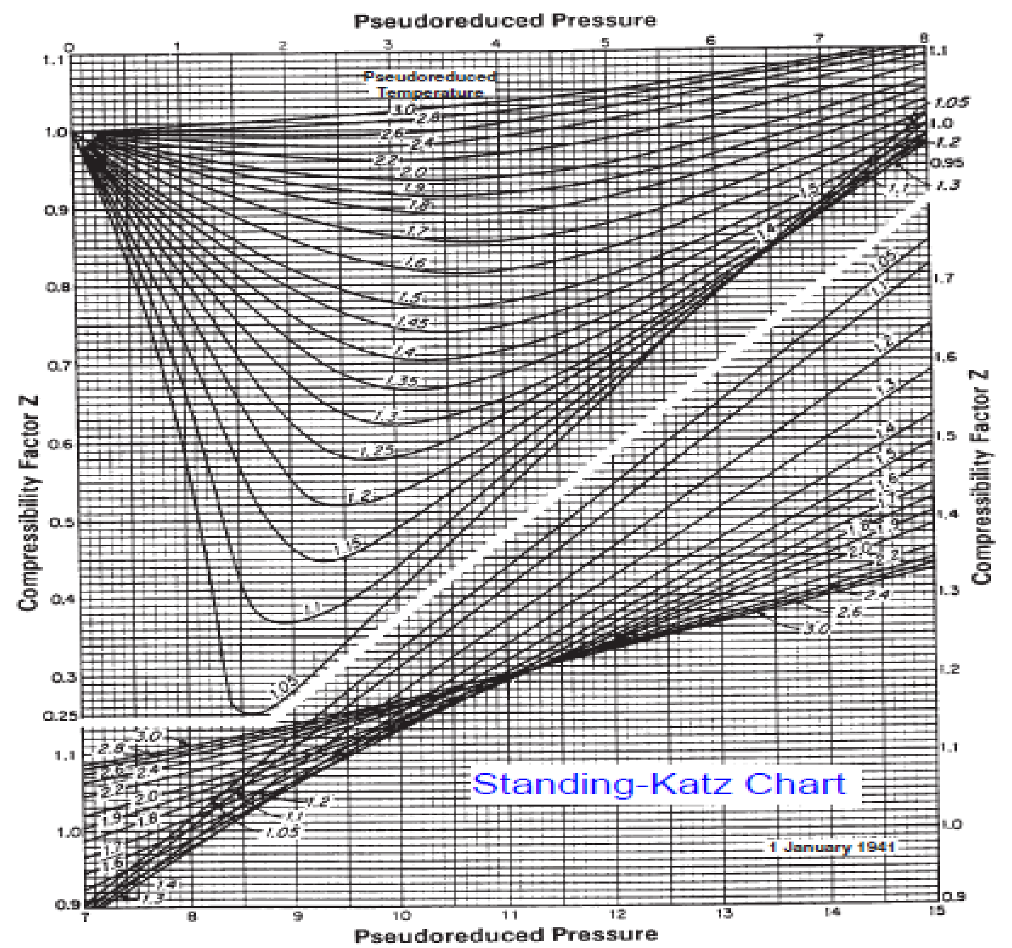
If any two gases have the same value of p_r & T_r then they will have the same $Z_g(T_r, p_r)$

(p_c, T_c) are the "critical" properties:



1940s : Donald Katz @ U. Michigan
Marshall B. Standing $\Big\}$ $Z_g(T_r, p_r)$

All existing data +
new data for petroleum mixtures



Mixtures :

*$(H_2S, CO_2), (C_{7+})$ requires special treatment Ch.3

$$\text{Average } \bar{T}_{pc} = \sum_{i=1}^{N : C_{7+}} y_i \cdot T_{ci}$$

pseudo

Reservoir Gas Mole Fraction

$$\bar{p}_{pc} = \sum_{i=1}^{N} y_i \, p_{ci}$$

✓ $T_{pr} = \dfrac{T}{T_{pc}}$ 1.3 – 2.5

✓ $p_{pr} = \dfrac{p}{p_{pc}}$ 0 – 20

$$\text{Est.} \quad \begin{matrix} T_{c7+} \\ p_{c7+} \end{matrix} = \begin{matrix} f(\overbrace{M_{7+}, \rho_{7+}}^{\text{Lab measured – different for every reservoir}}) \\ f(\underbrace{M_{7+}, \rho_{7+}}_{C_{7+} \text{ "characterization"}}) \end{matrix}$$

Matthews et al.

App. B: Example Calculations.

Real Gas Law :

$$pV = nRT \cdot \underbrace{z(p_r, T_r)}_{\text{SK Chart}}$$

Equations that fit the chart (Ch.3)

0.7 – 2

van der Waals

Donald Katz

Example Calculation :

Troll Field

$T_R = 71\,°C$

$p_{Ri} = 158$ bara

Gas Composition $y_i = \frac{n_{ig}}{n_g}$

SK: Estimate T_{pc}, p_{pc} knowing only the
gas molecular weight
specific gravity
(relative density)

often measured, available

$$\boxed{\gamma_g \equiv \frac{\rho_{g\,sc}}{\rho_{air\,sc}}} = \left(\frac{M_g}{M_{air}}\right)$$

of Reservoir Gas

$$\rho_g = \frac{m_g}{V_g} = \frac{n_g \cdot M_g}{V_g} = \underbrace{\frac{n_g}{V_g}}_{} \cdot M_g = \underbrace{\left(\frac{p}{RTZ}\right)}_{@\,s.c.} M_g$$

same for any g or air

$$\gamma_g = 0.6 \quad (air = 1)$$

SK Correlation $T_{pc}(\gamma_g)$

$p_{pc}(\gamma_g)$

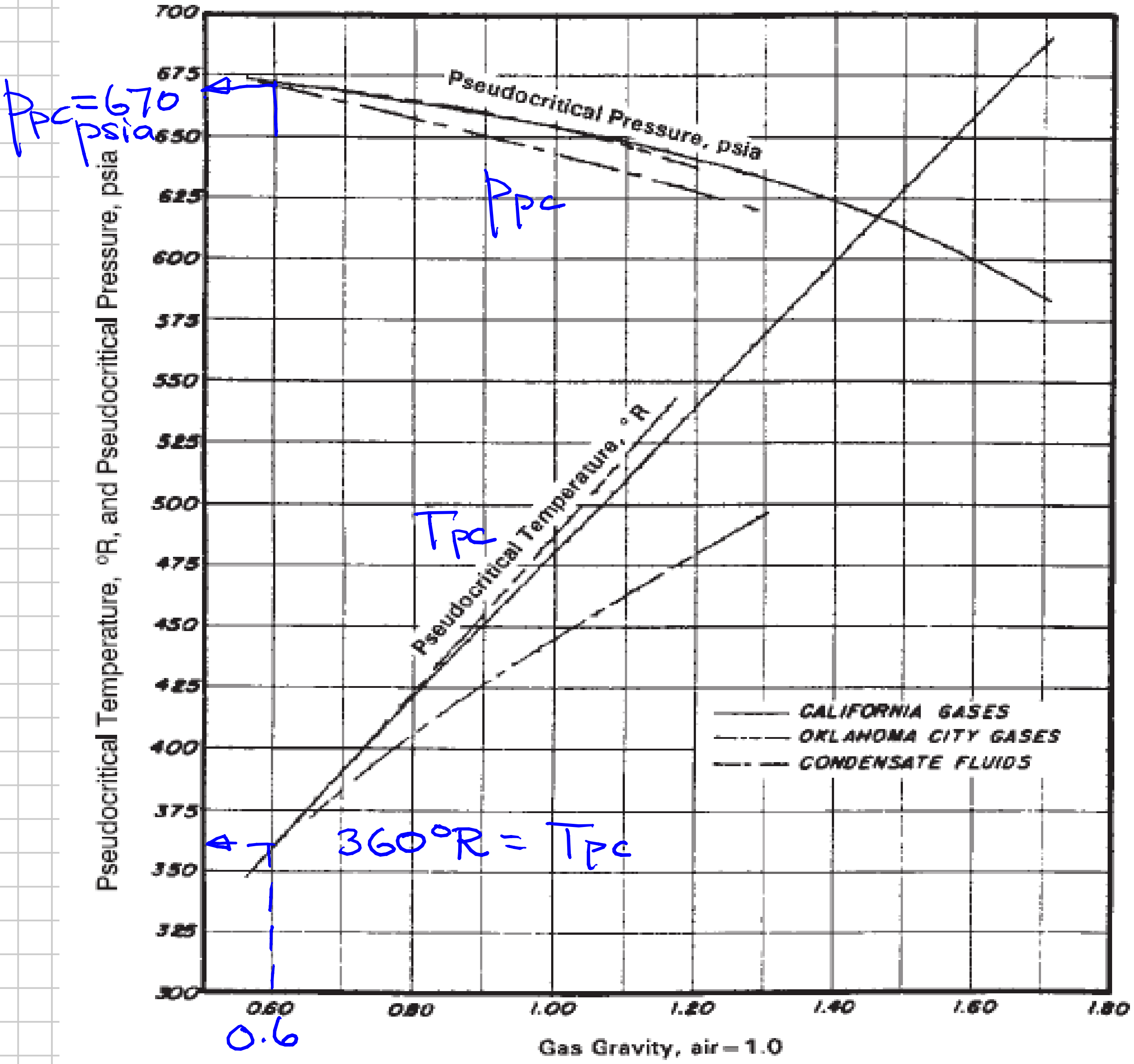


Fig. 3.7—Gas pseudocritical properties as functions of specific gravity.

Troll $\gamma_g \simeq 0.6$

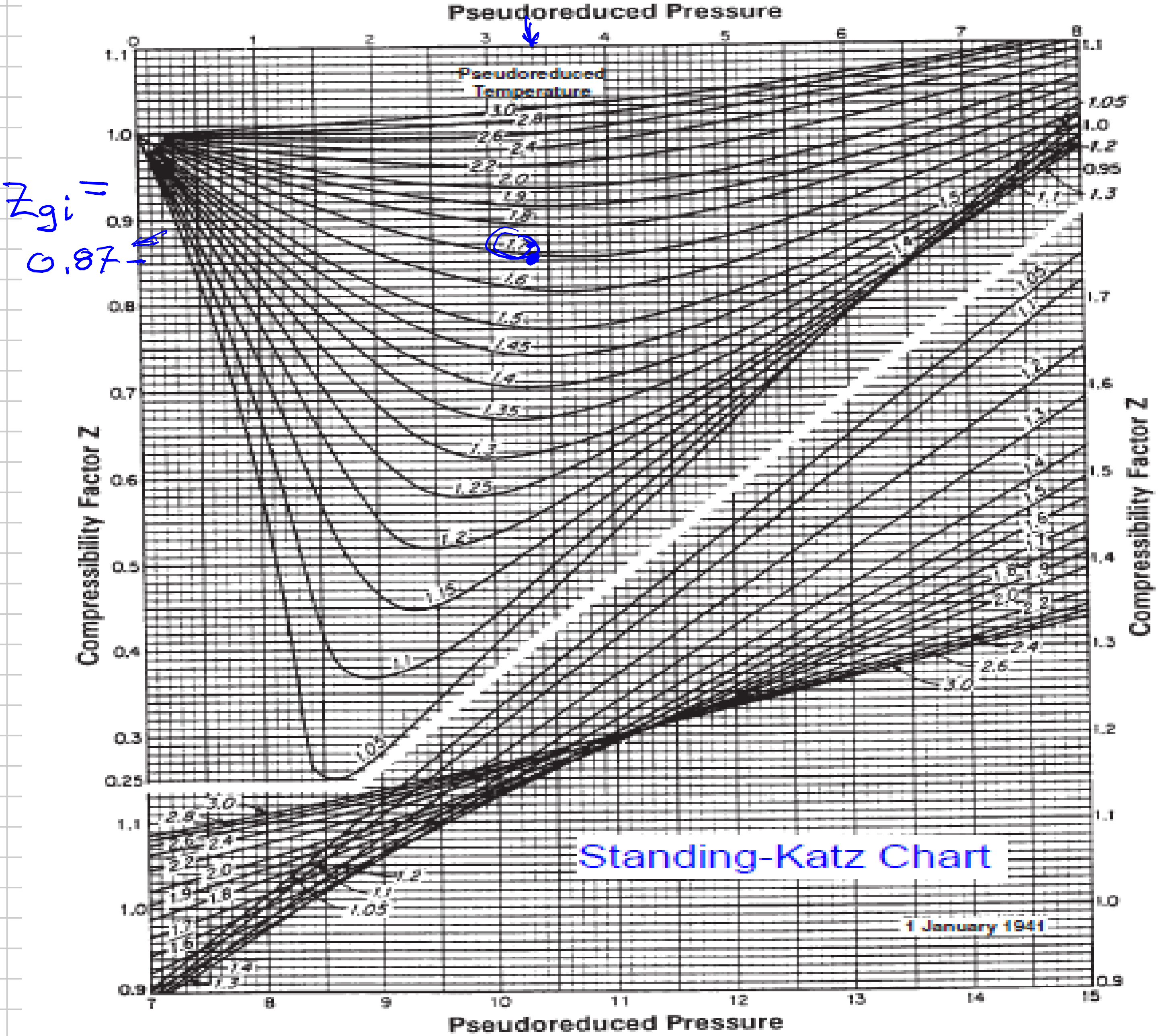
$T_{pc} = 360\,°R = 200\ K$

$p_{pc} = 670\ psia = 46.2\ bara$

14.5 psi/bar

$$T_{pr} = \frac{273+71}{200} = \frac{344\ K}{200\ K} = \underline{1.72}$$

$$(p_{pr})_i = \frac{158\ bara}{46.2\ bara} = \underline{3.42}$$



Pseudoreduced Pressure
0
1
2
3
4
5
6
7
8
Pseudoreduced Temperature
3.0
2.8
2.6
2.4
2.2
2.0
1.9
1.8
1.7
1.6
1.5
1.45
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
Compressibility Factor Z
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.25
1.05
0.95
1.7
1.6
1.5
1.4
1.3
1.2
Standing-Katz Chart
1 January 1941
7
8
9
10
11
12
13
14
15

Zgi =
0.87

GAS PVT Properties

Note Title 2012-08-31

Real Gas Law : $pV = nRTZ_g$

$Z_g(T_{pr}, p_{pr})$ – Standing-Katz Chart

Equation Fits – BWR EOS

Yarborough & Hall (special version)

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

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

$C_{7+}(T_c, p_c)$ Matthews

$$T_{pc} = \sum_{i=1}^{N} y_i T_{ci} \qquad p_{pc} = \sum_{i=1}^{N} y_i p_{ci}$$

Most petroleum gases : same / "lot" (0.x – 15 mol-%) heavier components C_{7+}

→ Estimate $\{T_{c7+} \quad p_{c7+}\}$

Liquid sp. Gravity

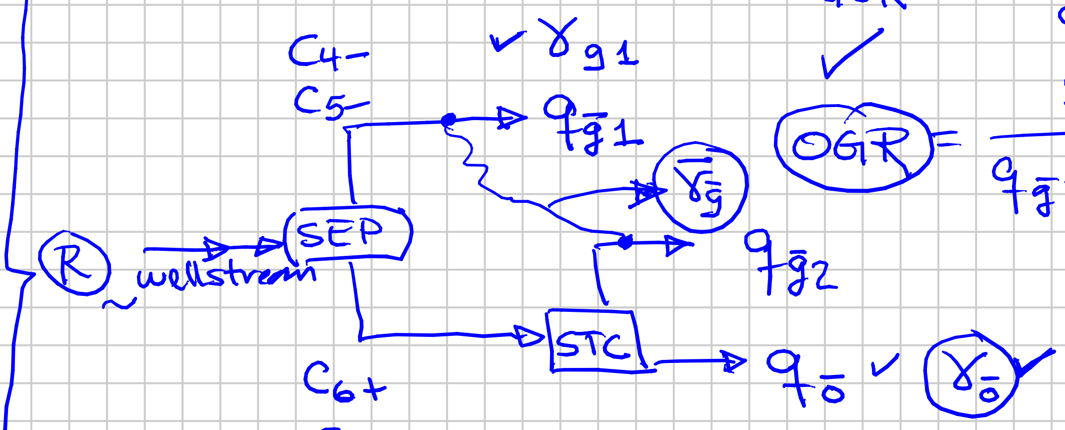
$$\text{Methods: } \left.\begin{matrix} \text{Est. } T_c \\ C_{7+} \ \text{"Fractions"} \ p_c \end{matrix}\right\} = f(T_b, \gamma) \qquad \gamma \equiv \frac{(\rho_L)_{sc}}{(\rho_w)_{sc}}$$

Ch. 5

TROLL

i	$(y_i)_R$
N_2	1.98
CO_2	0.42
C_1	93.04
C_2	3.38
C_3	0.35
iC_4	0.30
nC_4	0.07
iC_5	0.10
nC_5	0.02
C_6	0.10
C_{7+}	0.25

NOT SAME $(y_{sp_1 i})$



$$GOR = \frac{q_{\bar{g}1} + q_{\bar{g}2}}{q_{\bar{o}}} \ ✓$$

$$\boxed{OGR} = \frac{q_{\bar{o}}}{q_{\bar{g}1} + q_{\bar{g}2}}$$

$M_{7+} = 108 \qquad \gamma_{7+} = 0.69$

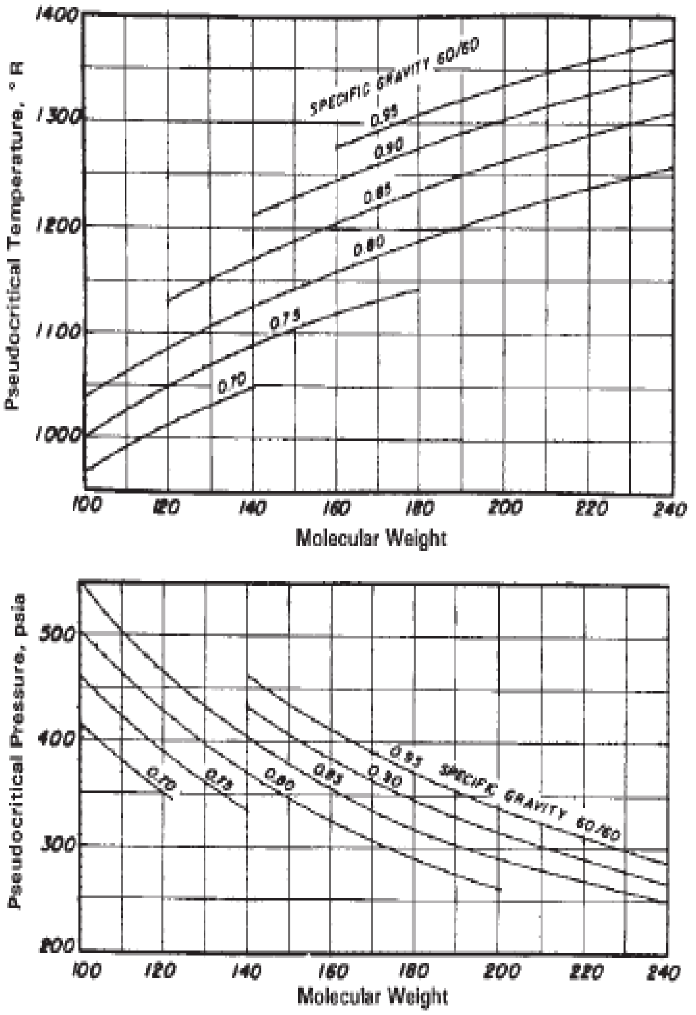


Fig. 3.8—Heptanes-plus (pseudo)critical properties recommended for reservoir gases (from Standing,[33] after Matthews *et al.*[32]).

Matthews :

$$T_{cC_{7+}} = 608 + 364 \log\left(M_{C_{7+}} - 71.2\right) + \left(2{,}450 \log M_{C_{7+}} - 3{,}800\right) \log \gamma_{C_{7+}} \quad \ldots\ldots (3.51a)$$

$$\text{and } p_{cC_{7+}} = 1{,}188 - 431 \log\left(M_{C_{7+}} - 61.1\right) + \left[2{,}319 - 852 \log\left(M_{C_{7+}} - 53.7\right)\right]\left(\gamma_{C_{7+}} - 0.8\right).$$

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

Specific Gravity of the Reservoir Gas γ_{gR}

Assuming Wellstream $\simeq$ Reservoir Gas

$\equiv$ Stream of fluid entering the first separator

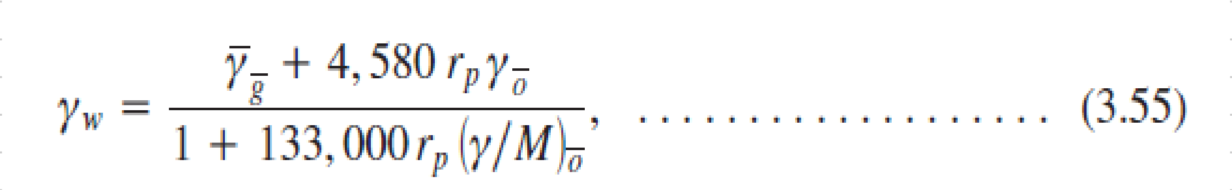
Calculate M_w $\left(\gamma_w = \dfrac{M_w}{M_{air}}\right)$

from minimal production data

$\left\{ \text{OGR or GOR} \quad \bar{\gamma}_{\bar{g}} \quad \gamma_{\bar{o}} \right\} \rightarrow$ Estimate γ_w

$$\left.\begin{array}{l} T_{pc} = f(\gamma_g = \gamma_w) \\ p_{pc} = f(\gamma_g = \underset{\uparrow}{\gamma_w}) \end{array}\right\}$$

Charts SK
Sutton
} Ch. 3



$$\gamma_w = \frac{\bar{\gamma}_{\bar{g}} + 4,580\, r_p \gamma_{\bar{o}}}{1 + 133,000\, r_p (\gamma/M)_{\bar{o}}}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.55)$$

r_p = OGR

$\bar{\gamma}_{\bar{g}}$ = average total surface gas gravity

$$= \frac{\{q_{\bar{g}1} \cdot \gamma_{\bar{g}1} + q_{\bar{g}2} \cdot \gamma_{\bar{g}2}\}_{mass}}{\{q_{\bar{g}1} + q_{\bar{g}2}\}_{mole}}$$

$\gamma_{\bar{o}}$ = STO gravity

Est. $M_{\bar{o}}$ = STO molar mass (molecular weight)

Cragoe:

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

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

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

$\gamma_{API} = 10$: $\gamma_o = 1$

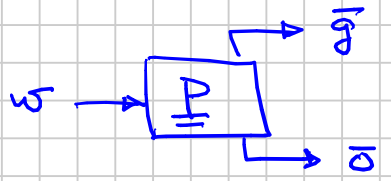
Gases : $\gamma_{API} \gtrsim 45 \rightarrow 80\,(90)$
Heavier Light

OGR $r_p\ [\text{Sm}^3/\text{Sm}^3]$

$\rho_{\bar{o}}\ [\text{kg}/\text{m}^3] \quad = 1000 \cdot \gamma_{\bar{o}}$

$\gamma_{\bar{g}}$

$$\gamma_w = \frac{M_w}{M_{air}}$$



$$M_w = \frac{m_w}{n_w}$$

Basis: 1 Sm³ $\bar{g}$

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

$$= \left\{ \underbrace{\frac{1 \text{ Sm}^3\ \bar{g}}{23.68 \text{ Sm}^3/\text{kg-moLe}}}_{} + r_p\, [\text{Sm}^3\ \bar{o}] \times \frac{\rho_{\bar{o}} \left[\frac{\text{kg}}{\text{Sm}^3}\right]}{M_{\bar{o}} \left[\frac{\text{kg}}{\text{kg-mole}}\right]} \right\}$$

$$m_w = n_{\bar{g}} M_{\bar{g}} + n_{\bar{o}} \cdot M_{\bar{o}}$$

$$M_w = \frac{\dfrac{M_{\bar{g}}}{23.68} + r_p \rho_{\bar{o}}}{\dfrac{1}{23.68} + r_p \dfrac{\rho_{\bar{o}}}{M_{\bar{o}}}} \quad \begin{array}{l} \times 23.68 \\ \\ \times 23.68 \end{array}$$

$$= \frac{M_{\bar{g}} + 23.68\, r_p \rho_{\bar{o}}}{1 + 23.68 \dfrac{\rho_{\bar{o}}}{M_{\bar{o}}} r_p}$$

$$= \frac{M_{\bar{g}} + 23680\, r_p \gamma_{\bar{o}}}{1 + 23680 (\gamma_{\bar{o}}/M_{\bar{o}}) r_p}$$

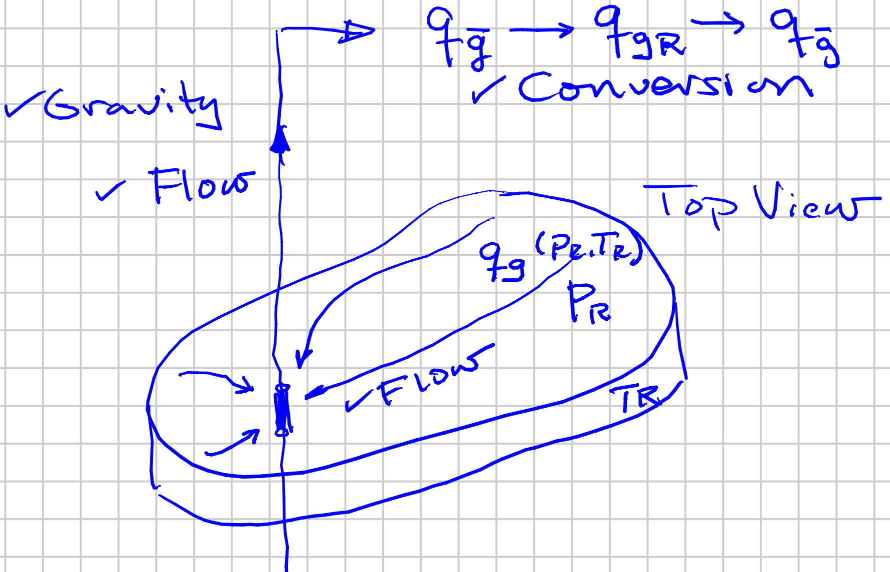
$$\gamma_w = \frac{M_w}{M_{air}} = \frac{(M_{\bar{g}}/M_{air}) + 23680\, r_p \gamma_{\bar{o}} / M_{air}}{1 + 23680 (\gamma_{\bar{o}}/M_o) r_p}$$

$$= \frac{\gamma_{\bar{g}} + \left(\frac{23680}{28.97}\right) r_p \gamma_{\bar{o}}}{1 + 23680 (\gamma_{\bar{o}}/M_{\bar{o}}) r_p}$$

$$\boxed{\gamma_w = \frac{\bar{\gamma}_{\bar{g}} + 817\, r_p\, \gamma_{\bar{o}}}{1 + 23680 \left(\frac{\gamma_{\bar{o}}}{M_{\bar{o}}}\right) r_p}}$$

$$\gamma_w = \frac{\bar{\gamma}_{\bar{g}} + 4,580\, r_p \gamma_{\bar{o}}}{1 + 133,000\, r_p (\gamma/M)_{\bar{o}}}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.55)$$

PVT Gas Properties:



Z_g

$\left.\begin{array}{l} B_g \\ b_g \end{array}\right\}$ conversion

ρ_g Gravity

c_g

μ_g ~0.02-03 cp → 0.1 cp HP + high C_{7+} content

$\left(\frac{p}{\mu_g Z_g}\right.$ or $\left.\frac{1}{\mu_g B_g}\right)$ } Flow

Gas (Formation) Volume Factor

$$B_g \equiv \frac{V_g(p,T)}{V_{\bar{g}}(p_{sc},T_{sc})} \quad : \quad 0.01 - 0.003 \frac{m^3}{Sm^3} \quad \frac{ft^3}{scf}$$

$$b_g \equiv \frac{1}{B_g} = \frac{V_{\bar{g}}}{V_g(p,T)} \quad : \quad \sim 100 - 300 \text{ typically} \quad \frac{Sm^3}{m^3} \quad \frac{scf}{ft^3}$$

(gas expansion)

Assume $n_g(p,T) = n_g(p_{sc},T_{sc}) = \frac{pV}{RTZ}$

$$B_g = \frac{p_{sc}}{T_{sc}} \cdot \frac{T\,Z(p,T)}{p}$$

$$b_g = \frac{T_{sc}}{p_{sc}} \frac{p}{TZ}$$

Reservoir Barrel bbl

Sometimes in Field Units : B_g RB/scf

RB/Mscf

Be careful!

$$B_g = 0.005 \frac{(\cancel{ft^3})}{\cancel{scf}} \times \frac{RB}{5.615\ \cancel{ft^3}} \times \frac{1000\ \cancel{scf}}{Mscf}$$

$$= 0.89\ RB/Mscf$$

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

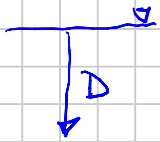
$$\frac{n_g}{V_g} = \frac{p}{RTZ_g}$$

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

Static Column of Gas

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

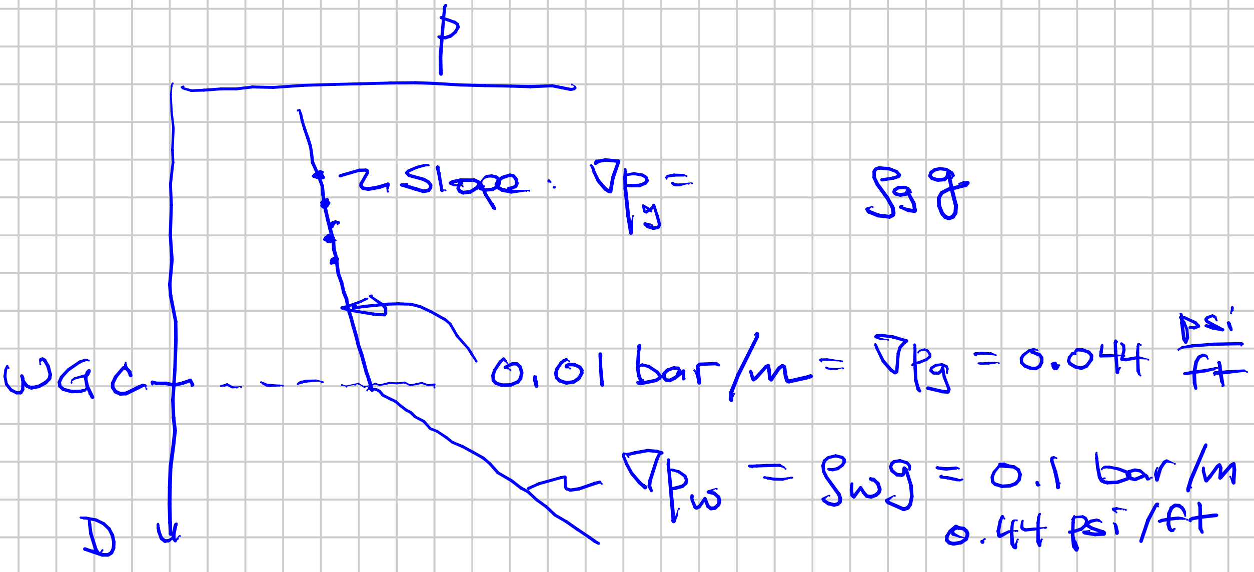
depth



Gradient of p w.r.t. depth $\nabla p = \frac{dp}{dD}$

important for Petroleum engineering.

e.g. Estimating IGIP (G) : HCPV$_g$



Slope : $\nabla p_g = \rho_g g$

$0.01 \text{ bar/m} = \nabla p_g = 0.044 \frac{\text{psi}}{\text{ft}}$

$\nabla p_w = \rho_w g = 0.1 \text{ bar/m}$
0.44 psi/ft

e.g. $\rho_g = 100 \text{ kg/m}^3$ Pa : $\frac{\text{kg}}{\text{m} \cdot \text{s}^2}$

$$\nabla p_g = 100 \frac{\text{kg}}{\text{m}^3} \cdot 9.8 \frac{\text{m}}{\text{s}^2} = 1000 \underbrace{\frac{\text{kg}}{\text{m}^2 \text{s}^2}}_{\frac{\text{Pa}}{\text{m}}}$$

$$\times \frac{\text{bar}}{10^5 \text{ Pa}}$$

$$= \frac{1000}{10^5} = 0.01 \text{ bar/m}$$

Field units:

$$\frac{\rho \left[\text{lbm/ft}^3 \right]}{144 \text{ in}^2/\text{ft}^2} \rightarrow \underbrace{\frac{\text{psi}}{\text{ft}}}$$

lb_f/in^2

$$\rho_g = 6.3 \text{ lb/ft}^3 \rightarrow \frac{6.3}{144} = 0.0437 \frac{\text{psi}}{\text{ft}} = \nabla p_g$$

$$\rho_w = 63. \text{ lb/ft}^3 \rightarrow 0.437 \text{ psi/ft}$$

Flow:

Tubing (Pipe)
Reservoir

$\rightarrow \mu_g$

$\rightarrow c_g$

$$\left\{ \frac{p}{\mu_g Z_g} \quad \text{or} \quad \frac{1}{\mu_g B_g} \right\}$$

Reservoir Flow
(Darcy's law)

Al-Hussainy & Ramey & Crawford
Texas A&M

Pseudopressure $\underbrace{m(p) \qquad p_p}$ LHS of PDE

$$= \int \frac{p}{\mu_g Z_g} dp \quad \text{or} \quad \int \frac{1}{\mu_g B_g} dp$$

Linearized PDE

c_g: Diffusivity Term
RHS of PDE

$$\left(\frac{k}{\phi \mu_{gi} c_{ti} r_w^2} \right) \sim \text{constant}$$

$$c_{ti} = c_f + c_w \cdot S_w + c_{gi} (1 - S_w)$$

pore volume comp.

$$= \frac{1}{p_i} - \left[\frac{1}{Z_i} \left(\frac{dZ}{dp} \right)_T \right]_{@ p_i}$$

$$c \equiv -\frac{1}{V} \left(\frac{dV}{dp} \right)_T$$

$$\mu_g = f(\rho_g, T)$$

involves Z_g

Lee-Gonzalez (Ch.3)
~ 5% accuracy

PHYSICAL PROPERTIES REVIEW

Note Title 2012-09-04

Phase Properties

42 gal/bbl

$\star$ DENSITY ρ [kg/m³, g/cc, g/cm³; lb/ft³, ppg]

kg/m³

1000+ Water (salinity): Brine

OILS

300 ← Near-Critical Petroleum Mixtures

100 GAS ↓

10

1 Standard Condition (1 atm)

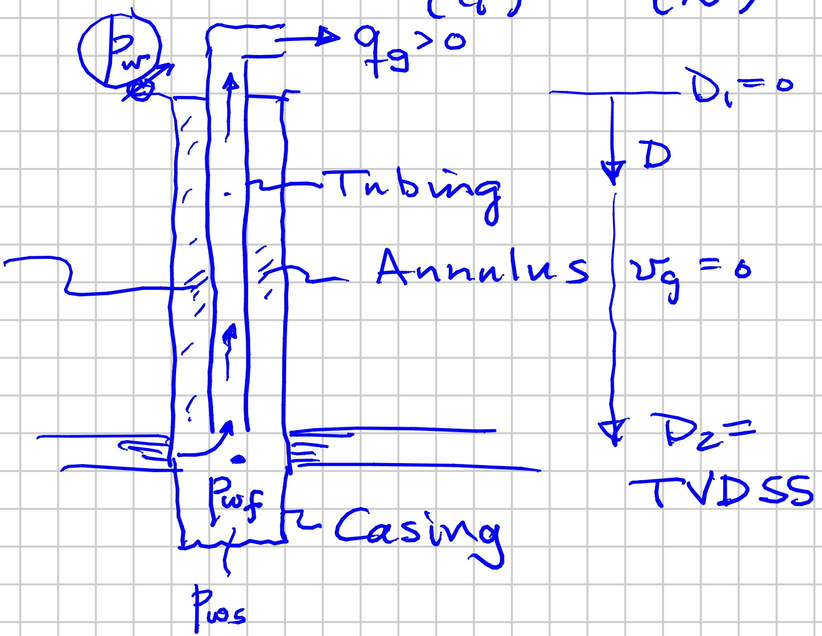
(1) Static Column Pressure-Depth $\qquad \underline{\frac{dp}{dD} = \rho g}$

(a) In reservoir, helping figure out $HCPV_g$ & $HCPV_o$

"Fluid Initialization" ⇒ IGIP (G), IOIP (N)

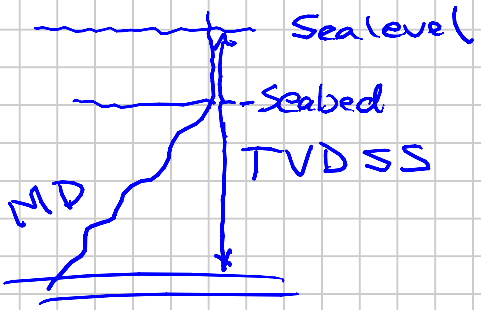
(b) Shut-in Wells (& Flow Wells)

Assume: $\underbrace{\bar{T}, Z_{(\bar{p},\bar{T})}}_{\sim \text{Constant}}$



$$\rho_g = \underbrace{\frac{M_g}{Z\bar{T}R}}_{\sim \text{const.}} \cdot p$$

$$\Rightarrow \frac{p(D_1)}{p(D_2)} = \text{constant}$$



(2) Flow equations

(a) Darcy in Reservoir

(b) Pipeflow

- Gravity
- Friction

$(\underline{v_z})$

$$Re = \frac{\rho \overset{\downarrow}{v} d}{\mu}$$

Gas : $\rho_g \propto p$ 1st order effect

Oil : $\rho_o = f$(gas dissolved)

C_1 content

VISCOSITY [Pa·s cp]

Poisse

[cp]

1 cp = 1 mPa.s

10^x

⋮

10

1

OILS ← Water (0.5 cp)

0.1 — Near Critical GAS

0.01 Gas @ S.C.

Jean Louise Marie Poiseuille

Flow equations :

(1) Reservoir (Darcy) $v \propto \frac{k}{\mu}$

(2) $Re \propto \frac{1}{\mu}$

Henry d'Arcy

Dynamic Viscosity μ

Kinematic — " — $\nu = \frac{\mu}{\rho}$

Estimation of μ by equation

Gases 2-5%

Oils 5-20 - 50 - 100%⁺

$\mu_g = f(\rho_{g_o}, T)$

$$\ln \mu_o = f(\overset{\uparrow}{\rho_o^4}, \overset{\uparrow}{T}, P\text{-}A)$$

$f(x_i, P, T)$

[vol/Vol/psi]

Isothermal Compressibility [1/bar 1/Pa 1/psi]

$$c \equiv -\frac{1}{V}\left(\frac{dV}{dp}\right)_T$$

[1/psi]

Ideal Gas 1/P

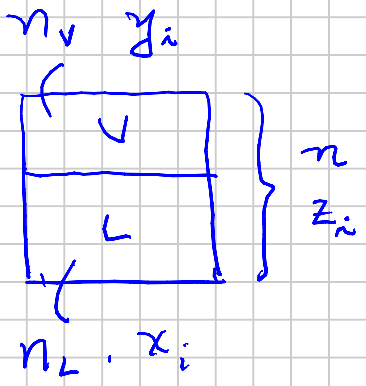
Transient Flow (PTA, DCA)

[1/bar]

↑	GAS	1
30 E-6	OIL	450 E-6
3. E-6	{Water, Pore}	45 E-6

COMPOSITION: Component (i) Amounts in a Mixture

Molar Fractions	z_i Total	y_i Vapor Gas	x_i Liquid Oil
Moles	n_i	n_{gi} n_{Vi}	n_{oi} n_{Li}



$$z_i = \frac{n_i}{\sum_{j=1}^{N} n_j} = \frac{n_i}{n} \quad ; \quad y_i = \frac{n_{Vi}}{n_V}$$

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

Conservation

$$\left\{\begin{array}{l} n_i = n_{Vi} + n_{Li} \\ n = n_V + n_L \end{array}\right\}$$

$F_V \equiv n_V/n$ Vapor Mole Fraction

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

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

Air : ~79 mol-% N_2 ~21 mol-% O_2

$V_{room} \sim 300\, Sm^3$

$$n_{air} = 300 \,/\, 23.68\ Sm^3/\text{kg-mole} = 12.67\ \text{kg-mole}$$

$$V_{H_2O} = 0.7\ L \Rightarrow \left\{0.7 \cdot 10^{-3}\ \cancel{m}^3 \times 1000\ \frac{kg}{\cancel{m}^3}\right\} \times \frac{\text{kg-mole}}{18\ kg}$$

$$= n_{H_2O} = 0.0389\ \text{kg-mole}$$

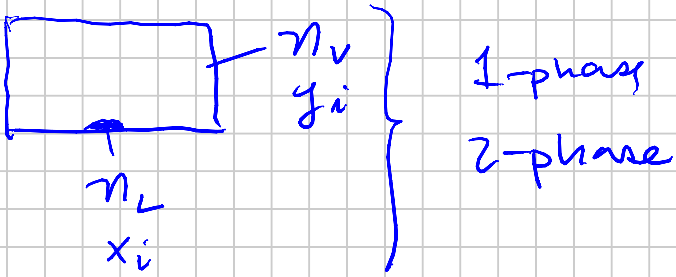
$\boxed{z_i}$

$$z_{N_2} = \frac{n_{N_2}}{n} = \frac{0.79(12.67)}{12.67 + 0.0389} = 0.7876 \quad +$$

$$z_{O_2} = \frac{0.21\ (12.67)}{12.67+0.0389} = 0.2097 \quad +$$

$$z_{H_2O} = \frac{0.0389}{12.67+0.0389} \qquad 0.0027$$

$$\overline{\qquad\qquad 1.0000}$$



Mass Fractions

w_i	w_{gi}	w_{oi}
Total	Gas	Oil

$$w_i \equiv \frac{m_i}{m}$$

$$w_{H_2O} = \frac{m_{H_2O}}{m_{air}+m_{H_2O}}$$

$$m_{H_2O} = 0.7 \text{ kg}$$

$$m_{air} = 300 \text{ m}^3 \times 1.22 \text{ kg/m}^3 = 366$$

$$w_{H_2O} = \frac{0.7}{366.7} = 0,00191$$

To do "phase" equilibrium calculations: Given z_i, p, T

- How many phases form?
- How much (moles or mass) in each phase
- Phase compositions y_i x_i?

Equation of State (EOS): pVT

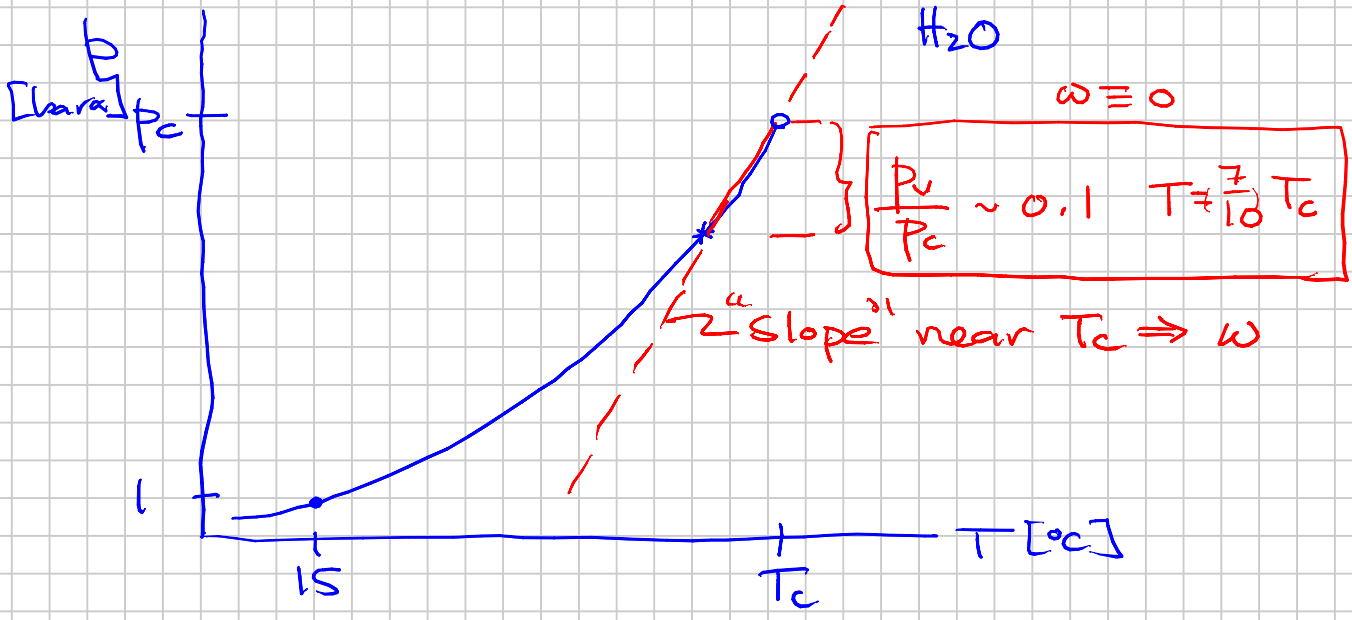
Ch. 4

- Good for both Gas and Liquid
- Needs information about each component

T_c, p_c } van der Waals (Corresponding State)

M $m \leftrightarrow n$

{ ω Acentric Factor } $0 \rightarrow 1$ (2)

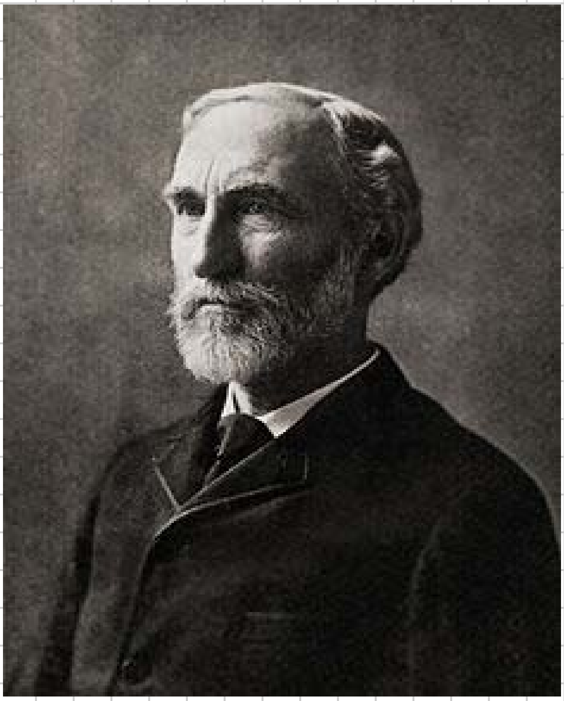


$$\omega \equiv -1 - \log_{10} \frac{P_v(T_r=0.7)}{P_c}$$

Pitzer

$\omega = 1$

$\frac{P_v}{P_c} = 0.01 \qquad \frac{T}{T_c} = 0.7$



J. Willard Gibbs

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

$\{ C_6 \quad C_7 \quad C_8 \ \ldots \ C_{20} \ \ldots \ C_{50} \ \ldots \ C_{100} \ \ldots \}$ 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 $$\boxed{K_w} \equiv \frac{T_{b(°R)}^{1/3}}{\gamma}$$ 8-10 Compounds

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

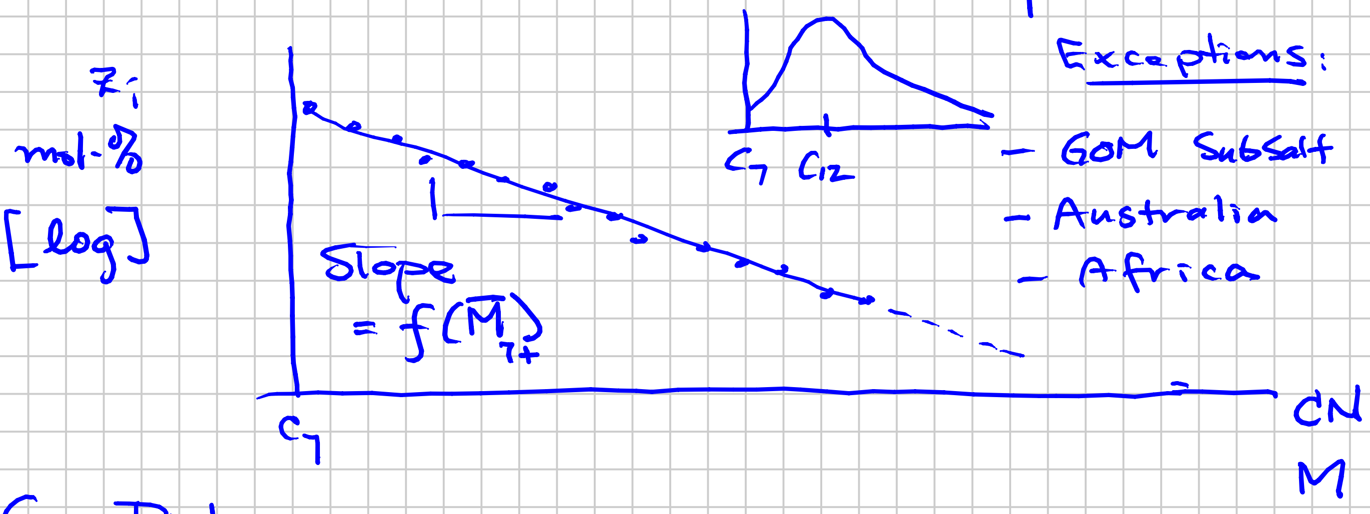
12.5 Oils (STO) 10

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

e.g. N.S. 11-12.2

C_{7+} Molar Distribution can be important

(Exponential)



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: $h = +2$

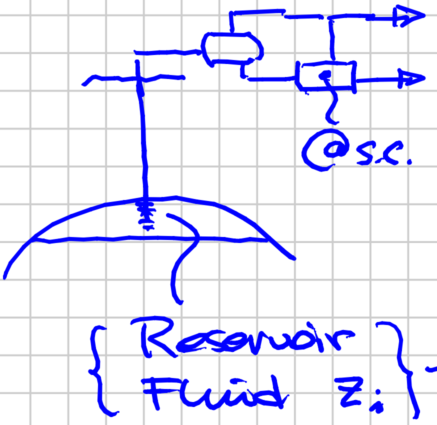
A: $h = -6$

TABLE 2.1—COMPOSITION AND PROPERTIES OF SEVERAL RESERVOIR FLUIDS

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	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) ~ C_{5-}

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

{Reservoir Fluid z_i} → $\underline{R, GOR} = \frac{V_{\bar{g}}}{V_{\bar{o}}} \left[\frac{Sm^3}{Sm^3}\right] \left[\frac{scf}{STB}\right]$

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

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 ~ C_{5-} 90.70

SO ~ 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

$$V_{\bar{o}} \sim V_{6+} = \underset{\cancel{\text{kgmole}}}{n_{6+}} \cdot \underset{\frac{\cancel{\text{kg}}}{\cancel{\text{Kgmole}}}}{M_{6+}} \cdot \underset{\frac{\text{S m3}}{\cancel{\text{kg}}}}{\frac{1}{\rho_{6+}}} = 9.30(175)/800 = 2.03 \text{ Sm}^3$$

$$= 12.75 \text{ STB}$$

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

$\sim$ Ideal Gas Law @ s.c.

$$\frac{\text{m}^3 ✓}{\text{kg} ✓} \quad \frac{V_{\bar{g}}}{n} = \frac{R\,T_{sc}}{p_{sc}} = \underbrace{(0.08314)\frac{\overset{K}{(273.15+15.56)}}{\underset{\text{bar}}{1.0135}}}$$

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

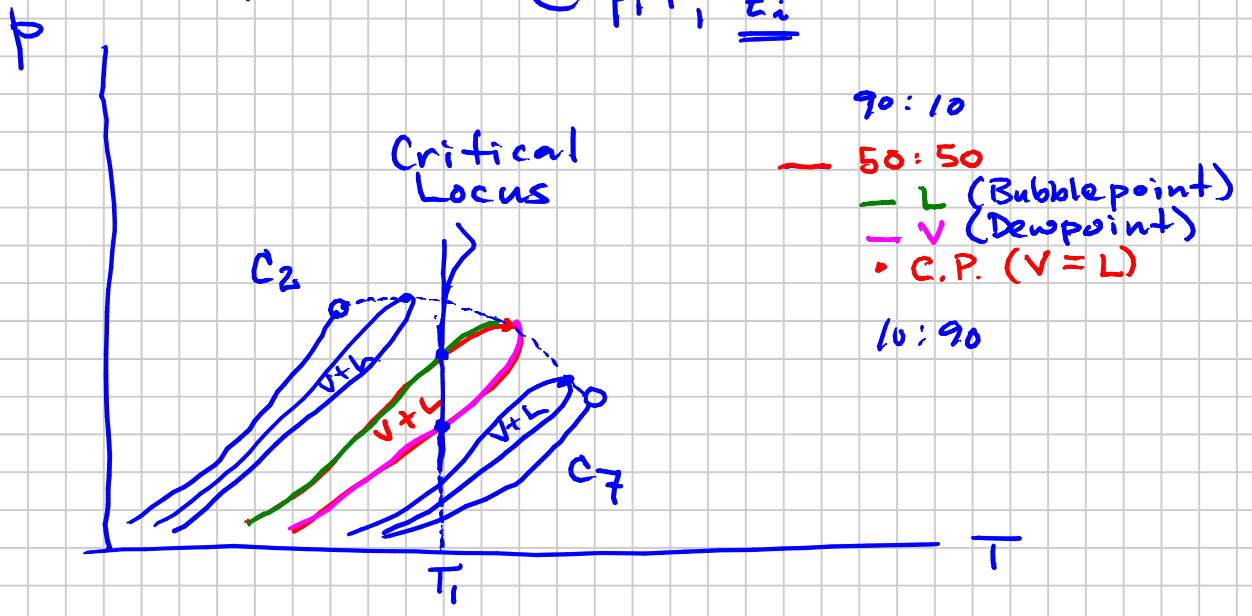
6.28 bbl / Sm^3
35.31 scf / Sm^3 } App. A

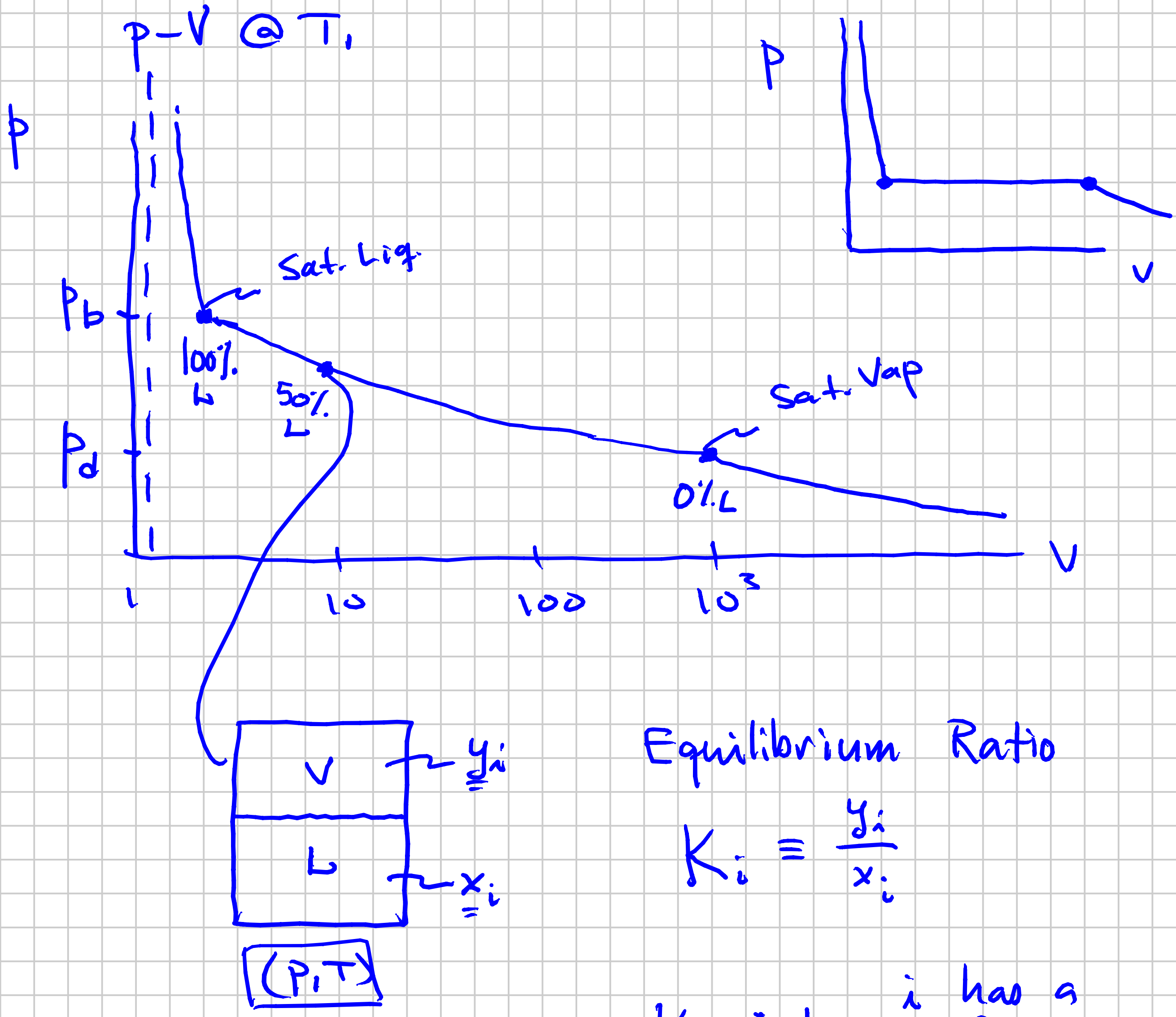
0.03531 Mscf / Sm^3

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

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

Vapor (Gas)
Liquid } How much of each phase @ p, T, 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

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

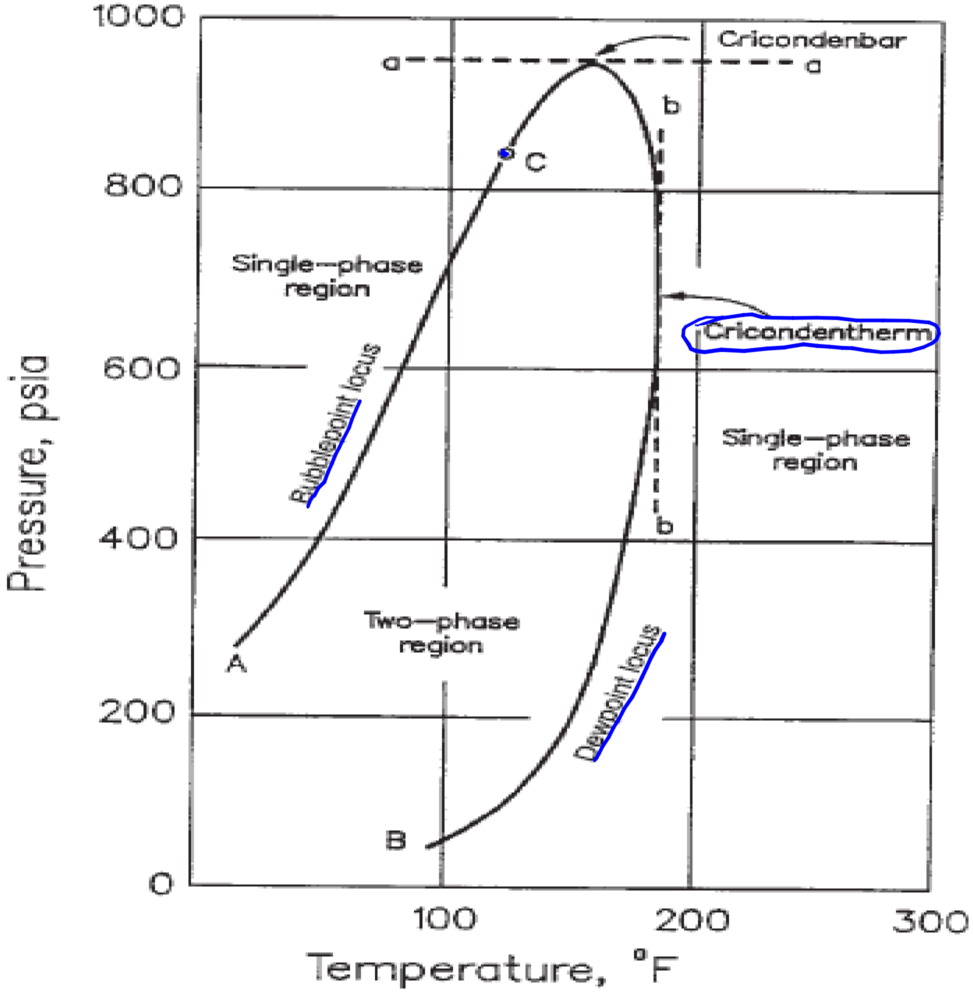


Fig. 2.9—*p-T* diagram for a C_2/*n*-C_7 mixture with 96.83 mol% ethane (from Standing[26]).

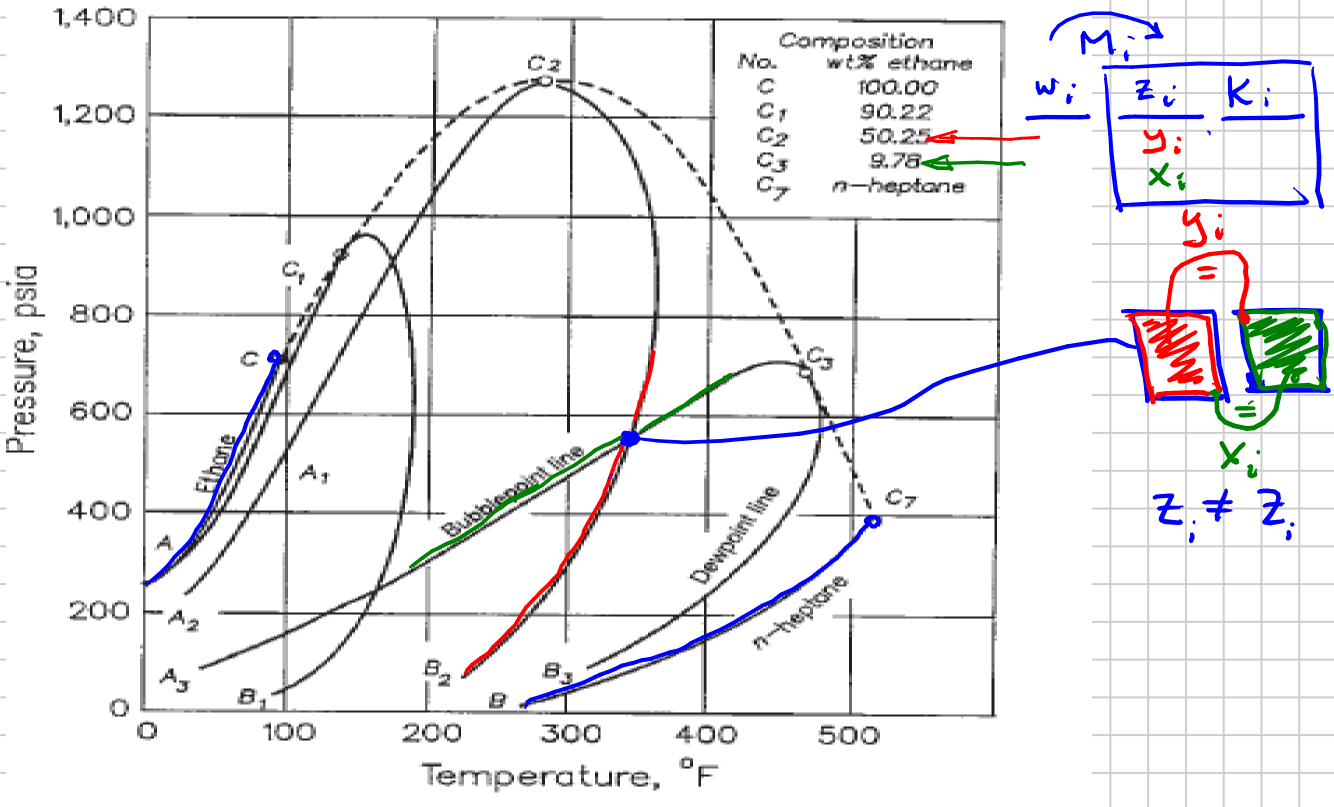
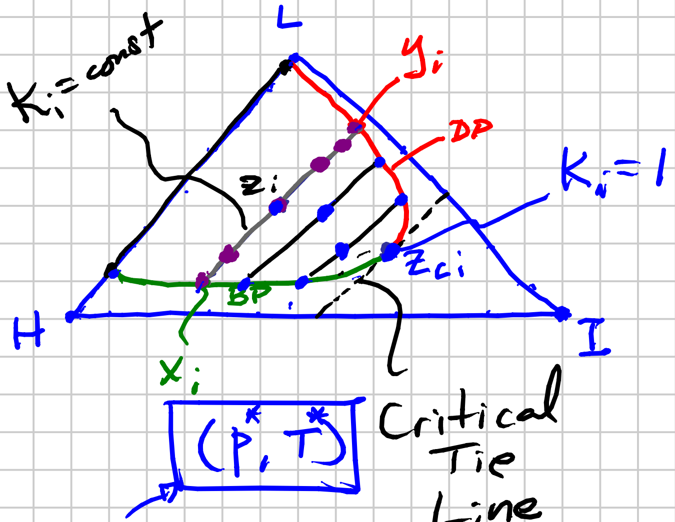


Fig. 2.10—*p-T* diagram for the C_2/*n*-C_7 system at various concentrations of C_2 (after Kay[30]).

3-Component Phase Behavior

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



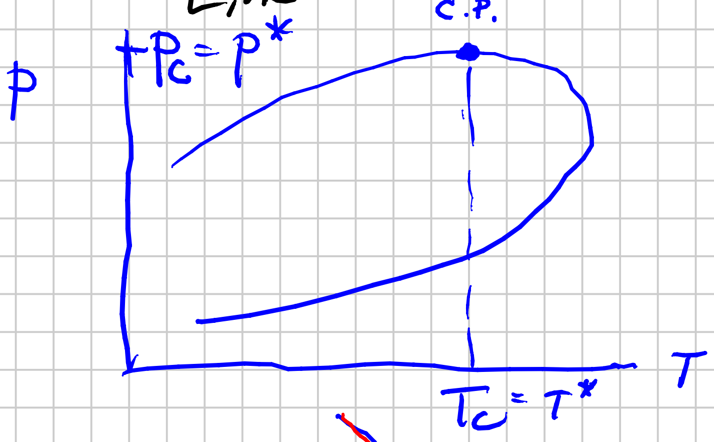
$z_L = 0.3$ (30%)

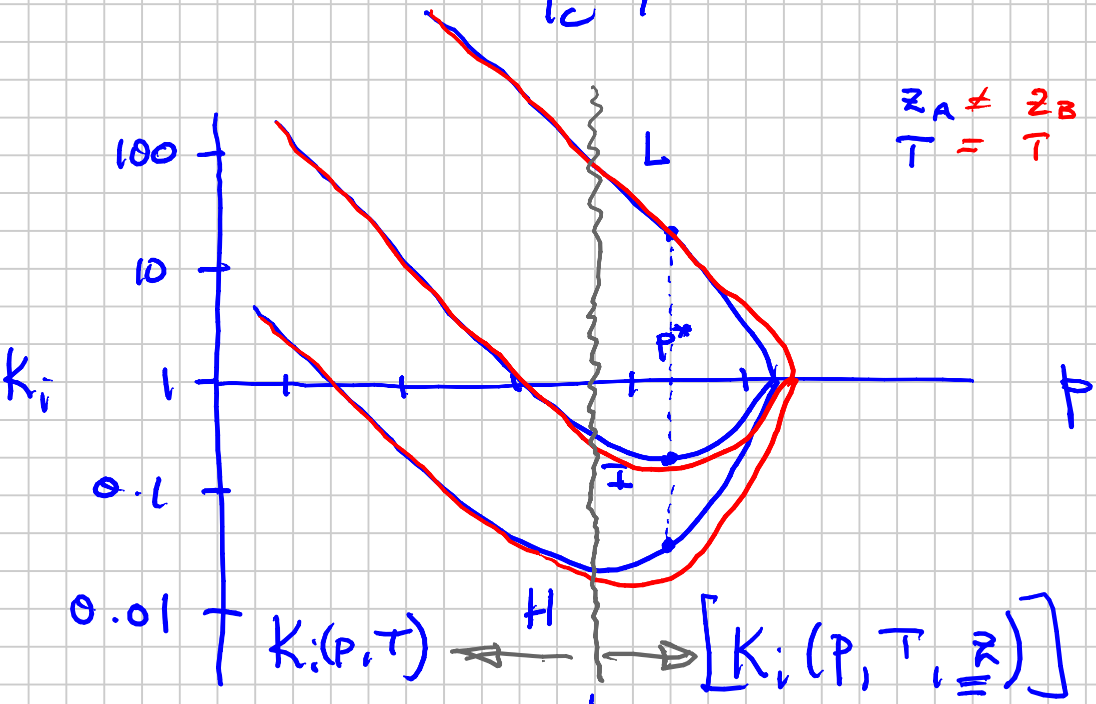
$z_I = 0.3$ (30%)

$z_H = 0.4$ (40%)

$\overline{}$

1.0





y_i
x_i
n_v
n_L

"Low Pressure"
$p \lesssim 50$ bar
↓
80 bar

Surface Processing

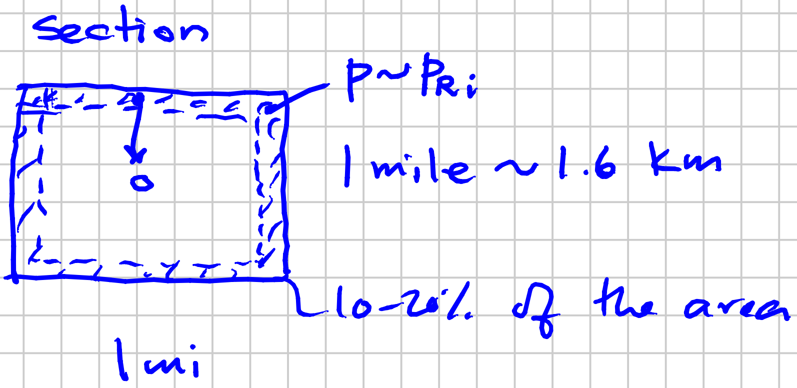
Reservoir Conditions

Multicomponent Phase Behavior

www.npd.no

$(\underbrace{p-T}, \ p-V)$

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



$t_{final} \sim$ "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

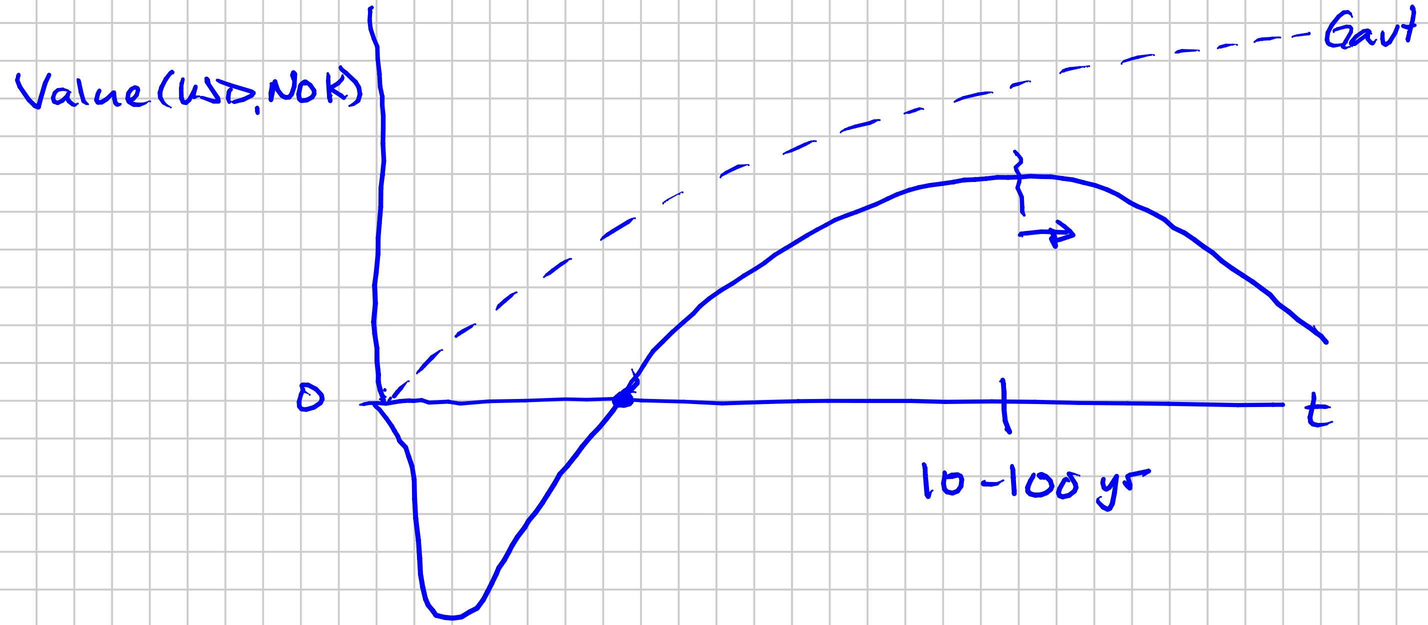
$\downarrow$

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

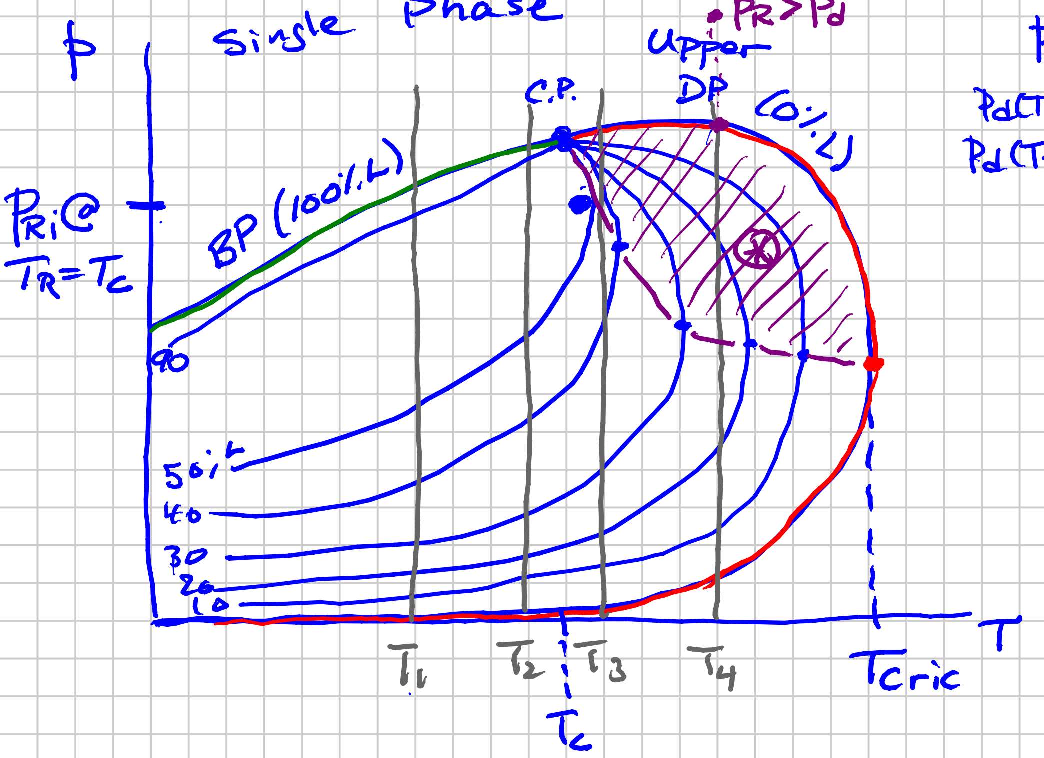
Gases ↑

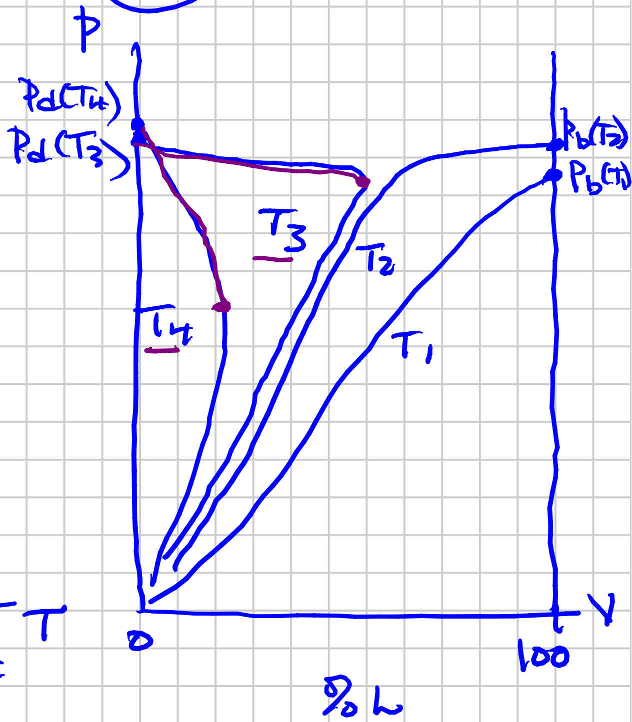
Oils ↓

↑ life expectancy gets longer



For a Reservoir Fluid – Composition z_{Ri}

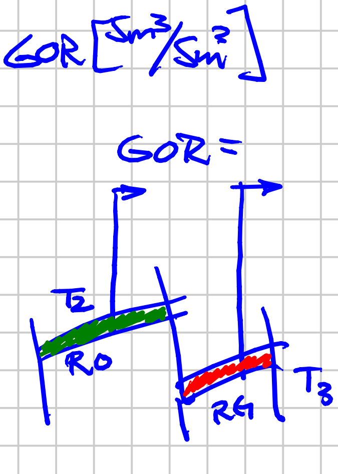




* Increasing L% as pressure decreases:
"Retrograde Condensation"

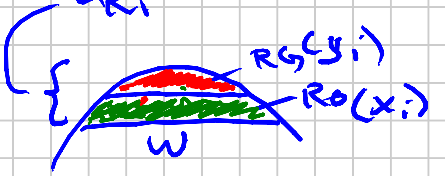
Reservoir Fluid Types

GOR	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

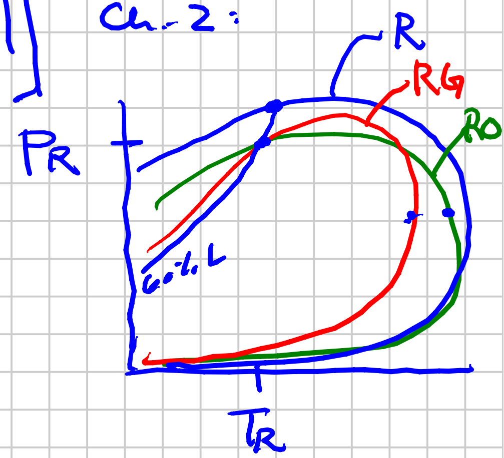


>500-700	≤ 12	GAS ($T_R > T_c$)
↓		G.C. { Near-Critical Gas Cond Rich Gas Condensate Lean Gas Condensate
20 000		
>20 000	<1	Wet Gas
∞	0	Dry Gas

Z_{Ri} = Total R



Ch. 2:



Dead
Black
Volatile } Oils
N.C

N.C.
Rich } Gas Cond
Lean
Wet } Gas
Dry

Decreasing "Size" of Envelope

Decreasing Tcricondentherm

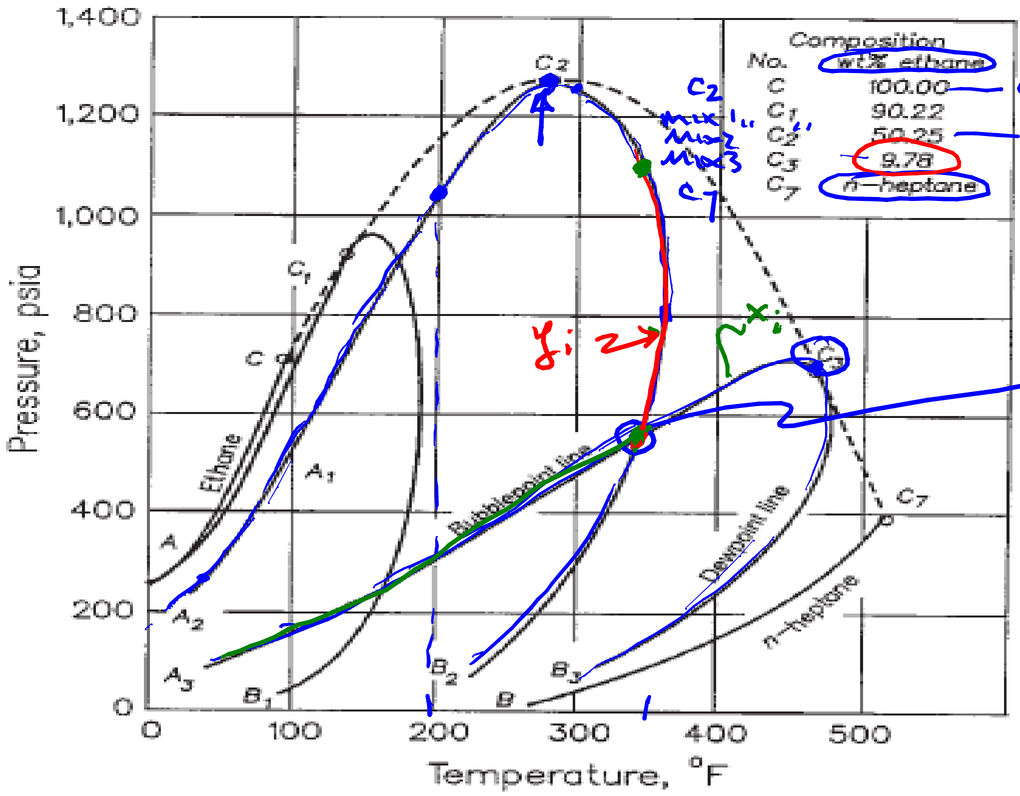
Decreasing T_c

Decreasing Surface Oil Opaqueness

PhazeComp Calculations

- C_2-C_7 Binary : Model Verification ✓
  1. P-T Mix 2 Good
     - T_c slightly high
  - x_i @ 330 F, 550 psia good
- Table 2.1

  (Dry Gas, Wet Gas, Gas Condensate)



C2 : 100% wt

C2 : 50 wt-%

C2 : 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 C₂/n-C₇ system at various concentrations of C₂ (after Kay30).

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

C_2 : $M_{C2} = 30$

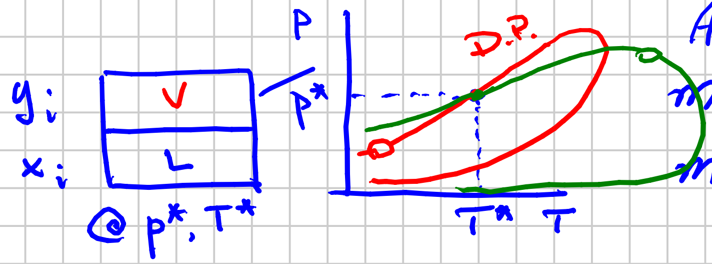
n-C_7 : $M_{C7} = 100$

wt-% <-> mol-%

w_i	z_i
m_i	n_i

Mix : 50 wt-% C_2

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



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

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

Assume $m = 100$ g

$m_{C2} = 50$ g

$m_{C7} = 50$ g

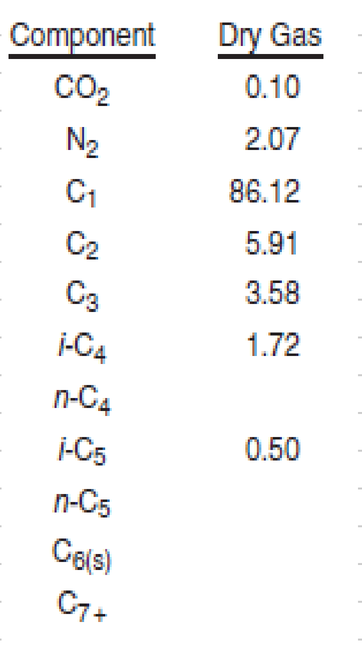
$$z_{C_2} = \frac{50/30}{(50/30) + (50/100)} \times 100$$

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

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

DRY GAS SYSTEM

✓

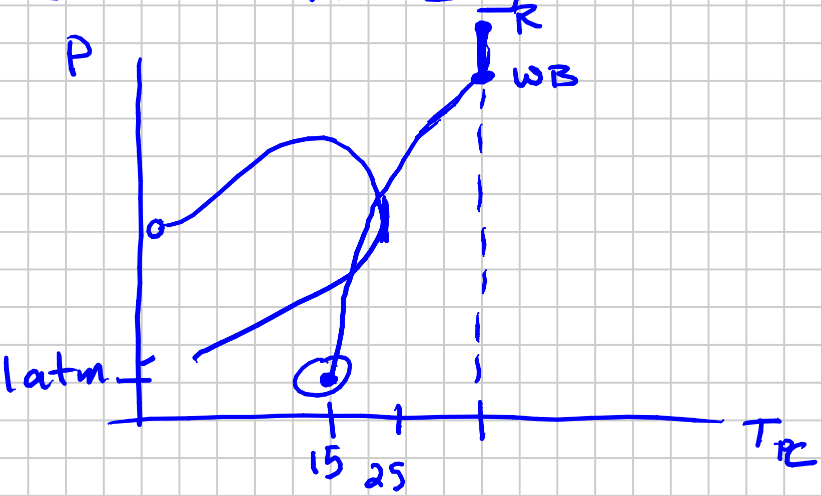


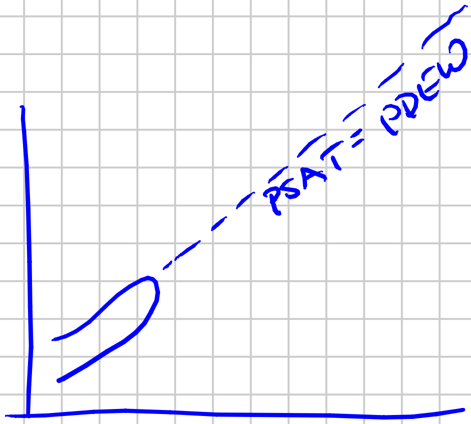
Component	Dry Gas
CO_2	0.10
N_2	2.07
C_1	86.12
C_2	5.91
C_3	3.58
i-C_4	1.72
n-C_4	
i-C_5	0.50
n-C_5	
$C_{6(s)}$	
C_{7+}	

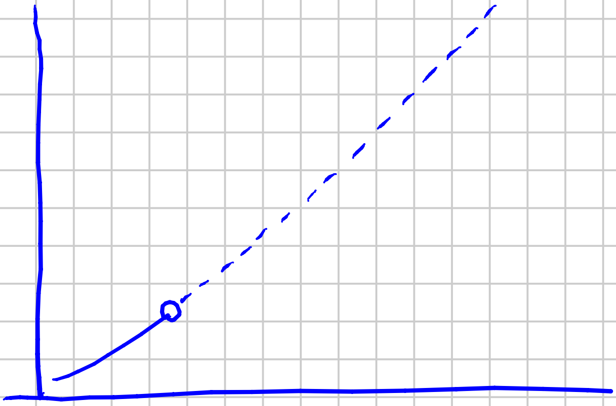
$T_{cric} < 0°C$

Realistic Reservoir Temperatures

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

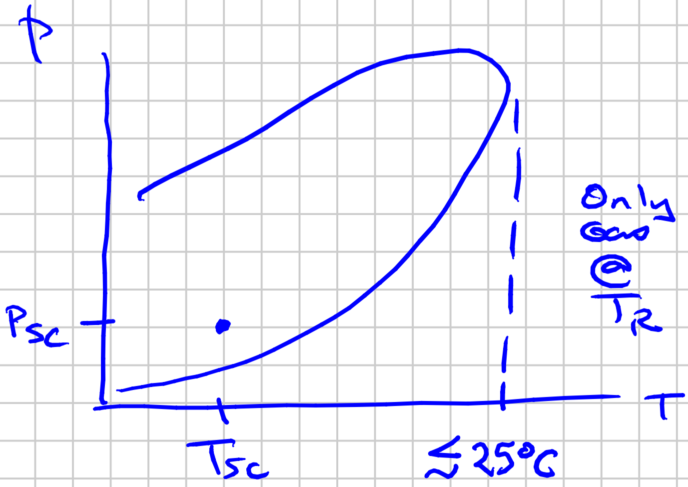






Component	Dry Gas	Wet Gas
CO_2	0.10	1.41
N_2	2.07	0.25
C_1	86.12	92.46
C_2	5.91	3.18
C_3	3.58	1.01
i-C_4	1.72	0.28
n-C_4		0.24
i-C_5	0.50	0.13
n-C_5		0.08
$C_{6(s)}$		0.14
C_{7+}		0.82

C_7
C_8
C_9
$\vdots$
C_N



T_{cric} ~100°C

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

$T_R \leq 100°C \Rightarrow$ Gas Cond.

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

Component	Dry Gas	Wet Gas	Gas Condensat
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-C_4	1.72	0.28	0.71
n-C_4		0.24	1.45
i-C_5	0.50	0.13	0.64
n-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
$\gamma_{C_{7+}}$		0.763	0.816

← SPLIT

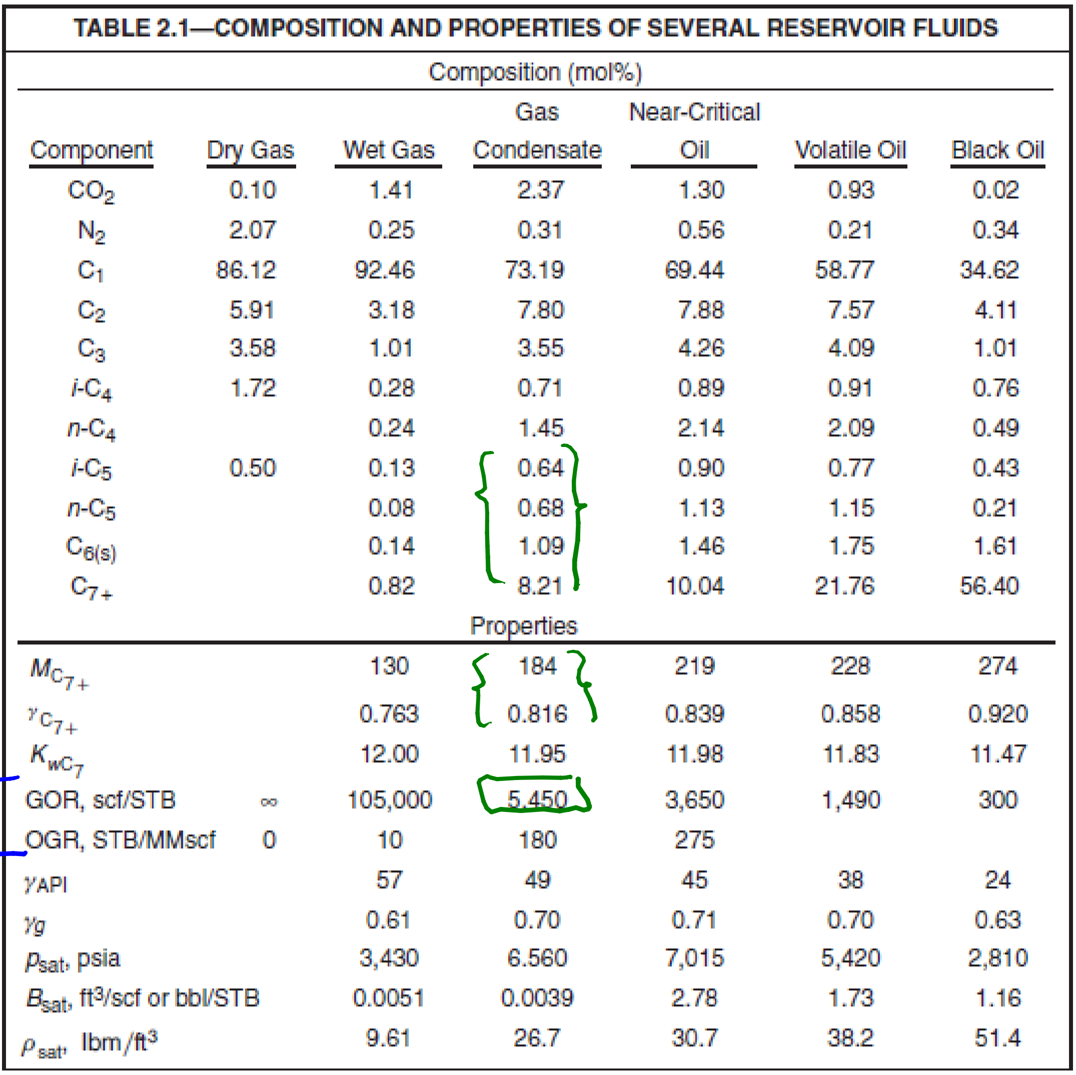


TABLE 2.1—COMPOSITION AND PROPERTIES OF SEVERAL RESERVOIR FLUIDS

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
$i\text{-}C_4$	1.72	0.28	0.71	0.89	0.91	0.76
$n\text{-}C_4$		0.24	1.45	2.14	2.09	0.49
$i\text{-}C_5$	0.50	0.13	0.64	0.90	0.77	0.43
$n\text{-}C_5$		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		
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: $\bar{o} = C_{6+}$

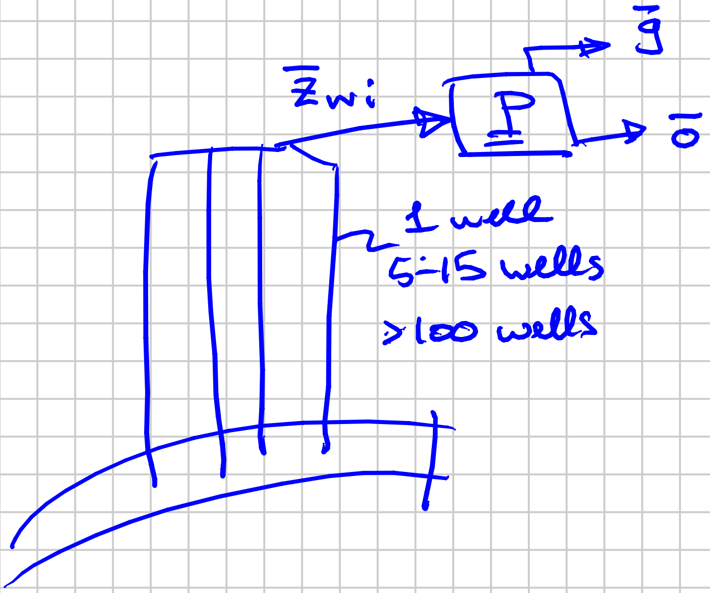
$$\boxed{\frac{\rho_{\bar{o}}}{M_{\bar{o}}} \sim \frac{816}{184} \sim 4.5}$$

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

Molar Composition z_{Ri} (↔ ↕) spatial variation

↓ $\boxed{P}$

Sales Surface Products

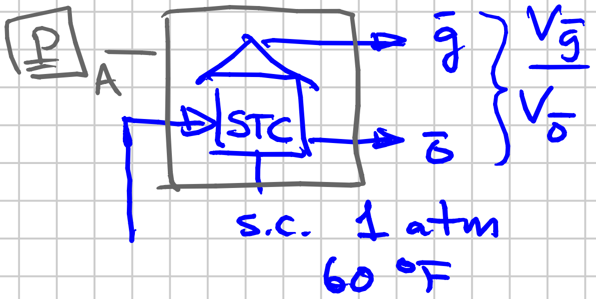


$3-4/Mscf

$115/bbl

$\boxed{\underline{P}}$

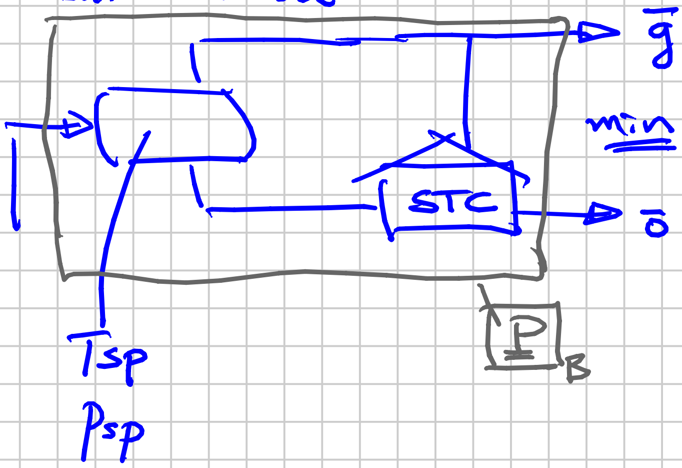
Simple (Single Well Testing in Podunck OK)



Inefficient Process

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

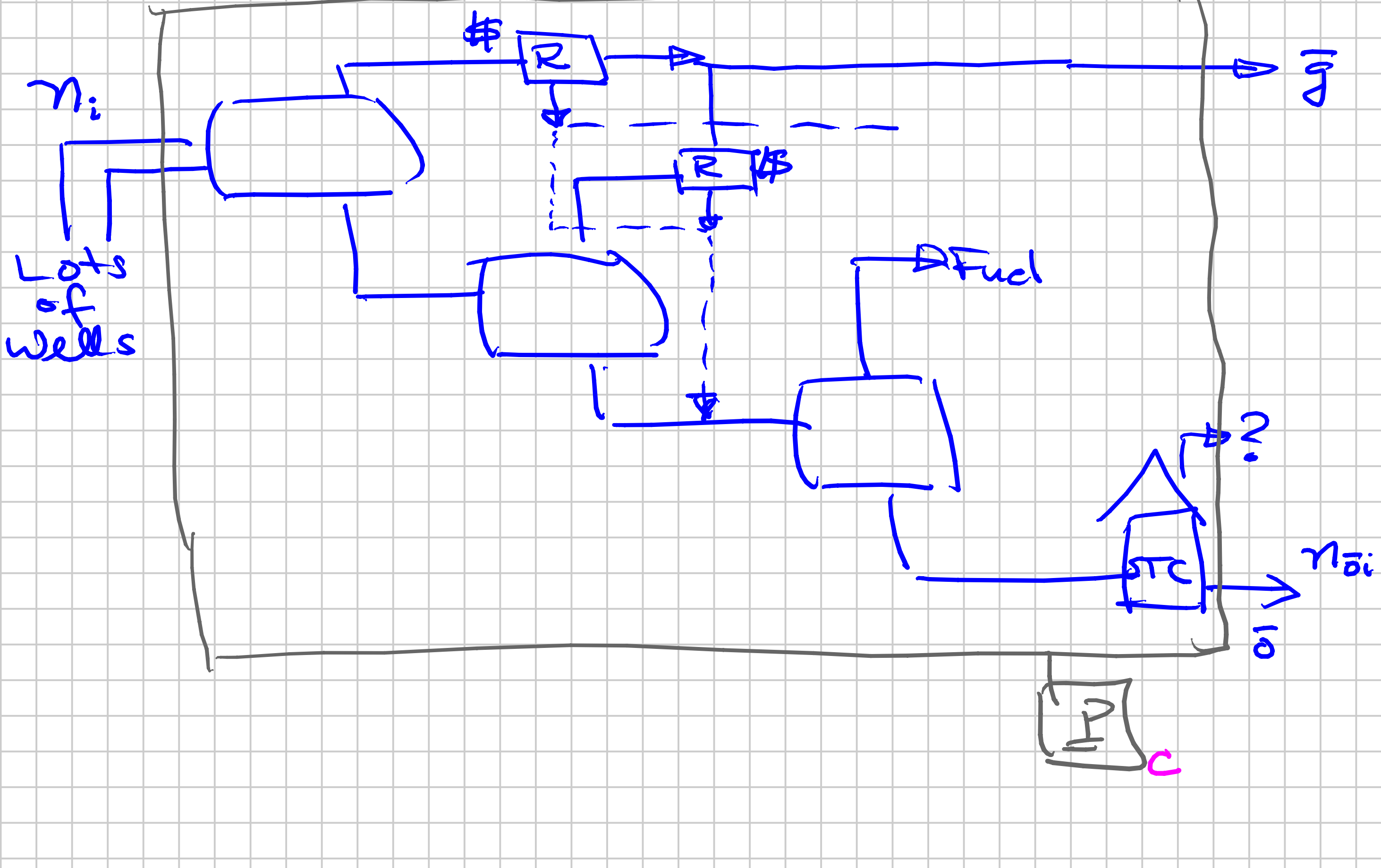
Simple-But-Normal



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

$\Rightarrow$ max Value $

Offshore/Larger Projects



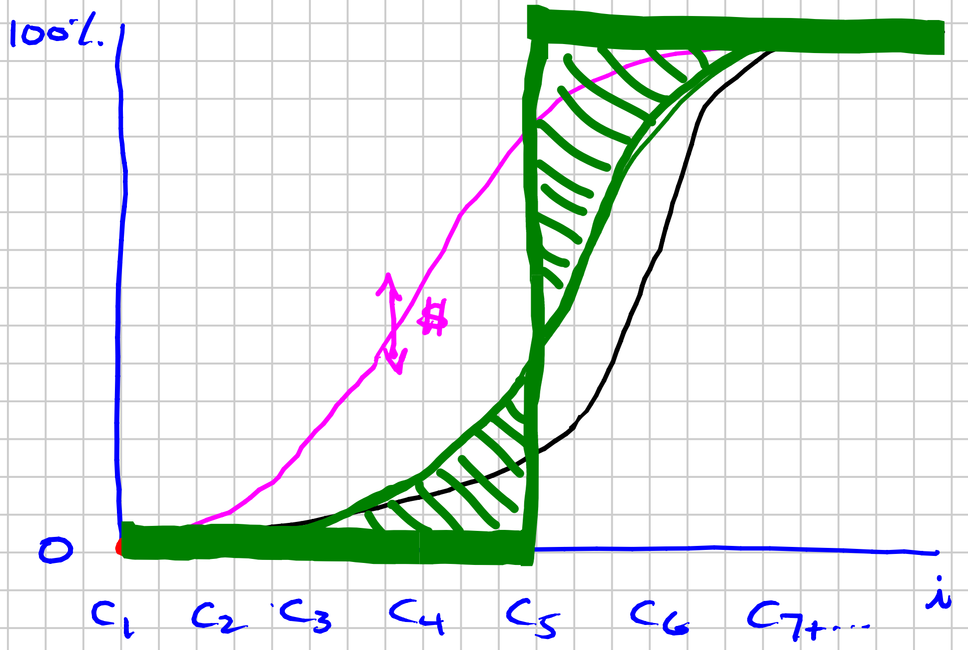
$$E_i \equiv \frac{n_{\bar{o}i}}{n_i}$$

$RF_{\bar{o}i}$

$\boxed{\underline{P}}_A$

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

$\boxed{\underline{P}}_C$



±5-15%

$\approx$

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

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

Given $z_i \propto n_i$

$23.6\ \text{Sm}^3/\text{kg-mole}$

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

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

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

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

$\rho\ [\text{kg/m}^3]$

	M	ρ	(ρ/M)
Table 5.2 : C_7 C_8 C_9 $(\bar{C}_{13})$			$\sim$ const

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

$\nearrow$

°API

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

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

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

= 808 sm³/Sm³ [Note: $(\rho_{\bar{o}}/M_{\bar{o}}) = 4$]

Book GOR $= \dfrac{5450}{5.615} = 970$ Sm³/Sm³

C_{5+} (Girls) GOR = 961 Sm³/Sm³ $z_{5+} = 9.98$ mol-%

C_{6+} (Boys) GOR = 1024 Sm³/Sm³ $z_{6+} = 9.3$ mol-%

EQUATIONS OF STATE – "CUBIC"

Note Title 2012-09-18

EOS : p – V – T – n

Phase specific : e.g. Ideal Gas Law
SK Z-factor (Gas)

e.g. Liquids

$$c \equiv -\frac{1}{V}\left(\frac{dV}{dp}\right)_T = \text{constant}$$

Cubic EOS :

Applies to Gases, Liquids, and "Fluid" (G & L)
& Critical Fluids

187x : van der Waals

$$\boxed{p = \underbrace{\left[\frac{RT}{v-b}\right]}_{\text{Repulsive}} - \underbrace{\left[\frac{a}{v^2}\right]}_{\text{Attractive}}} \Rightarrow p = \frac{RT\cdot v^2 - a(v-b)}{(v-b)(v^2)}$$

$$= \frac{\qquad}{v^{③} - bv^2}$$

→ solve for volume v
cubic eq.

$$v \equiv \frac{V}{n} \quad \text{molar volume}$$

Two Constants a, b

Every component (N_2, C_1, Hg, H_2O, ...) has its own (a, b)

Mixture n_i z_i y_i x_i : Average $\underbrace{\bar{a} \quad \bar{b}}_{\text{molar averages}}$

Q: Simplify to Ideal Gas Law as $p \to 0$
$v \to$ "Big"

$$\lim_{p\to 0} p = \frac{RT}{v-b} \to \frac{RT}{v} = p$$

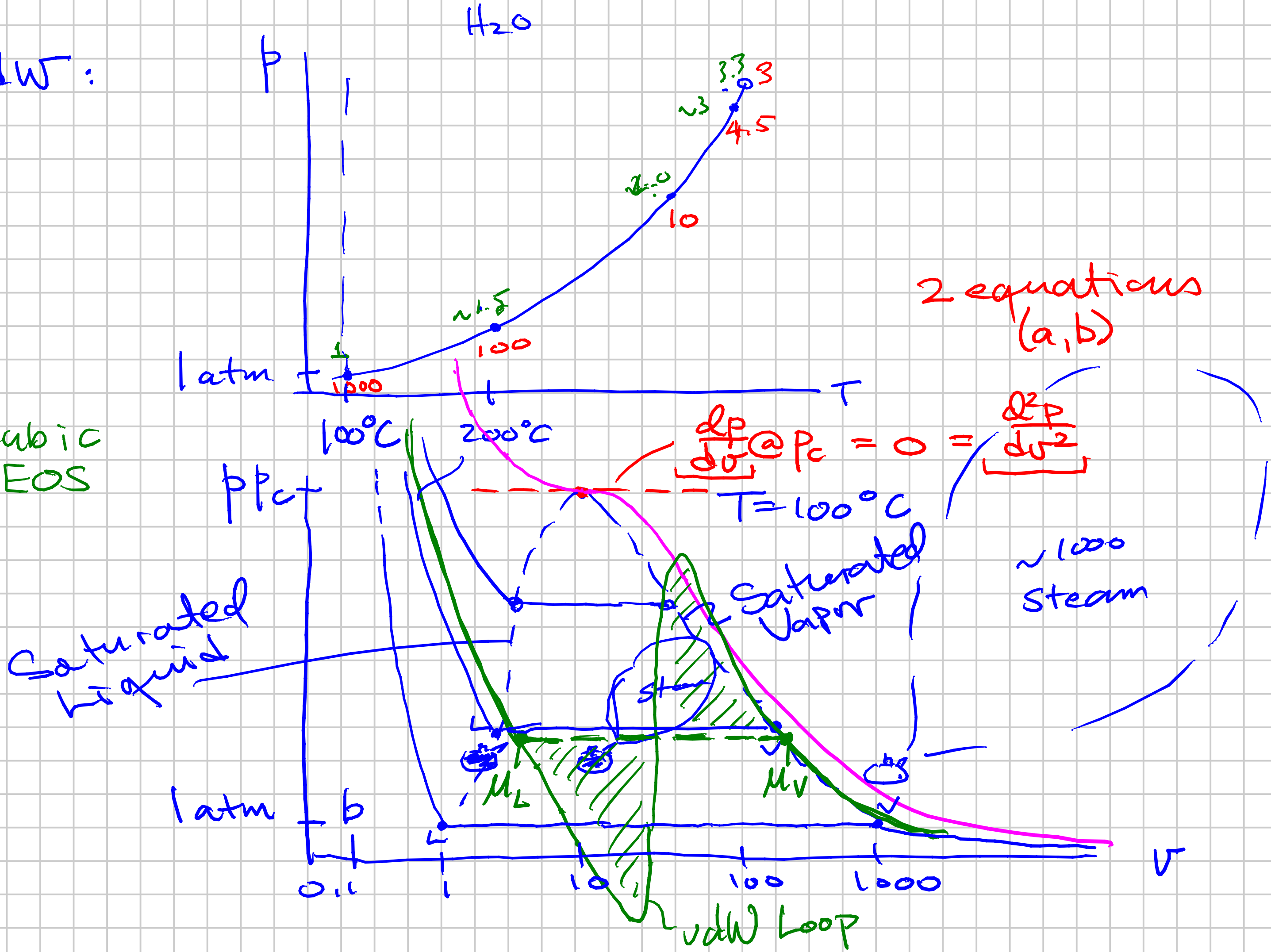
Q: As $p \to \infty$

$v \to b$ $\quad p \to \infty$ } ~Incompressible Liquid

In between these extreme limits gets $p(v,T)$ pretty dang good.

vdW:

Cubic — EOS



$\frac{dp}{dv}$ @ $P_c = 0 = \frac{d^2p}{dv^2}$

van der Waals Critical Criteria: $\frac{dp}{dv} = \frac{d^2p}{dv^2} = 0$ @ T_c, P_c

$$\Rightarrow \quad a = \Omega_a \frac{R^2 T_c^2}{P_c}$$

$$b = \Omega_b \frac{R T_c}{P_c}$$

vdW

$\Omega_a = 27/64$

$\Omega_b = 1/8$

} same for all components

Soave – Redlich – Kwong

197x $\quad$ 1949

Correction Term

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

Not real good calc' v_L of oils

$\rho = M/v$

SRK: 10–35%

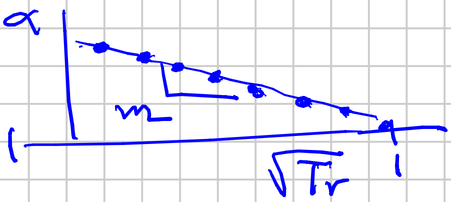
$$a = \Omega_a \frac{R^2 T_c^2}{p_c} \;;\; \Omega_a^{RK} = 0.42478\ldots$$

RK: $\alpha = \frac{1}{\sqrt{T_r}}$ ✓ CH_4

$$b = \Omega_b \frac{RT_c}{p_c} \;;\; \Omega_b^{RK} = 0.08664\ldots$$

$$\underline{\underline{S}}RK : \alpha = \left[1 + m\left(1 - \sqrt{T_r}\right)\right]^2$$

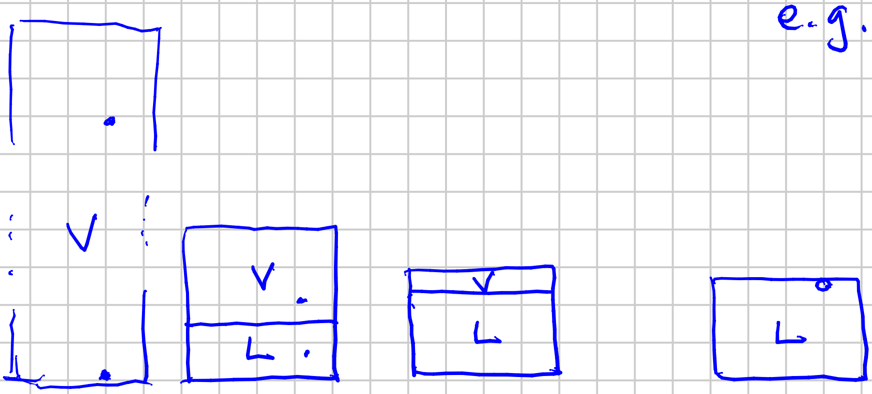
slope



$m = f(\omega)$ ← Acentric Factor

m differs for each component, it was found so that the EOS would predict the "correct" $\underline{\underline{p_v(T)}}$!

e.g. $p_v = 1$ atm @ 100°C for H_2O



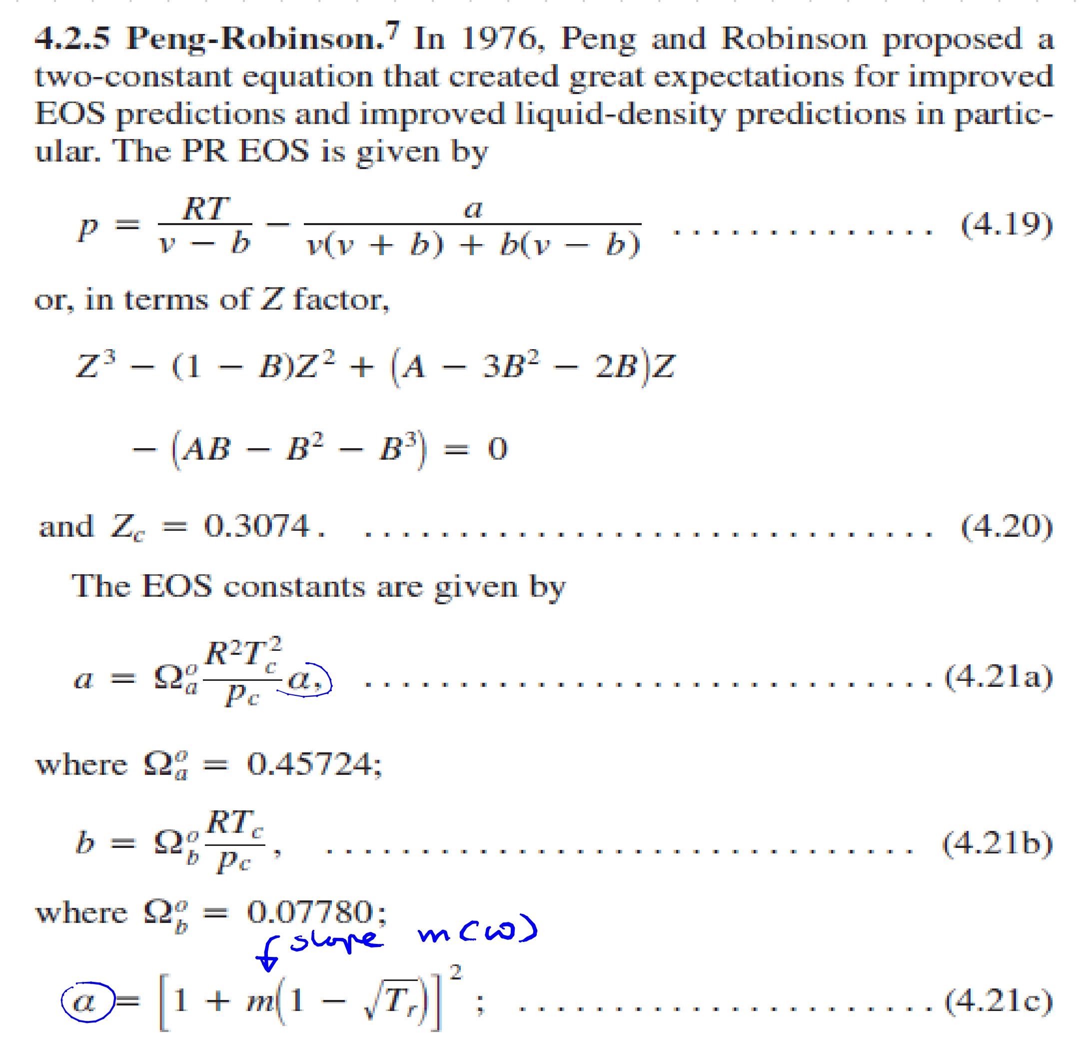
$p_v(T)$ — same 1 atm, 100°C

Gibbs Energy

$\mu_v = \mu_L$

$\mu = f(EOS)$

If your EOS correctly predicts the $p_{v_i}(T)$ then the EOS will automatically predict accurately the way component i partitions in L & V phases of a mixture containing i ...



4.2.5 Peng-Robinson.[7] In 1976, Peng and Robinson proposed a two-constant equation that created great expectations for improved EOS predictions and improved liquid-density predictions in particular. The PR EOS is given by

$$p = \frac{RT}{v - b} - \frac{a}{v(v + b) + b(v - b)} \quad \text{.............. (4.19)}$$

or, in terms of Z factor,

$$Z^3 - (1 - B)Z^2 + \left(A - 3B^2 - 2B\right)Z - \left(AB - B^2 - B^3\right) = 0$$

and $Z_c = 0.3074$. .... (4.20)

The EOS constants are given by

$$a = \Omega_a^o \frac{R^2 T_c^2}{p_c} \alpha, \quad \text{............................ (4.21a)}$$

where $\Omega_a^o = 0.45724$;

$$b = \Omega_b^o \frac{RT_c}{p_c}, \quad \text{.............................. (4.21b)}$$

where $\Omega_b^o = 0.07780$;

$$\alpha = \left[1 + \overset{\text{slope } m(\omega)}{m}\left(1 - \sqrt{T_r}\right)\right]^2; \quad \text{........................ (4.21c)}$$

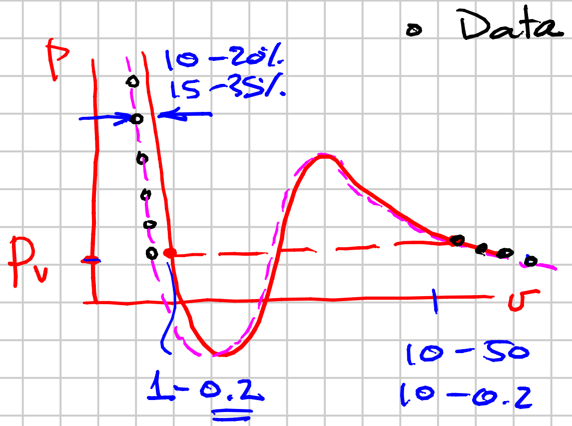
~~→~~ ⊕ ρ_L better than SRK (5-15% errors)
PR

→ ⊖ Methane properties (ρ) not as good as SRK

SRK: warmly adopted by the process industry
early 1970s

PR: First $\underline{\underline{\text{SPE}}}$ paper on cubic EOS 1978
Katz & Firoozabadi

1980 (82): Volume Translation
Peneloux, et al. ✓



SRK or PR ρ_L ± 1-2(3)%
(VT)

$$v = v^{EOS} + c$$

$$v = v_{EOS(2)} - c$$

different for each component

Mixtures :

Binary Interaction Parameter (BIP)

$$\bar{a} = \sum_{i=1}^{N} \sum_{j=1}^{N} z_i z_j (a_i a_j)^{1/2} \underbrace{(1-k_{ij})}_{\text{fix-it correction term}}$$

SRK : $k_{C_1-HC} \sim 0$

PR : $k_{C_1-HC} \sim 0.02-0.2$

$$\bar{b} = \sum_{i=1}^{N} z_i b_i$$

$$SRK(c_i^{SRK}) \simeq PR(c_i^{PR}, k_{ij}^{PR})$$

Gibbs :

Michael Michelsen (DTU Lyngby)

ISOTHERMAL FLASH CALCULATION (Rachford-Rice)

PROBLEM Statement: (1) How many phases (V L)
: 1 or 2 o G

Under-saturated

Saturated: 2 phases
$1-\epsilon$ ϵ

Overall Composition z_i Known

(p, T) Fixed, Known, Specified

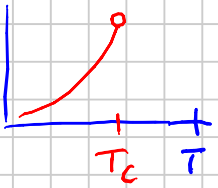
(2) How much of each phase
(moles or mole fraction)
n_v / n_L $\qquad f_v \equiv \dfrac{n_v}{n}$

(3) Molar composition of each phase V: y_i
L: x_i

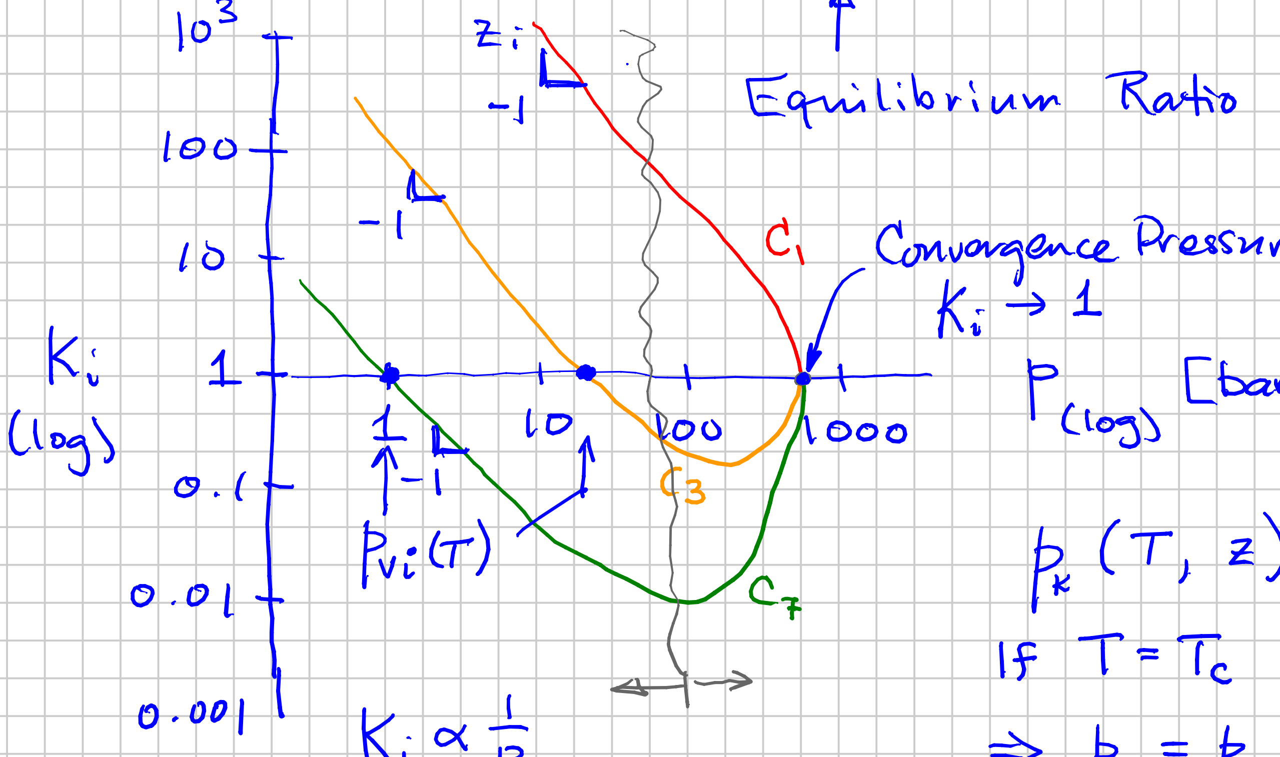
SOLUTION:

Requires <u>estimate</u> of $K_i = \dfrac{y_i}{x_i}$ @ (p, T, z_i)

Equilibrium Ratio



T = constant



$K_i \propto \dfrac{1}{p}$

$p_K(T, z)$

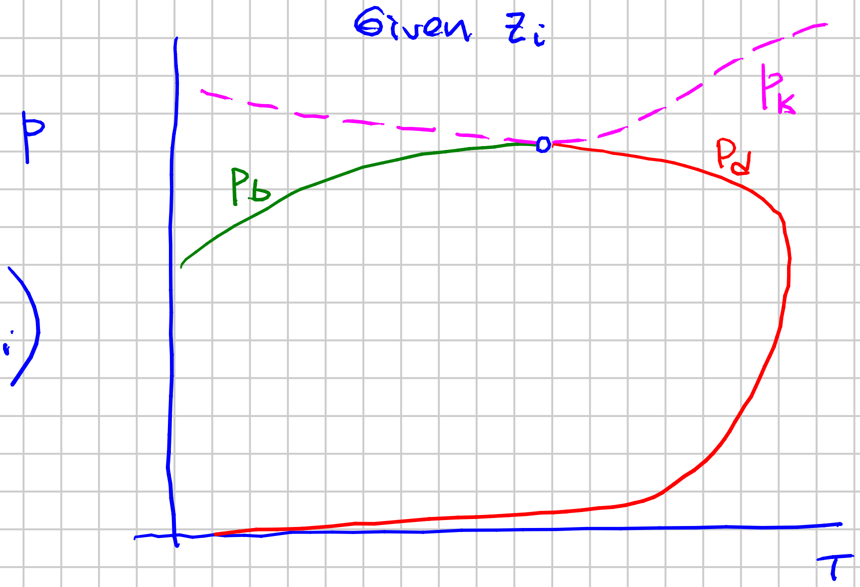
If $T = T_c$ of z_i

$\Rightarrow p_K = p_c$ of z_i

SPE PBM

* Modified Wilson Eq.

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



Component Material Balance:

$$\begin{cases} n_i = n_{Li} + n_{vi} \quad \longleftarrow \\ \text{Total Material Balance} \\ n = n_L + n_V \end{cases}$$

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

Define:

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

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

Also show:

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

$$K_i \equiv \frac{y_i}{x_i} \quad \text{know}$$

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

$$K_i = y_i / x_i$$

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

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

Solve this for x_i

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

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

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

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

1949 : Muskat - McDowell

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

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

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

"Rachford-Rice":
195x

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

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

1949 : M-M

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

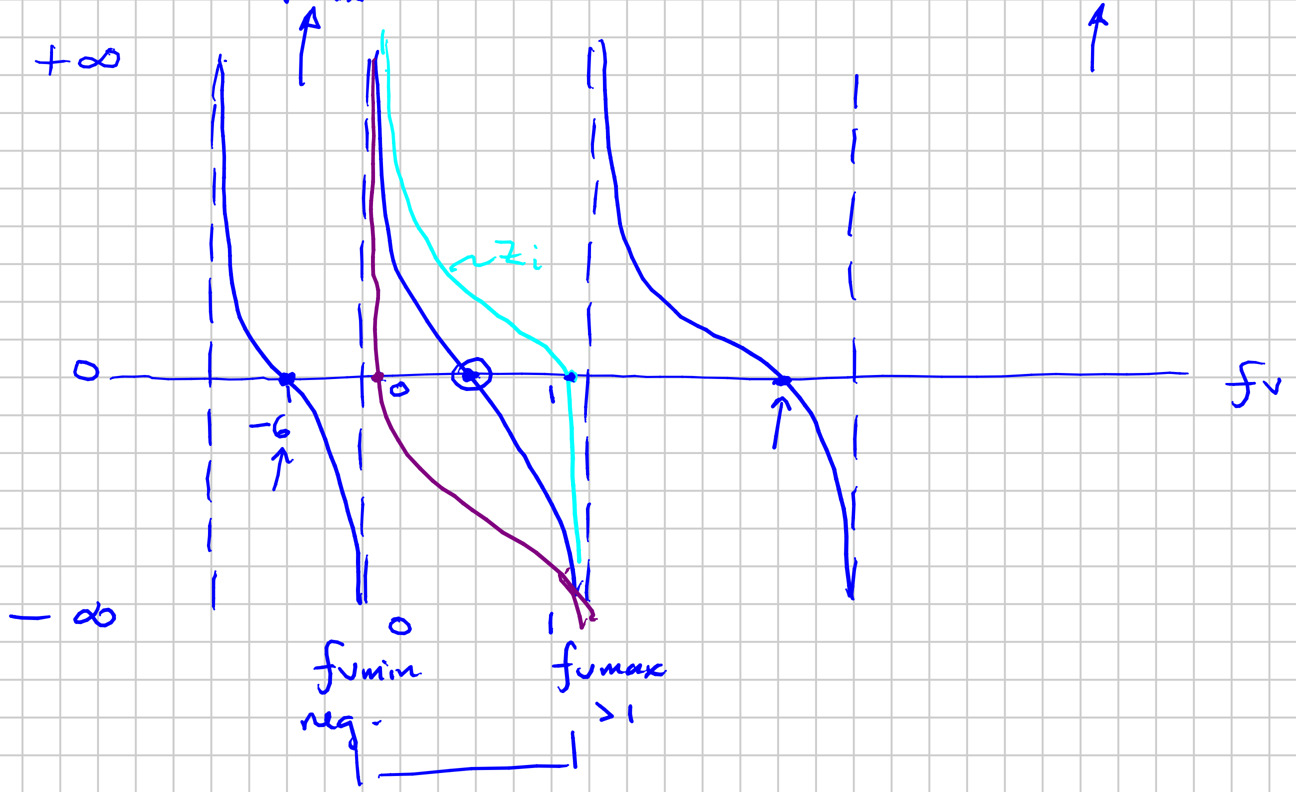
$$h(f_v) = \sum_{i=1}^{N} \left[\frac{z_i}{f_v + c_i} \right] = 0 \qquad (1')$$

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

(2) N-1 solutions

- Only one of these yields $\underbrace{\text{physical solution}}_{\substack{x_i \ge 0 \\ y_i \ge 0}}$

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



∴ Solved f_v^*

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

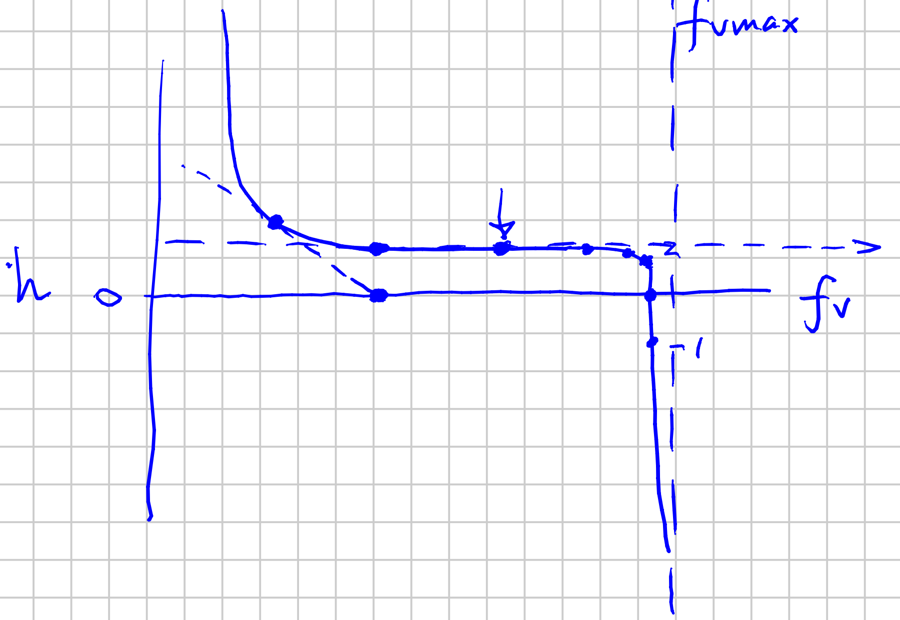
Liquid $\quad f_v^* = 0$
Vapor $\quad f_v^* = 1$ } : saturated single phase

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

<1% of calculations ...

$z_i \to \epsilon$

$K_i \to \epsilon$ or huge



Setup for Solution:

p, T, z_i Given

Guesstimate
Estimate

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

Guess $\boxed{f_v}$

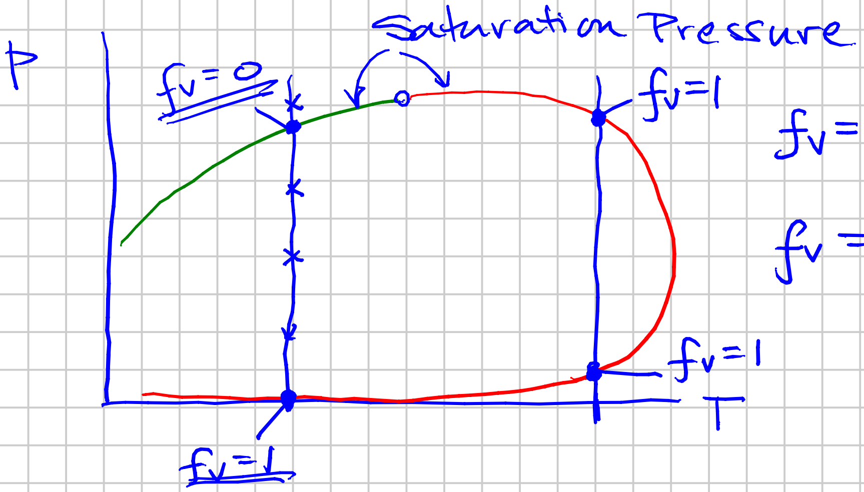
Calc $\boxed{f_{vmin}}$ $\boxed{f_{vmax}}$

2. Setup a Table

i	z_i	K_i	$c_i = \frac{1}{K_i - 1}$	Term$_i$	y_i	x_i
1						
2		Kmax				
⋮						
N		Kmin				

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

Special Cases of Flash Calculation:



$f_v = 0$: Bubblepoint

$f_v = 1$: Dewpoint

Bubblepoint : $f_v = 0$

"Bubble"

$$\Rightarrow \sum y_i = 1 \quad \text{equation}$$

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

$$y_i = x_i K_i$$

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

search

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

$$\sum x_i = 1$$

$$x_i = y_i / K_i$$

$$x_i = z_i / K_i(\overset{\uparrow}{p} ; T, p_K)$$

?

Fixed T, p_K

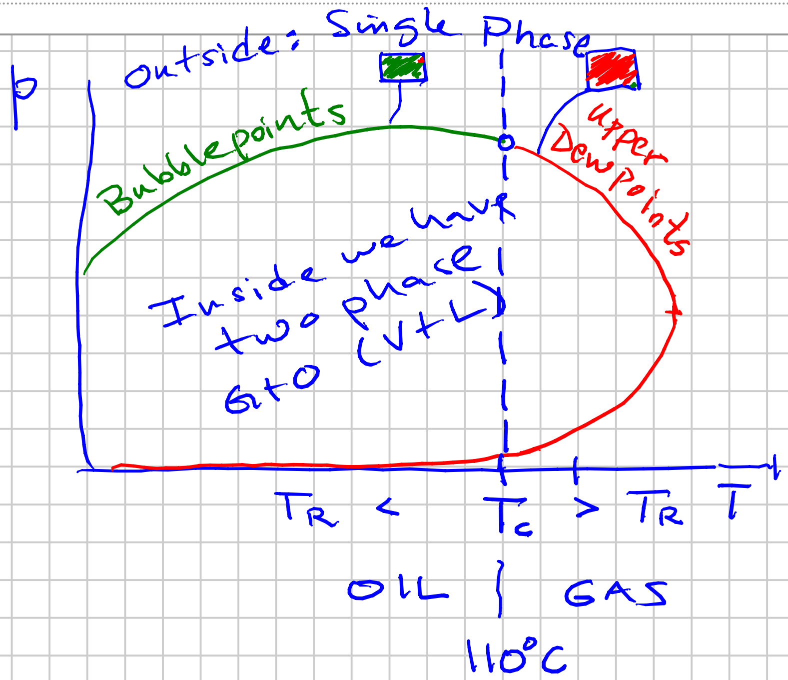
$$\boxed{h_{DP} = 1 - \sum x_i = 0 = 1 - \sum \frac{z_i}{K_i(p)}}$$

Two Solutions:

Upper DP

Lower DP

FLASH & SATURATION PRESSURE CALCULATIONS



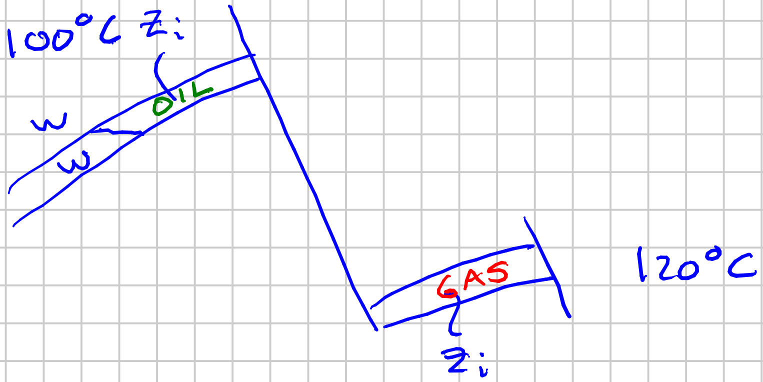
Given z_i

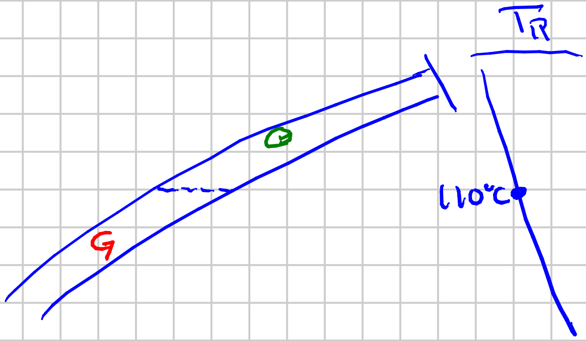
Flash (p, T)

⇒ # phases (1 or 2)

⇒ amount of each phase $f_v = \frac{n_v}{n}$

⇒ phase compositions y_i & x_i





Ch. 6 Lab PVT Tests

* – Oil Example p_b 2620 psig = 2635 psia

– Gas Condensate Example

K-values Estimation : Modified Wilson Eq. (Ch. 3)

$T_{ri} = T/T_{ci}$

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

Guess ?

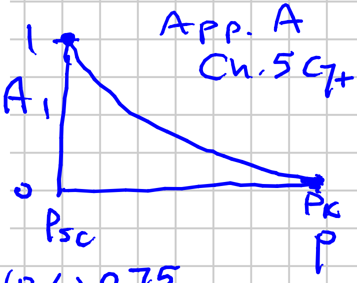
$p_{ri} = p/p_{ci}$ . . . . (3.159)

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

$p_K \sim 5000$ psia

$\underbrace{i \quad p_{ci} \quad T_{ci} \quad \omega_i}_{}$

App. A
Ch. 5 C_{7+}



$A_1 \simeq 1 - (p/p_K)^{0.75}$

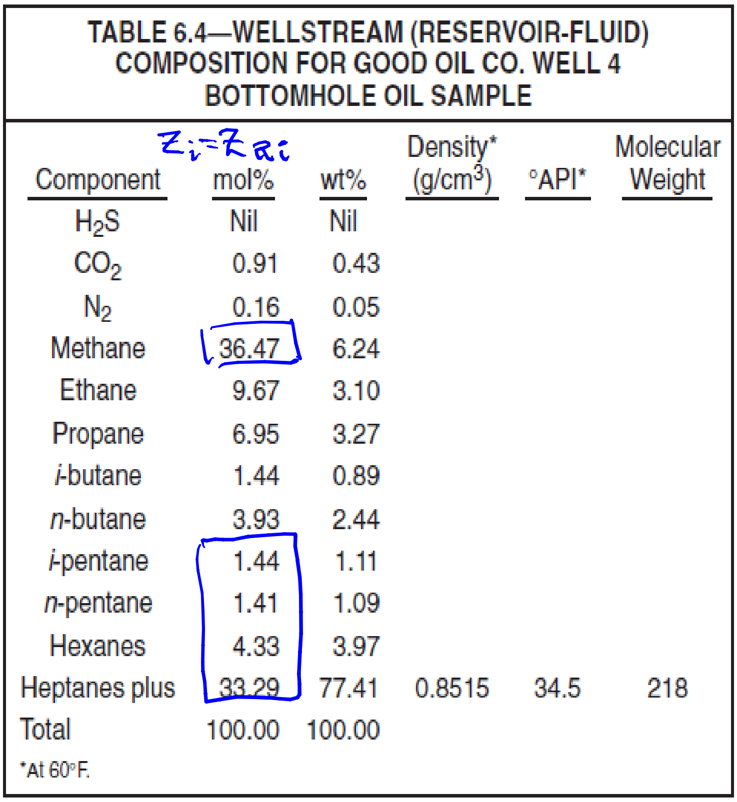


TABLE 6.4—WELLSTREAM (RESERVOIR-FLUID) COMPOSITION FOR GOOD OIL CO. WELL 4 BOTTOMHOLE OIL SAMPLE

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

*At 60°F.

Troll oil:

	z_i	
C_1	36	mol-%
C_2-C_4	20	
C_5+	40	

RR Equation: 195x

$$h(f_v) = \sum_{i=1}^{N} \frac{z_i(K_i-1)}{1+f_v(K_i-1)} = 0$$

MM (1949)

or

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

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

$$\frac{1}{1-K_{max}} = f_{v_{min}} < f_v < f_{v_{max}} = \frac{1}{1-K_{min}}$$

x : integer > 1

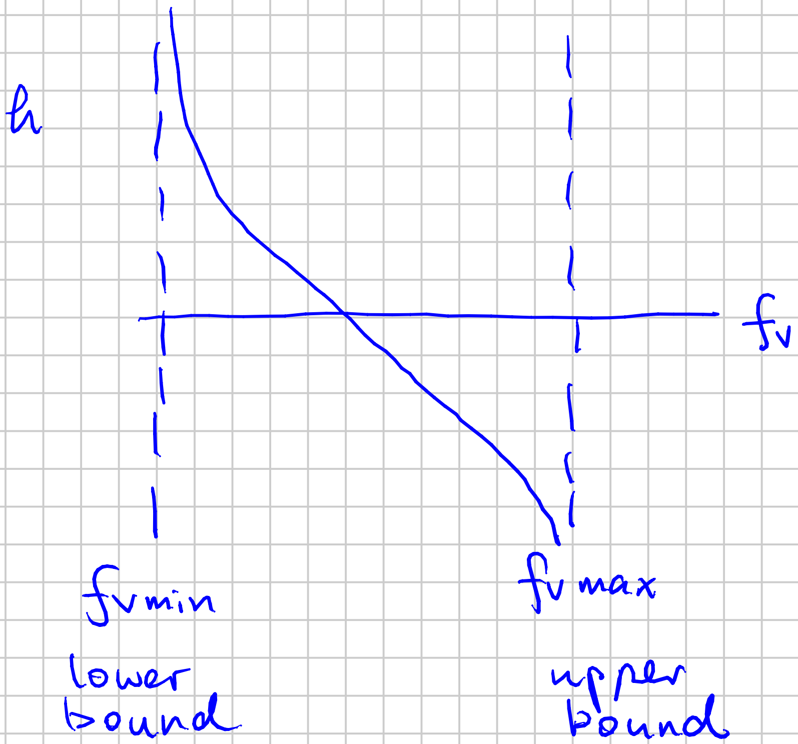
$(x-1) \times (x+1)$ divide by 6

SOLVER:

① A cell "target" to
- Minimize
- Maximize
- To = value

② Define "Variables"
i.e. the cells you want to change to achieve ①

③ Optionally, you can limit "bound" the variables ② we are changing



$$x_i = \frac{z_i}{fv \cdot (K_i - 1) + 1}$$

Bubblepoint Calculation

$$\sum y_i = 1$$

$$y_i = K_i \cdot x_i$$

$x_i = z_i$ for an oil @ p_b

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

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

$$g = 1 - \sum z_i K_i (T, p_b, p_K) = 0$$

Known from Lab data

Solve for p_K

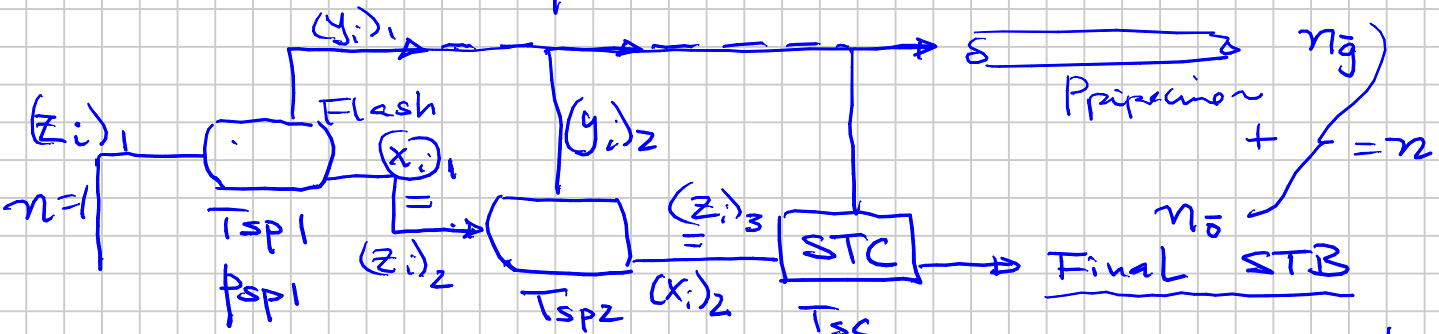
Equivalent to solving RR flash for $f_v = \underline{\underline{0}}$.

But much easier numerically to solve.

This will be part of Problem 2

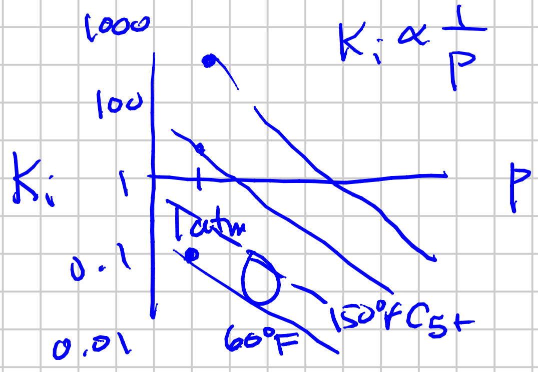
Flash calculation is the basis for estimate amount of "stock tank oil" \$115/STB and surface sales gas \$3.50/Mscf

MULTI-STAGE SURFACE SEPARATOR



$$n_{\bar{o}} = \left[\left[n \cdot (1 - f_{v1})\right](1 - f_{v2})\right](1 - f_{v3})$$

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

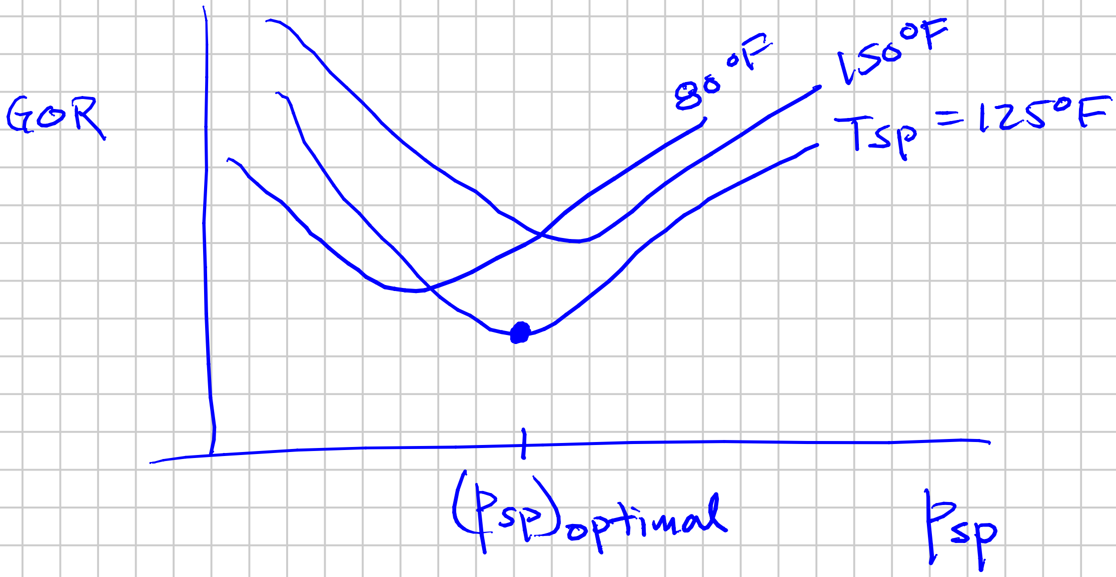


$$\frac{V_{\bar{g}} = 23.68 \cdot n_{\bar{g}}}{V_{\bar{o}} = n_{\bar{o}} \cdot (M_{\bar{o}} / \rho_{\bar{o}})} = \frac{Sm^3}{Sm^3} = GOR$$

$$M_{\bar{o}} = \sum (x_i)_{\underset{\uparrow}{3}} M_i$$

$$\rho_{\bar{o}} = \frac{\sum (x_i)_{\underset{\uparrow}{3}} M_i}{\sum \frac{(x_i)_3 M_i}{\rho_{Lsc\,i}}} \qquad \frac{\text{mass}}{\text{volume}}$$

$\leftarrow$ App. A ; C_{7+} lab



BLACK-OIL PVT (Ch. 7)

Note Title 2012-09-28

Flash Calculations

- Multi-stage separator test

z_{wi} → Sellable Volumetric Products
(Wellstream)

$\bar{g}$: surface gas
$\bar{o}$: stock-tank oil

"Black-Oil" PVT Formulation:

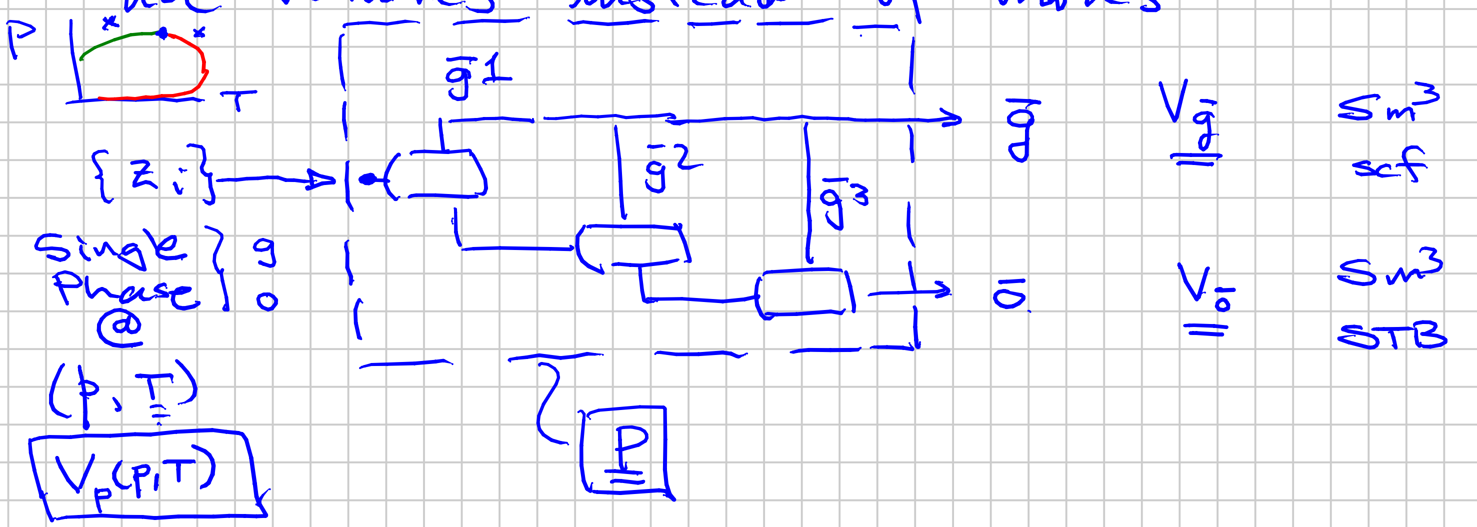
Uses two pseudo-components to describe the gas and oil phases @ (p,T)

INSTEAD of composition (H_2 CO_2 C_1 C_2, ... C_7 ... C_{35+})

Two Pseudo-Components are:

"Surface Gas" ($\bar{g}$)
"Surface Oil" ($\bar{o}$)
} results of a specific surface process $\boxed{\underline{P}}$

use volumes instead of moles



$p \in (g,o)$

Black-Oil PVT Model uses <u>VOLUME RATIOS</u> to define PVT phase & volumetric behavior

$\{f_g\ y_i\ x_i\}$ $\{n, m, \rho\}$: Compositional

① Surface Volume Ratios

$$R_s \equiv \frac{V_{\bar{g}o}}{V_{\bar{o}o}} \quad \underbrace{\text{for an oil phase}}$$

"Solution GOR" (R_s)

$R_s \neq \frac{1}{r_s}$ ✓

$$r_s = \frac{V_{\bar{o}g}}{V_{\bar{g}g}} \quad \underbrace{\text{for a gas phase}}$$

"Solution OGR" (r_s)

These quantities are the "pseudo" equivalents of x_i : $\underline{\underline{R_s}}$ and y_i : $\underline{\underline{r_s}}$

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

$R_s \rightarrow x_i$

$$\frac{[Sm^3]\ V_{\bar{g}o} \times \frac{1}{23.68}\frac{\text{kg-mole}}{Sm^3}}{[Sm^3]\ \underbrace{V_{\bar{o}o}}_{\substack{R_s\\(300)}} \times \rho_{\bar{o}o}/M_{\bar{o}o}} = \frac{n_{\bar{g}o}}{n_{\bar{o}o}} = 300\,\frac{200}{(850)(23.68)}$$

$$= 0.03$$

Ekofisk ~ 300 $Sm^3/Sm^3 = R_s$

$\rho_{\bar{o}o}$ ~ 850 kg/m^3

$M_{\bar{o}o}$ ~ 200 kg/kg-mole

$$x_{\bar g} \equiv \frac{n_{\bar g o}}{n_{\bar g o} + n_{\bar o o}} \, \frac{\frac{1}{n_{\bar o o}}}{\frac{1}{n_{\bar o o}}} \qquad x_{\bar g} = \frac{\frac{n_{\bar g o}}{n_{\bar o o}}}{\frac{n_{\bar g o}}{n_{\bar o o}} + \frac{n_{\bar o o}}{n_{\bar o o}}}$$

$$= \frac{\frac{n_{\bar g o}}{n_{\bar o o}}}{\frac{n_{\bar g o}}{n_{\bar o o}} + 1} = \frac{1}{1 + \left(\frac{n_{\bar o o}}{n_{\bar g o}}\right)}$$

$$\frac{n_{\bar o o}}{n_{\bar g o}} = \frac{1 \quad 23.68 \left(\rho_{\bar o o} / M_{\bar o o}\right)}{R_s}$$

$$\boxed{x_{\bar g} = \left\{ 1 + \frac{1}{R_s} \cdot 23.68 \left(\frac{\rho_{\bar o o}}{M_{\bar o o}} \right) \right\}^{-1}}$$

$$x_{\bar o} = 1 - x_{\bar g}$$

$R_s \left[Sm^3 / Sm^3\right]$
$\rho \left[kg / m^3\right]$
$M \left[kg / kg\text{-mole}\right]$

$$\boxed{y_{\bar g} = \left\{ 1 + r_s \; 23.68 \left(\frac{\rho_{\bar o g}}{M_{\bar o g}} \right) \right\}^{-1}}$$

$$y_{\bar o} = 1 - y_{\bar g}$$

Note: surface oil from oil phase $\bar o o$ is physically NOT going to be the surface oil from gas phase $\bar o g$

But in our use of Black-Oil PVT we use the assumption that

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

$\rho_{\bar{o}o} \cong \rho_{\bar{o}g}$ Used Not particulary good

$(M_{\bar{o}o} = M_{\bar{o}g})$

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

$\rho_{\bar{g}o} \cong \rho_{\bar{g}g}$ Used so-so

Volume balance → 0 (ϵ)

- Still get a mass balance error ✓

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

Affects the calculation accuracy of <u>phase</u> densities $\}$

② (FORMATION) VOLUME FACTOR "FVF" (B)

$$B_p \equiv \frac{V_p(P,T)}{V_{\bar{p}p}}$$

$$B_o = \frac{V_o(P,T)}{V_{\bar{o}o}}$$

Oil FVF

1.0x - 3

(1.2 - 2) Most Oil Fields

$$b_o = \frac{1}{B_o} = \frac{V_{\bar{o}o}}{V_o(P,T)}$$

$\Rightarrow$ Shrikage Term

$$\text{Shrinkage Factor} = 100\% \left(1 - \frac{1}{B_o}\right) = 100\% \left(1 - b_o\right)$$

$B_o = 2 \quad b_o = \frac{1}{2} \quad SF = 50\%$

$B_o = 1.5 \quad b_o = \frac{2}{3} \quad SF = 33\%$

$B_o = 3 \quad b_o = \frac{1}{3} \quad SF = 67\%$

$B_o = 1.1 \quad b_o = 0.9 \quad SF = 10\%$

Gas FVF: B_g

$$B_g \equiv \frac{V_g(\underline{\underline{p}},T)}{V_{\bar{g}g}}$$

$$b_g = \frac{1}{B_g} = \frac{V_{\bar{g}g}}{V_g(p,T)} = \text{gas expansion factor}$$

100 − 250

99% Text books assume $r_s = 0$

$$B_{gw} = \frac{p_{sc}}{T_{sc}} \cdot \frac{T Z_{(p,T)}}{p} \quad : \quad n_{\bar{g}g} = n_g, \quad n_{\bar{o}g} = 0$$

$$\underset{\sim\sim\sim}{\text{True}}\ B_{gd} = \frac{V_g(p,T)}{V_{\bar{g}g}}$$

Gas Condensate Reservoirs

$$\boxed{B_{gd}} = \underbrace{\left[\frac{p_{sc}}{T_{sc}} \cdot \frac{TZ}{p}\right]}_{\text{Text Book Gas FVF } B_{gw}} \cdot \frac{1}{\left(1 - \frac{n_{\bar{o}g}}{n_g}\right)}$$

Use in your engineering !

$$\frac{n_{\bar{g}g}}{n_g} \sim 0.85 - 0.99$$

$$\left(\frac{n_{\bar{o}g}}{n_g}\right) \sim 0.15 - 0.01$$

Est.
$\sim \underline{\underline{y_{6+}}}$ or $\underline{\underline{y_{5+}}}$

d: dry means that the surface gas is "dried" by removing surface oil $\bar{o}g$ from the surface gas

w: wet means that we assume all of the surface gas = reservoir gas ($n_{\bar{g}g} = n_g$)

wet surface gas because it still contains $\bar{o}g$

How to calculate oil phase and gas phase densities:

Know $\{ R_s \quad B_o \quad r_s \quad B_{gd} \}$ @ $(\underline{\underline{p,T}})$

? $\rho_o(p,T)$ $\rho_g(p,T)$

Need for eng. calculations involving transport or hydrodynamics influence by gravity.

$$\left[\begin{aligned} \rho_g(p,T) &= \frac{\rho_{\bar{g}} + \rho_{\bar{o}} \cdot r_s(p,T)}{B_g(p,T)} \\[2ex] \rho_o(p,T) &= \frac{\rho_{\bar{o}} + \rho_{\bar{g}} \cdot R_s(p,T)}{B_o(p,T)} \end{aligned} \right]$$

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

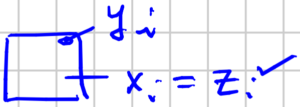
~ TWO CONSTANTS ~

even though $\rho_{\bar{g}g}(p,T) \neq \rho_{\bar{g}o}(p,T)$

$\rho_{\bar{o}o}(p,T) \neq \rho_{\bar{o}g}(p,T)$

$K_i(p, T, \underset{?}{\overset{\uparrow}{p_K}})$

p_b = Lab value 2620 psig



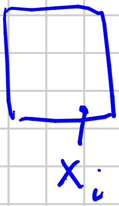
@ T

Bubblepoint Calc: $\sum y_i = 1$

$$y_i = K_i \cdot x_i = K_i z_i$$

$$\longrightarrow \quad h_{BP}(p_b \mid p_K) = 0 = 1 - \sum y_i = 1 - \sum z_i K_i(T, p_K, \underset{\text{know}}{\overset{}{p_b}})$$

Dewpoint: $\sum x_i = 1$



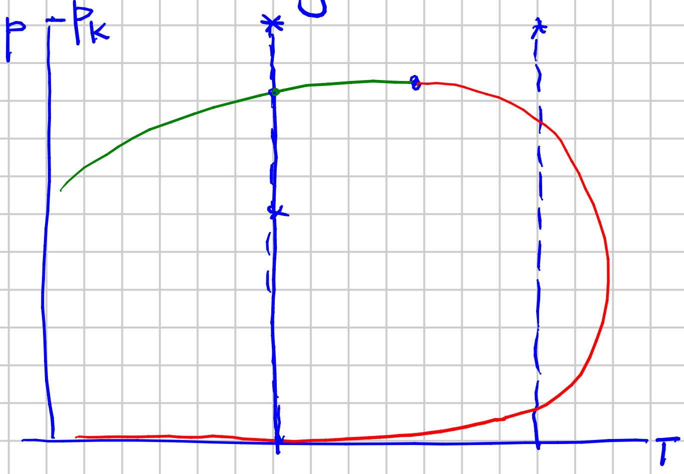
$$x_i = z_i / K_i$$

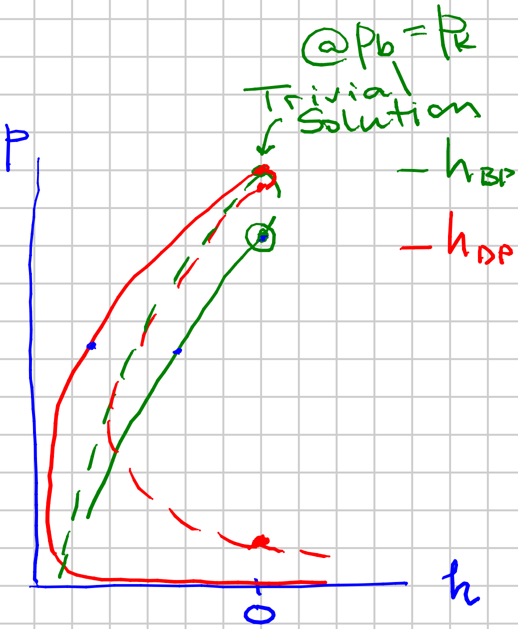
$$h_{DP} = 0 = 1 - \sum x_i = 1 - \sum z_i / K_i(T, p_K, p_d)$$

Know p_K, solve $p_b(T)$ or $p_d(T)$

Upper Sat. — Upper Sat — Lower Sat

Saturation Pressure Calculations (without knowing BP or DP):





Solve $h_{sp} = h_{BP}(p_s) \times h_{DP}(p_s) = 0$

Once found p_s, see if h_{BP} or h_{DP} that drove the $h_{sp} \to 0$

Black-Oil PVT Formulation (Ch. 7)

<u>Review</u>: Gas Phase : r_s – solution OGR $\sim y_i$

B_{gd} – gas FVF $\sim \rho_g$; expansion

Oil Phase : R_s – solution GOR $\sim x_i$

B_o – oil FVF $\sim \rho_o$; shrink

BO PVT are specific to a particular surface process $\underline{P}$

May be a strong dependence of BO PVT on the $\underline{P}$ used :

GOR $\gtrsim$ 200 Sm^3/Sm^3 measureable → large effect

< 100 little effect

$\boxed{\underline{P}}$ <u>Worst</u>

Single Stage Flash
→ ambient conditions

Best Recovery of i in $\bar{o}$

Multi-Stage Flash + GP

Applications of Black-Oil PVT:

To convert reservoir (p, T_R) Volumes
or @ any (p, T) Tubing, Flowlines etc.
to "surface" (sellable) gas $(\bar{g})$ and oil $(\bar{o})$

$$b_{gd} = \frac{V_{\bar{g}}}{V_g(p,T)} \sim 50 \text{ to } 250 \ \frac{Sm^3}{m^3 @ (p,T)}$$ Expansion

$B_{gd} \sim 0.02 - 0.004 \ m^3 @ (p,T) / Sm^3$

$$b_o = \frac{V_{\bar{o}}}{V_o(p,T)} \sim 0.9 \rightarrow 0.3$$ Shrinkage

$$B_o \sim \underbrace{1.1 \rightarrow 3}_{\text{loss of mass into gas phase}}$$ $m^3 @ (p,T) / Sm^3$

RB / STB

bbl / STB

B_{gd}

- $V_g \propto \frac{1}{p}$
- condense (loose mass) into a liquid: 1-15% change in final surface gas volume

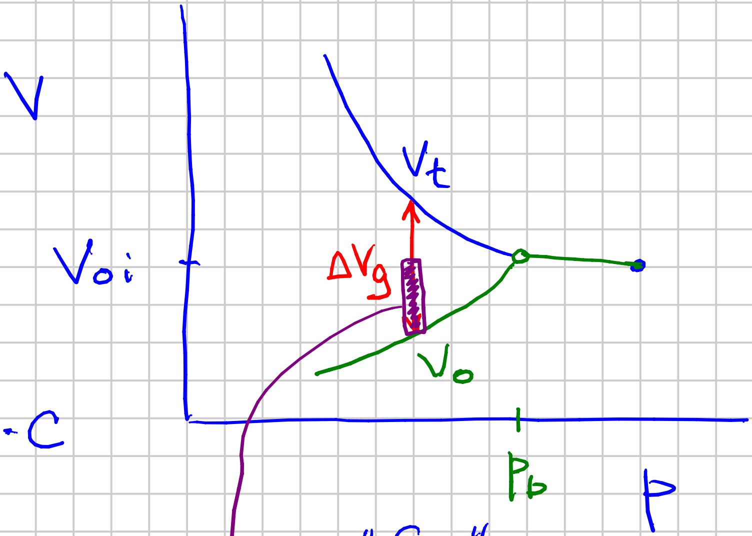
R_s : $\frac{V_{\bar{g}o}}{V_{\bar{o}o}}$ keep track of the (component surface) gas $\bar{g}o$ that is (still) in solution in the oil phase

$$\overbrace{\left[R_{si} - R_s(p) \right]}^{\Delta R_s} = \text{Liberated (Surface) Gas}$$

$300 \ Sm^3/Sm^3 - 200 \ Sm^3/Sm^3$

$$\underset{(p,T)}{\Delta V_g} = \left[\Delta R_s \times B_g(p,T)\right]$$

$$\frac{m^3}{Sm^3\,\bar{o}} \qquad \frac{\cancel{Sm^3}}{Sm^3\,\bar{o}} \qquad \frac{m^3}{\cancel{Sm^3}}$$



Solution OGR $r_s \propto \frac{\boxed{y_{5+}}}{(1-y_{5+})} \cdot C$

$r_s \propto y_{\underline{\underline{C5+}}}(p,T)$ mol-%

if you produce alotta "free" reservoir gas

\$115 / bbl

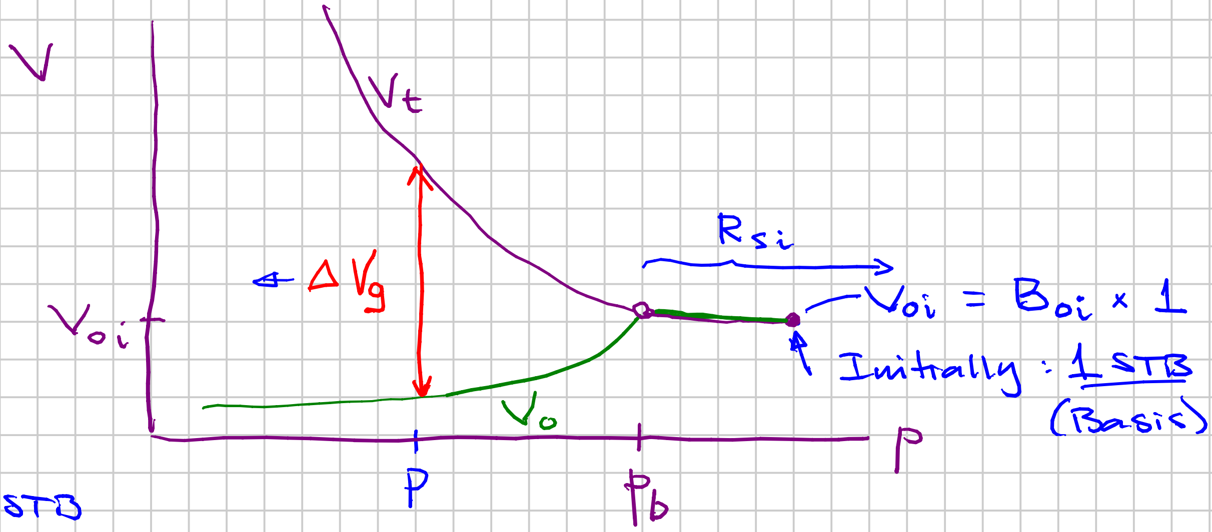
\$ 3/Mscf

$$\left(\frac{\$}{\text{mol-}\%}\right)_{\bar{o}} >> \left(\frac{\$}{\text{mol-}\%}\right)_{\bar{g}}$$

$\bar{o} = \bar{C}_{5+}$

$$\boxed{\Delta V_{\bar{o}} \quad Sm^3\,\bar{o}} = \underbrace{0.6(\Delta V_g) \times \frac{1}{B_{gd}}}_{\cancel{Sm^3\,\bar{g}}} \times r_s \qquad \frac{Sm^3\,\bar{o}}{\cancel{Sm^3\,\bar{g}}}$$

$$\Delta V_{\bar{o}g} = 0.6 \cdot \Delta R_s \cdot r_s$$



Basis : 1 STB

$$\Delta V_g(p) = \overbrace{\underbrace{\left(R_{si} - R_s(p)\right)}_{\text{Liberated Gas}} B_{gd}}$$

Liberated Gas ~~scf~~ Sm^3

$\frac{ft^3}{\cancel{scf}}$

$$\Delta V_{\bar{o}g} = r_s(p)\left(R_{si} - R_s(p)\right) = r_s(p) \; \Delta V_g \; \frac{1}{B_{gd}(p)}$$

<u>condensate</u> $\frac{STB}{scf}$ $\frac{V_{\bar{o}g}}{V_{\bar{g}g}}$

Black Oil PVT Properties

vary w/ pressure @ T=const

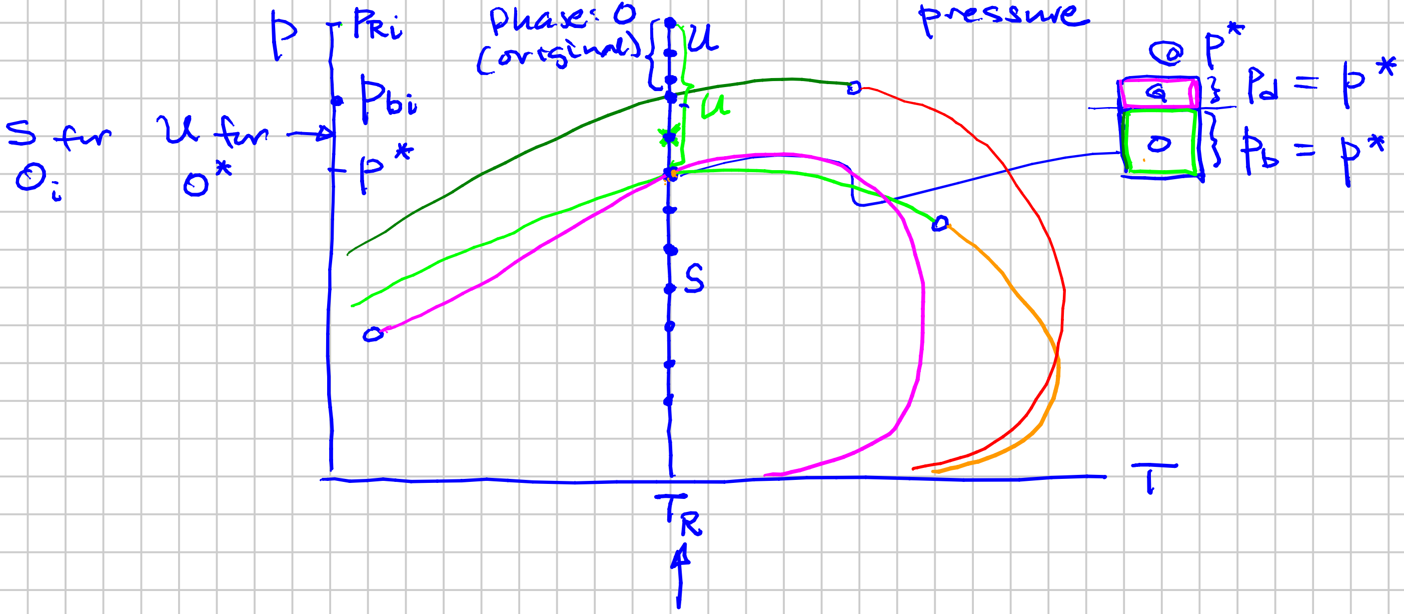
OIL: R_s B_o μ_o

GAS: r_s B_{gd} μ_g

} Saturated & Undersaturated

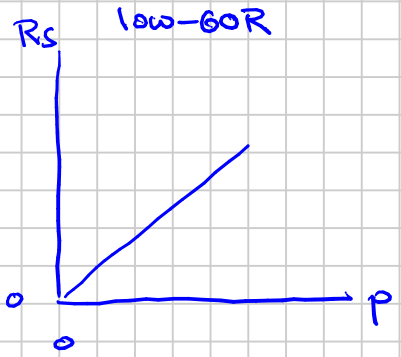
- "2-phases"
- phase is at its saturation pressure

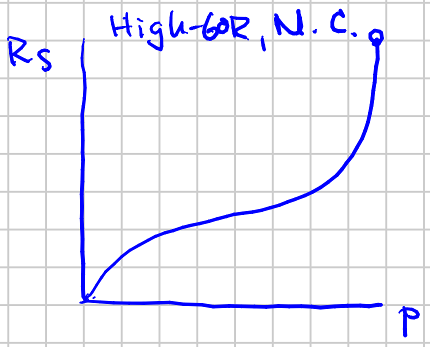
phase is @ $p>p_s$

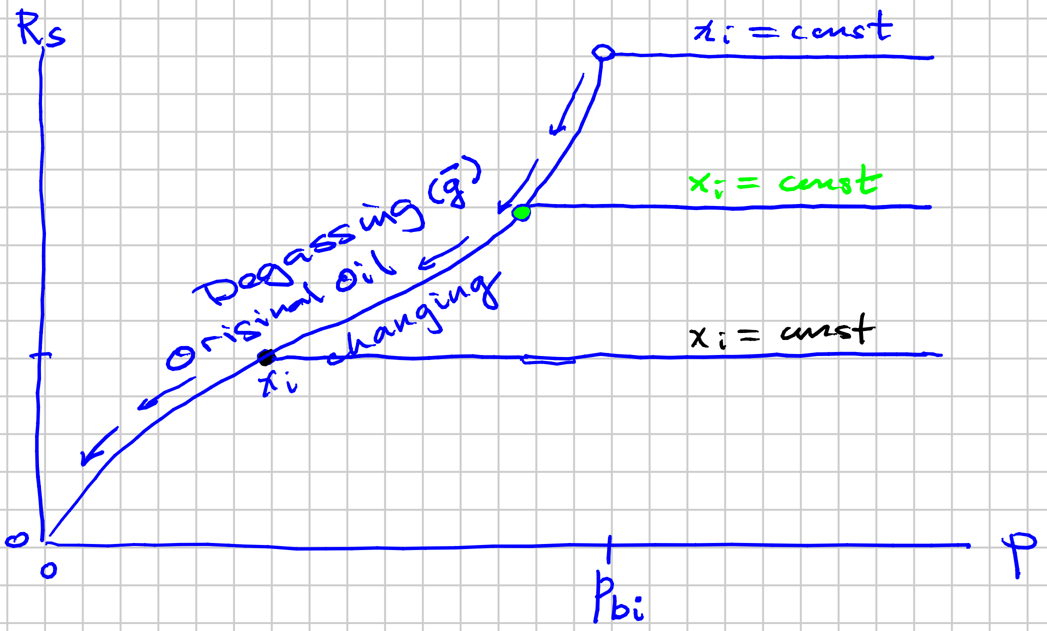


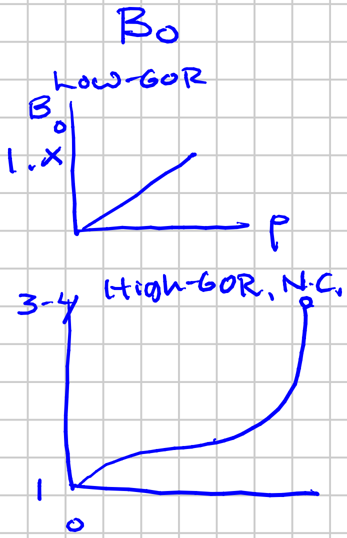
OIL PHASE BO PVT: R_s B_o μ_o

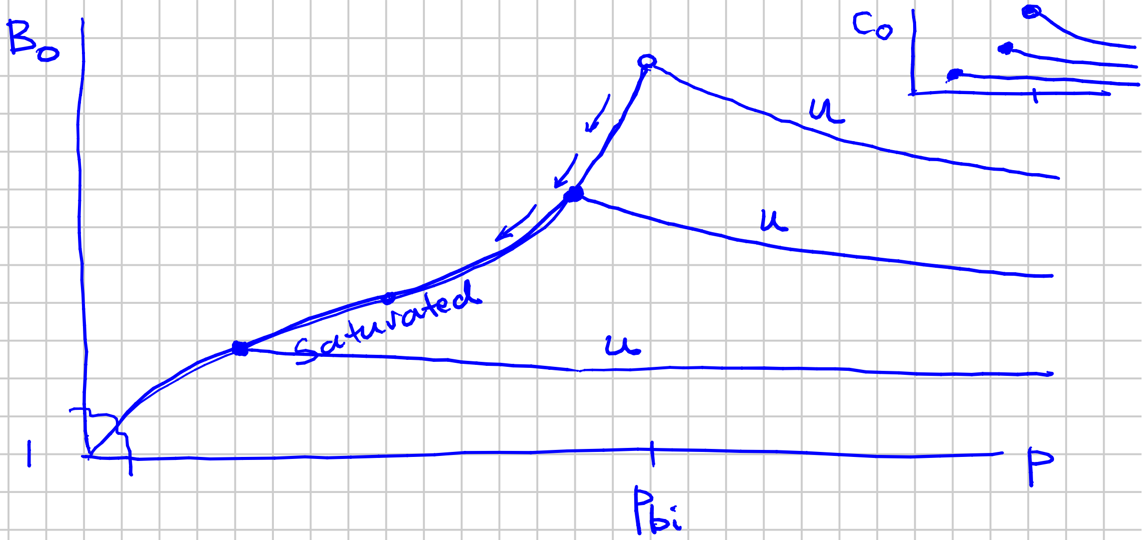
(x_i) (V_o, ρ_o)



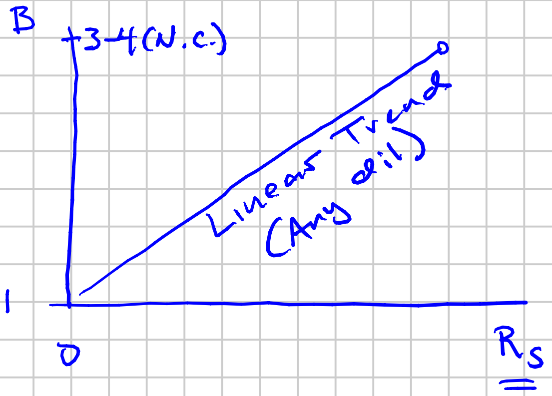








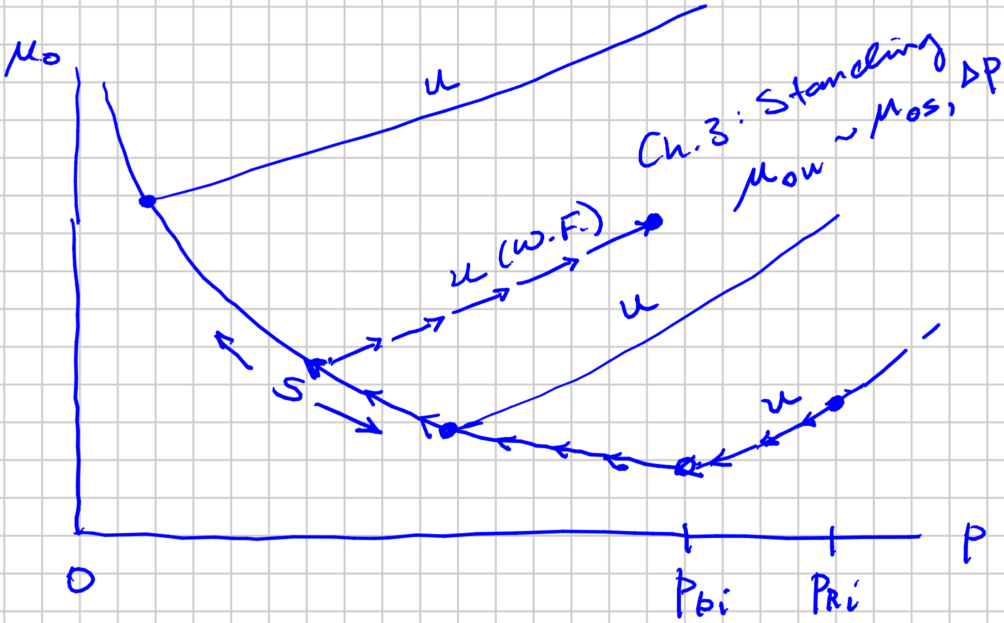
Saturated B_o vs R_s



$$\mu_o \propto \rho_o^{n \sim 3-4}$$

$$\rho_o \propto \frac{1}{B_o}$$

$$\mu_o \sim \left(\frac{1}{B_o}\right)^n$$



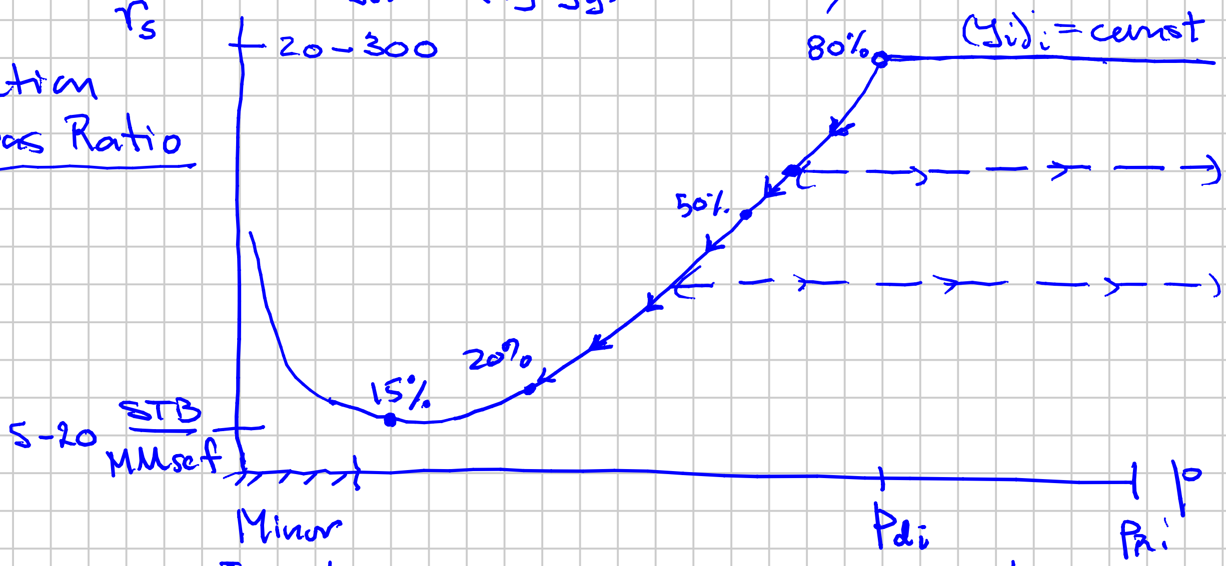
Ch. 3: Standing

$\mu_{ow} \sim \mu_{os}, \Delta P$

GAS BO PVT r_s (y_i) B_{gd} $(V_g\ \rho_g)$ μ_g

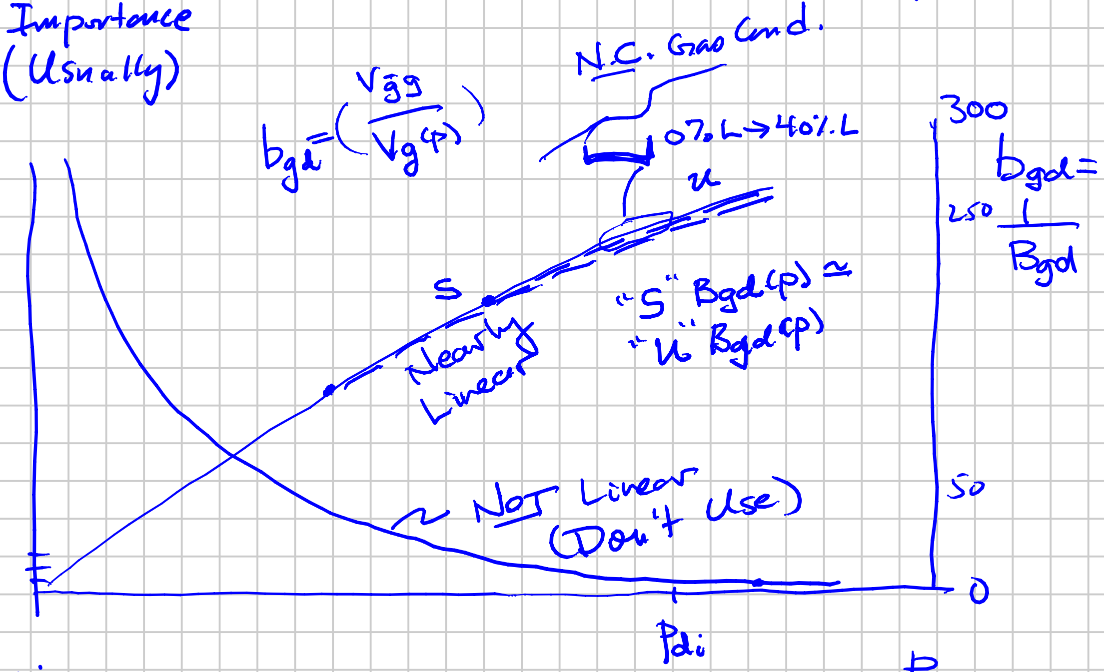
r_s

Solution Oil-Gas Ratio

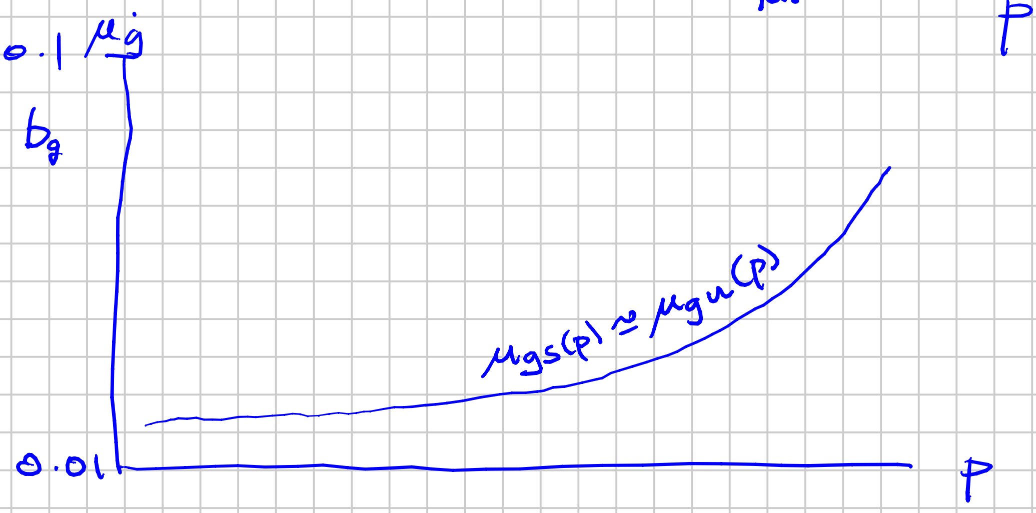


Minor Importance (Usually)

$B_{gd} \propto \frac{1}{p}$



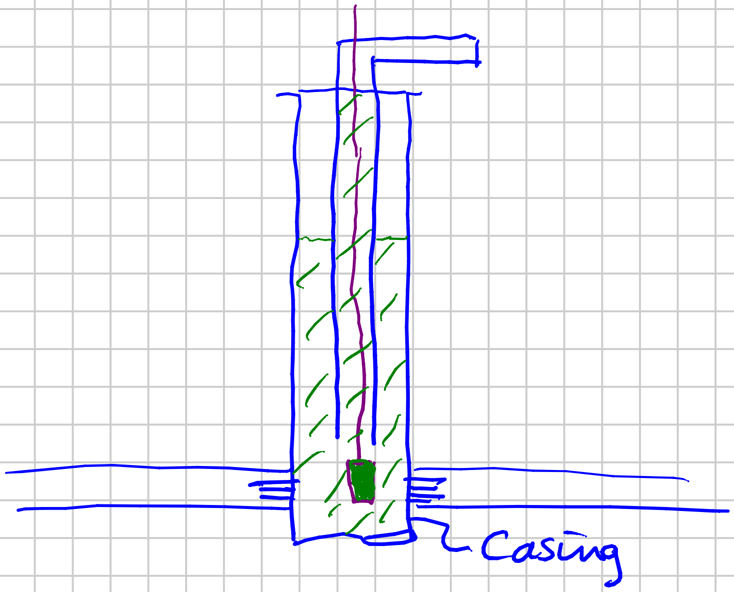
$\mu_g \propto \rho_g^m \propto b_g$



PVT Laboratory Tests (Ch. 6)

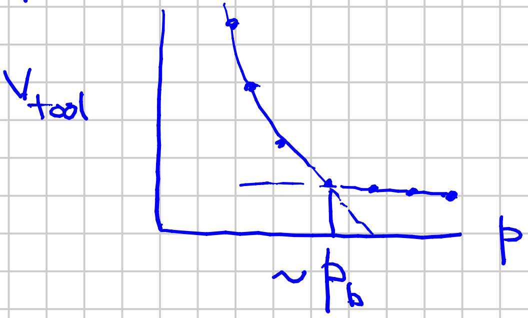
Collect Samples from the Well

① Wireline Bottomhole Sample



- Typically collected when the well is shut-in (OR with well producing @ low rates ($p_{wf} \gtrsim p_R$)
- Only (recommended) for oil wells.
- Collected @ T_R (Avoid wax precipitation) ↑ n-C_{C20+}
- (Avoid Asphaltene precipitation)

@ Surface: Measure @ wellsite ~p_b ($\underline{T_{ambient}}$)



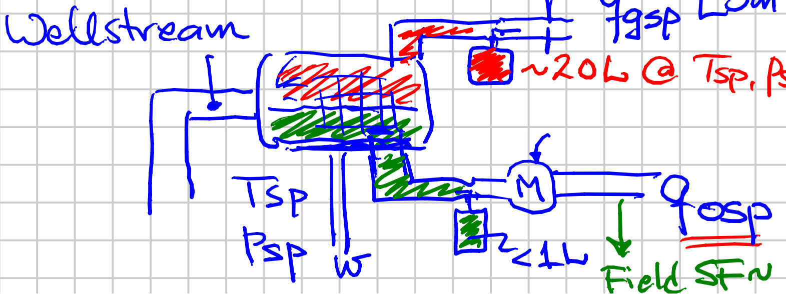
Checking for Leakage

② Surface Separator Samples — BOTH OILS* & GAS CONDENSATES

@ Primary (1st stage) Separator

"Orifice Meter" → (q_m) / ($\rho_{g\,est.}$) ($\frac{M_g}{Z_g}$)

q_{gsp} [Sm^3/d or scf/D]



q_{osp} [sep-m^3/d or sep-bbl/D]

QC @ Lab:

Gas: @ T_{sp} open valve $P_{opening} \sim P_{sp}$

Oil: Lab measure $p_b(T_{sp})$ of sep. oil $\sim p_{sp}$

Lab will physically recombine sep gas + sep oil in the producing GOR $\frac{scf}{sep\text{-}bbl}$ $\frac{Sm^3}{sep\text{-}m^3}$

⇒ create wellstream ~ reservoir fluid (that entered the wellbore)

Testing company often report STB/D std-m³/d OIL

If they report STB/D find out (ask test company) WHAT OIL SHRINKAGE FACTOR was used!

Use that SF_{Field} to $q_{\bar{o}}$ (STB/D) ⟶ q_{osp} (sepbbl/D)

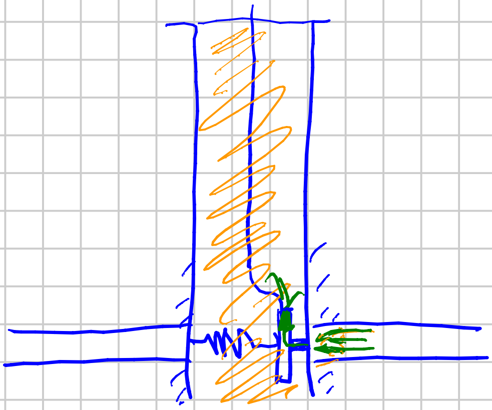
Actual Metered Rate

$$q_{osp} = \frac{q_{\bar{o}}}{(SF)_{Field}}$$

0.95 – 0.5

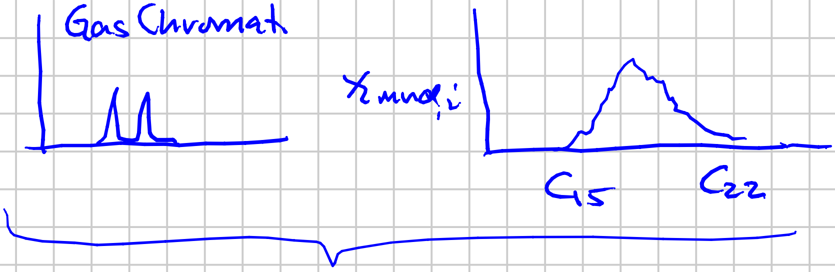
③ Openhole Formation Sampler

– MDT ; RCI ; ...



- Collected @ ~p_R, T_R
- Mini Production Test
- Early "mud" production
  - Water based mud ✓
  - Oil based mud

C_{15} & C_{17} "Diesel"



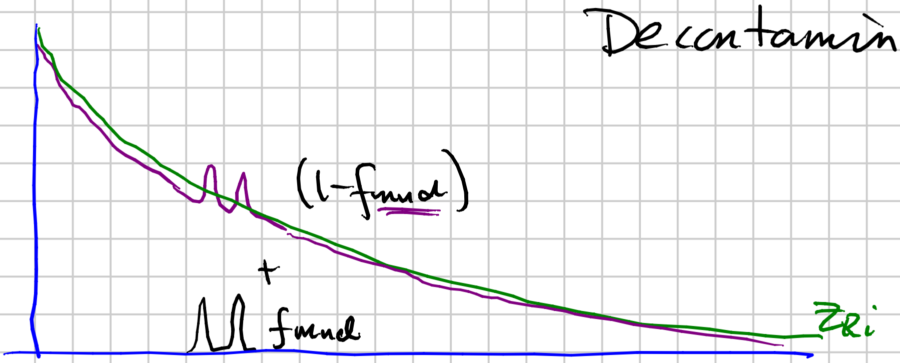
"Contaminate" the reservoir fluid

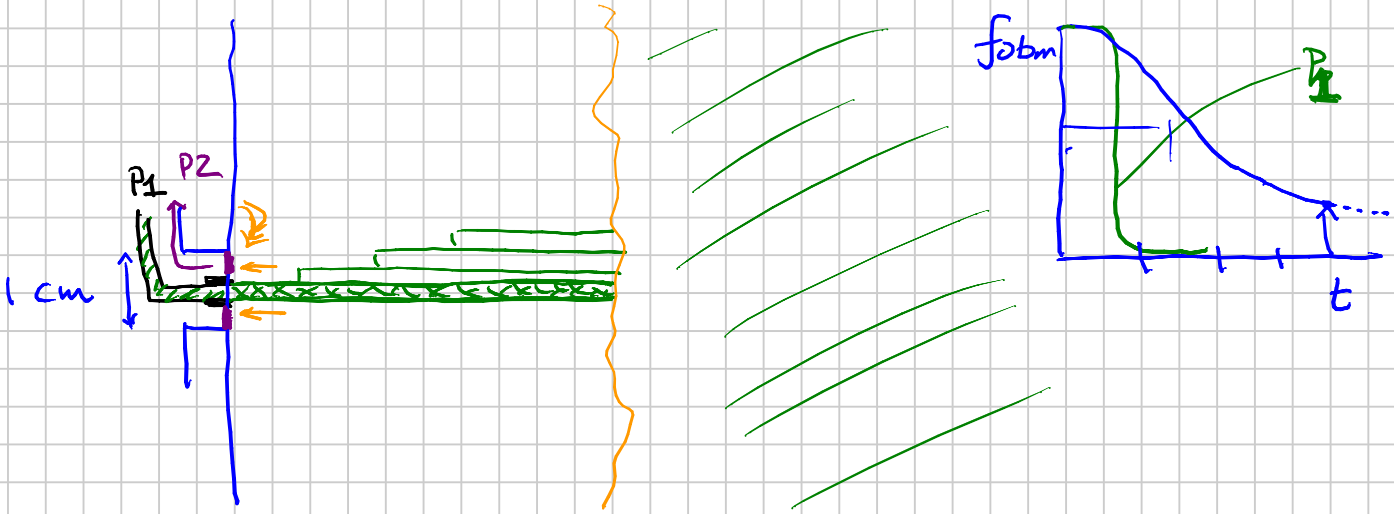
Back-Calc.

$$\text{Sample}\quad \boxed{z_{S_i}} = \boxed{z_{R_i}}(1-f_{mud}) + \boxed{x_{mud_i}} \cdot f_{mud}$$

Estimate

Decontamination

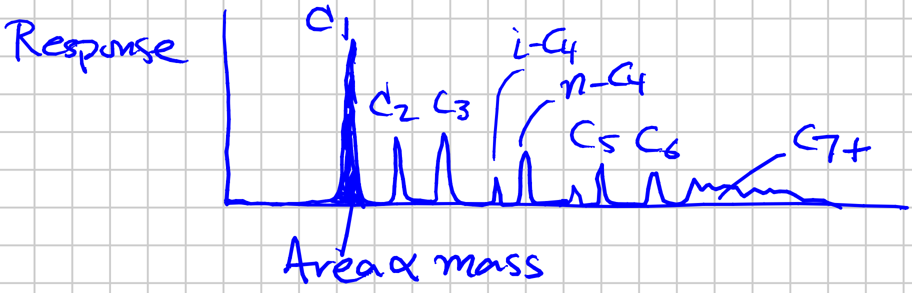




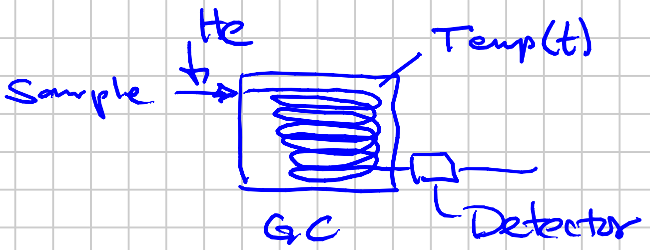
COMPOSITIONAL ANALYSIS

Sep. Gas or any other low-pressure gas

⇒ Direct analysis w/ Gas Chromatograph (GC)



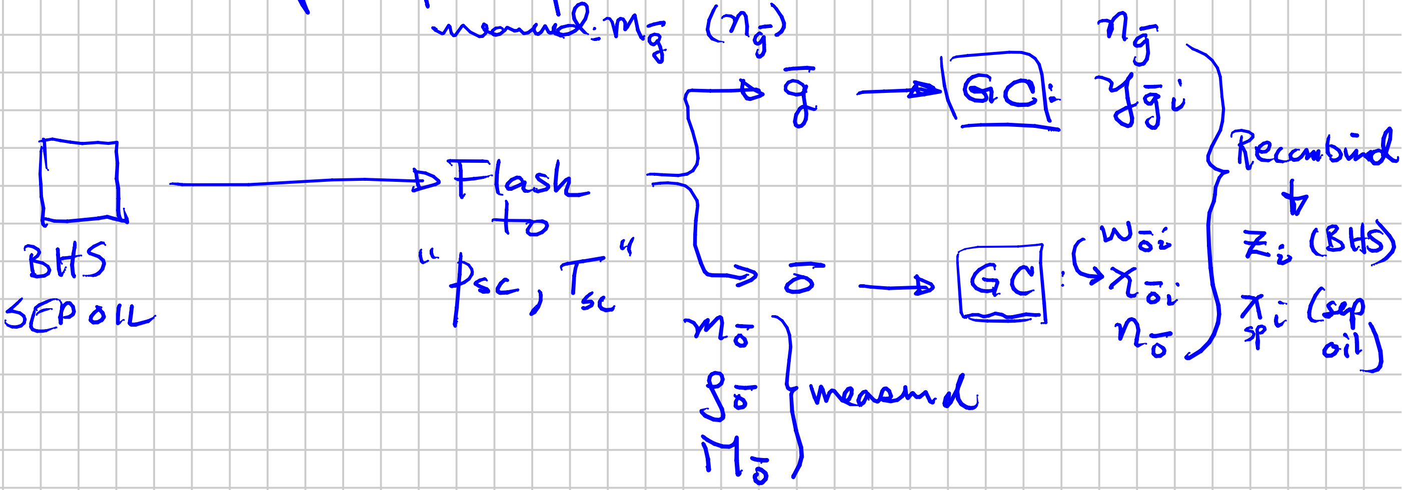
y_i



→

i	m_i	M_i	$n_i = \frac{m_i}{M_i}$	y_i
C_1	measured			reported
C_2				
C_3				
⋮				

Bottomhole Samples & Separator Oil



Flash-GC Process → z_i x_{spi}

PVT Experiments:

Phase Behavior Data
$(= f(K_i))$

p_s (BP, DP, CP)

y_i

x_i

$K_i = y_i / x_i$

f_v $f_g = \frac{n_g}{n}$

n_g n_o "flash"

Volumetric Data
(Also reflecting phase beh.)

ρ_o

ρ_g

V_o (V_o / V_{ref})

V_g (Z_g)

R_s B_o (μ_o)

r_s B_{gd} (μ_g)

Ch. 6: Oil Well 4 Sample

Gas Condensate Well 7 Sample

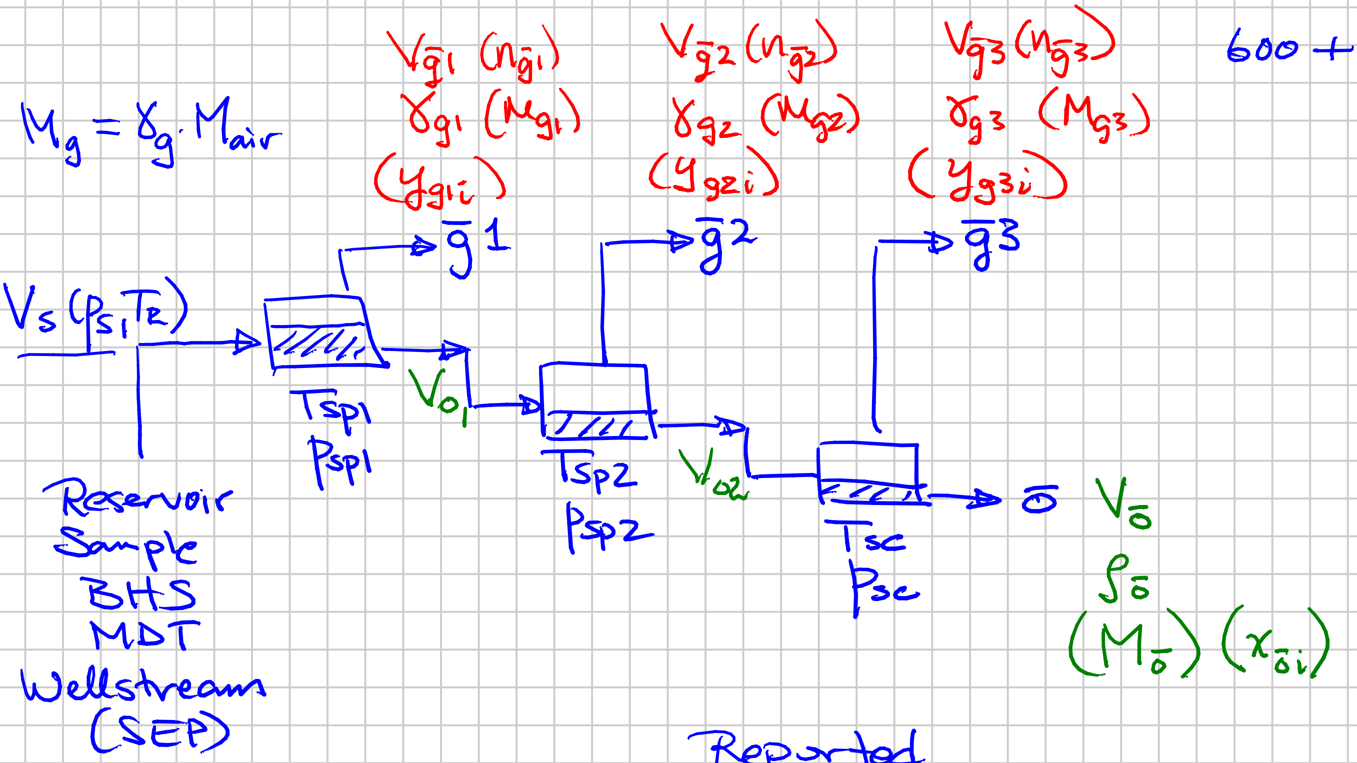
App. D: Oil PVT Tests & Their Application
(Standing; +)

① Multi-Stage Separator Test

- Always for OILS
- Sometimes for "Rich" Gas Condensates $\left(OGR \geq 150\text{-}200 \frac{STB}{MMscf}\right)$

$600 + \frac{Sm^3}{10^6 Sm^3}$

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



Reported

OIL

$$B_{ob} = \frac{V_s}{V_{\bar{o}}} = \frac{V_{ob}}{V_{\bar{o}}}$$

$$R_s = \frac{(V_{\bar{g}})_{total}}{V_{\bar{o}}}$$

GAS

$$(B_{gd})_d = \frac{V_{g@p_d}}{(V_{\bar{g}})_{total}}$$

$$r_s = \frac{V_{\bar{o}}}{(V_{\bar{g}})_{total}}$$

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

"$\bar{M}_{\bar{g}}$"

$$(\bar{\gamma}_g) = \frac{\gamma_{g1} \cdot R_{s1} + \gamma_{g2} R_{s2} + \gamma_{g3} R_{s3}}{(R_s)_{total}}$$

$R_{s1} = \frac{V_{\bar{g}1}}{V_{\bar{o}}}$; $R_{s2} = \frac{V_{\bar{g}2}}{V_{\bar{o}}}$; $R_{s3} = \frac{V_{\bar{g}3}}{V_{\bar{o}}}$

$\parallel$

Sometimes $\left(\tilde{R}_{s1} = \frac{V_{\bar{g}1}}{V_{o1}} \right.$; $\tilde{R}_{s2} = \frac{V_{\bar{g}2}}{V_{o2}}$; $\left. \tilde{R}_{s3} = \frac{V_{\bar{g}3}}{V_{\bar{o}}} \right)$

Don't add $\tilde{R}_s$ values!

$$\left(B_{osp1} = \frac{V_{o1}}{V_{\bar{o}}} \right)$$

$$\left(B_{osp2} = \frac{V_{o2}}{V_{\bar{o}}} \right)$$

$$\left(SF_{o1} = \frac{1}{B_{osp1}} \right)$$

$$\left(SF_{o2} = \frac{1}{B_{osp2}} \right)$$

TABLE 6.7—SEPARATOR TESTS (RESERVOIR-FLUID) OF GOOD OIL CO. WELL 4 OIL SAMPLE

Four!
2-stage Sep Test

	Separator Pressure (psig)	Separator Temperature (°F)	$\tilde{R}_s$ GOR^b (ft^3/bbl)	R_s GOR^c (ft^3/bbl)	Stock-Tank Gravity (°API)	B_{ob} FVF^d (bbl/bbl)	Separator Volume Factor^e (bbl/bbl)	Flashed-Gas Specific Gravity	
I	50 P_{sp1}	75 T_{sp1}	715	737 R_{s1}			1.031 B_{o1}	0.840 γ_{g1}	$R_s = 778 \frac{scf}{STB}$
	to								
	0 P_{sp2}	75 T_{sp2}	41	41 R_{s2}	40.5	1.481	1.007 B_{o2}	1.338 γ_{g2}	
II	100	75	637	676			1.062	0.786	
	to								
	0	75	91	92	40.7	1.474	1.007	1.363	
III	200	75	542	602			1.112	0.732	
	to								
	0	75	177	178	40.4	1.483	1.007	1.329	
IV	300	75	478	549			1.148	0.704	
	to								
	0	75	245	246	40.1	1.495	1.007	1.286	

[a] Gauge.

[b] In cubic feet of gas at 60°F and 14.65 psi absolute per barrel of oil at indicated pressure and temperature.

[c] In cubic feet of gas at 60°F and 14.65 psi absolute per barrel of stock-tank oil at 60°F.

[d] In barrels of saturated oil at 2,620 psi gauge and 220°F per barrel of stock-tank oil at 60°F.

[e] In barrels of oil at indicated pressure and temperature per barrel of stock-tank oil at 60°F.

$$\bar{\gamma}_g = \frac{0.840(737) + 1.338(41)}{778} = 0.8xx$$

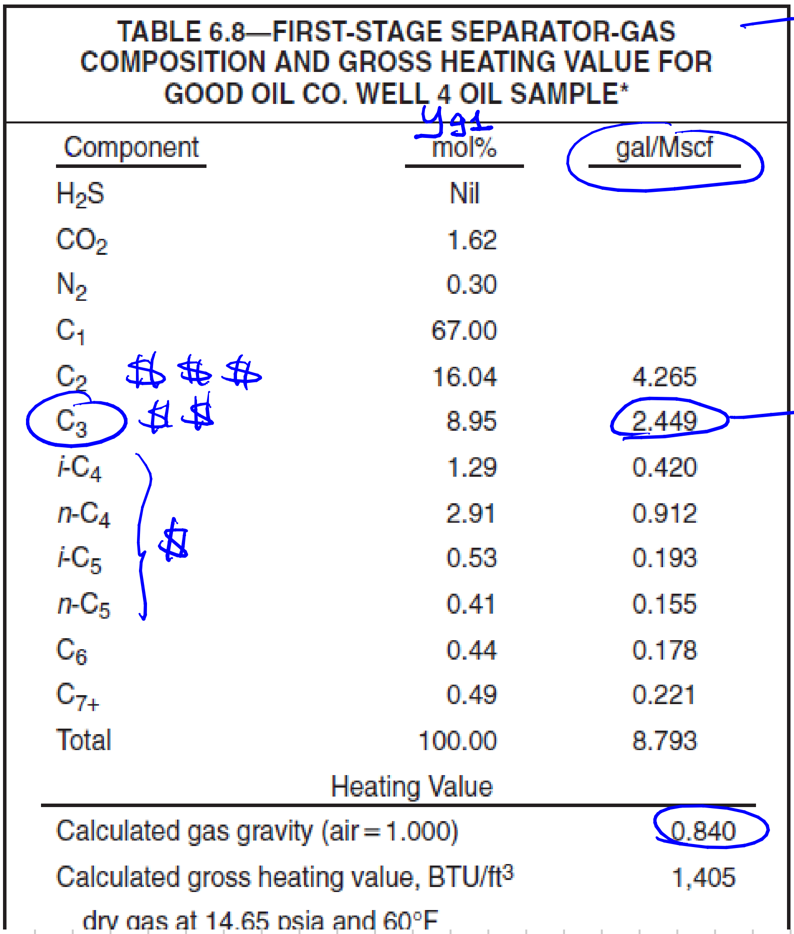


TABLE 6.8—FIRST-STAGE SEPARATOR-GAS COMPOSITION AND GROSS HEATING VALUE FOR GOOD OIL CO. WELL 4 OIL SAMPLE*

Component	y_{g1} mol%	gal/Mscf
H_2S	Nil	
CO_2	1.62	
N_2	0.30	
C_1	67.00	
C_2 $\$\$\$$	16.04	4.265
C_3 $\$\$$	8.95	2.449
i-C_4	1.29	0.420
n-C_4 $\$$	2.91	0.912
i-C_5	0.53	0.193
n-C_5	0.41	0.155
C_6	0.44	0.178
C_{7+}	0.49	0.221
Total	100.00	8.793

Heating Value

Calculated gas gravity (air = 1.000)	0.840
Calculated gross heating value, BTU/ft³ dry gas at 14.65 psia and 60°F	1,405

$T_{sp1} = 75°F$

$P_{sp1} = 50$ psig

1 Mscf sep. gas

2.449 gallons "Liquid" Propane @ T_{sc}, P_{sc}

PVT Lab Tests (Ch. 6)

Note Title

2012-10-19

CONSTANT COMPOSITION EXPERIMENT (CCE)

(MASS)

TEPERATURE = constant (T_R ✓ ; some (few) times $T < T_R$ 1 or 2 → 5°C min

* Charge a PVT Cell with a reservoir mixture ("Fill")

(1) Hg cell

(2) Piston

-
-
-

(Hg-free)

* "Blind" Cell (no visual) $p - V_{cell}$ } "Lower" GOR oils ($\lesssim$ 200-300 Sm^3/Sm^3)

* Windowed Cell

- Visual observation of gas-liquid interface → $V_g + V_o = V_{cell}$

} "Higher" GOR fluids $\gtrsim 300 \frac{Sm^3}{Sm^3}$

→ $5\text{-}10{,}000 \frac{Sm^3}{Sm^3}$

* Wellstream from separator—recombined samples

* Bottomhole sample

- Conventional cased hole wireline (oils)
- Openhole ("MDT") Formation BHS (oil, gas condensate)

Data Measured:

(1) Saturation Pressure

- Bubblepoint

- Dewpoint

(2) Single-phase ($p > p_s$) Density (Z_g)

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

Isothermal Compressibility

$$c = -\frac{1}{V}\left(\frac{dV}{dp}\right)_T = \frac{1}{\rho}\left(\frac{d\rho}{dp}\right)_T$$

| PTA RTA } "Well Testing"

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

(3) In Windowed PVT Cell (Higher GOR fluids)

V_g, V_o @ $p < p_s$ $\left\{ \frac{V_o(p)}{V_t(p)} \text{ or } \frac{V_o(p)}{\boxed{V_s}} \right\}$ — constant

Be careful of the ref. vol.

Oil Relative Volume V_{ro}

$$V_{ro} \sim \left(\frac{n_o}{n}\right) = \underbrace{1 - f_v}_{\text{Flash}}$$

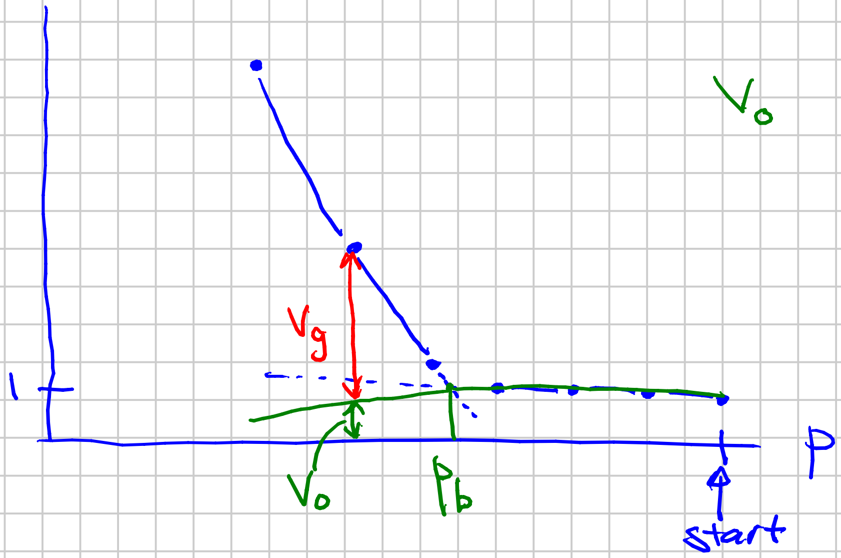
$$= f(K_i)$$

Important "Phase Equilibria" Data "K_i"

Bubblepoint in a Blind Cell : V_{cell} vs p

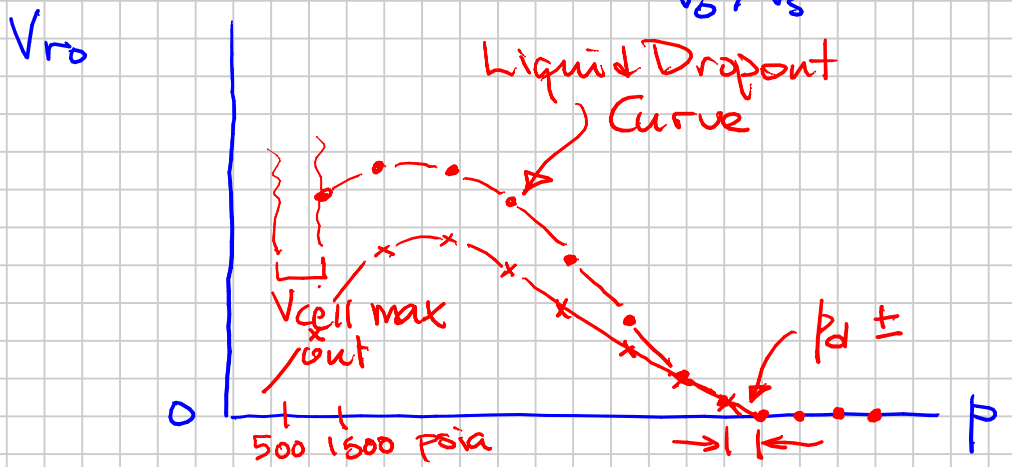
Reported

$$V_{rt} = \frac{V_{cell}}{V_{ob}}$$



Windowed Cell:

p $\{V_g \quad V_o \quad V_t\}$ $V_{ro} = V_o/V_t$ or V_o/V_s

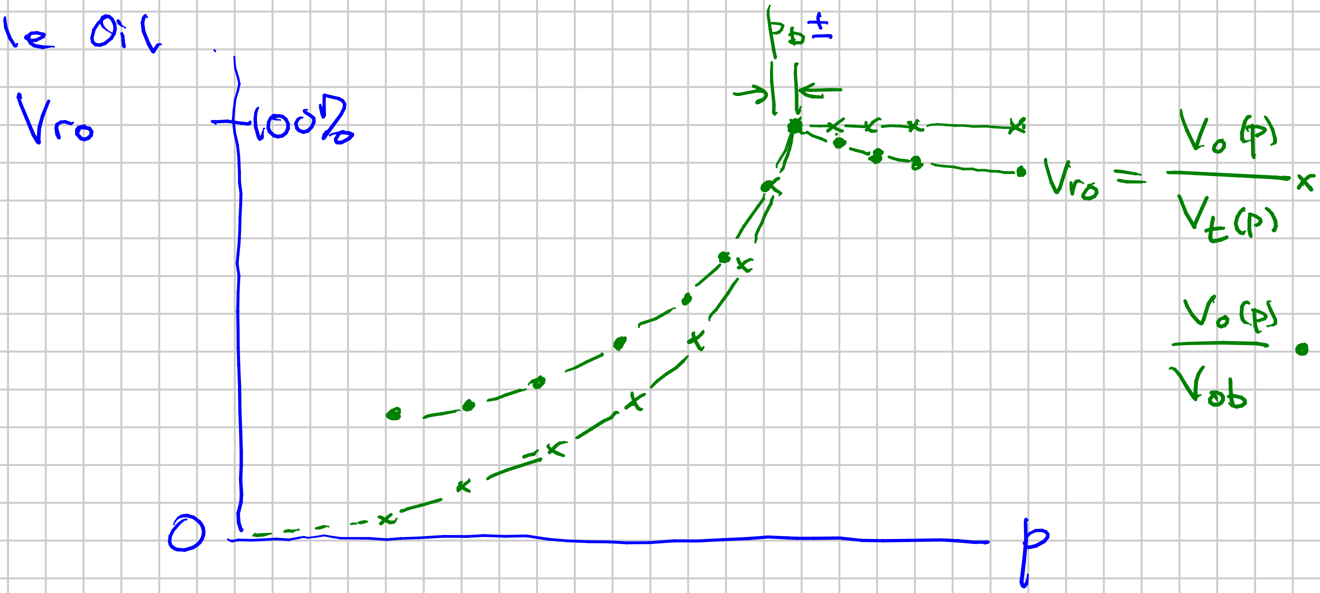


– Gas Condensate (V_{ro})

• $V_{ro} = V_o/V_d$

× $= \frac{V_o}{V_t(p)}$

Volatile Oil



DEPLETION PVT TESTS:

OILS: Differential Liberation Experiment (DLE)
Ch. 6 & App. D

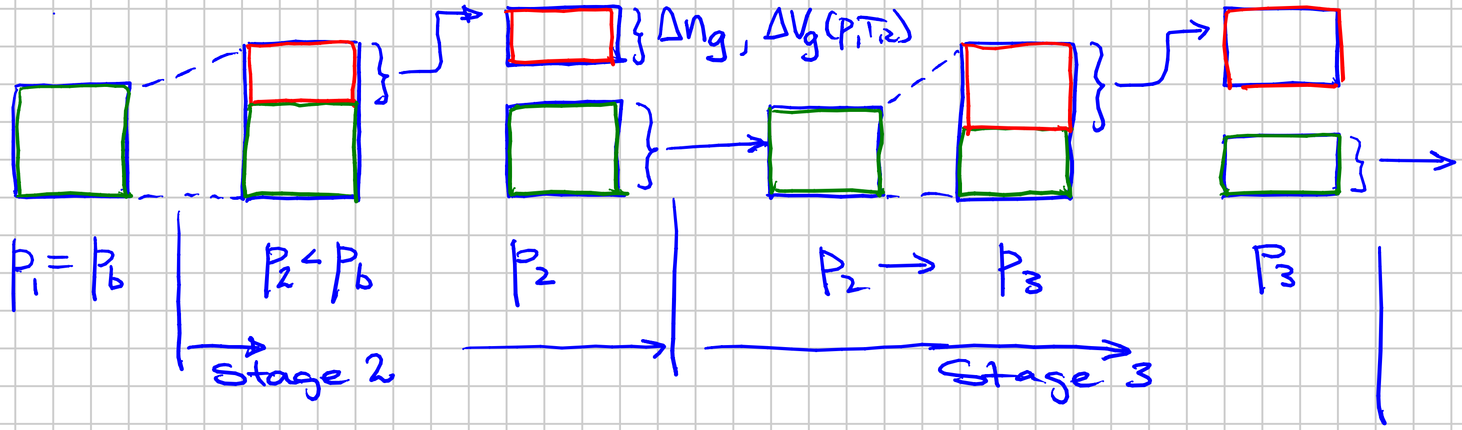
GAS CONDENSATES & VERY VOLATILE OILS: Constant Volume Depletion (CVD)
Ch. 6 & SPE publication on "my server sight"
SPE 10067

Tests designed to provide gas & oil phase & volumetric behavior data @ $p < p_s$.

$M_g (\gamma_g)$ $\{y_i\}$

$\Delta V_{\bar{g}}$

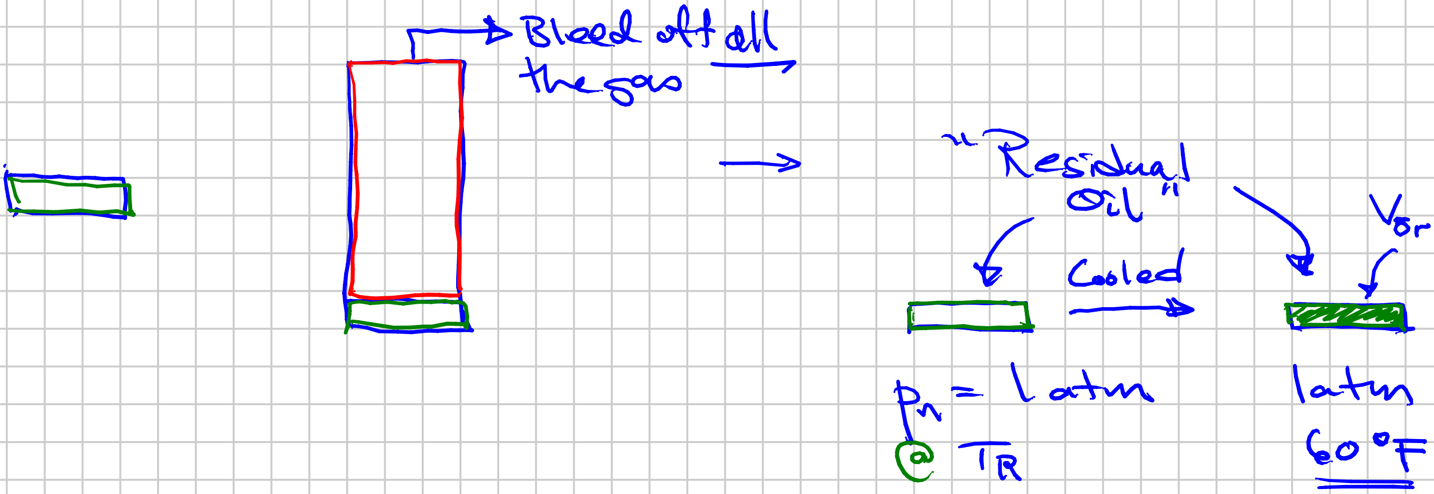
DLE: T_R = constant



6–10 stages

Final Stage (n)

$p_{n-1} \rightarrow p_n$ – where cell volume moves out



Reported:

OIL PHASE:

$B_{od} \equiv V_o(p, T_R) \,/\, V_{\bar{o}r}$ ✓ : Oil shrinkage

ref. volume is a constant

$\rho_o : \dfrac{m_o}{V_o}$ ✓ ± 1-3%

$\{x_{\bar{o}r,i}\}$

Btw: $\mu_o(p)$ "DLE" type test

GAS PHASE:

$\Delta R_{sd} = (\Delta V_g) \,/\, V_{\bar{o}r}$ ✓

γ_g (M_g) ✓

$\{y_i\}$

$Z_g = \dfrac{p \Delta V_g}{RT \Delta n_g}$ ✓

$$m_{o,k} = \underset{\text{measured}}{m_{\bar{o}r}} + \underbrace{\sum_{i=N}^{k+1} \Delta m_g}_{\text{measured}}$$

CANNOT (SHOULD NOT) WILL NOT EVER

use $\left\{ \begin{array}{l} B_{od} \\ R_{sd} \ (\Delta R_{sd}) \end{array} \right\}$ directly in any engineering program/calculation that ask for B_o and R_s

Must be transformed:

Simple: Ch. 6 App. D

Rigorous: Ch. 7

Gas Cond & Highly-Vol. oils : CVD

$T_R = \text{const.}$

Conventional Gas Cond. Reservoirs

$$\underbrace{\Delta V_g \quad \Delta n_g}_{Z_g} \qquad \underset{\downarrow\; M_g(\gamma_g)}{y_i} : \; z_{wi}(p_R) \simeq y_i^{CVD}(p=p_R)$$

$p_1 = p_s$

Stage 2 : $p_2 < p_s$

$$V_o / V_s \equiv V_{ro}^{CVD} \Rightarrow \bar{S}_o(p_R) \simeq V_{ro}^{CVD}(p=p_R) \times (1-\bar{S}_w)$$

Very good ~

SORRY GUYS I SCREWED UP AND DIDN'T SAVE THE NOTES ... JUST USE THE VIDEO

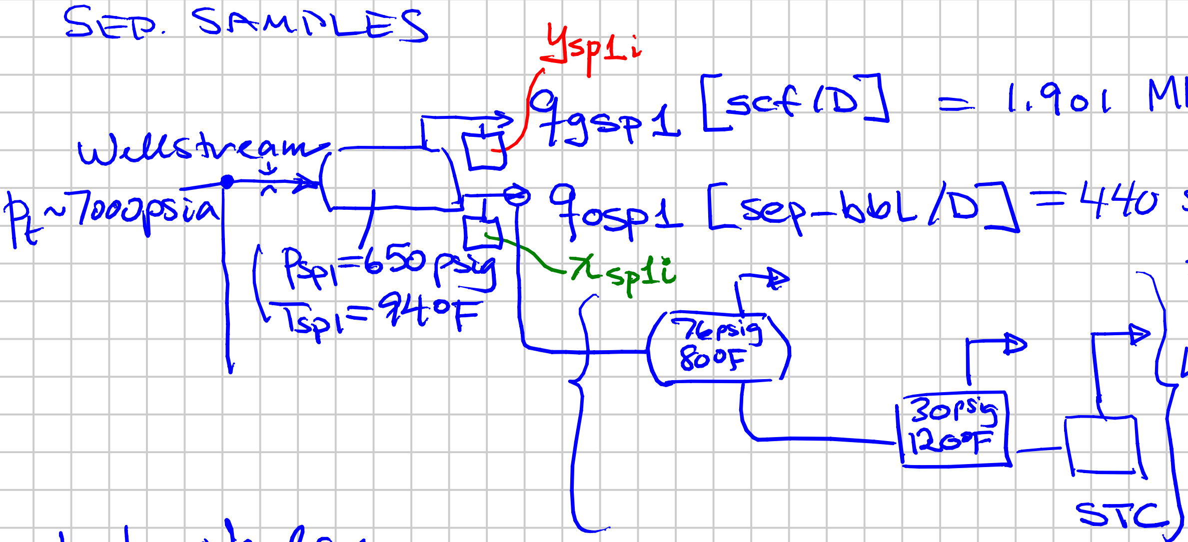
Note Title 2012-10-23

GAS CONDENSATE PVT STUDY

Note Title 2012-10-26

- PVT Report (JK1GC.pdf on server w/ videos)
- CVD Material Balance (not "required" - for exam)

SEP. SAMPLES



q_{gsp1} [scf/D] = 1.901 MMscf/D

q_{osp1} [sep-bbl/D] = 440 STB/D × 1.258 $\frac{\text{sep bbl}}{\text{STB}}$

=

$q_{\bar{o}}$ [STB/D] = 440 STB/D

Lab Needs:

$$GOR_{sp1} \quad \frac{scf}{sep\text{-}bbl} \text{ or } \frac{Sm^3}{sep\text{-}m^3} = \frac{q_{gsp1}}{q_{osp1}}$$

$$= 3436 \frac{scf}{sep\text{-}bbl}$$

$$4320 \frac{scf}{STB} = \frac{q_{gsp1}}{q_{\bar{o}}}$$

"Shrinkage Factor" Sep 1 → STO : $\frac{q_{\bar{o}}}{q_{osp1}} = \frac{3436}{4320} = 0.795$

$$b_{osp1} = \frac{1}{B_{osp1}}$$

$B_{osp1} = 1.258 \frac{\text{sep bbl}}{\text{STB}}$

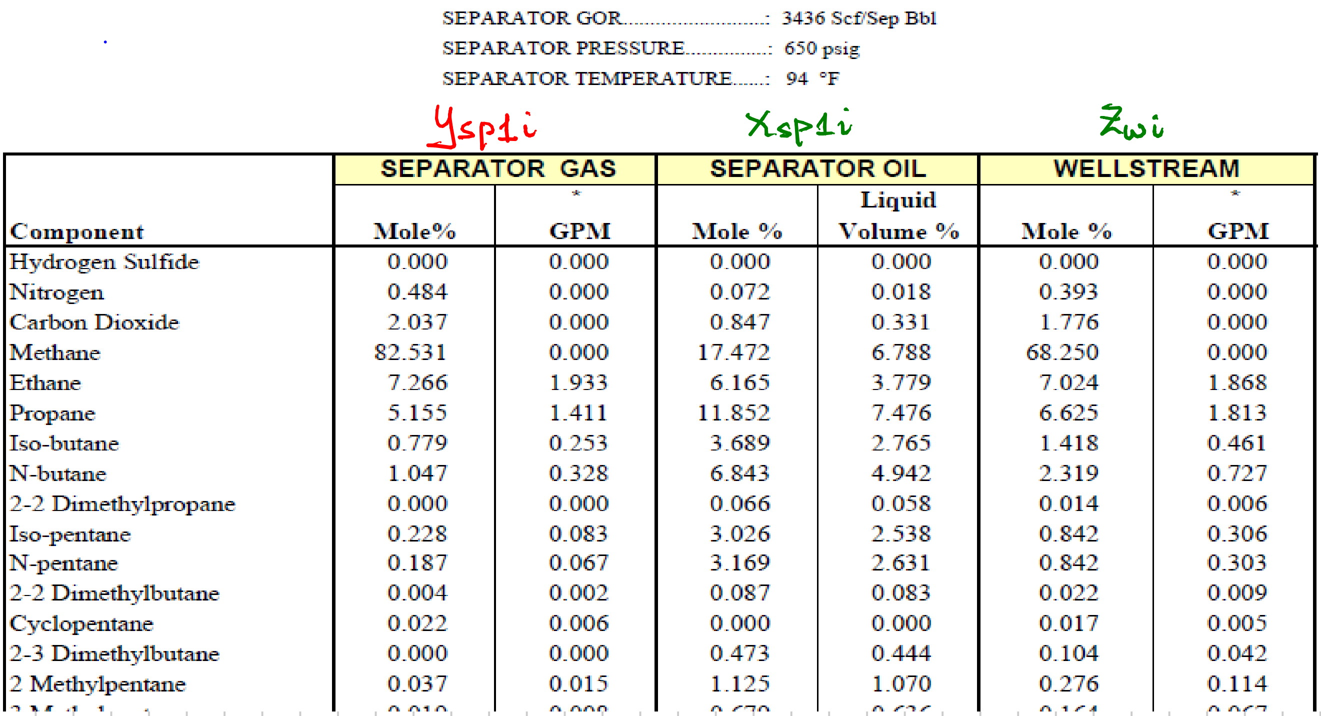
"Expansion Factor" $= \frac{1}{B_{gs}} = b_{gs} = \frac{V_{\bar{g}w}\ [scf]}{V_{gs}\ [bbl]}$

V_{gs} = 1 bbl

@ sat. Pressure $= \frac{T_{sc}}{p_{sc}} \cdot \frac{p_s}{Z_g T_R}$

$V_{\bar{g}w}$ (no condensate)

"Wet Gas" FVF



SEPARATOR GOR..........................: 3436 Scf/Sep Bbl
SEPARATOR PRESSURE...............: 650 psig
SEPARATOR TEMPERATURE......: 94 °F

	y_{sp1i}		x_{sp1i}		Z_{wi}	
	SEPARATOR GAS		SEPARATOR OIL		WELLSTREAM	
		*		Liquid		*
Component	**Mole%**	**GPM**	**Mole %**	**Volume %**	**Mole %**	**GPM**
Hydrogen Sulfide	0.000	0.000	0.000	0.000	0.000	0.000
Nitrogen	0.484	0.000	0.072	0.018	0.393	0.000
Carbon Dioxide	2.037	0.000	0.847	0.331	1.776	0.000
Methane	82.531	0.000	17.472	6.788	68.250	0.000
Ethane	7.266	1.933	6.165	3.779	7.024	1.868
Propane	5.155	1.411	11.852	7.476	6.625	1.813
Iso-butane	0.779	0.253	3.689	2.765	1.418	0.461
N-butane	1.047	0.328	6.843	4.942	2.319	0.727
2-2 Dimethylpropane	0.000	0.000	0.066	0.058	0.014	0.006
Iso-pentane	0.228	0.083	3.026	2.538	0.842	0.306
N-pentane	0.187	0.067	3.169	2.631	0.842	0.303
2-2 Dimethylbutane	0.004	0.002	0.087	0.083	0.022	0.009
Cyclopentane	0.022	0.006	0.000	0.000	0.017	0.005
2-3 Dimethylbutane	0.000	0.000	0.473	0.444	0.104	0.042
2 Methylpentane	0.037	0.015	1.125	1.070	0.276	0.114

Sep Gas Direct to GC

Flashed to STC in the lab

$$\left.\begin{matrix} y_{gFi}^{\pm} \\ x_{oFi}^{\pm} \end{matrix}\right\} GOR_F^{\pm} \Rightarrow x_{sp1i}^{\pm}$$

$$Z_{wi} = f_g \cdot y_{sp1i} + (1-f_g)\, x_{sp1i}$$

$$f_g = \frac{n_{gsp1}}{n_{gsp1} + n_{osp1}}$$

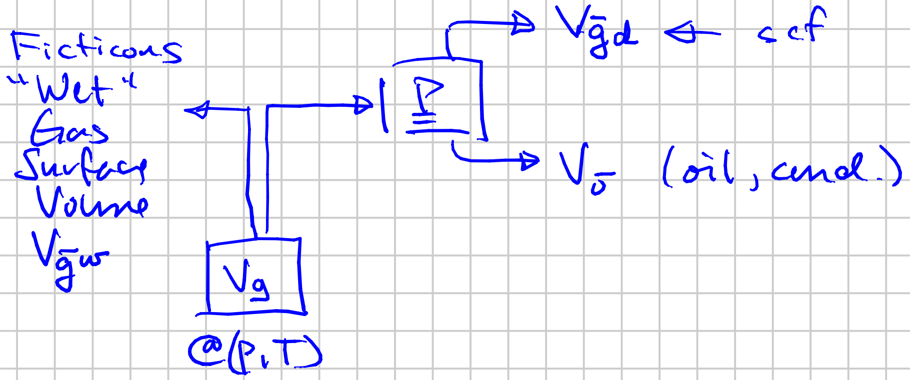
$$n_{gsp1}$$

Basis: 1 sep. bbl

$$n_{osp1} = 1\ \cancel{bbl} \cdot 5.615 \frac{\cancel{ft^3}}{\cancel{bbl}} \cdot \overset{\downarrow}{\rho_{osp1}} \frac{\cancel{lb}}{\cancel{ft^3}} \cdot \frac{1}{\overset{\downarrow}{M_{osp}}} \frac{lbmole}{\cancel{lb}}$$

$$n_{gsp1} = \underset{\uparrow}{3436}\ scf \times \frac{1}{379} \frac{lbmole}{scf}$$

GoR_{sp1}



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

$$B_{dg} = \frac{V_g(p,T)}{V_{\bar{g}d}}$$

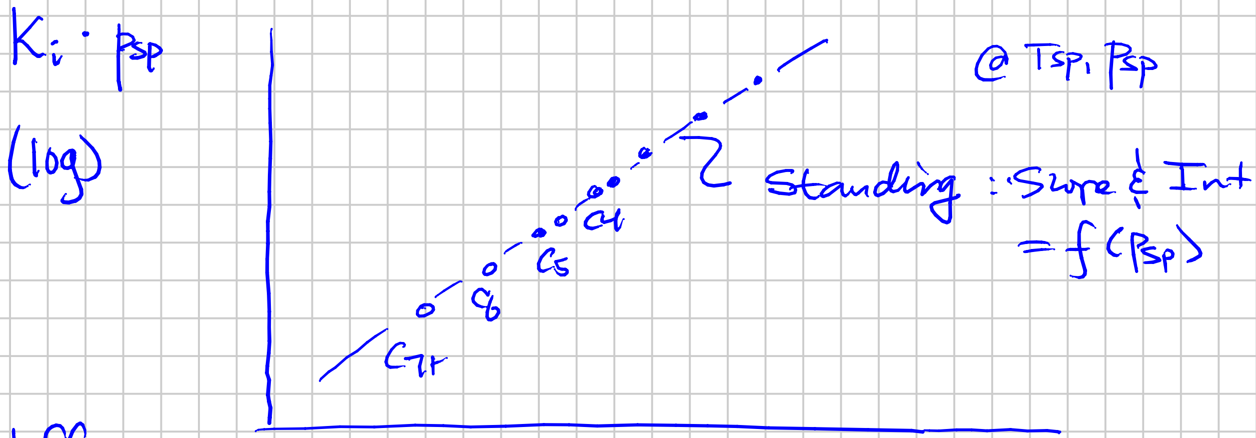
QC $y_{spi} / x_{spi} = K_{isp}$

HOFFMAN PLOT

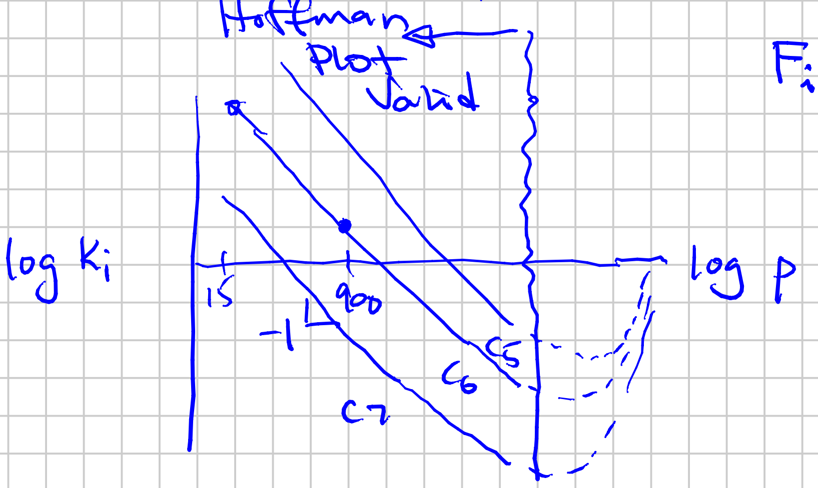
EQUILIBRIUM CHECK of SEPARATOR LIQUID and GAS COMPOSITIONAL ANALYSES

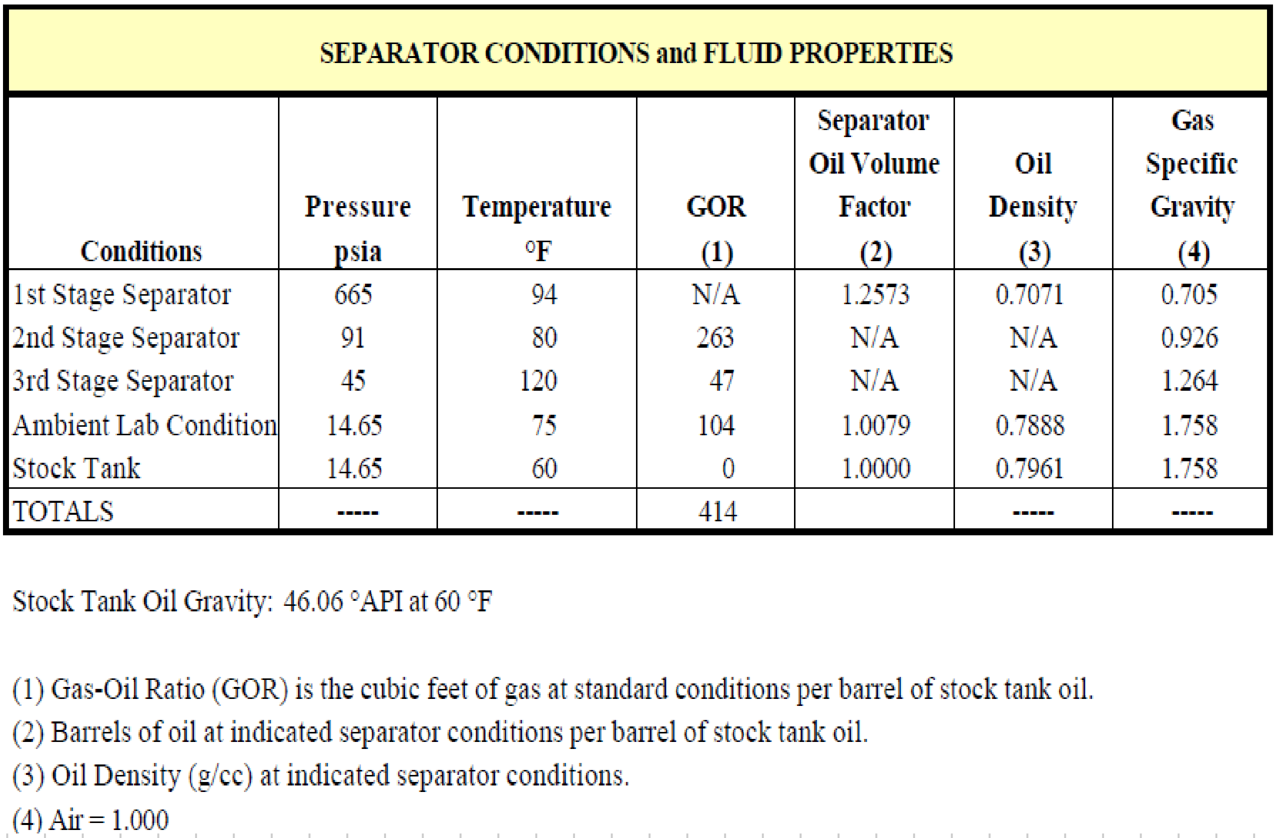
Separator Pressure = 650 psig
Separator Temperature = 94 °F

Components	Gas (X) Mole %	Oil (Y) Mole %	Equil. Ratio (K=Y/X)	K*Psep (psiA)	Normal BP (NBP) °R	$T_{NBP}^{-1} - T_{SEP}^{-1}$	Critical Pressure (Pc) psiA	Critical Temperature (Tc) °R	B-Factor	Graph Results B(1/Tb-1/Tsp)	Graph Results Log(K*Psep)
N2	0.484	0.072	6.758	4491.50	139	0.005373	493	227	551	2.958	3.652
CO2	2.037	0.847	2.404	1598.02	350	0.001048	1071	548	1811	1.898	3.204
C1	82.531	17.472	4.724	3139.57	201	0.003169	668	343	805	2.552	3.497
C2	7.266	6.165	1.179	783.39	332	0.001204	708	550	1413	1.701	2.894
C3	5.155	11.852	0.435	289.10	416	0.000598	616	666	1799	1.076	2.461
IC4	0.779	3.689	0.211	140.35	471	0.000319	529	735	2038	0.650	2.147
NC4	1.047	6.843	0.153	101.70	491	0.000231	551	765	2158	0.498	2.007
IC5	0.228	3.092	0.074	49.01	542	0.000040	490	829	2383	0.095	1.690
NC5	0.187	3.169	0.059	39.22	557	-0.000009	489	845	2483	-0.023	1.594
C6	0.121	3.978	0.030	20.22	615	-0.000181	437	913	2784	-0.504	1.306
C7+	0.165	42.822	0.004	2.56	763	-0.000496	332	1070	3607	-1.789	0.408
Total	100.000	100.000									



$F_i \; (T_{ci}, P_{ci}, T_{bi} ; T_{sp})$





SEPARATOR CONDITIONS and FLUID PROPERTIES

Conditions	Pressure psia	Temperature °F	GOR (1)	Separator Oil Volume Factor (2)	Oil Density (3)	Gas Specific Gravity (4)
1st Stage Separator	665	94	N/A	1.2573	0.7071	0.705
2nd Stage Separator	91	80	263	N/A	N/A	0.926
3rd Stage Separator	45	120	47	N/A	N/A	1.264
Ambient Lab Condition	14.65	75	104	1.0079	0.7888	1.758
Stock Tank	14.65	60	0	1.0000	0.7961	1.758
TOTALS	-----	-----	414		-----	-----

Stock Tank Oil Gravity: 46.06 °API at 60 °F

(1) Gas-Oil Ratio (GOR) is the cubic feet of gas at standard conditions per barrel of stock tank oil.
(2) Barrels of oil at indicated separator conditions per barrel of stock tank oil.
(3) Oil Density (g/cc) at indicated separator conditions.
(4) Air = 1.000

$$\text{Total 4-stage Well GOR} = \underset{\text{Stage 1}}{4320 \frac{scf}{STB}} + \underbrace{414 \frac{scf}{STB}}_{\text{Stages 2-4}}$$

$$GOR = 4734 \ scf/STB$$

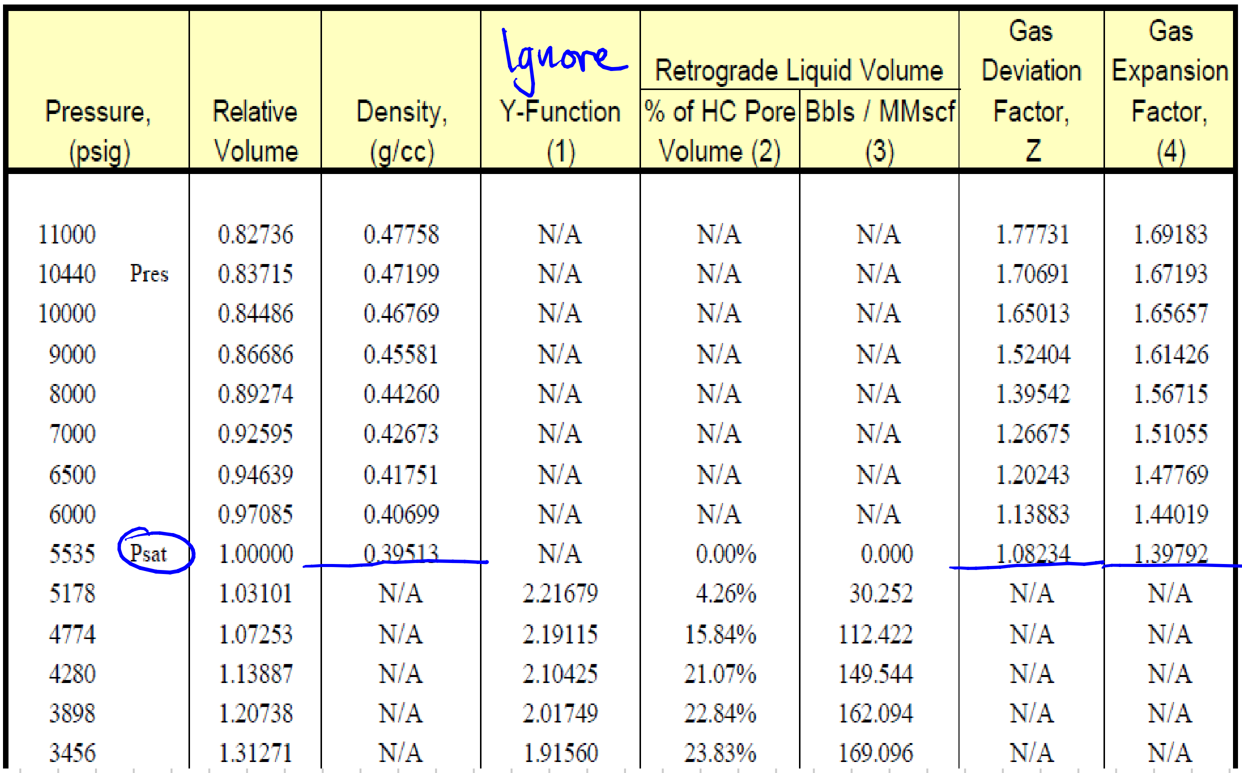
$$\text{Gas Condensates "Liquid Yield"} = \frac{1}{GOR} = r = OGR$$

$$(p_R, p_{wf}) >> p_d$$

$$r_p = r_{si} = \frac{10^6 \frac{scf}{MMscf}}{4734 \frac{scf}{STB}} = 211 \frac{STB}{MMscf}$$

Producing OGR

Solution OGR



	$\frac{V_t}{V_s}$	ρ_g	Ignore	$\frac{V_o}{V_s}$	$\frac{V_o}{(V_{\bar{g}w})_s}$	b_{gw}	$\frac{Mscf}{RB}$
				Retrograde Liquid Volume		Gas Deviation Factor, Z	Gas Expansion Factor, (4)
Pressure, (psig)	Relative Volume	Density, (g/cc)	Y-Function (1)	% of HC Pore Volume (2)	Bbls / MMscf (3)		
11000	0.82736	0.47758	N/A	N/A	N/A	1.77731	1.69183
10440 Pres	0.83715	0.47199	N/A	N/A	N/A	1.70691	1.67193
10000	0.84486	0.46769	N/A	N/A	N/A	1.65013	1.65657
9000	0.86686	0.45581	N/A	N/A	N/A	1.52404	1.61426
8000	0.89274	0.44260	N/A	N/A	N/A	1.39542	1.56715
7000	0.92595	0.42673	N/A	N/A	N/A	1.26675	1.51055
6500	0.94639	0.41751	N/A	N/A	N/A	1.20243	1.47769
6000	0.97085	0.40699	N/A	N/A	N/A	1.13883	1.44019
5535 Psat	1.00000	0.39513	N/A	0.00%	0.000	1.08234	1.39792
5178	1.03101	N/A	2.21679	4.26%	30.252	N/A	N/A
4774	1.07253	N/A	2.19115	15.84%	112.422	N/A	N/A
4280	1.13887	N/A	2.10425	21.07%	149.544	N/A	N/A
3898	1.20738	N/A	2.01749	22.84%	162.094	N/A	N/A
3456	1.31271	N/A	1.91560	23.83%	169.096	N/A	N/A

RESERVOIR GAS DEPLETION STUDY AT 263 °F

CVD $y_{CVDi} \rightarrow r_s$

Reservoir Pressure, psig	(D.P.) 5535 Pd	4500	3500	2500	1700	900	0
Wellstream Components	mole %	mole %	mole %	mole %	mole %	mole %	mole %
Hydrogen Sulfide	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Nitrogen	0.393	0.405	0.433	0.442	0.437	0.428	0.335
Carbon Dioxide	1.776	1.829	1.863	1.899	1.936	1.945	1.612
Methane	68.250	71.913	74.339	75.538	76.049	74.723	60.118
Ethane	7.024	7.178	7.244	7.464	7.621	7.691	7.178
Propane	6.625	6.501	6.501	6.501	6.501	7.112	8.091
Iso-butane	1.418	1.352	1.312	1.300	1.324	1.462	1.991
N-butane	2.319	2.178	2.113	2.113	2.113	2.360	3.243
Iso-pentane	0.857	0.800	0.766	0.724	0.690	0.815	1.213
N-pentane	0.842	0.787	0.757	0.716	0.681	0.762	1.151
Hexanes	0.968	0.857	0.771	0.701	0.647	0.701	1.268
C_{7+} Heptanes Plus	9.529	6.200	3.900	2.600	2.000	2.000	13.800
TOTALS	100.000	100.000	100.000	100.000	100.000	100.000	100.000
r_s [STB/MMscf]	220	160	110	70	20	22	

HEPTANES PLUS (C_{7+}) FRACTION CHARACTERISTICS

Molecular Weight	169.530	149.703	136.501	126.627	120.849	116.400	131.537
Specific Gravity	0.8163	0.8013	0.7897	0.7803	0.7746	0.7699	1.3869

Calc.

CONDENSED RETROGRADE LIQUID VOLUME

HC Pore Volume %	0.000	17.000	22.842	23.832	22.309	19.063	14.967
Bbls/MMscf of DP Gas	0.000	120.639	162.094	169.122	158.316	135.277	106.213

(V_o/V_d)

GAS DEVIATION FACTOR

Equilibrium Gas	1.0823	0.9202	0.8515	0.8369	0.8568	0.9069	N/A
Two-Phase	1.0823	0.9568	0.8786	0.8169	0.7645	0.6848	N/A

$\rightarrow Z_g$

$\rightarrow Z_2$ (Ch.6)

CUMULATIVE PRODUCED WELLSTREAM VOLUME

V_{gw}

Vol % of Initial DP Gas	0.000	7.976	21.980	39.965	56.259	73.951	93.845

$\rightarrow \underline{n_p} / \underline{\underline{n_s}}$

C_{n+} : C_{5+} or C_{6+}

211 0.12

$$r_s \simeq \frac{y_{Cn+}}{(1-y_{Cn+})} \cdot C'$$

0.88

Consistent Units

$$C' = \frac{(M_{Cn+}/\rho_{LCn+})}{(RT_{sc}/p_{sc})}$$

Know initial gas

$(r_s)_{Pd} = 211$ STB/MMscf

$(y_{5+})_{Pd} = 0.12$

$$\hookrightarrow C' = 211 \cdot (0.88)/0.12 = 1547 \ \frac{STB}{MMscf}$$

Book : $C_{og} = \frac{1}{C'}$ scf/STB 600–900 $\frac{scf}{STB}$

Two Component/Phase Material Balances to QC CVD Data

① "Forward" M.B.

Ch.6

$$n_s (z_i)_s - (y_i^{CVD}) \Delta n_p = \underbrace{\overset{\overset{g+o}{\nearrow}\ \downarrow}{n_R z_{Ri}}}_{}$$

$$\underset{\checkmark}{n_{Rg}} \ \underset{\checkmark}{y_i^{CVD}} + \overset{\checkmark}{n_{Ro}} \ \underset{\boxed{\text{Calc}}}{\underbrace{x_i^{CVD}}}$$

$$n_{Ro} \uparrow \ \underset{\checkmark}{n_R} - \underset{\checkmark}{n_{Rg}}$$

$$n_s - \Delta n_p = n_R$$

$$\underline{(V_o/V_d) > 0.1}$$

② Backward M.B.

Requires Final Oil Composition $\boxed{\underline{x_{residual,i}}}$

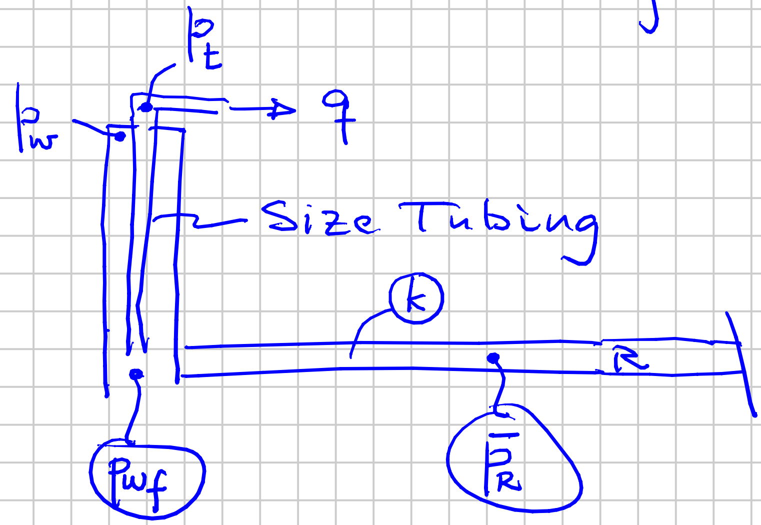
$$(z_i)^{lab}_{pd} \text{ vs } (z_i)^{calc}_{pd} \longleftarrow \Delta n_g y_i^{CVD} + x_{res,i} \cdot n_{ores}$$

C_{5+} ± 0.5 mol-%

DRY
GAS FLOW & VOLUMETRIC MATERIAL BALANCE

GAS PRODUCTION PERFORMANCE

- Forecasting $\underbrace{q_g \ (q_o \quad q_w)} = f(t)$
- History Matching Performance Data } Tune Models
  - $q(t)$
  - $p(t)$

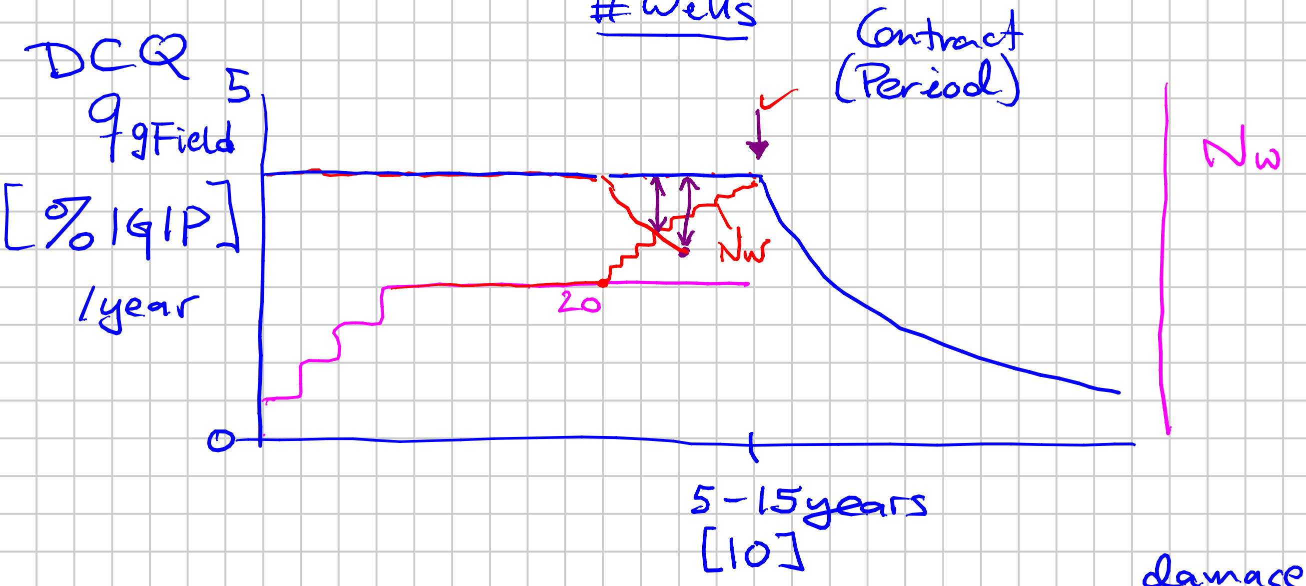


Hewett

- Design "Optimally" Field/Wells

#Pipelines
#Wells ⇐ Least Cost
#Platforms Most Revenue }

$\underbrace{\text{Most Revenue}}$
#Wells



$$\underset{\sim\sim\sim}{q_{gField}} = \sum q_{gw}\left(\bar{k}_w, \underset{\uparrow}{d_{tw}}, \bar{h}_w, \overset{\overset{\text{damage}}{\downarrow}}{\underset{\uparrow}{\underline{\underline{s_w}}}}\right)$$

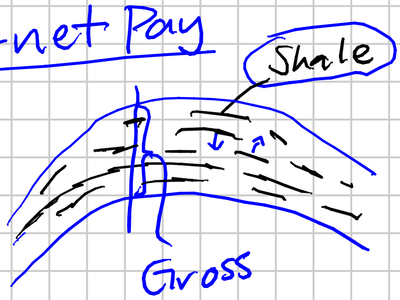
① GAS MATERIAL BALANCE (M.B.)

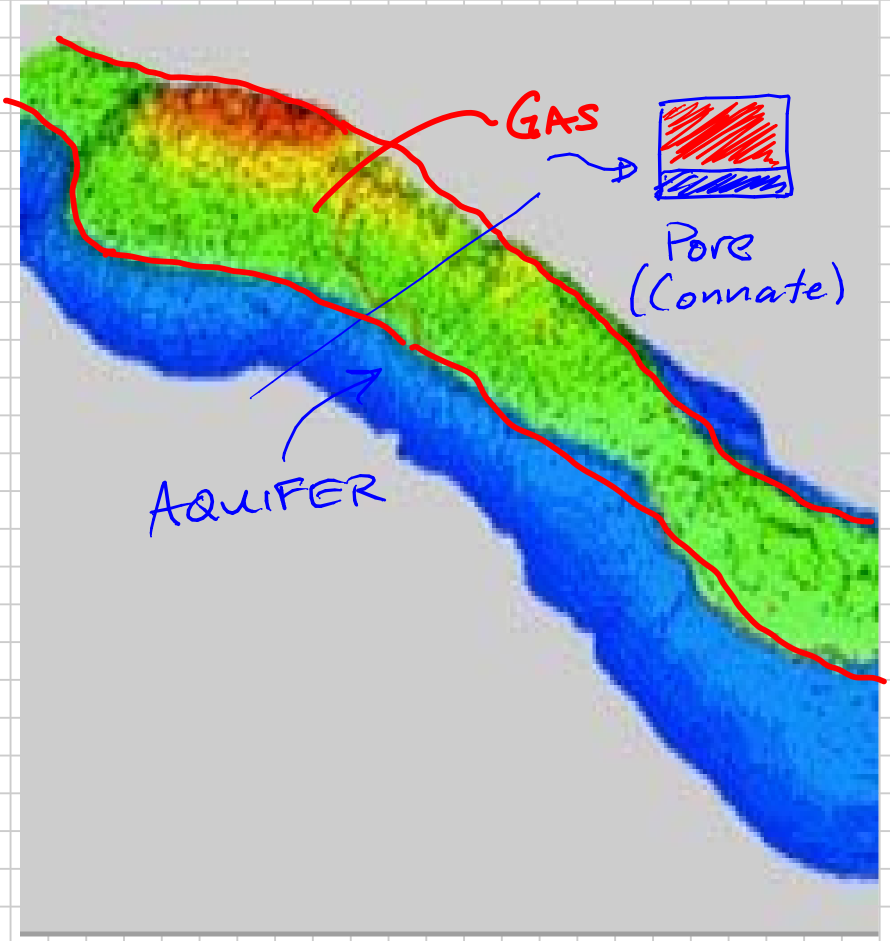
$$\bar{p}_R = f\left(G_p \; ; \; \overset{\checkmark}{\underline{\underline{V_w}}} \; ; \; \overset{\checkmark}{p_{Ri}} \; ; \; \overset{\checkmark}{c_f}\right)$$

Cumulative Gas Produced

non-net Pay

Shales
Dirty
sands





ORMEN
LANGE
FIELD

② Reservoir (Rock) Flow Eq.
- "Darcy" d'Arcy
- Forchheimer

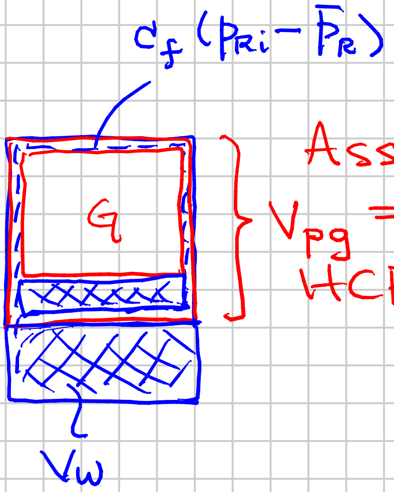
③ Pipe (Tubing) Flow Eq.

Henry
Darcy

Professor Philipp Forchheimer

Philipp
Forchheimer
(Austrian)

Gas M.B.



Assume:
V_{pg} = constant
HCPV

Avg. Vol. Pressure after Producing G_p

Cum Gas Prod Sm^3 scf

$$\boxed{\frac{\bar{p}_R}{Z_g(\bar{p}_R)} = \frac{p_{Ri}}{Z_g(p_{Ri})}\left(1-\frac{G_p}{G}\right)}$$

IGIP (scf or Sm^3)

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

"p over z"
Straight-Line Gas M.B.

- Initially n_i
- Later n_R
- after Producing n_p

$$pV = nRT \cdot Z$$
$$p_{sc}V_{sc} = nRT_{sc}Z_{sc}$$

Z_{sc} = 1 @ p_{sc}, T_{sc}

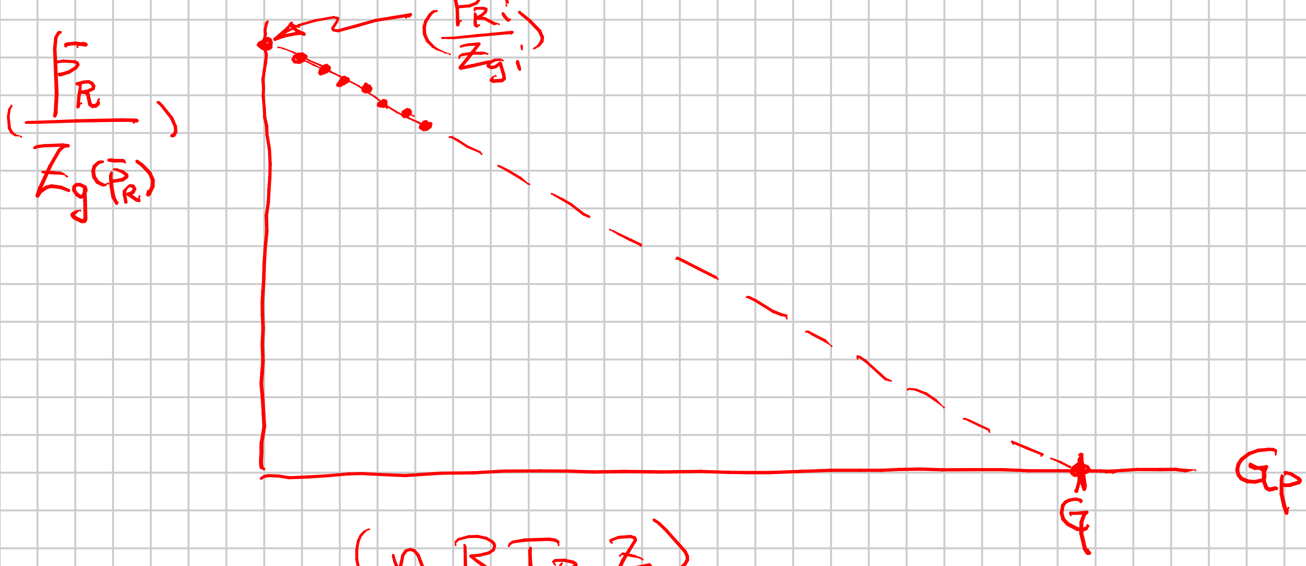
$$\frac{V_{gsc}}{n} = \frac{V_g}{n} = \frac{RT_{sc}}{p_{sc}} = 23.68 \frac{Sm^3}{kg\text{-}mole}$$

$$379 \frac{scf}{lb\text{-}mole}$$

$$n_i = n_R + n_p$$
$$G = \frac{RT_{sc}}{p_{sc}} \cdot n_i \quad : \boxed{V_{pg}}$$
$$G_p = \frac{RT_{sc}}{p_{sc}} \cdot n_p$$
$$G_R = G - G_p = \frac{RT_{sc}}{p_{sc}}(n_i - n_p) \quad : \boxed{V_{pg}}$$

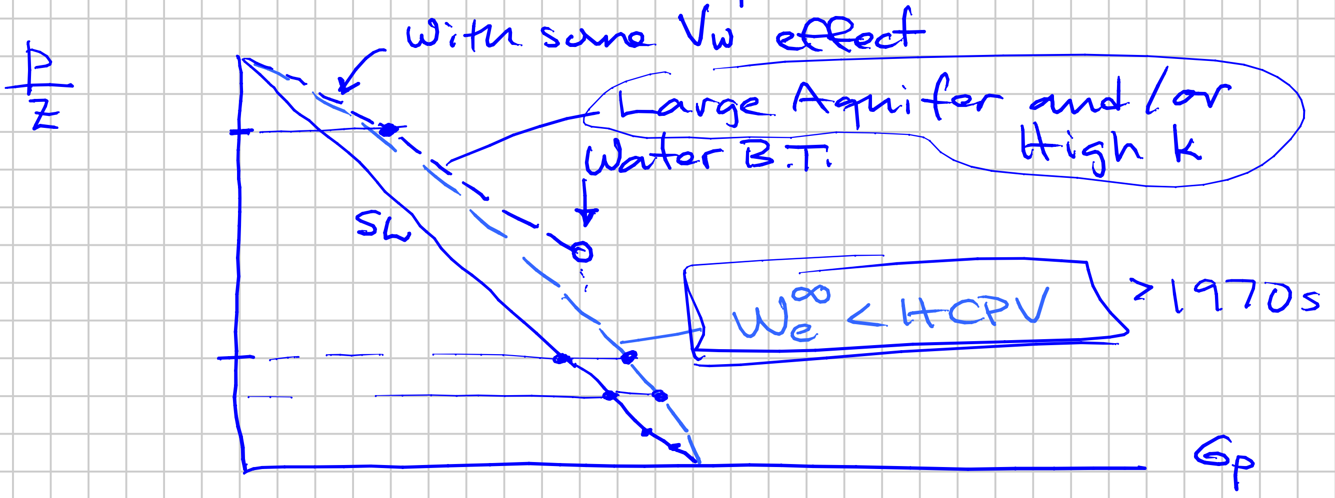
HCPV = constant

Data



$$\uparrow \; \bar{p}_R = \frac{(nRT_R Z)}{V_g}$$

Water Effect gives a higher $\bar{p}_R$ after a given amount of production ($\underline{G_p/G}$) compared with the straight line M.B.



W_e = encroachment of Water

$= V_w \cdot (c_f + c_w) \cdot (p_{Ri} - p_R)$ at $\underline{t = \infty}$

$> HCPV$

$W_e < HCPV$

"Pot" Aquifer M.B. $(k > 10 \text{ md})$

$\Delta t \sim 6 \text{ mo} - 1 \text{ yr}$

$$\boxed{\frac{p_R}{Z_{gR}}\left[1 - c_e(p_{Ri} - p_R)\right] = \frac{p_i}{Z_i}\left(1 - \frac{G_p}{G}\right)}$$

$$\underline{W_e(p_{Ri} - p_R) \simeq W_e^\infty}$$

"Instantaneous" Water Support

$$c_e = \frac{c_f + c_w \bar{S}_{wi} + M(c_f + c_w)}{1 - \bar{S}_{wi}}$$

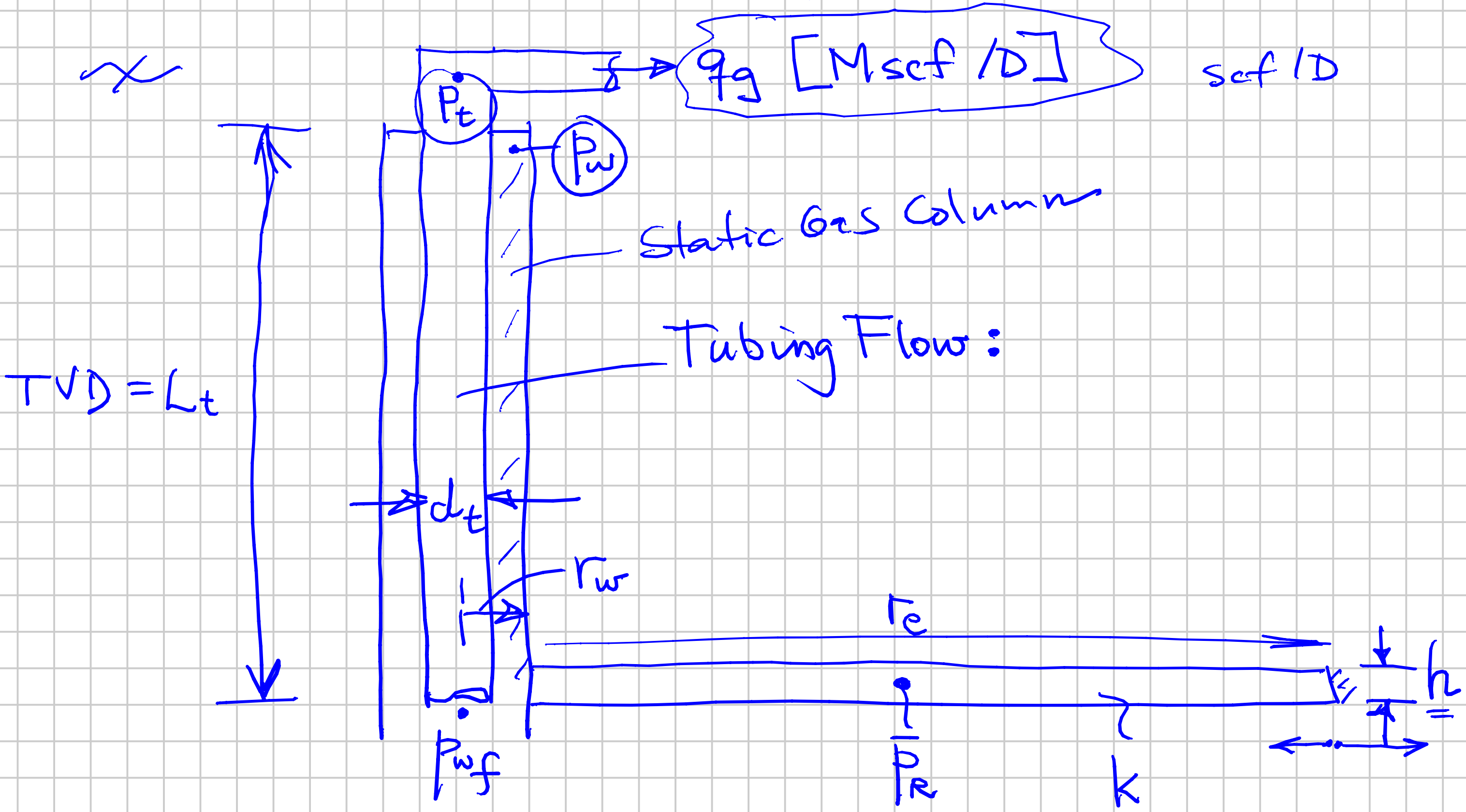
$\bar{S}_{wi}$ in the original HCPV pores

$$M \equiv \frac{\rightarrow V_w}{V_{pR}} = \frac{V_w}{HCPV/(1-S_{wi})}$$

Aquifer

Non-Net Pay (Shale + Dirty Sand)
interbedded

SPE 22921 Fetkovich, Reese, Whitson
in e-notes\Gas-Papers



Units   Reservoir Flow: IPR

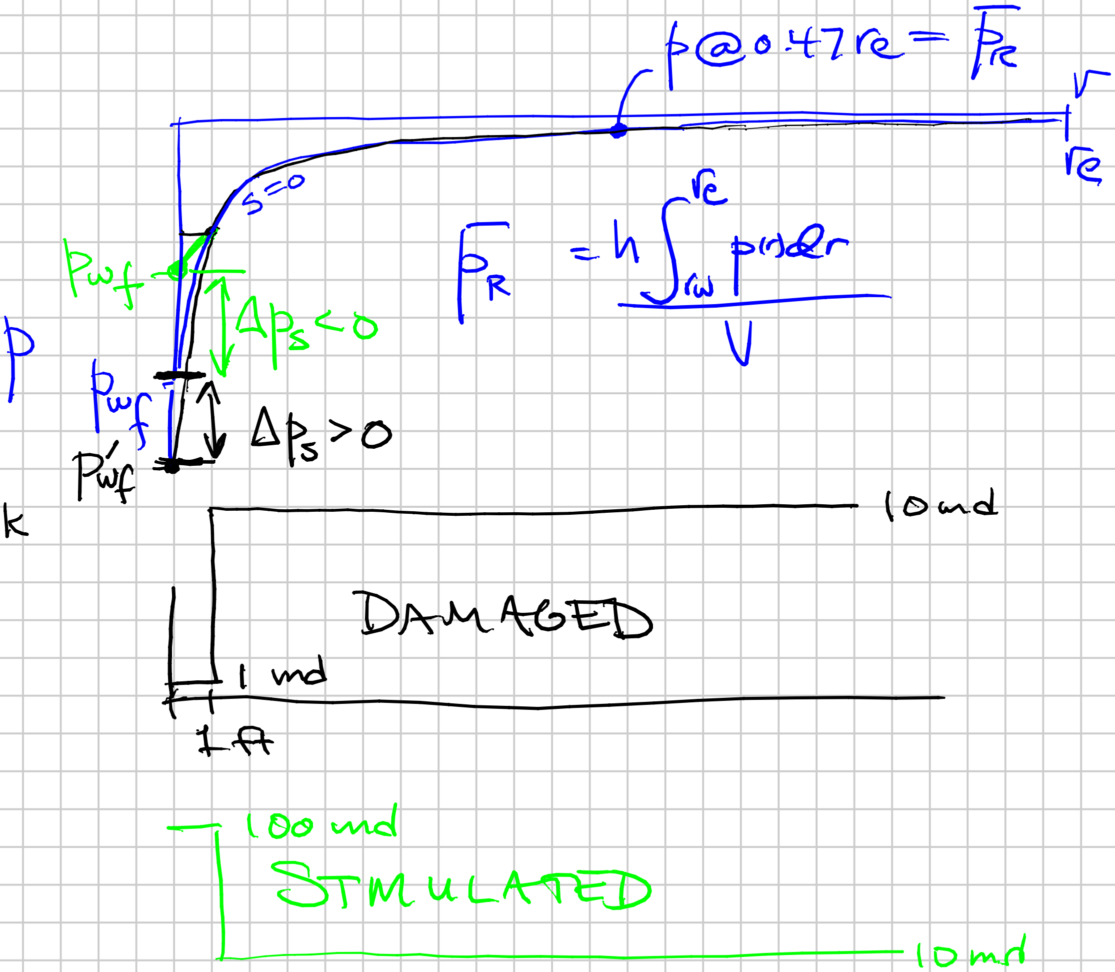
$$\boxed{q_g = \frac{\alpha\; kh\left[p_{pR} - p_{pwf}\right]}{T_R\left[\ln\left(\frac{r_e}{r_w}\right) - \frac{3}{4} + s + Dq_g\right]}}$$

Pseudosteady   skin

$$p_p = 2 \cdot \int_0^p \frac{p}{\mu_g Z_g}\, dp$$

Al-Hussainy,
Ramey,
Crawford

$$\ln\frac{r_e}{r_w} - \frac{3}{4} = \ln\left(\frac{0.47 r_e}{r_w}\right) \simeq \ln\left(\frac{0.5 r_e}{r_w}\right)$$



$$\boxed{\text{Apparent Wellbore Radius} \quad r_w' = r_w \cdot e^{-s}}$$

$$\ln\frac{r_e}{r_w'} = \ln\frac{r_e}{r_w} + s$$

Muskat 1930s Rock Re ~ 1-8

Dq_g = rate-dependent skin $\quad \underline{\text{GASES}}$ (OILS)

High Velocities

$$\frac{\Delta p}{\Delta x} = \underbrace{\left(\frac{\mu}{k}\right) v}_{\text{Darcy}} + \overset{\text{Rock}}{\beta}\ \underset{\text{Fluid Density}}{\rho}\ v^2$$

$$v = \left(\frac{k}{\mu}\right)\frac{dp}{dx}$$

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

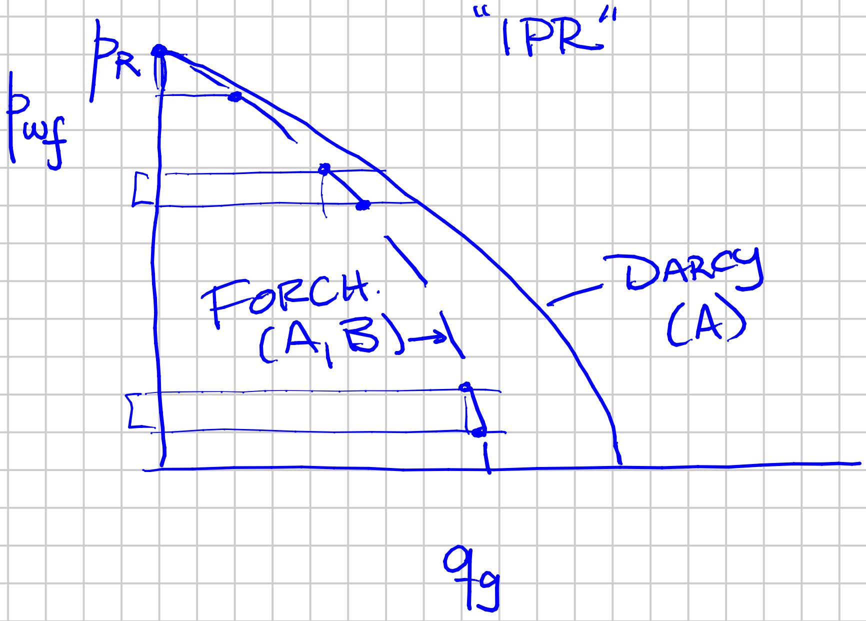
1850

Forchheimer
190x

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

$$\underset{(kh,\, D)}{\uparrow} \qquad \underset{(kh,\, s,\, \ln \frac{r_e}{r_w})}{\uparrow}$$

$D \propto \beta$

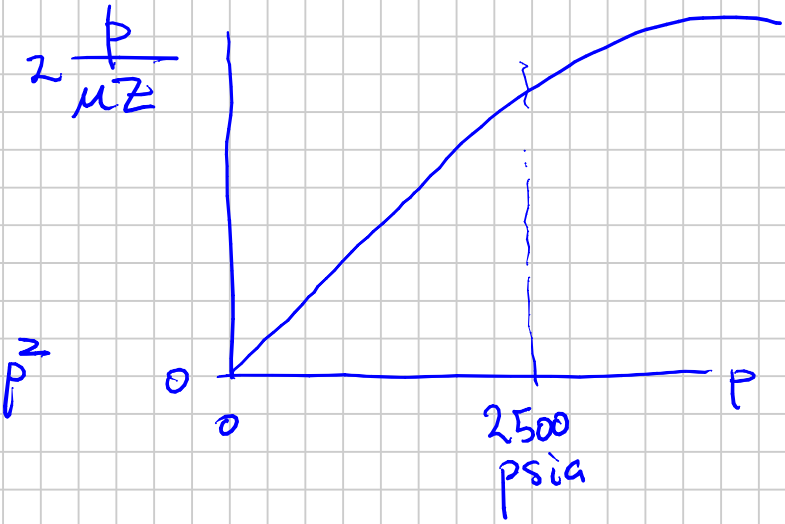


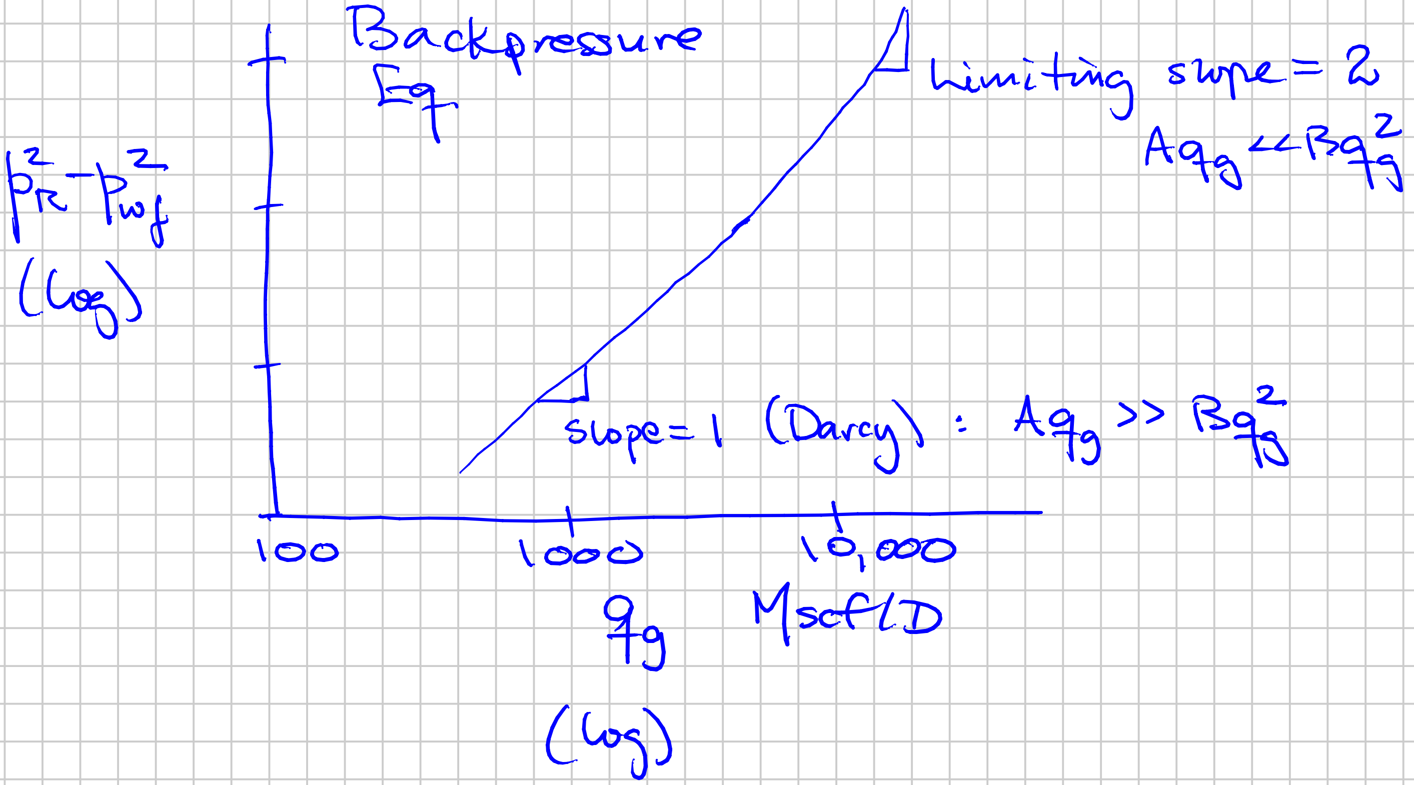
1950s → 1960s → 1970s

$p_{Ri} \lesssim 3000$ psia

$$p_p = a \cdot p^2$$

$$= 2 \int \frac{p}{\mu Z} dp \simeq a \cdot p^2$$





③ Tubing Flow:

$$q_g = C \cdot (\underbrace{p_w^2 - p_t^2}_{\text{Friction only}})^{0.5}$$

$$C \propto d_t^{2.7}$$

$$f(L_t)$$

99% : $$\underbrace{p_w^2 - p_t^2} = \frac{1}{C^2} \cdot q_g^2$$ Minimize

vs

1% $$p_R^2 - p_{wf}^2$$

② Fetkovich-Gas-Deliverability-Paper.pdf

WELLHEAD DELIVERABILITY EQUATION

RESERVOIR RATE EQ. (Darcy or Forchheimer)

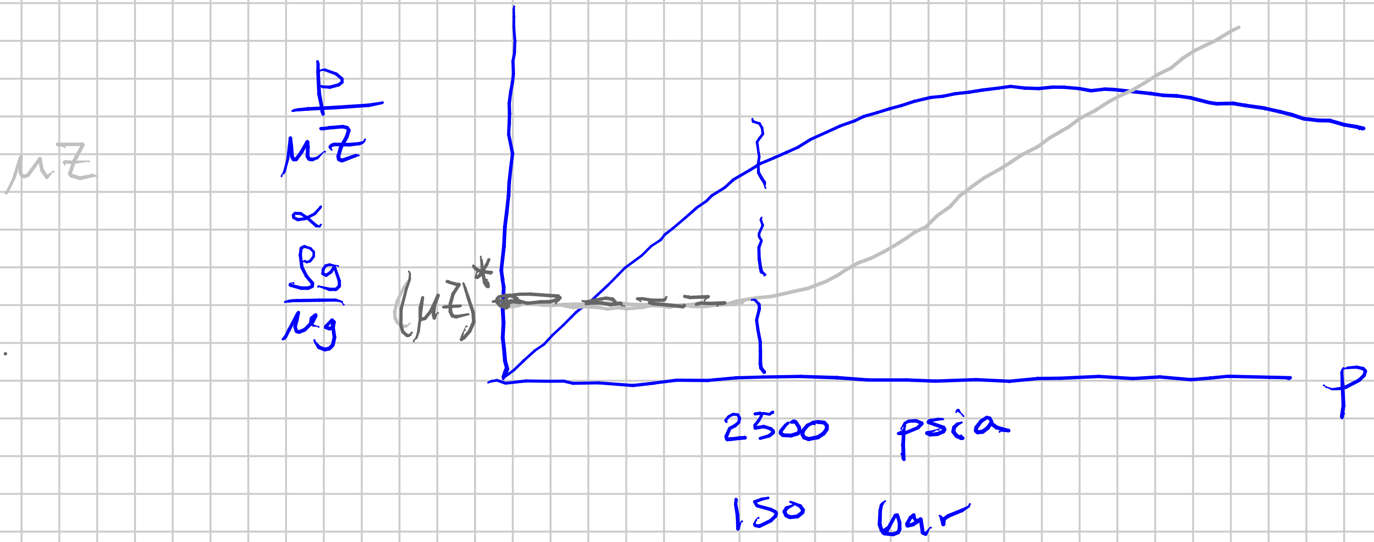
$$\frac{\Delta p}{\Delta x} = \frac{dp}{dx} = \frac{\overset{\text{Fluid}}{\mu}}{\underset{\text{Rock}}{K}} v + \underset{\text{Rock}}{\beta} \overset{\text{Fluid}}{\rho} v^2$$

[scf/D] [md][ft][psia] [cp][°R]

$$q_g = \frac{0.703\ kh\ [\bar{p}_{pR} - p_{pwf}]}{T_R\left[\underbrace{\ln\frac{r_e}{r_w} - \frac{3}{4}}_{8} + s + Dq_g^2\right]}$$

$$q_g = \frac{0.703\ kh\ [\bar{p}_R^2 - p_{wf}^2]}{T_R\,\underline{(\mu Z)^*}\,[\ln r_e/r_w - 3/4 + s + Dq_g]}$$

$$p_p \equiv \textcircled{2}\cdot \int_0^p \frac{p}{\mu Z}\,dp \simeq \underbrace{\left(\frac{1}{\mu Z}\right)}_{\sim\text{const}} \cdot p^2$$



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

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

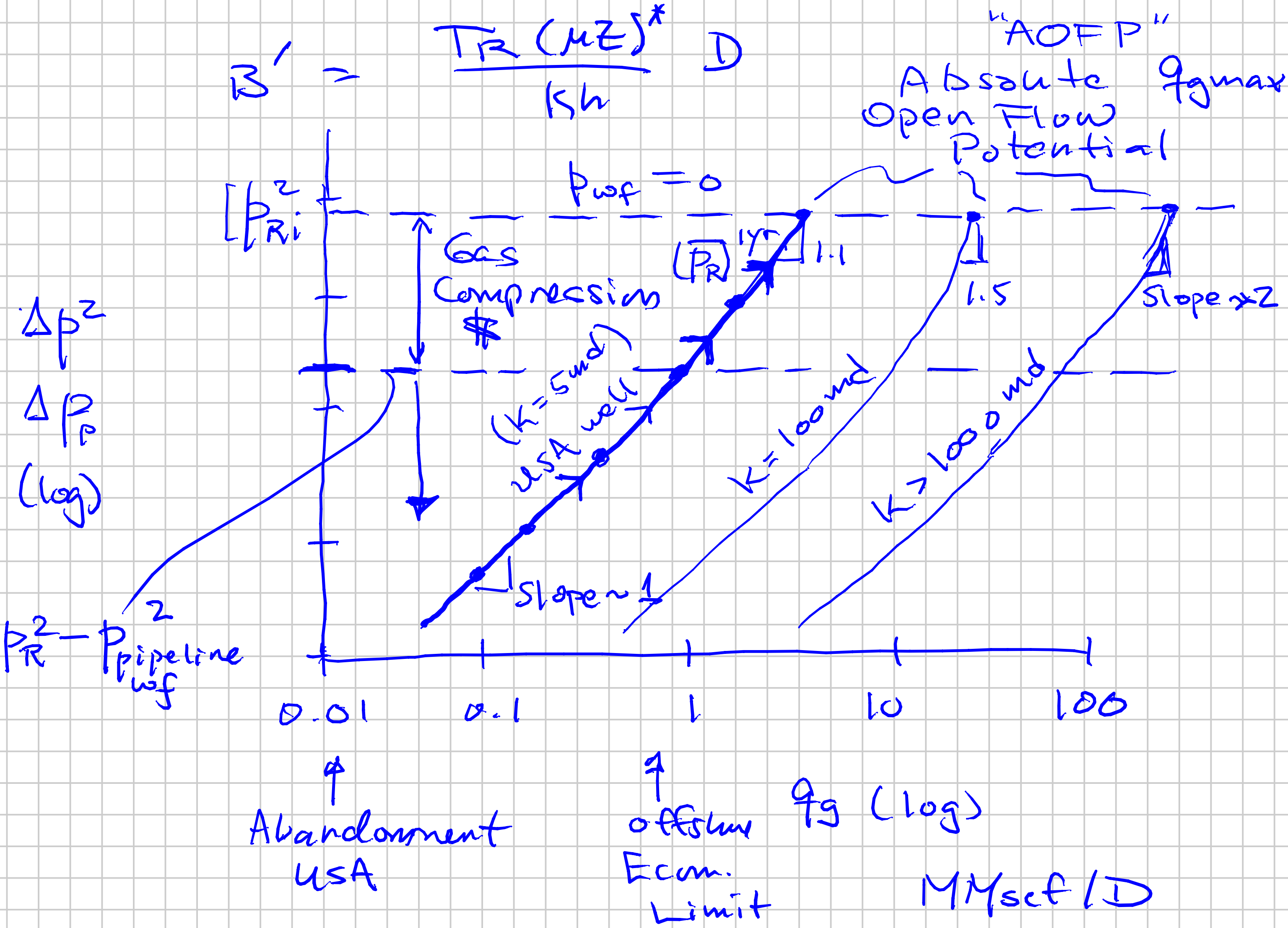
$$B = \frac{T_R D}{kh}$$

~

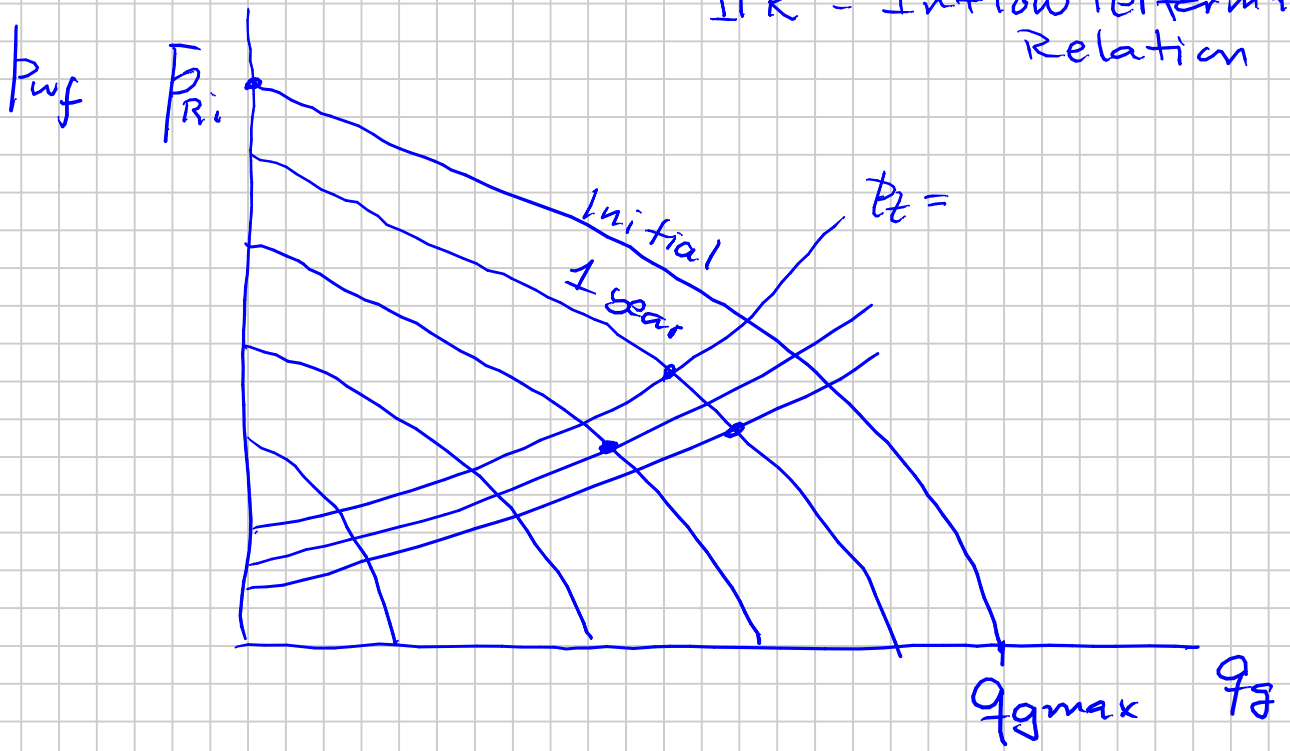
$$B' q_g^2 + A' q_g - \overbrace{\left(p_R^2 - p_{wf}^2\right)}^{\Delta p^2} = 0$$

$$A' = \frac{T_R (\mu Z)^* \left[\ln \overbrace{\boxed{\frac{r_e}{r_w}}}^{8.5-7.5} - \frac{3}{4} + s\right]}{kh}$$

$$B' = \frac{T_R (\mu Z)^*}{kh} D$$



IPR = Inflow Performance Relation



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

"R" $$\boxed{B'' q_g^2 + A'' q_g - (p_c^2 - p_w^2) = 0}$$

Tubing Eq. $$q_g = C_T \cdot (p_w^2 - p_t^2)^{0.5}$$

"T" $$\frac{1}{C_T^2} q_g^2 - (p_w^2 - p_t^2) = 0$$

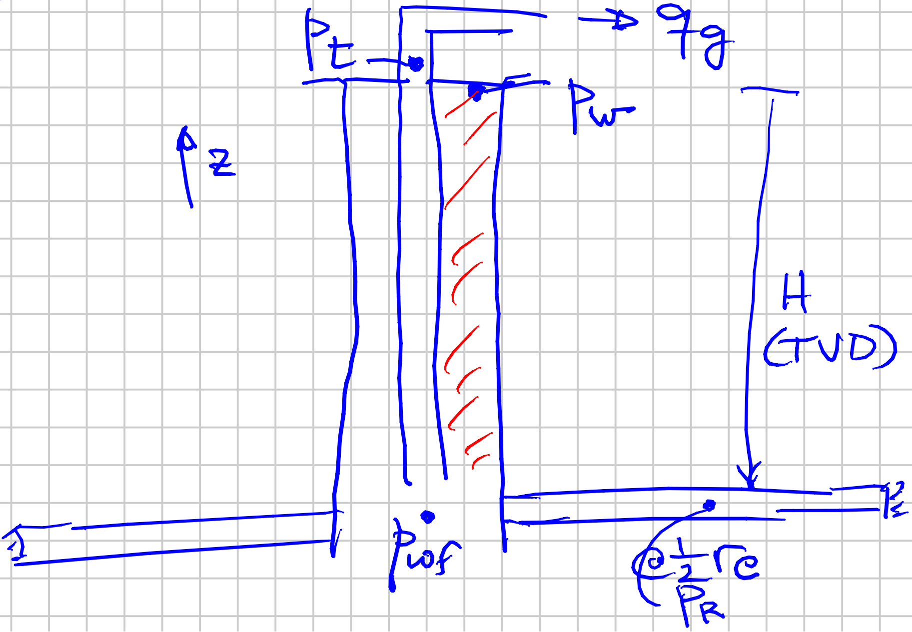
$$\boxed{\left(B'' + \frac{1}{C_T^2}\right) q_g^2 + A'' q_g - (p_c^2 - p_t^2) = 0}$$

Static Gas Column

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

$$= \frac{M}{R \bar{T} \bar{Z}} p g$$

$$\int_T^B \frac{1}{p} dp = \left(\frac{M}{R \bar{T} \bar{Z}}\right) g \int_0^H dz$$



$$\ln \frac{p_B}{p_T} = \underbrace{\left(\frac{M g H}{R \bar{T} \bar{Z}}\right)}_{\sim \text{const}}$$

$$p_B = p_T \cdot \underbrace{\exp(S/2)}_{\text{constant}}$$

1.x   1.1 – 1.4

$$\frac{p_{wf}}{p_w} = \exp(S/2) \Rightarrow p_{wf} = p_w \cdot \exp(S/2)$$

Define p_c as p_w when shut-in

reflects p_R

$$\frac{p_R}{p_c} = \exp(S/2) \Rightarrow p_R = p_c \cdot \exp(S/2)$$

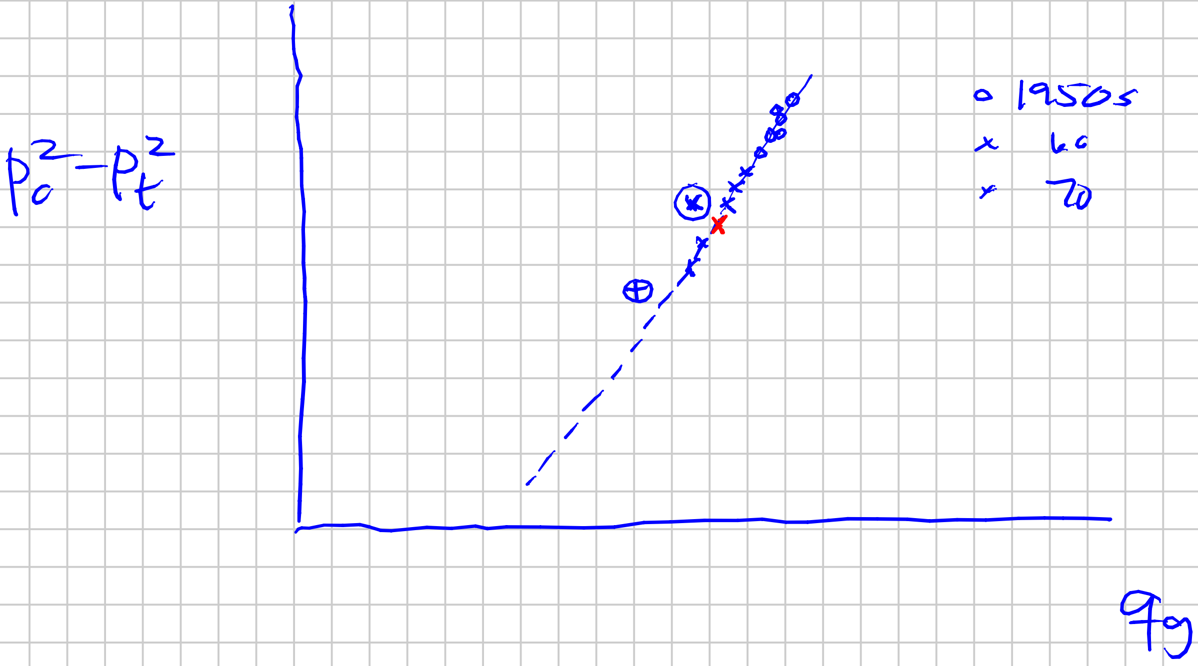
Controlled by Material Balance $\left(\frac{G_p}{G}\right)$, V_w, Z_J

p_c = Wellhead Shut-In pressure

p_t = Wellhead (Tubing) Flowing Pressure

– WE CONTROL

$$B'''_{R+T}\, q_g^2 + A''_R\, q_g - (p_c^2 - p_t^2) = 0$$

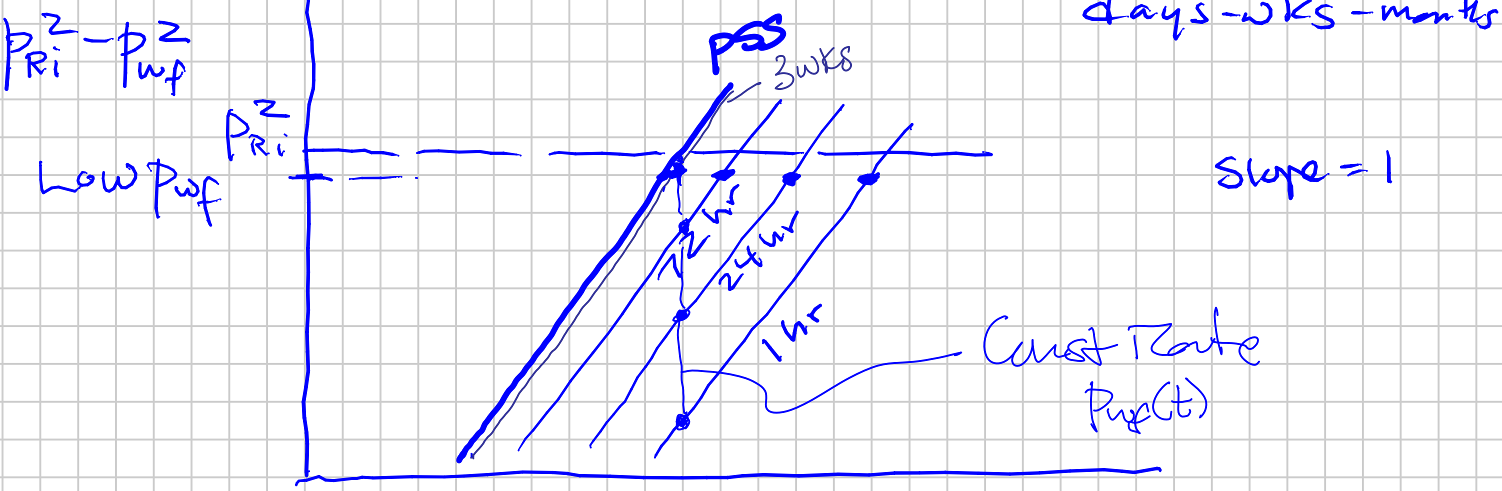


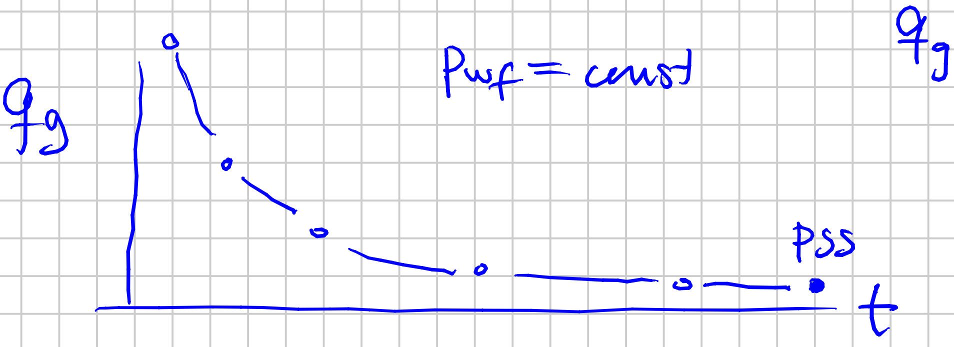
Tighter (lower-k) reservoirs

$$\left[\ln \frac{r_e}{r_w} - 3/4\right] \longrightarrow p_D(t_D)$$

$$\underbrace{\bar{P}_R}_{PSS} \longrightarrow P_{Ri}$$

Transient
(Infinite-Acting)
days-wks-months





$\boxed{p_D} \sim \ln \frac{r_e(t)}{r_w}$

$\longrightarrow 8-10$

$\sigma \xrightarrow{\qquad\qquad} 10$ in the IA period

PRODUCTION FORECASTING OF GAS RESERVOIRS

* WELL RATE EQUATIONS $q_{gw} = f(\overset{N}{\downarrow}\bar{p}_R , \overset{u}{\downarrow}p_t)$

- RESERVOIR
- TUBING

} WELLHEAD DELIVERABILITY

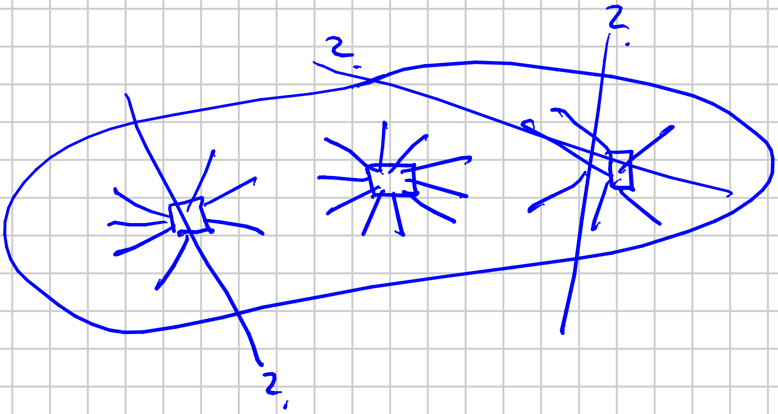
* RESERVOIR MATERIAL BALANCE

$$\bar{p}_R = f(\overset{u}{G_p} ; \overbrace{G , V_w}^{N})$$

$$G_p = \int_0^{\boxed{t}} q_{gF}(t)\,dt$$

WHY: $q_{gF}(t) = \sum_{w=1}^{N_w(t)} q_{gw}(t)$

COST: $N_w \Rightarrow N_{platforms}$



Methods of Production Forecasting

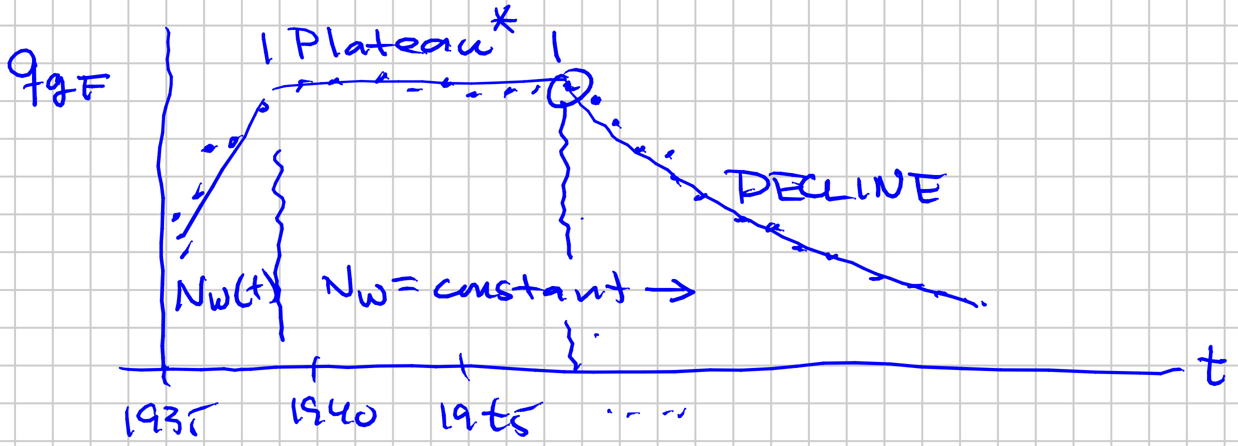
① Combine $q_{gw}(\bar{p}_R , p_t)$ & M.B. $\bar{p}_R(G_p)$

Iteratively, numerically - e.g. Excel sheet

② Use simplified assumptions about rate equations & M.B. to solve for $q_{gw}(t)$ ANALYTICALLY

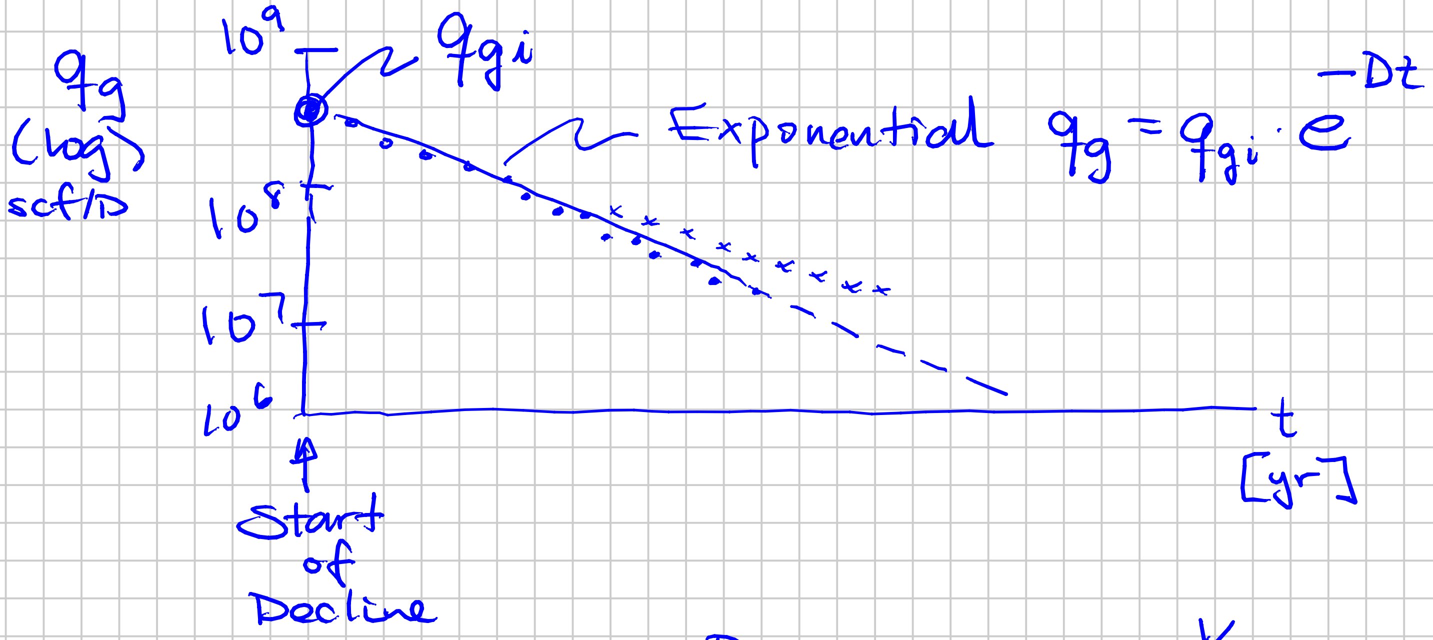
DECLINE CURVE ANALYSIS (DCA)

– Graphical (1940s → 1950s ?)



* Existing N_w have "excess capacity"

$P_t > P_{pipeline}$



$D \sim 0.05 - 0.15$ 1/yr

$D = 0.1$ 1/yr

Every year q_g decreases by 10%

J. J. ARPS (1945)

$$q_g = \frac{q_{gi}}{[1 + bDt]^{1/b}} \qquad \left\{ \begin{matrix} q_{gi} \\ b \\ D \end{matrix} \right\} \text{Empirical parameters}$$

$b = 0 \Rightarrow$ Exponential $q_g = q_{gi}\, e^{-Dt}$

$0 \leq b < 1$ $b \lesssim 0.5$

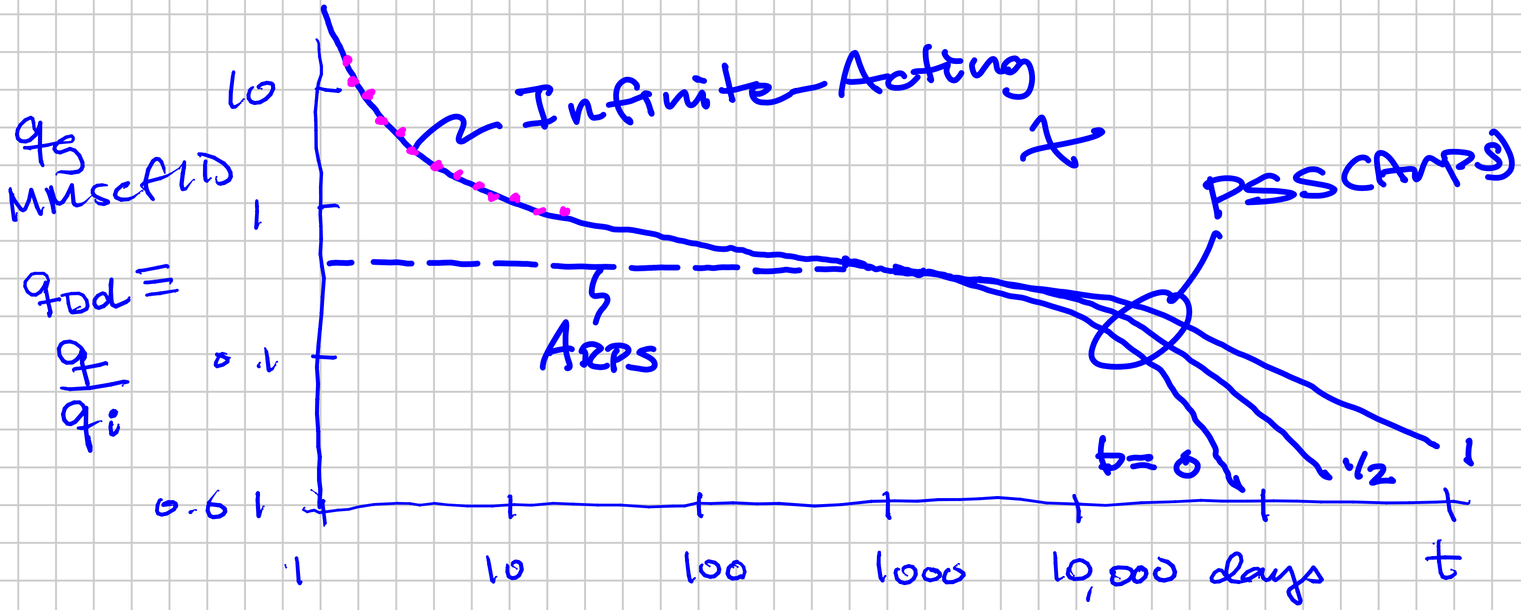
($b = 1$: Harmonic)

1975 : Fetkovich

PSS Boundary-Dominated Flow (A) Put science into q_i D b in the Arp's equation

Infinite-Acting (B) Long-term transient (low-k) rate-time performance

(c) Harmoniously & consistently bridged (A) Arp's into "Type Curve Charts"

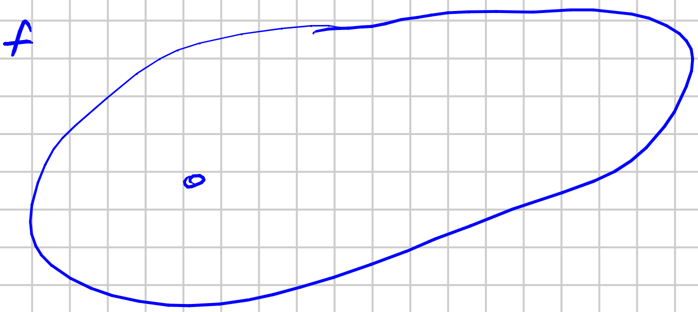


③ Gridded, Full-Field Reservoir Simulation

$t_{Dd} = \frac{t}{t_{pss}}$

GEOLOGISTS:

$G = 6 \cdot 10^{12}$ scf



GAS FIELD

$T_R = 130°F$

$P_{Ri} = 2200$ psia

$D = 5000$ ft

$\exp(S/2) = 1.15$

$\frac{P_R}{P_c} = \frac{P_{wf}}{P_w} \simeq 1.15$

$d_t = 4.5$ inches (I.D.)

↓ "7 in"

6·inch (ID)

Discovery Well:

$q_{gw} = 60$ MMscf/D

$p_t = 1600$ psia

$P_{wf} = 2000$ psia

Δp_R : 2200 → 2000

"Darcy" little "Dq_g" "β"

S_{damage} : 50 of the 200 psi (potentially removeable)

$r_e = \left(\frac{A_{Field}}{\pi N_w}\right)^{1/2}$

$$q_g = \frac{kh\,(P_R^2 - P_{wf}^2)}{T_R\left[\ln\frac{r_e}{r_w} - \frac{3}{4} + s + Dq_g\right]}$$

R: $\underset{\sim 0}{\underset{\uparrow}{\cancel{B_R q_g^2}}} + A_R q_g - (P_c^2 - P_w^2) = 0$

T: $\frac{1}{C_T^2} q_g^2 \qquad - (P_w^2 - P_t^2) = 0$

Find: A_R, C_T : $q_g = 60 \cdot 10^6$ scf/D

$P_{ci} = P_{Ri} / \underline{\exp(S/2)} = 2200$ psia$/1.15 =$

$P_w = P_{wf} / 1.15 = 2000/1.15 =$

Well with Damage

$$(A_R)_s = \frac{(2200^2 - 2000^2)/(1.15^2)}{60 \cdot 10^6}$$

$$= 1.06 \cdot 10^{-2} \sim 0.011$$

Well with No Damage

$$(A_R)_{s=0} = \frac{(2200^2 - 2050^2)/(1.15)^2}{60 \cdot 10^6}$$

$$= 0.008 \qquad \text{better}$$

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

$$(C_T)_{4.5''} = \frac{60 \cdot 10^6}{\left[\left(\frac{2000}{1.15}\right)^2 - 1600^2\right]^{1/2}} = 8.8 \cdot 10^4 \ \frac{\text{scf/D}}{\text{psi}}$$

$$(C_T)_{7''} = (C_T)_{4.5''} * \left(\frac{6''}{4.5''}\right)^{2.612}$$

$$= 18.7 \cdot 10^4 \quad \text{scf/D/psi}$$

For an undamaged well (s=0) with 7" tubing (6" I.D) how much q_g for P_t = 1600 psia

$$\frac{1}{C_T^2} q_g^2 + A_R q_g \overset{\cancel{+}}{-} (P_{ci}^2 - P_t^2) = 0$$

$$(18.7 \cdot 10^4)^{-2} q_g^2 + 0.008 q_g - \left[\left(\frac{2200}{1.15}\right)^2 - 1600^2\right] = 0$$

$$2.87 \cdot 10^{-11}\ q_g^2 + 0.008\ q_g - 1.10 \cdot 10^6 = 0$$

$$q_g = 10^8 = 100\ \text{MMscf/D}$$

$Z = 1$ (ugh)

$$p_R\left[1 + c_e\left(p_{Ri} - p_R\right)\right] = p_i\left(1 - \frac{G_p}{G}\right)$$

$$c_e = \frac{c_w S_w + c_f + M\left(c_w + c_f\right)}{1 - S_{wc}}$$

Solve in "short" time steps (e.g. 1 mo)

- During Δt, $\bar{p}_R$ doesn't change
- 〃 , q_{gw} is constant
- 〃 p_t 〃

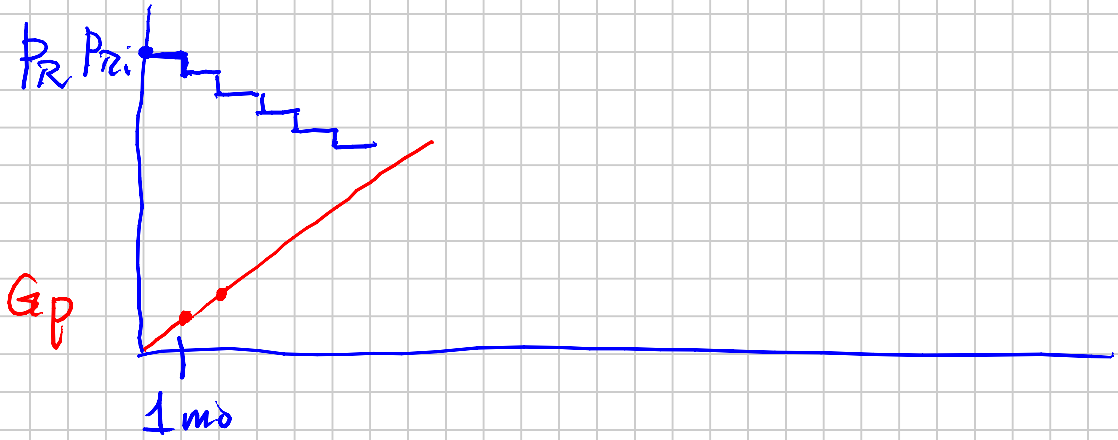
Δt (mo)	t (yr)	p_R	$\rightarrow \{\underline{p_c}$ ✓	Pipeline ↓ ✓ $\underline{p_{tmin}}\}$	$\boxed{q_{gmax,w}}$	DCQ × Δt = $\boxed{\Delta G_p}$	G_p
$\frac{1}{2}$		0					MB ↺

q_{gField} Demand? DAILY CONTRACT QUOTA (DCQ)

$t_{plateau}$ (DCQ Contract)

$$\boxed{N_w(t) = \frac{DCQ}{q_{gmax,w}(t)}}$$

Drilling Program



$$q_g = \frac{-A + \left[A^2 + 4B\Delta p^2\right]^{1/2}}{2B}$$

PRODUCTION FORECASTING OF GAS RESERVOIRS

Note Title 2012-11-13

* WELL RATE EQUATIONS $q_{gw} = f(\overset{N}{\bar{p}_R}, \overset{u}{p_t})$

$\left.\begin{array}{l}\text{- RESERVOIR} \\ \text{- TUBING}\end{array}\right\}$ WELLHEAD DELIVERABILITY

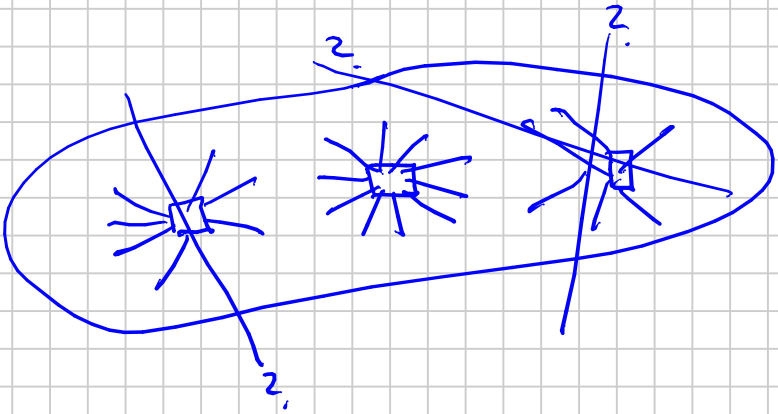
* RESERVOIR MATERIAL BALANCE

$$\bar{p}_R = f(\overset{u}{G_p}; \overbrace{G, V_w}^{N})$$

$$G_p = \int_0^{\boxed{t}} q_{gF}(t)\,dt$$

WHY: $q_{gF}(t) = \sum_{w=1}^{N_w(t)} q_{gw}(t)$

COST: $N_w \Rightarrow N_{platforms}$



Methods of Production Forecasting

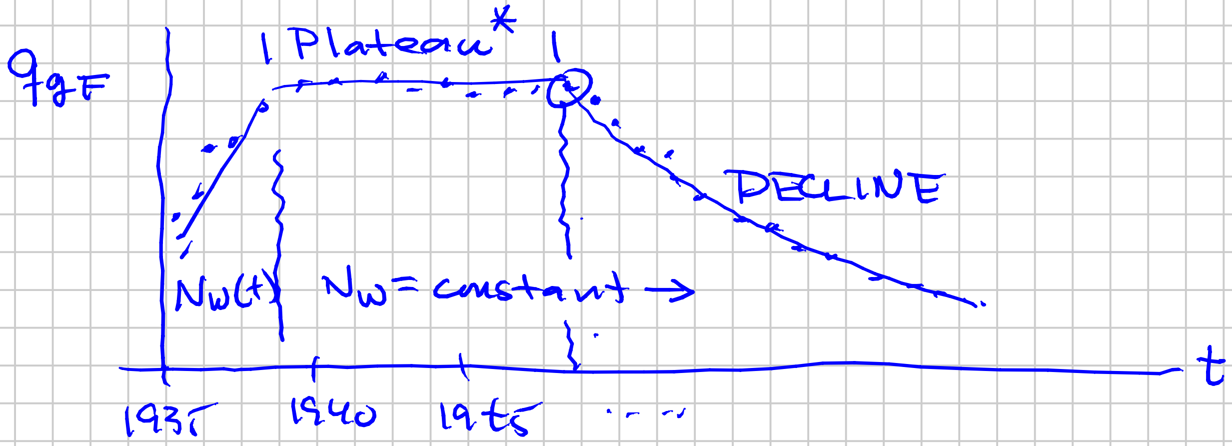
① Combine $q_{gw}(\bar{p}_R, p_t)$ & M.B. $p_R(G_p)$

Iteratively, numerically - e.g. Excel sheet

② Use simplified assumptions about rate equations & M.B. to solve for $q_{gw}(t)$ ANALYTICALLY

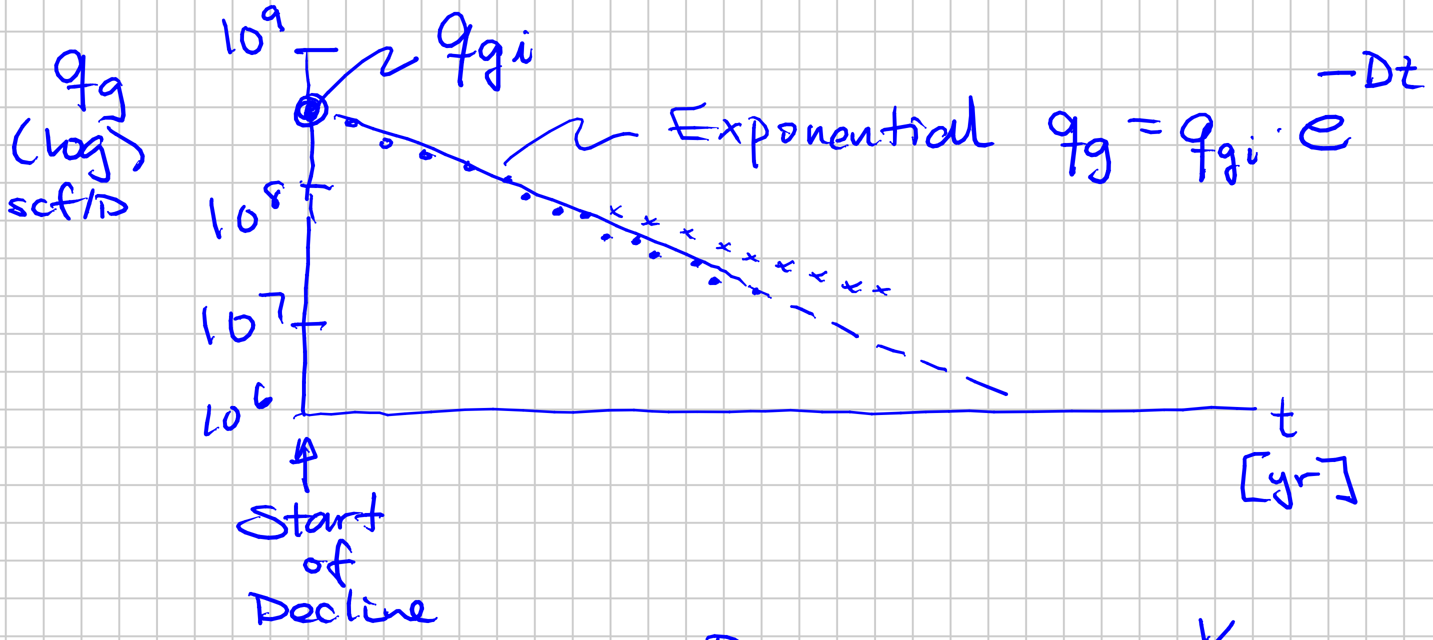
DECLINE CURVE ANALYSIS (DCA)

– Graphical (1940s → 1950s ?)



* Existing N_w have "excess capacity"

$p_t > p_{pipeline}$



$D \sim 0.05 - 0.15 \; 1/yr$

$D = 0.1 \; 1/yr$

Every year q_g decreases by 10%

J. J. ARPS (1945)

$$q_g = \frac{q_{gi}}{\left[1 + bDt\right]^{1/b}}$$

$\left\{ \begin{matrix} q_{gi} \\ b \\ D \end{matrix} \right\}$ Empirical parameters

$b = 0 \Rightarrow$ Exponential $q_g = q_{gi} e^{-Dt}$

$0 \leq b < 1$ $b \lesssim 0.5$

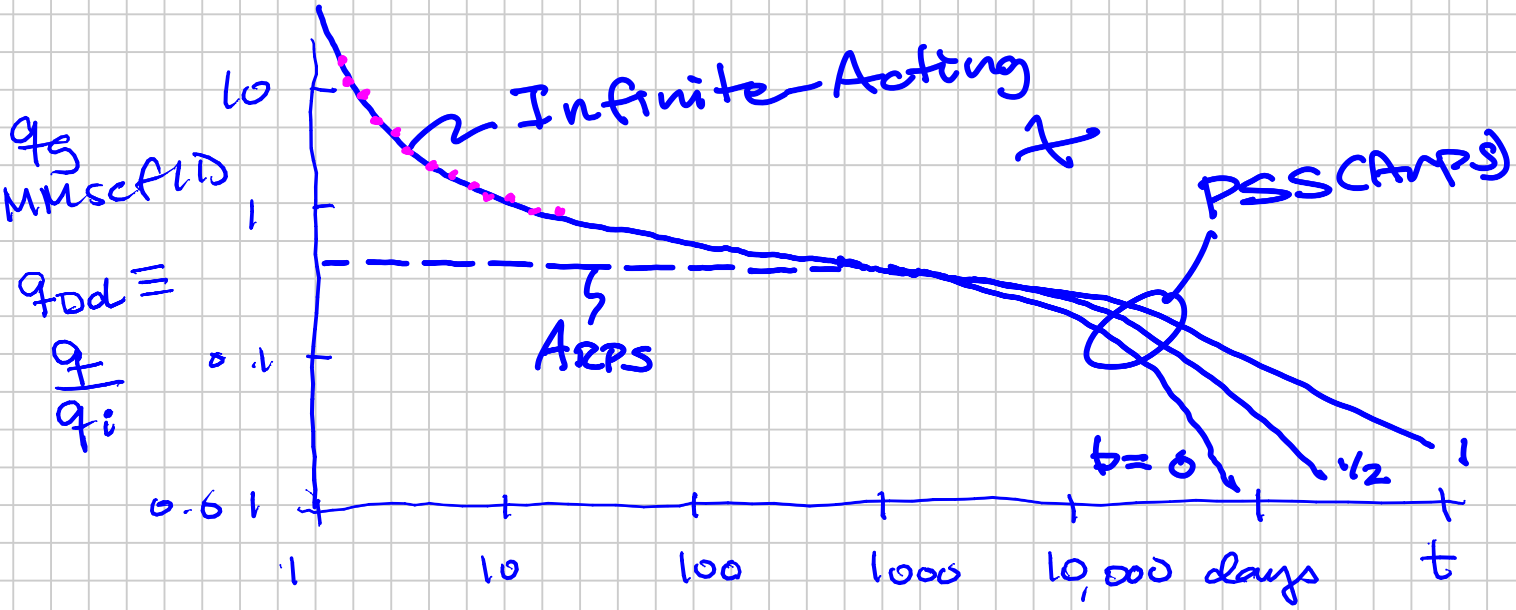
($b = 1$: Harmonic)

1975 : Fetkovich

PSS Boundary-Dominated Flow (A) Put science into q_i D b in the Arp's equation

Infinite-Acting (B) Long-term transient (low-k) rate-time performance

(C) Harmoniously & consistently bridged (A) Arp's into "Type Curve Charts"

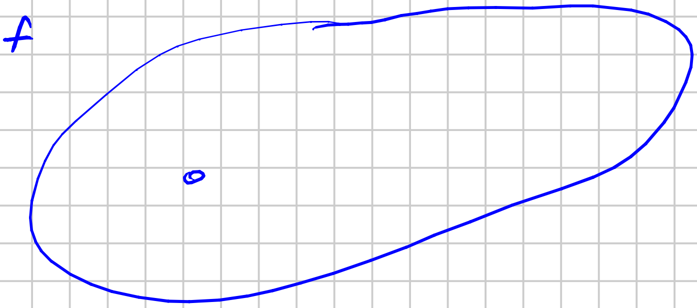


③ Gridded, Full-Field Reservoir Simulation

$t_{Dd} = \frac{t}{t_{pss}}$

GEOLOGISTS:

$G = 6 \cdot 10^{12}$ scf



GAS FIELD

$T_R = 130°F$

$p_{Ri} = 2200$ psia

$D = 5000$ ft

$\exp(S/2) = 1.15$

$\frac{p_R}{p_c} = \frac{p_{wf}}{p_w} \cong 1.15$

$d_t = 4.5$ inches (I.D.)

↓ "7 in"

6· inch (ID)

Discovery Well:

$q_{gw} = 60$ MMscf/D

$p_t = 1600$ psia

$p_{wf} = 2000$ psia

Δp_R : 2200 → 2000

"Darcy" little "Dq_g" "β"

S_{damage} : 50 of the 200 psi (potentially removeable)

$r_e = \left(\frac{A_{Field}}{\pi N_w}\right)^{1/2}$

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

R: $\cancel{B_R q_g^2} + A_R q_g - (p_c^2 - p_w^2) = 0$

$\uparrow$ ~0

$p_w = \left(p_c^2 - B_R q_{gwmax}^2 - A_R q_{gwmax}\right)^{1/2}$

T: $\frac{1}{C_T^2} q_g^2 - (p_w^2 - p_t^2) = 0$

Find: A_R, C_T : $q_g = 60 \cdot 10^6$ scf/D

$p_{ci} = p_{Ri} / \underline{\exp(S/2)} = 2200$ psia$/1.15 =$

$p_w = p_{wf} / 1.15 = 2000/1.15 =$

Well with Damage

$$(A_R)_s = \frac{(2200^2 - 2000^2)/(1.15^2)}{60\cdot 10^6}$$

$$= 1.06\cdot 10^{-2} \sim 0.011$$

Well with No Damage

$$(A_R)_{s=0} = \frac{(2200^2 - 2050^2)/(1.15)^2}{60\cdot 10^6}$$

$$= 0.008$$ better

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

$$(C_T)_{4.5''} = \frac{60\cdot 10^6}{\left[\left(\frac{2000}{1.15}\right)^2 - 1600^2\right]^{1/2}} = 8.8\cdot 10^4 \ \frac{scf/D}{psi}$$

$$(C_T)_{7''} = (C_T)_{4.5''} * \left(\frac{6''}{4.5''}\right)^{2.612}$$

$$= 18.7\cdot 10^4 \quad scf/D/psi$$

For an undamaged well (s=0) with 7" tubing (6" I.D) how much q_g for $P_t = 1600$ psia

$$\frac{1}{C_T^2} q_g^2 + A_R q_g \overset{\cancel{+}}{-} (P_{ci}^2 - P_t^2) = 0$$

$$(18.7\cdot 10^4)^{-2} q_g^2 + 0.008\, q_g - \left[\left(\frac{2200}{1.15}\right)^2 - 1600^2\right] = 0$$

$$2.87\cdot10^{-11}\, q_g^2 + 0.008\, q_g - 1.10\cdot10^6 = 0$$

$$q_g = 10^8 = 100 \text{ MMscf/D} \quad ✓$$

$Z = 1$ (ugh)

$$p_R\left[1 - c_e(p_{Ri} - p_R)\right] = p_i\left(1 - \frac{G_p}{G}\right)$$

$$c_e = \frac{c_w S_w + c_f + M(c_w + c_f)}{1 - S_{wc}}$$

Solve in "short" time steps (e.g. 1 mo)

- During Δt, p_R doesn't change
- — " — , q_{gw} is constant
- — " — p_t — " —

Pipeline ↓ ✓ $DCQ \times \Delta t =$

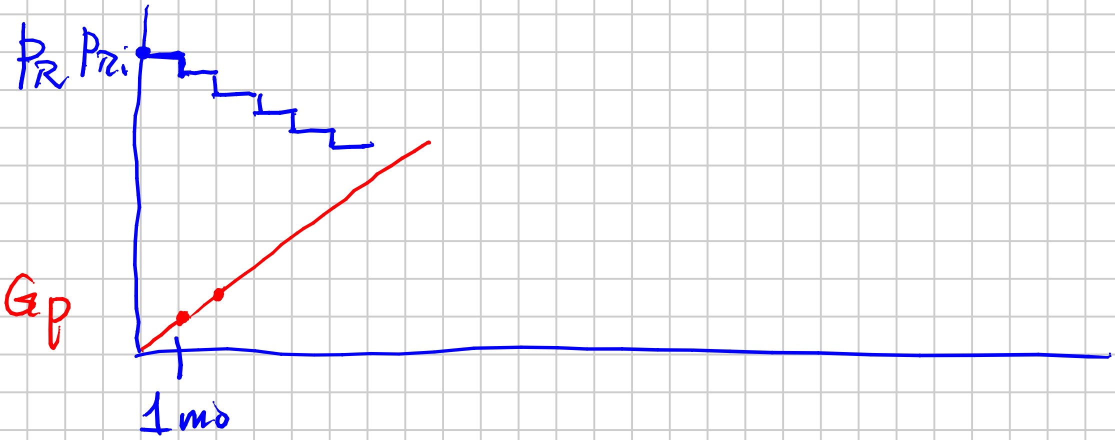
Δt (mo)	t (yr)	p_R	$\rightarrow \left\{ \overset{✓}{\underline{p_c}} \quad \underline{p_{tmin}} \right\}$	$\boxed{\underline{q_{gmax,w}}}$	$\boxed{\Delta G_p}$	G_p
$\frac{1}{2}$		0				MB

q_{gField} Demand? DAILY CONTRACT QUOTA (DCQ)

$t_{plateau}$ (DCQ contract)

$$\boxed{N_w(t) = \frac{DCQ}{q_{gmax,w}(t)}}$$

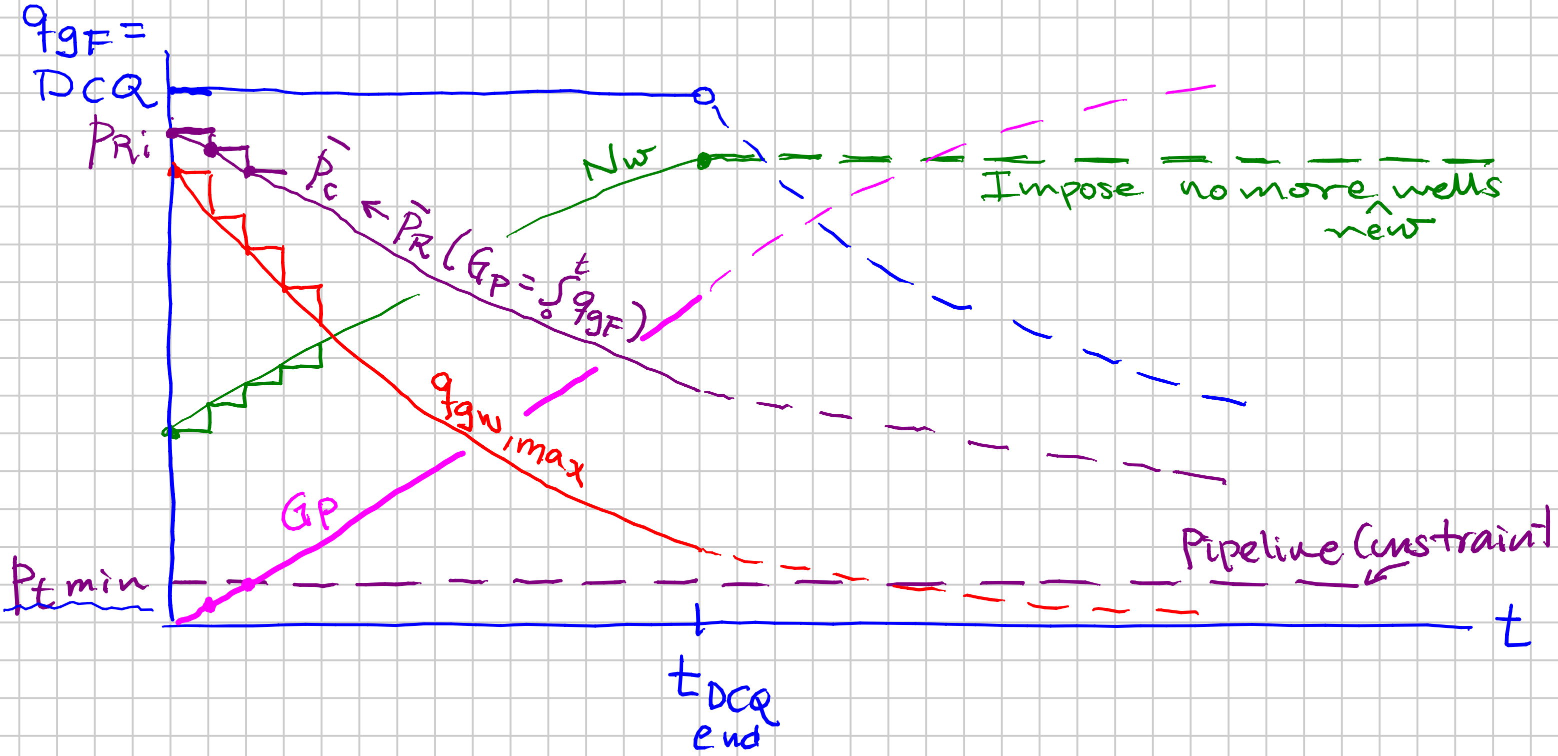
Drilling Program



$$q_g = \frac{-A + \left[A^2 + 4B\Delta p^2\right]^{1/2}}{2B}$$

Nov. 13 ↑

Nov. 16 continuation...



$$B_{WH}\, q_{gw}^2 + A_{WH}\, q_{gw} - \left(p_c^2 - p_t^2\right) = 0$$

→ solve for $q_{gw\,max}$ (OFP) using $P_t = P_{tmin}$

→ $N_w^{(t)} = q_{gF} / q_{gw,max}(t)$

$$\Delta G_p = q_{gwmax} \cdot N_w$$

$$G_p^{n+1} = G_p^{n} + \Delta G_p^{n+1}$$

$$p_R^{n+1} = M.B.\left(G_p,\ G,\ c_e,\ p_i\right)$$

$$\boxed{p_R\left[1 - c_e\left(p_{Ri} - p_R\right)\right] = p_i\left(1 - \frac{G_p}{G}\right)}$$

$\uparrow$

$(G_p/G)_{End\ Plat.}$

$$p_R - p_R c_e p_{Ri} + p_R c_e p_R =$$

$$(c_e)\, p_R^2 - (c_e p_{Ri})\, p_R + p_R =$$

$$\underbrace{c_e}_{\text{"a"}}\, p_R^2 + \underbrace{\left(1 - c_e p_{Ri}\right)}_{\text{"b"}} p_R \underbrace{- p_i\left(1 - \frac{G_p}{G}\right)}_{\text{"c"}} = 0$$

$$\Rightarrow \quad p_R = \frac{-\left(1 - c_e p_{Ri}\right) + \left[\left(1 - c_e p_{Ri}\right)^2 + 4 c_e p_i\left(1 - \frac{G_p}{G}\right)\right]^{1/2}}{2\,(c_e)}$$

At 10 years, $\underline{\left|\, 40\%\ G_p/G = RF_g \,\right|}$

M.B.

$\downarrow$

$$(p_R)^* \rightarrow \underline{\underline{p_c^*}} > \underline{p_{t,min}} \quad \Big| \ \text{Constraint}$$

$\uparrow$ $\downarrow$

PRODUCTION FORECASTING

* Complete the Class Problem

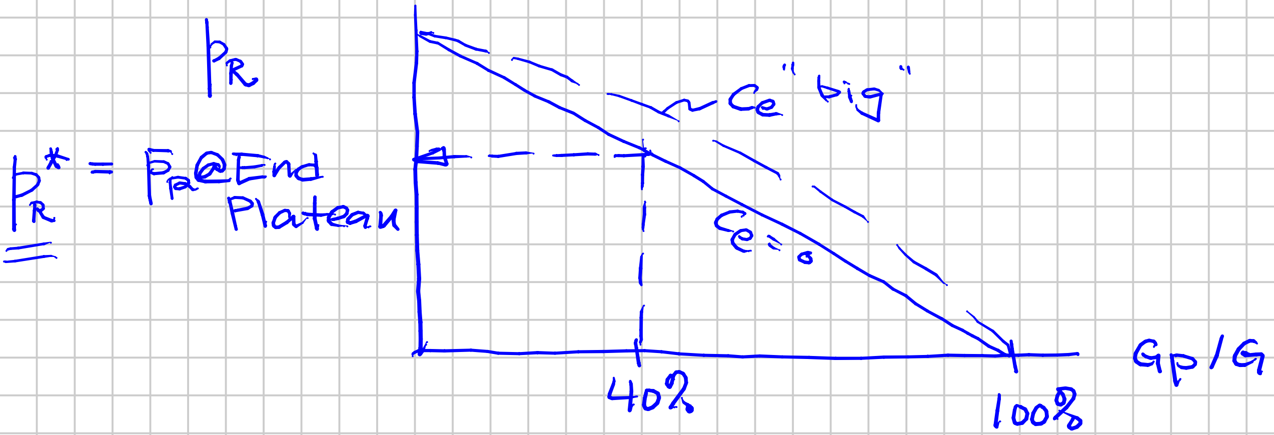
* Study some Cause-and-Effects

- N_w (Control Variables)

* DCA similarity to Excel solution

- Arp's 3 constants q_i D b

$\boxed{p_{t\,min}:}$ Upper Limit



$$\underline{\underline{p_c^*}} = \frac{p_R^*}{e^{S/2}} = \quad 1.15$$

$q_{gw} = 0$ as $p_t \to p_c$

MAJOR CONTROL VARIABLES

- * $P_{t\,min}$: {Ppipeline, Compression}
- * Tubing Diameter d_T : B_T
- * Well "skin" damage / stimulation

$$\rightarrow q_g = \overset{4.5''}{C_T}(\underset{\uparrow}{P_w^2} - \underset{\uparrow}{P_t^2})^{0.5}$$

$$B_T = \frac{1}{C_T^2} \qquad C_T \propto d_T^{2.6}$$

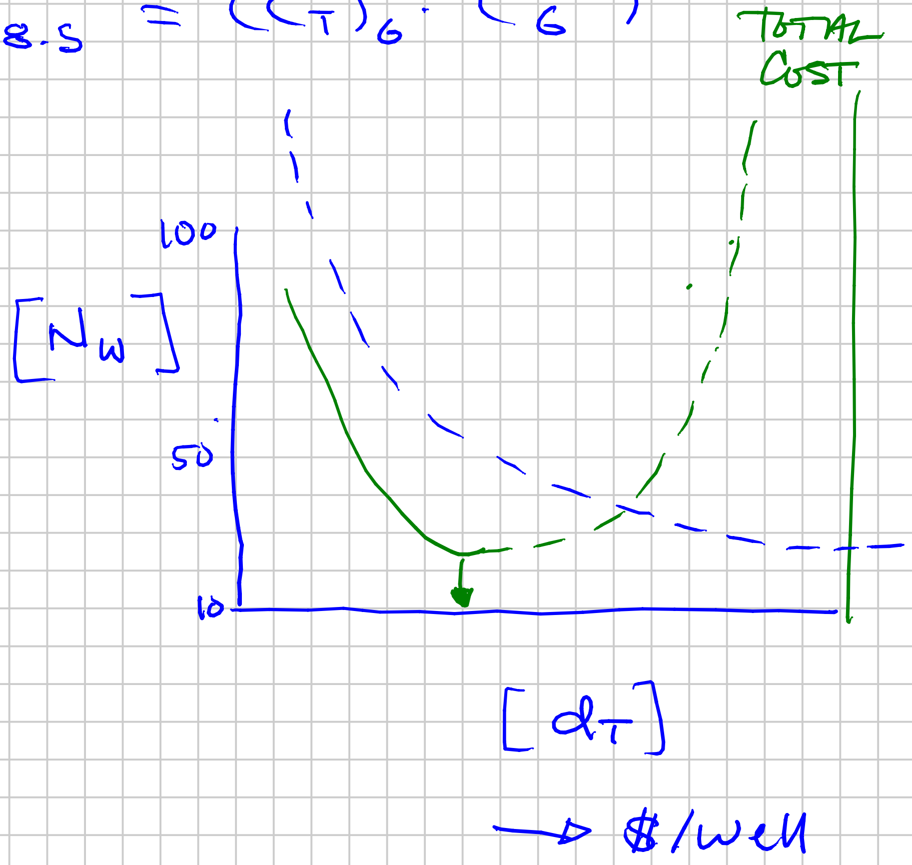
$$(C_T)_{6''} = (C_T)_{4.5} \cdot \left(\frac{6}{4.5}\right)^{2.6}$$

9-5/8"

$d_T = 8.5''$ I.D.

$$(C_T)_{8.5} = (C_T)_6 \cdot \left(\frac{8.5}{6}\right)^{2.6}$$

	d_T	N_w
(OK)	2	115
	4.5	23
	6	18
	8.5	16
	20	16



$$\Delta p_R = (\Delta p_R) \qquad\qquad (\Delta p_R)$$

$$\overbrace{kh}^{\text{Nature}},\ \textcircled{s} \qquad\qquad D:$$

$$\boxed{UL} \xrightarrow{?} D$$

"A" "B"

(-3 → -5)

$$\underbrace{A'} = A \cdot \frac{\overset{10}{\ln \frac{r_e}{r_w}} + S_{New}}{\underbrace{\ln \frac{r_e}{r_w}}_{10} + \underset{=0}{S_{Current}}}$$

\$ 1.2 m / well

$$\boxed{0.008 \cdot \frac{10 + (-5)}{10 + 0} = \frac{5}{10}}$$

0.004

$$A = \frac{\ln \frac{r_e}{r_w} - \frac{3}{4} + s}{kh}$$

s	N_w
0	17
-3	14
-4	12
-5	11

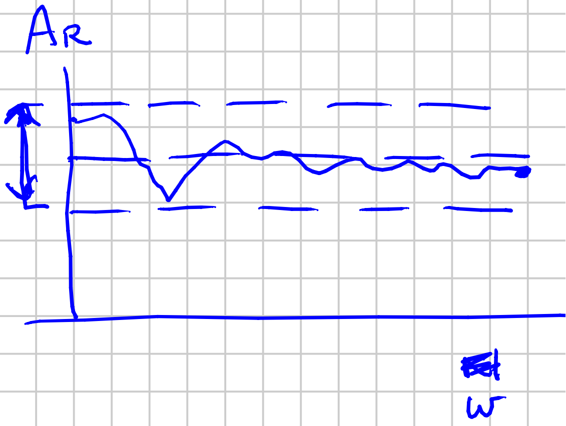
w	A_R
1	0.008
2	0.009
3	0.003
4	0.011
5	
⋮	
$\boxed{17}$	

$\Rightarrow \bar{A}_R$

"δ"

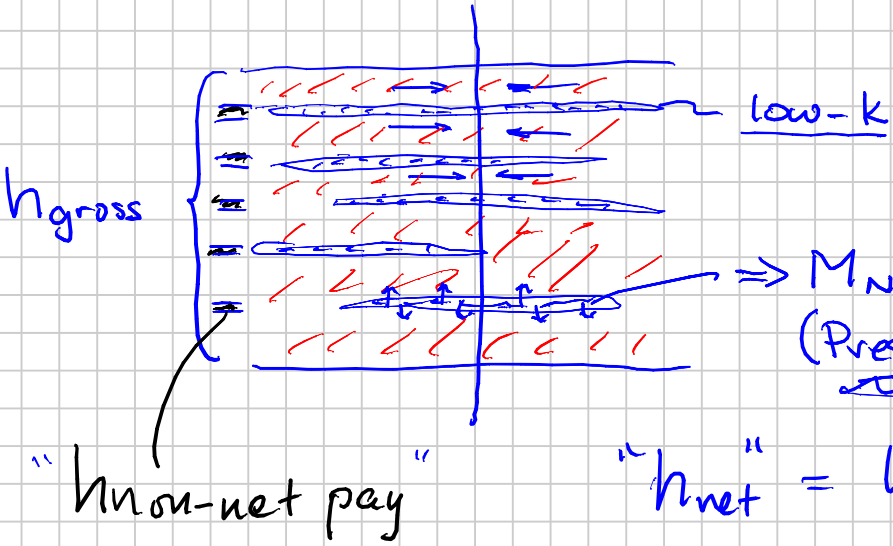
"d_T"

Compressi



$$q_{gw} = \frac{1}{A_R} \cdot \Delta p$$

$$q_{gF} = \sum q_{gw} = \Delta p \sum \left(\frac{1}{A_{Rw}}\right)$$



$\Rightarrow M_{NNP}$

(Pressure Support; Little gas flow)

Mat. Bal

$$M \sim \frac{V_w}{V_{pg}}$$

$$\text{"}h_{net}\text{"} = h_{gross} - h_{non\text{-}net\ pay}$$

$$\underset{\sim}{A} = \frac{1}{(\bar{k}h)_{net}}$$

Arp's DCA

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

$b = 0$

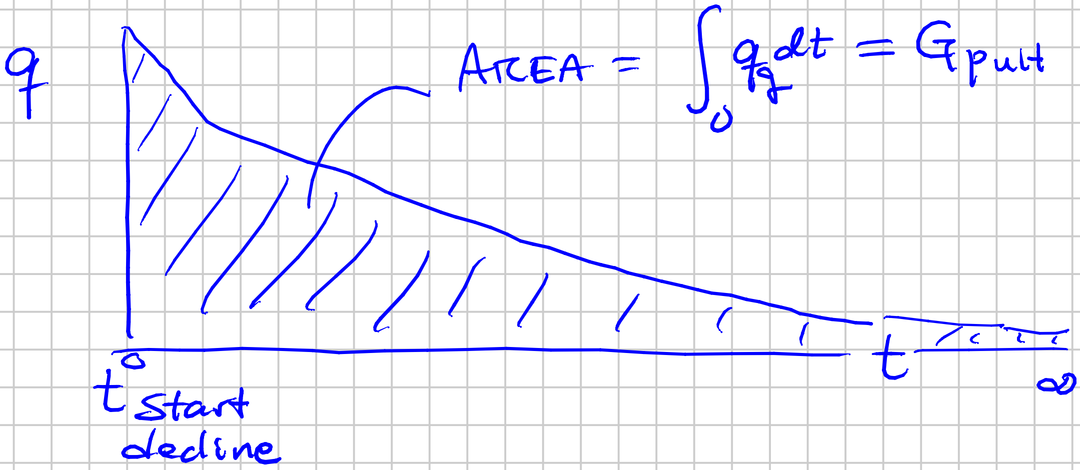
$$q = q_i \exp(-Dt)$$

q_i = rate when a well starts on decline ($p_t \to$ const, $p_{wf} \to$ const)

$$B q_g^2 + A q_g - (\overset{\substack{\text{RF}\\ \text{end Plateau}}\ \checkmark}{\bar{p}_{PR}} - \overset{\checkmark\ p_{\underline{t\,min}}}{p_{Pwf}}) = 0$$

Solve this for $\boxed{q_{gi}}$

D:



$$\text{AREA} = \int_0^\infty q_g\,dt = G_{pult}$$

Q_{Pult} = ultimate cum. production start of decline to ∞

$$\boxed{D \equiv \left(\frac{\overset{\searrow}{q_i}}{\underset{\nearrow}{Q_{pult}}}\right)\left(\frac{1}{1-b}\right)}$$

Assuming

$D \propto N_w$

How does D change as the number of wells change

$$A_w = \frac{A_F}{N_w} \Rightarrow r_{ew} = \sqrt{\frac{A_w}{\pi}}\Big\} \; \ln\frac{r_e}{r_w}$$

$\downarrow$

q_i effect is little

$$\underbrace{(Q_{pult})_w \propto A_w}$$

20 wells $D \sim 10\%$ 0.1

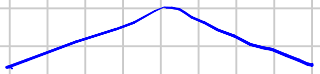
10 wells $D \sim 5\%$

2 wells $D \sim 1\%$ slow recovery

b: "Efficiency of Depletion"

e.g. Gas Reservoirs $0 \leq b \leq 0.5$

higher $\rightarrow \left(\frac{P_{wf}}{P_{Ri}}\right)$



	0.1		0.9
b	0.5	?	0

$$\underbrace{A \text{ vs } B \text{ "importance"}}$$

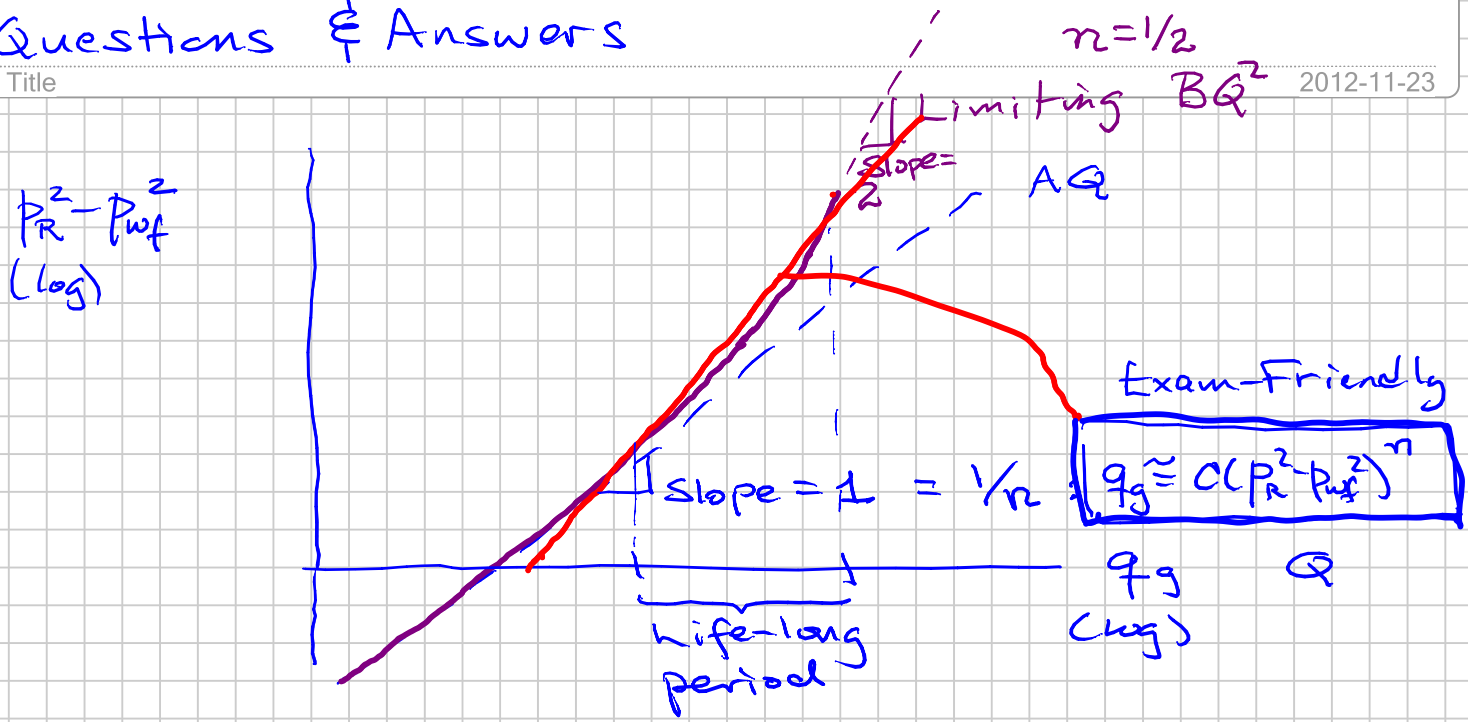
$$q_g \cong C_{wH}(P_c^2 - P_t^2)^n$$

$$\begin{array}{l} \underline{b} \\ \left[\begin{array}{l} 0.5 \\ \updownarrow \\ 0 \end{array}\right. \end{array} \quad \begin{array}{c} n \sim 1 \\ \downarrow \\ n \sim 0.5 \end{array}$$

Reser $\boxed{\frac{kh}{s}}$

$\boxed{\text{Tubing "Dq"}}$

Questions & Answers



Fluid, Rock

$$\frac{dp}{dx} = \underbrace{\frac{\mu}{k} v}_{\text{Darcy}} + \underbrace{\beta \rho v^2}_{\text{Fluid}} \quad \text{"}B_R\text{"}$$

Rock, Fluid

"A_R"

⇒ Dq_g in the rate equation

$D \propto \beta \underset{\sim}{\propto} \frac{1}{k} \leftarrow$

$$\underbrace{B_R\, q_g^2}_{\text{may be negligible for "lower" rates}} + A_R q_g - (p_{pR} - p_{pwf}) = 0$$

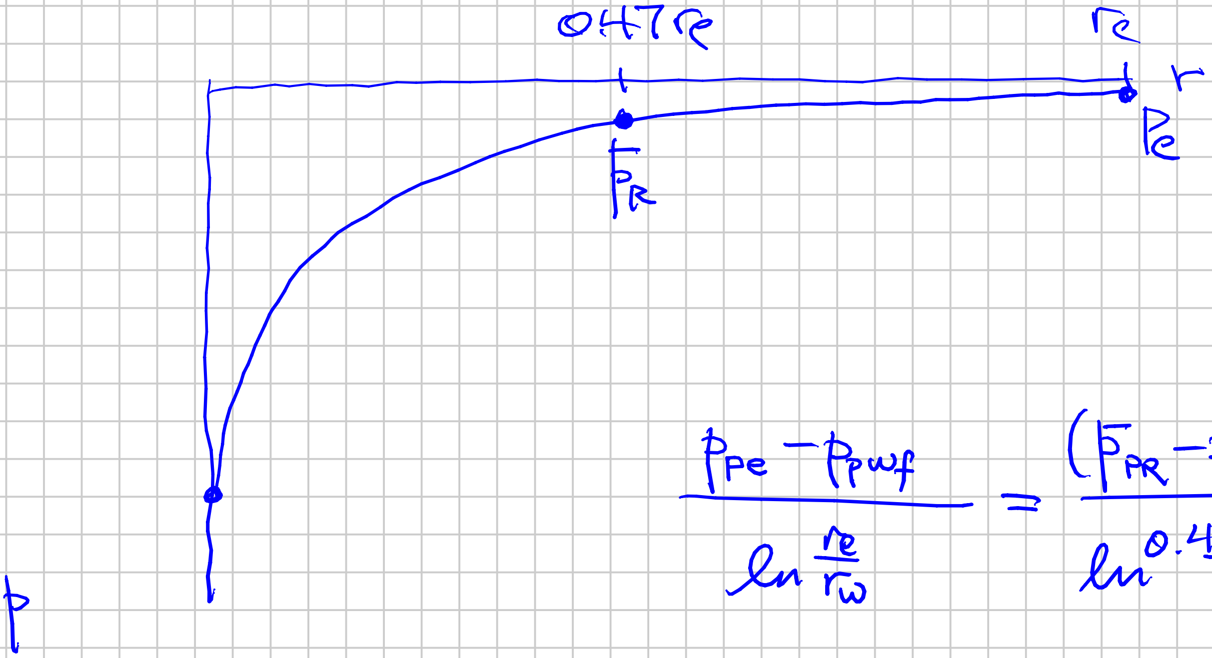
(~ lower-k reservoirs)

$$\int \frac{p}{\mu Z}\,dp$$

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

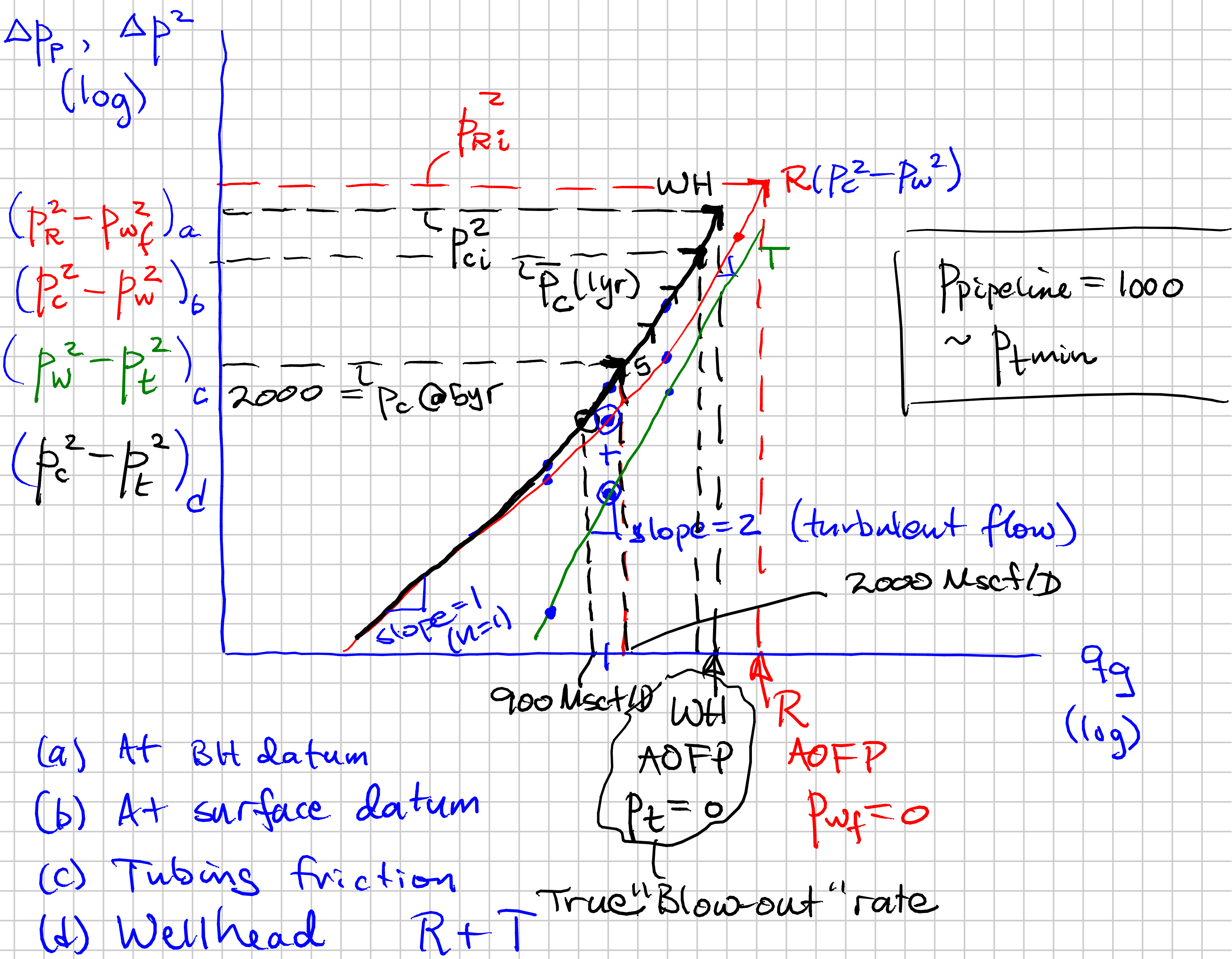
$$\underbrace{\int \frac{1}{\mu_g B_g}\,dp}_{} = \underbrace{\left(\frac{T_{sc}}{p_{sc}\,T_R}\right)}_{const} \cdot \underbrace{\int \frac{p}{\mu_g Z_g}\,dp}_{}$$

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



$$\frac{p_{pe} - p_{pwf}}{\ln \frac{r_e}{r_w}} = \frac{(\bar p_{pR} - p_{pwf})}{\ln \frac{0.47\,r_e}{r_w}}$$

$$\ln \frac{0.47\,r_e}{r_w} = \ln \frac{r_e}{r_w} - \frac{3}{4}$$



1000 900

$p_t = 100 \Rightarrow q_g = 1600$ Mscf/D $\Big\}$ $\Delta q_g =$ 700 Mscf/D

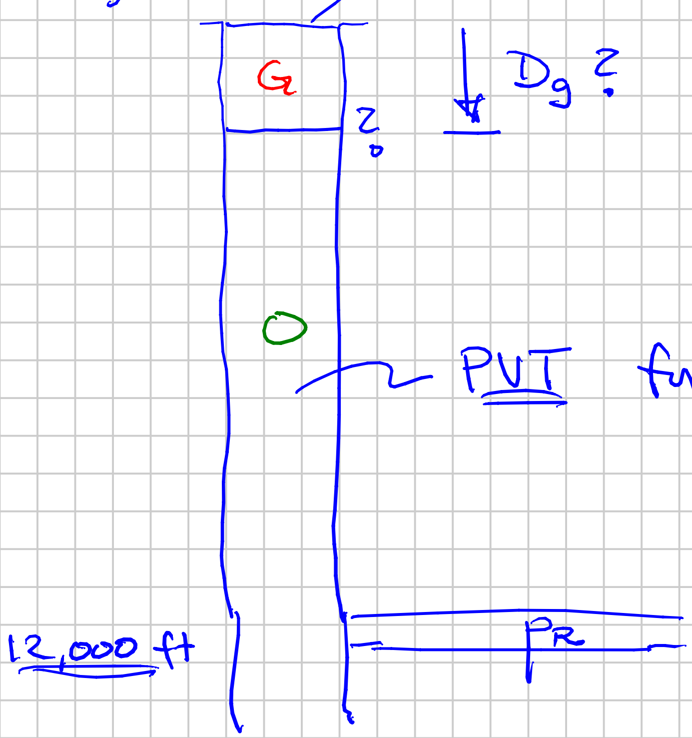
0 2000

$$700 \frac{\text{Mscf}}{\cancel{D}} \times 30 \frac{\cancel{D}}{\text{mo}} \times 3 \frac{\$}{\text{Mscf}} = \$63{,}000/\text{mo}$$

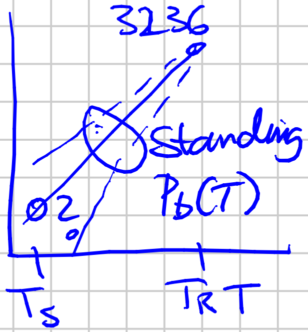
$3,000/mo

$60,000/mo

$T_s \leq T_R$ $p_s = 2128$ psig $< p_b(T_R)$



p_b



$\rho_g(p, T_R)$

PVT for reservoir fluid

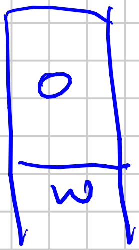
$p_b(T_R) = 3236$ psia

$\rho_o(p, T_R) = 40 \, lb/ft^3 \pm 2$

$\boxed{5784 \text{ psig}}$

Assume : Full of Oil

$p_R^{est} = p_s + \overset{\pm}{\bar{\rho}_o} g H$



3500–4200

5500–5900

$= 6200–6600 \pm$ psia

oil or oil + Gas

→ Gas on Top ✓

H_g by assuming $\bar{\rho}_o$

@p_s

$$\overset{\checkmark}{p_R} = \overset{\checkmark}{p_s} + \overset{\checkmark}{\bar{\rho}_g} H_g + \overset{\checkmark}{\bar{\rho}_o}(H - H_g)$$

solve for H_g

Q & A SESSION

Note Title 2012-12-11

$$[Sm^3]\ G = \underset{[\text{kg-mole}]}{n_{R\,\text{Initial}}} \times \underset{\frac{R\,T_{sc}}{p_{sc}}}{23.68}\ \frac{Sm^3}{\text{kg-mole}}$$

$$G_p = n_p \times 23.68 \qquad \frac{G_p}{G} = \left(\frac{n_p}{n}\right)$$

$$\frac{p_R}{Z_R} = \frac{p_{Ri}}{Z_{Ri}}\left(1 - \frac{G_p}{G}\right) \qquad c_e = 0$$

$$\boxed{\frac{p_R}{Z_R}\left[1 - c_e(p_{Ri} - p_R)\right] = \frac{p_{Ri}}{Z_{Ri}}\left(1 - \frac{G_p}{G}\right)}$$

why not low-p_{Ri} reservoirs ?

$c_e(p_{Ri} - 0) \sim$ small

$\sim$

CCE (T = const)

Thermal Expansion : CCE^+

$$\underset{\substack{\uparrow\\ 5000\text{psia}}}{V_o(p,}\underset{\substack{\uparrow\\ 220°F}}{T_R)} \,/\, V_o(5000, 76°F) = 1.0879$$

$$\rho_o = \frac{m}{V_o}$$

$$\left[\underline{V_o(p, T_R)} \,/\, \underline{V_o(p, 76°F)}\right] \simeq 1.088$$

$$\underline{\rho_o(p, 76°F)} \,/\, \rho_o(p, T_R) \simeq 1.\underbrace{088}$$

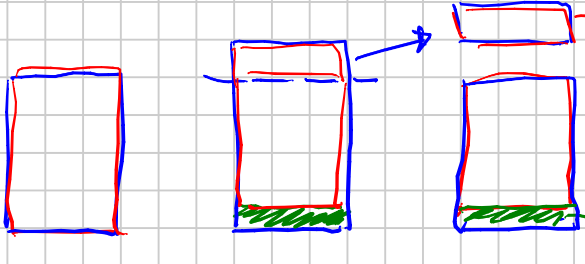
$$\frac{\rho_o(p, T)}{\left[\rho_o(p, T_R)\right]_{\substack{CCE\\ @\\ T_R;\ p>p_b}}} \simeq \left[1 + \left\{\underline{0.088}\ \overset{-220}{(\underset{\substack{\uparrow\\ T=76}}{T} - T_R)}\ \overset{/(76-220)}{/(T_{76} - T_R)}\right\}\right]$$

$$T = 0\,F \longrightarrow 220 \qquad > 1.088$$

CVD : Gas Condensate

Removed Gas ≃ Wellstream

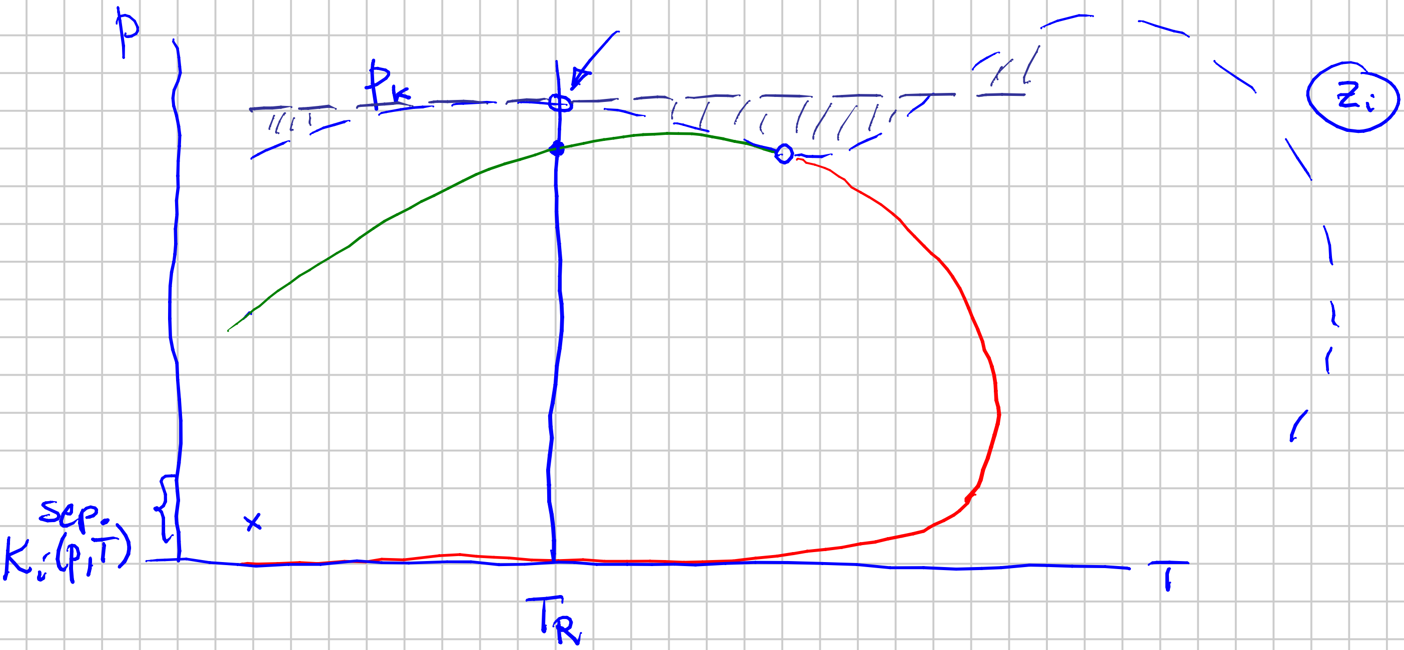
$\Delta n_p \; y_{CVD,i} \simeq z_{wi} \; (p_R \simeq p_{CVD})$



$\lambda_o \sim 0 \qquad \lambda_o = \frac{k_{ro}}{\mu_o}$

$p_{CVD1} = p_d$

$p_{CVD2} \cong p_R$



$\Delta n_g \cdot 379$

$$\Delta R_{sd} = \frac{\Delta V_{\bar{g}}}{V_{o\,residual}}$$

$$B_{od} = \frac{V_o}{V_{o\,residual}}$$

Problem 3.

not B_{ob}

Curtis B-

$$OOIP_o = (HCPV)_o / B_{oi}$$

$\cancel{R_s}$

$$B_{oi} = \frac{V_{oR}(p_{Ri}, T_R)}{V_{\bar{o}o}}$$

$$q_g = \frac{kh}{\left[\underbrace{\ln\frac{r_e}{r_w} - \frac{3}{4}}_{7-9} + \underset{\uparrow}{s} + Dq_g\right]}$$

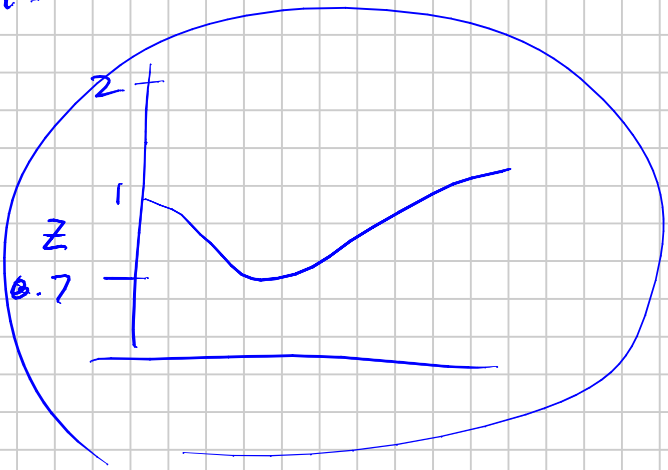
$$r_e \cong \left(\frac{A_w}{\pi}\right)^{1/2} \qquad A_w \simeq A_{field}/N_w$$

$$r_w \cong 0.1 \text{ m}$$

$$\ln\frac{r_e}{r_w} - \frac{3}{4} = \ln\left(\frac{1020}{0.1}\right) - \frac{3}{4} =$$

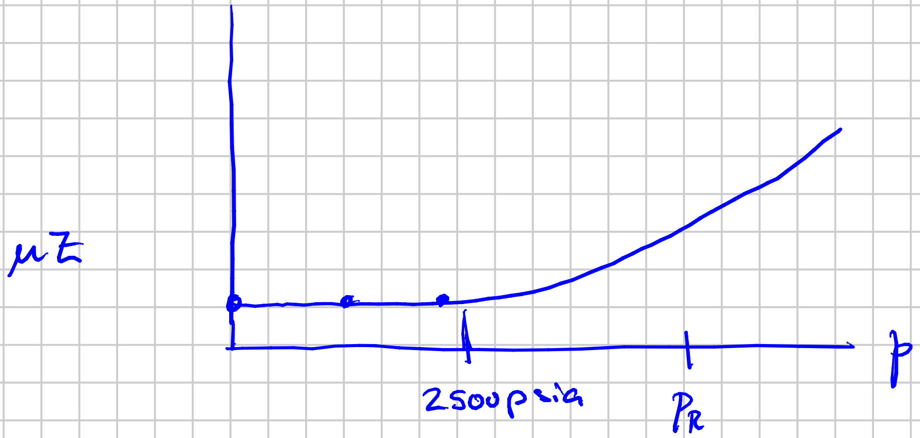
$$\underset{\nearrow}{\frac{p}{Z}} = \underset{\nearrow}{\frac{p_i}{Z_i}}\left(1 - \frac{G_p}{G}\right)$$

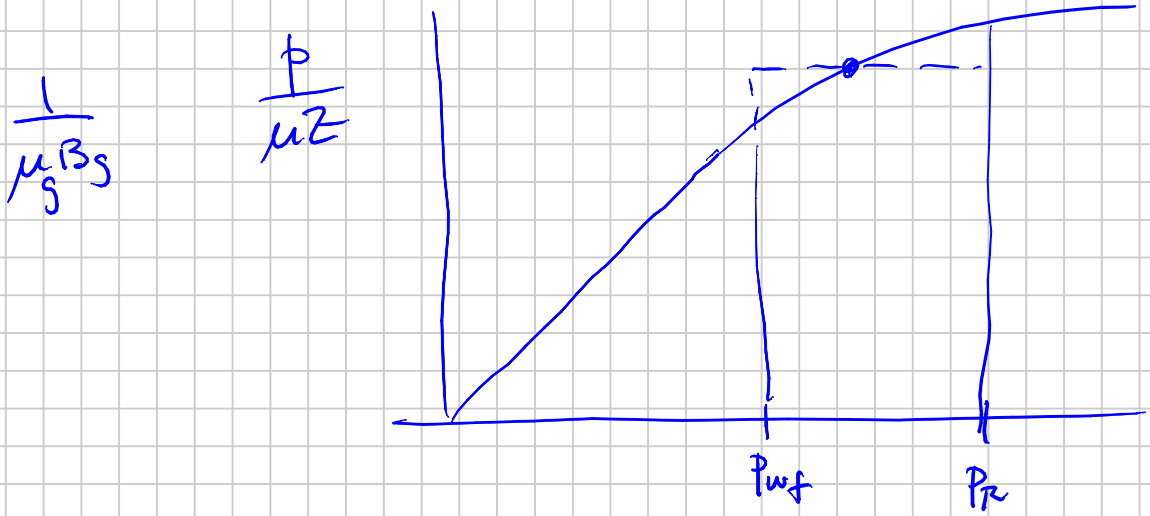
$$p \underset{\nearrow}{\simeq} p_i\left(1 - \frac{G}{G_p}\right)$$



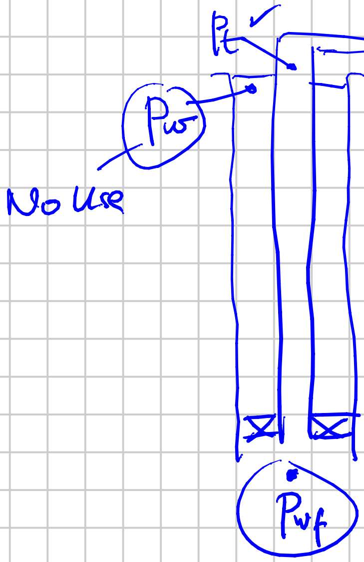
p^2 Gas Rate Eq.

$\boxed{(\overline{\mu Z})}$ @ $\frac{1}{2}(p_R + p_{wf})$ $(\mu Z)_i$ $(\mu Z)_{1atm}$





$$\frac{(p_R^2 - p_{wf}^2)}{(\overline{\mu Z})}$$



Est :

$p_w \cdot$

Gas + Condensate
Gas Only

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

$\uparrow$ Est L_t(TVD), d_T, M_g

Solve for $\underline{\underline{p_w}}$ $\rightarrow$ $p_{wf} = p_w \cdot e^{S/2}$

$p_c - p_w$: "Reservoir Pressure Drop"

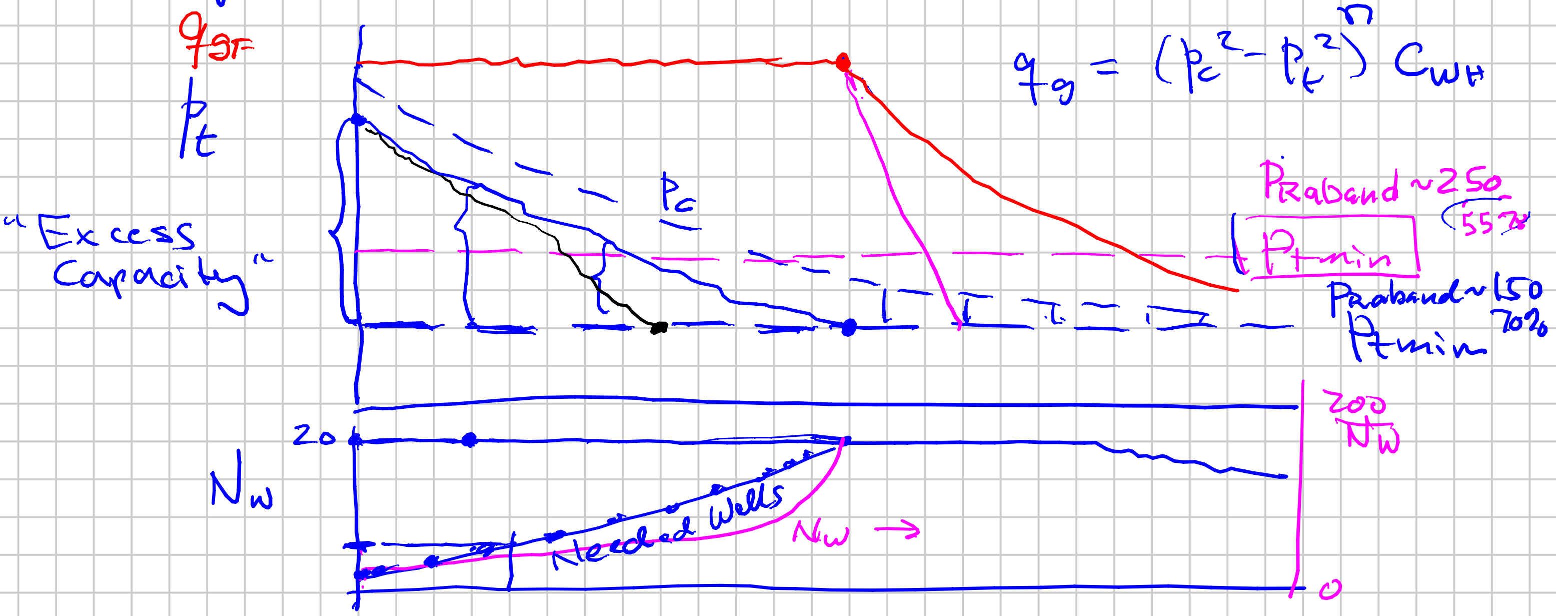
" "

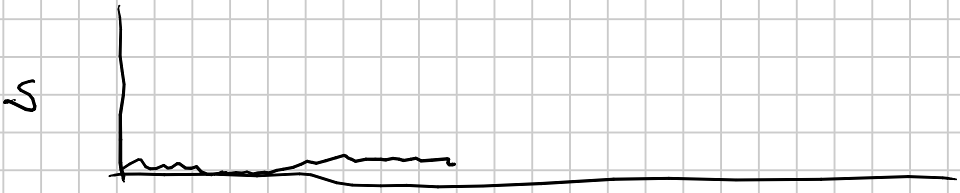
$$\frac{p_R}{e^{S/2}} - \frac{p_{wf}}{e^{S/2}} = \left(p_R - p_{wf}\right)\frac{1}{e^{S/2}} \sim \underbrace{\left(p_R - p_{wf}\right)}$$

Gas Prod. Forecasting

S

p_t = constant = p_{tmin}


$q_g = \left(p_c^2 - p_t^2\right)^n C_{WH}$



Arp's Decline Curve: D % decline/year

Field $D = \frac{(q_g N_w)}{\underline{\Delta G_{p\,decline}}}$ ( )

Δp $\frac{dp}{dr} = \frac{\mu}{k} v + \underbrace{\beta \rho v^2}_{\sim 0}$

$$q = \frac{kh(p_{pR} - p_{pwf})}{T_R\left[\ln\frac{r_e}{r_w} - \frac{3}{4} + s + \underbrace{Dq_g}_{\sim 0}\right]}$$

Maybe Neglect : Lower k ($\lesssim$ 10 md)

Don't Neglect : k $\gtrsim$ 100 md

~

Mat. Bal. $c_e \sim 0$ $c_e(p_{Ri} - p_R)$ $c_e p_{Ri} \lesssim 0.05$ ±?

$$\boxed{Z \equiv \frac{pv}{RT} = \frac{pV}{nRT}}$$

Ideal Volume Mixing @ $\underline{T_{sc}, P_{sc}}$

$\Sigma \, x_i \, M \, \boxed{\gamma_1}$