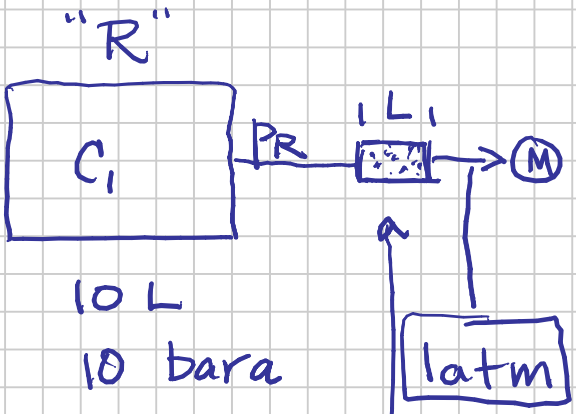
TPG 4145 CURTIS WHITSON

Note Title 8/20/2008



~1.0135 bara

10 L

10 bara

20°C

20°C

EQ.

Volumetric Gas Flow Rate

$\boxed{q_g(t)}$ Production Forecast

Darcy's Law

EQ: $\boxed{v = -\frac{k}{\mu}\left(\frac{dp}{dx}\right)}$

Ideal Gas Law

$$\boxed{pV = nRT}$$

const $\begin{cases} k: \text{permeability (D or md)} \\ \mu: \text{viscosity (cp} \equiv \text{mPa·s)} \end{cases}$

$$v \cdot \frac{\mu}{k} \int_0^L dx = \int_{p_{out}}^{p_{in}} dp$$

$$v \underbrace{\frac{\mu L}{k}}_{\text{const}} = (\underset{f(t)}{p_{in}} - \underset{\text{const}}{p_{out}})$$

Local Flow rate q is (at p)

$$q = v \cdot A_{\perp}$$

$$= v \cdot \pi r^2$$

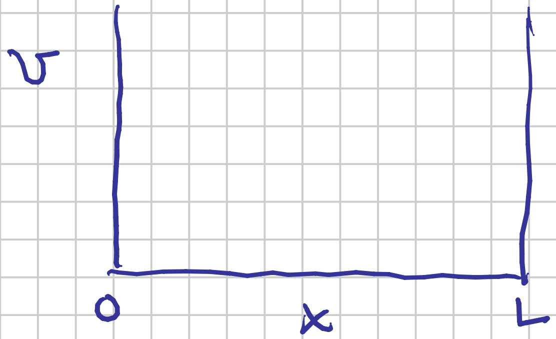
m^3/s

bbl/D

Convert to $\underline{\text{Surface Flow rate}}$

$\underline{q_g}$ at ambient conditions

1 atm 20°C

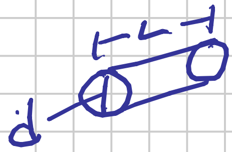


$$v = \left(\frac{k}{\mu}\right) \cdot \underbrace{\frac{dp}{dx}}_{?}$$

$\underline{P_{in}(t)} = 3\ \text{bar}$

$m_{in} = m_{out}$: Steady State Flow Condition

$$\dot{m}_{in} = v_{in} \cdot A_{\perp} \cdot \rho(p_{in})$$



$$\dot{m}_{out} = v_{out} \cdot A_{\perp} \cdot \rho(p_{out})$$

$$\boxed{\dot{m}(x) = v(x)\, A \cdot \rho_g(p(x)) = \text{constant}}$$

mass flow rate

$$\boxed{\underbrace{\frac{k}{\mu}\frac{dp}{dx}}_{} \cdot \underbrace{\pi r^2}_{A_{\perp}} \cdot \underbrace{\frac{pM}{RT}}_{\rho_g} = \text{constant} \left(\frac{kg}{s}\right)}$$

$$\frac{m_g}{V_g} = \rho_g(p) \text{ : Equation of State } p\text{-}V\text{-}T$$

$$\boxed{pV = nRT}$$

n = moles, kmol

p = pressure, Pa

V = volume, m^3

T = temperature, K

R =

$$\frac{n}{V} = \frac{p}{RT} \qquad \frac{kmol}{m^3}$$

$$\rho_g = \frac{m}{V} = \underbrace{\frac{p}{RT}}_{\frac{n}{V}} \cdot \left(\frac{m}{\cancel{n}}\right) \qquad \frac{kg}{m^3} = \frac{pM}{RT}$$

M [molecular weight]
molar mass

$$M_{C_1} = 16.04 \ \frac{kg}{kmol}$$

$$\boxed{\underbrace{\frac{K}{\mu}\frac{dp}{dx}} \cdot \underbrace{\pi r^2}_{A_\perp} \cdot \underbrace{\frac{pM}{RT}}_{\rho_g} = \text{constant} \left(\frac{kg}{s}\right)}$$

$$\dot{m} = q_m = \text{const} = \underbrace{\frac{K\pi r^2}{\mu}\left(\frac{M}{RT}\right)}_{\text{const}} \cdot p \frac{dp}{dx}$$

$$q_m \cdot \int_0^L dx = \frac{\pi r^2 K}{\mu}\left(\frac{M}{RT}\right) \int_{p_{out}}^{p_{in}} p \, dp$$

$$\boxed{q_m = \left(\frac{\pi r^2 K}{L}\right)\left(\frac{M}{\mu RT}\right)\left(p_{in}^2 - p_{out}^2\right)}$$

Geometry Rock Property Fluid Property & State

Nightmare: UNITS

P_R drops as a function of cumulative mass (moles) of gas removed.

$q(t)$

Note Title 8/21/2008

Darcy's Law & Units

d'Arcy

$$v = \underbrace{\frac{k}{\mu}}_{C} \frac{dp}{dx}$$

cgs Units	Pure SI Units
v [cm/s]	v [m/s] ← Correct!
p [atm]	p [Pa]
x [cm]	x [m]
μ [cp] ← centi Poise	μ [Pa·s]
k [D] ← "Darcy"	k [m^2]

Can be shown:

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

$$1\,(\mu m)^2$$

$$1\,(10^{-6}\,m)^2$$

$$10^{-12}\,m^2$$

$$1\,md = 10^{-3}\,D$$

$$1000\,md = 1\,D$$

Markus Hays Lab Exp Aug. 17, 2008

Core 1

$L = 5$ cm (2")
$d = 3.8$ cm (1.5")

barg bara bar

Gage

P_{in} [atm]	P_{out} [atm]	q [L/min]
2.01	1.87	3.0
0.98	0.90	1.5
0.36	0.325	0.75

Calculate k assuming a simplified Darcy equation.

?

$$v = \frac{k}{\mu}\frac{\Delta P}{\Delta x} \simeq \frac{k}{\mu}\frac{\Delta P}{L}$$

$\mu_{N2\,@\,Low\,P} \sim 0.012$ cp

Convert L/min $\rightarrow$ cm^3/s

$$(\quad)\frac{\cancel{L}}{\cancel{min}}\cdot\underbrace{\frac{1000\text{ cm}^3}{\cancel{L}}}_{1}\cdot\underbrace{\frac{\cancel{min}}{60\text{ s}}}_{1}$$

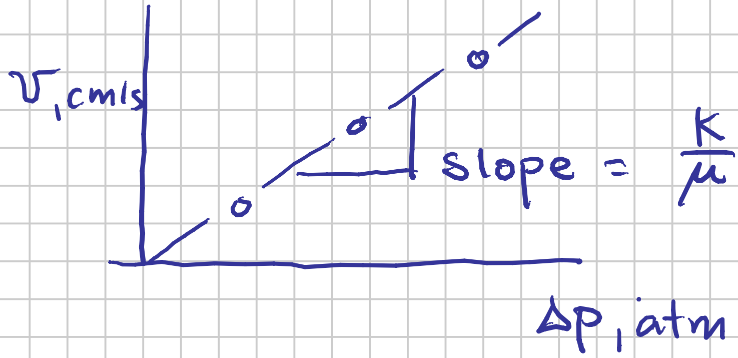
$q \rightarrow v = q/A$

Core 2

$$k \simeq v\frac{L}{\Delta p}\mu$$

$$\boxed{v = \underbrace{\frac{k}{\mu L}}_{m}\cdot\Delta p}$$

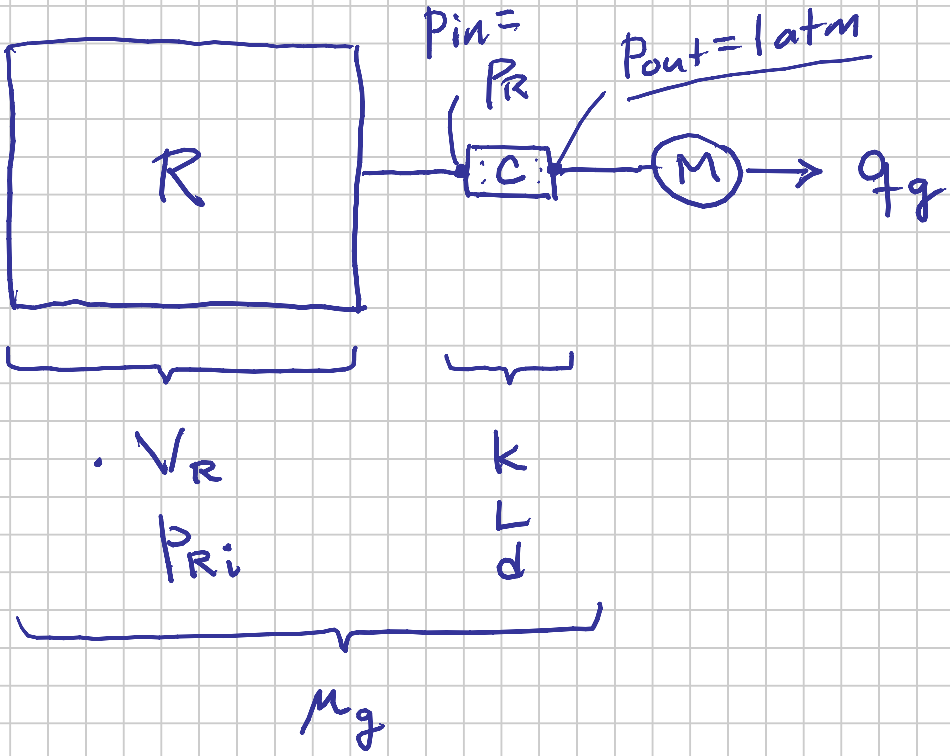
$$k = m\cdot\mu\cdot L$$



slope $= \frac{k}{\mu} = m \Rightarrow k = m \cdot \mu \cdot L$

Best-fit to 3 data

Reservoir Flow Analogue

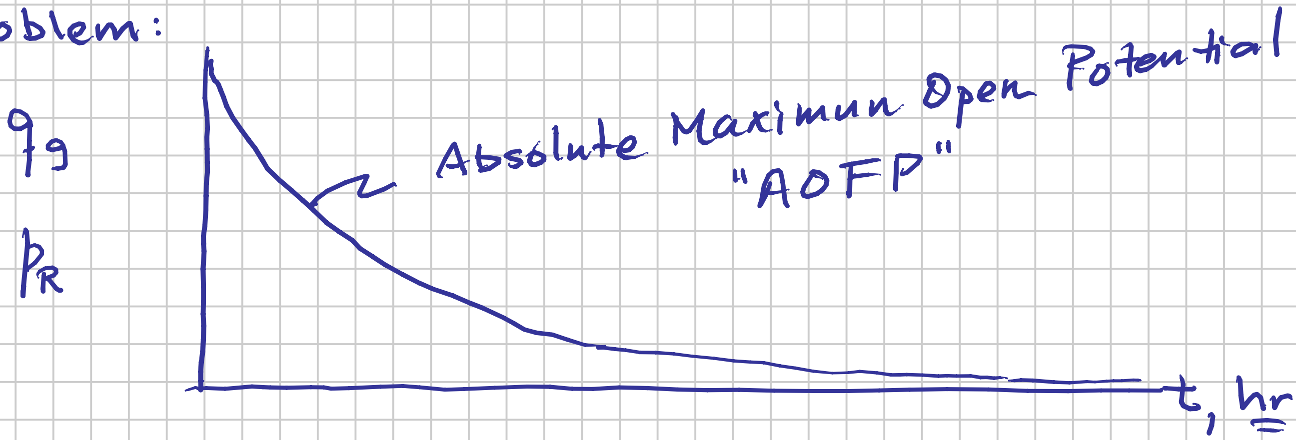


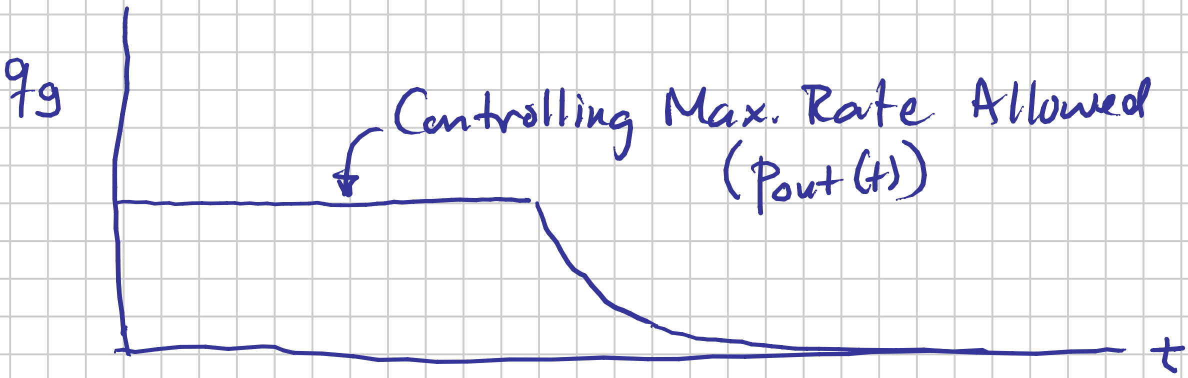
R : Reservoir

C : Core ("Rock")

M : Meter

Problem:





Gas Rate (Field & Lab)

Volumetric Rates at "Standard Conditions" (sc)

SPE : p_{sc} = 1 atm = 14.696 psia
= 1.0135 bara

T_{sc} = 60 °F
15.56 °C

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

Relationship between s.c. gas volume and moles of gas "n"

Ideal Gas Law: $p_{sc} V_{sc} = n R T_{sc}$

$$\Rightarrow \left(\frac{V_{gsc}}{n} \right) = \frac{R\, T_{sc}}{p_{sc}}$$

abs. (K or °R)

SI Units $\{ m^3 ,\ \text{kmol} / \text{Kg-mol} ,\ K ,\ \text{bara} \}$

Sm^3 m^3 of gas at s.c.

std m^3 (SPE)

$R = 0.083143$

$T_{sc} = 15.56 + 273.15$
$p_{sc} = 1.0135$ bara

ANY GAS:

$$\frac{V_{gsc}}{n} \left[\frac{Sm^3}{\text{Kg-mol}} \right] = \frac{R\, T_{sc}}{p_{sc}} = 23.68 \ \frac{Sm^3}{\text{Kg-mol}}$$

$$= 379.\ \frac{\text{scf}}{\text{lb-mol}}$$

TABLE A-2—UNIVERSAL GAS CONSTANT FOR DIFFERENT UNITS

Pressure Unit	Volume Unit	Temperature Unit	Mass (mole) Unit	Gas Constant R
psia	ft^3	°R	lbm	10.7315
psia	cm^3	°R	lbm	303,880
psia	cm^3	°R	g	669.94
bar	ft^3	°R	lbm	0.73991
atm	ft^3	°R	lbm	0.73023
atm	cm^3	°R	g	45.586
Pa	m^3	K	kg	8314.3
Pa	m^3	K	g	8.3143
kPa	m^3	K	kg	8.3143
kPa	cm^3	K	g	8314.3
bar	m^3	K	kg	0.083143
bar	cm^3	K	g	83.143
atm	m^3	K	kg	0.082055
atm	cm^3	K	g	82.055

Reservoir "Tank"

$$p_R V_R = n_R (R T_R)$$

Assume V_R = const. w.r.t. time

$R T_R$ = —— " ——

$$p_R(t) = \underbrace{\left(\frac{R T_R}{V_R}\right)}_{\text{const}} \cdot \underbrace{n_R(t)}_{\text{changing}}$$

$$n_R(t) = n_{Ri} - \int_0^t q_g \cdot \left(\frac{R T_{sc}}{p_{sc}}\right)^{-1} dt$$

e.g. 23.68

"Material Balance"

$$* \quad n_R(t) = n_{Ri} - \left(\frac{R T_{sc}}{p_{sc}}\right)^{-1} \int_0^t q_g \, dt$$

$$q_g = \underbrace{\left(\frac{R T_{sc}}{P_{sc}}\right)} \dot{n}_g$$

molar gas rate

Steady State Flow Assumptions

$$\dot{n}_{g\,in} = \dot{n}_{g\,out} = n_g(x)$$

$$\dot{n}_g = \underbrace{v_g \cdot A}_{m^3/s} \cdot \underbrace{\left(\frac{\rho_g}{M_g}\right)}_{c(x)}$$

$$v_g = \underbrace{\frac{k}{\mu_g} \frac{dp}{dx}} \qquad \text{Darcy}$$

Gas Law

$$\frac{\rho_g}{M_g} = \left(\frac{n}{V}\right)_c = \left(\frac{p}{RT}\right)_c = \underbrace{\left(\frac{1}{RT}\right) \cdot p_{(x)}}$$

$$q_g = \left(\frac{R T_{sc}}{P_{sc}}\right) \cdot \frac{k}{\mu_g} \frac{dp}{dx} \cdot A \cdot \frac{1}{RT} p$$

P_{in} 0

P_{out} L

$$q_g = \boxed{\underbrace{\left(\frac{1}{2} \frac{T_{sc}}{P_{sc} T_R}\right)}_{\text{Constant}} \underbrace{\frac{A}{L}}_{G \text{ (geometry)}} \underbrace{\left(\frac{1}{\mu_g}\right)}_{PVT} \underbrace{k}_{\text{Rock}} \underbrace{\left(P_{in}^2 - P_{out}^2\right)}_{\text{Driving Potential}}}$$

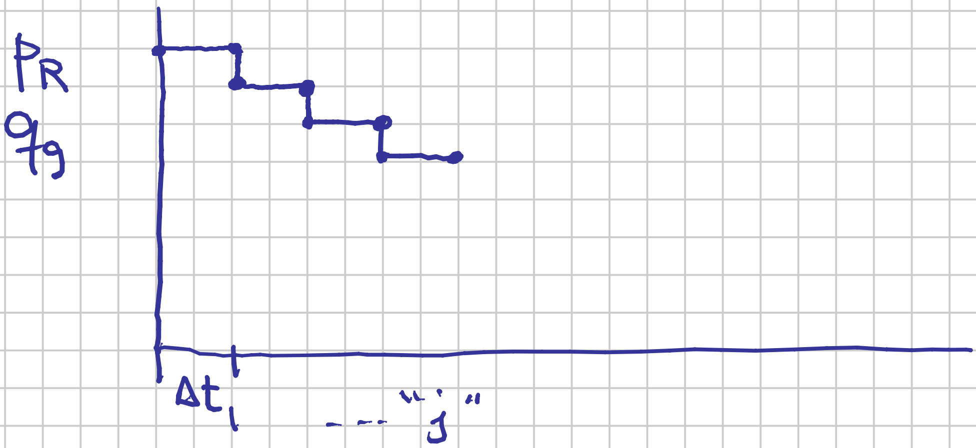
$$q_g = C \left(P_{in}^2 - P_{out}^2\right)$$

$p_R = P_{in}$

Solution Strategy:

T.S.

Time-Lag Solution (Direct @ each Time Step)



During Δt

(1) We know current p_{R_j}

(2) Calculate $q_g = C\,(p_{R_j}^2 - P_{out}^2)$

const

(3) Calculate remaining moles gas in R at end T.S.

(4) Calculate the new p_R for next T.S. $j+1$

(5) Goto (1)

$$\frac{(n_{Ri} - n_p)}{k}$$

n_p

$\frac{Sm^3}{d} \Rightarrow$ " $\frac{kg\text{-mole}}{s}$ "

constant = "10 L" P_R $\underline{P_{sc}} = 1$ atm $\underline{(1 \text{ bar})}$

<u>10 bara</u>

15.56 °C

(1) $\boxed{p\underline{\underline{V}} = n\underline{\underline{R}}\,\underline{T}}$

Ideal Gas Law

(2) $v = \frac{k}{\mu}\frac{\Delta p}{\Delta x}$

P_R L

$\Rightarrow \underline{\underline{q}} = C\,(\underline{\underline{P_R^2 - P_{sc}^2}})$ (2)

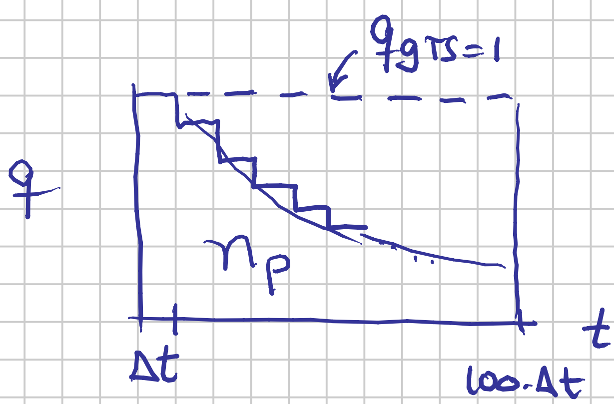
Problem:

* $\underline{\underline{\Delta t}}$ too big ⇒ garbage

<u>Limit</u>

100 TS is "default"

$$\underbrace{\left\{\frac{1}{\left(\frac{R\,T_{sc}}{P_{sc}}\right)}(q_g)_{TS=1}\right\}}_{kg\text{-mole}/s} \times \underbrace{\Delta t \times 100}_{s \text{ total}} = (n_p \le)\ \boxed{n_{Ri}}$$



Recommended Estimate $\Delta t \sim \dfrac{n_{Ri}}{\left\{ q_{g_{TS=1}} / (23.6) \right\} \cdot 100}$

$$\text{Ultimate Recovery} = \frac{n_P}{n_{Ri}} = \frac{n_{Ri} - n_R}{n_{Ri}}$$

$$= 1 - \frac{n_R}{n_{Ri}}$$

Ideal Gas Law

$$= 1 - \frac{P_R}{P_{Ri}}$$

$$= 1 - \frac{1}{10}$$

$$= 90\%$$

$$\times \quad \frac{\cancel{Sm}^3}{\cancel{s}} \cdot \frac{1}{\cancel{Pa}^2} \cdot \frac{35.31\ scf}{\cancel{Sm^3}} \cdot \frac{3600 \cdot 24\ \cancel{s}}{D} \cdot \left(\frac{10^5\ \cancel{Pa}}{\cancel{bar}} \cdot \frac{\cancel{bar}}{14.5\ psia} \right)^2 \sim$$

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

$\Rightarrow$

$$2.24\ \frac{lb}{Kg}$$

Note Title 8/28/2008

"Gas Law" p-V-T (PVT)

of "Real" Gases (N_2, CO_2, H_2S, C_1, C_2, C_3, C_4 ...)

at "Real" Conditions (States); "high" p, T

Ideal Gas Law

$$pV = nRT$$

absolute (K, R)

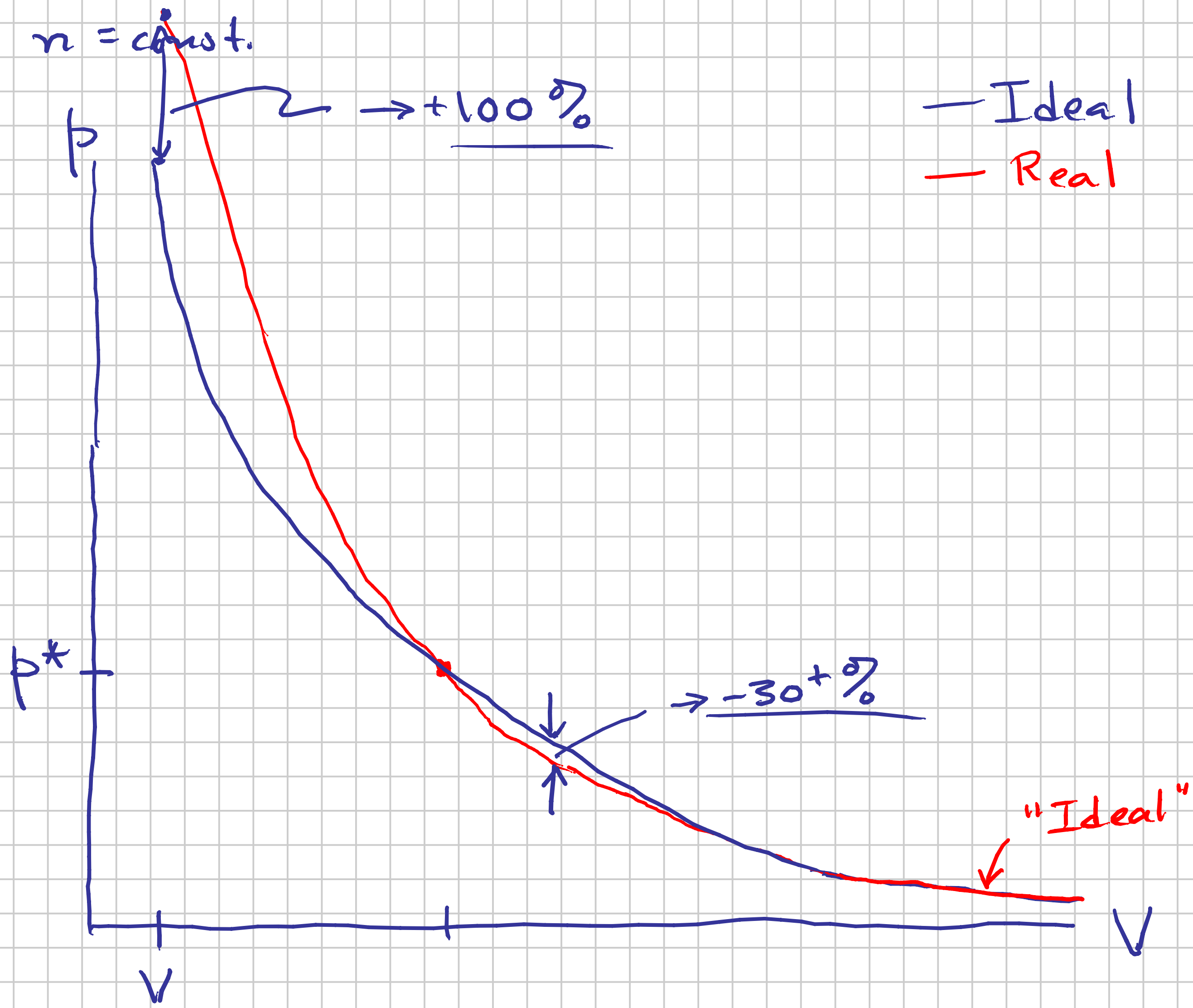
absolute

Be Careful (units)

T = const.

n = const.

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



Ideal Gas Law CAN NOT be used in engineering at $p \gtrsim 10$ bar

Introduce a "Correction Factor"

"Deviation Factor"

...

$$Z \equiv \frac{V_{actual}(p,T,n)}{V_{ideal}(p,T,n)}$$

"Z-factor"

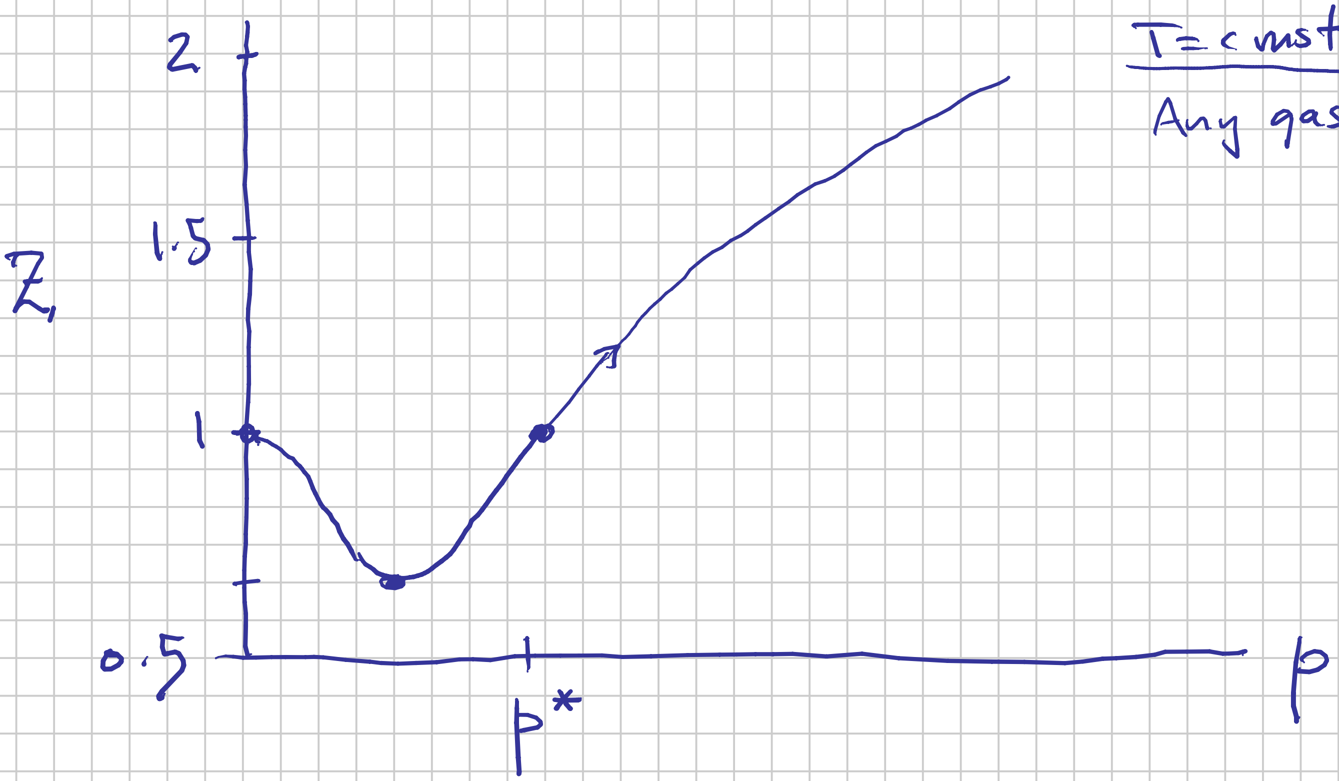
$$V_{actual} = V = \underset{\substack{\uparrow \\ \frac{nRT}{p}}}{V_{ideal}} \cdot Z$$

$$\Rightarrow V = \frac{nRT}{p} \cdot Z$$

$$\boxed{pV = nRT \cdot Z}$$

"Real Gas Law"

Class Excercise



$T = \text{const}$

Any gas

History:

(1) 1870s van der Waals

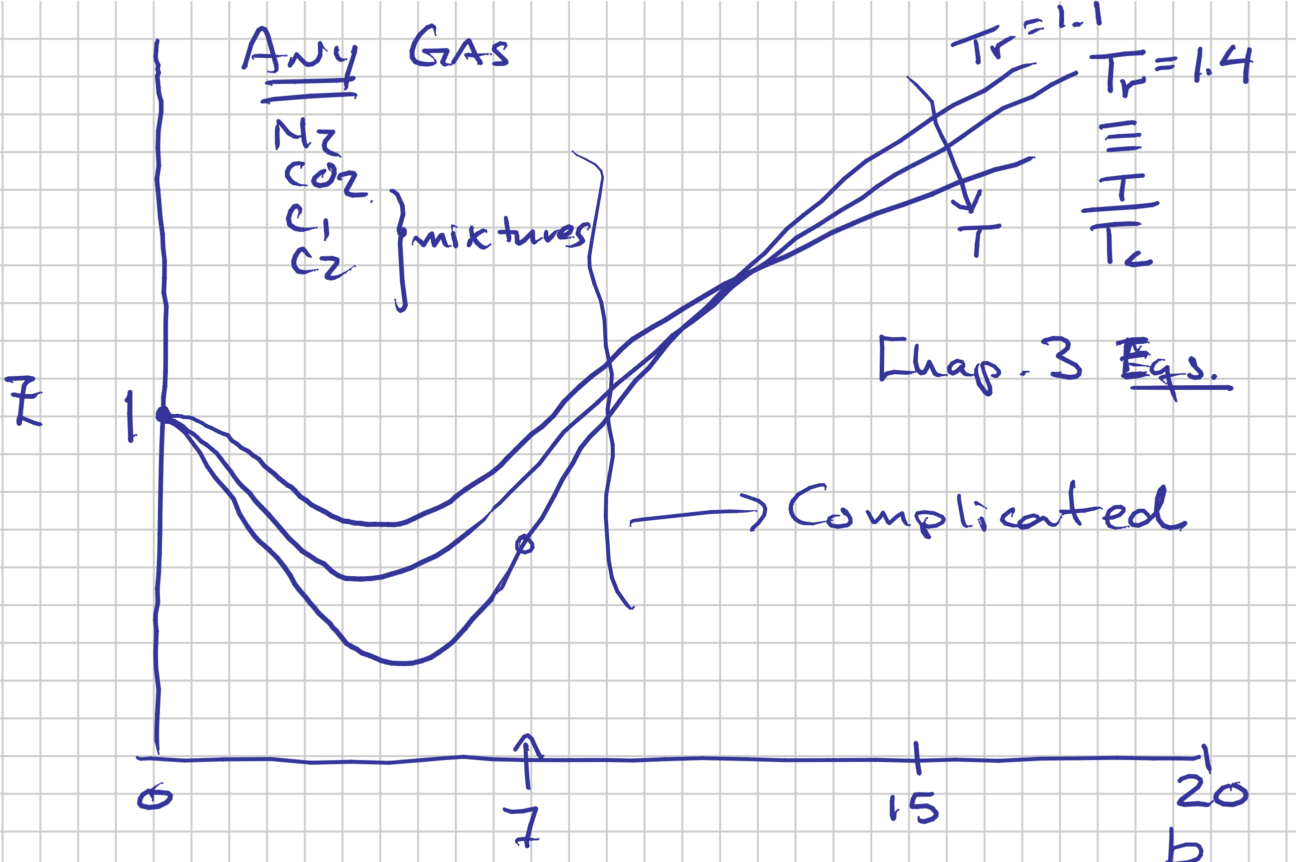
⇒ Law of Corresponding States

Any compound or mixture will behave "the same" in terms of p-V-T if you recast in terms of "reduced" (new) variables $\underbrace{p_r - V_r - T_r}_{\text{"Single"}}$

(2) Donald Katz U. Michigan

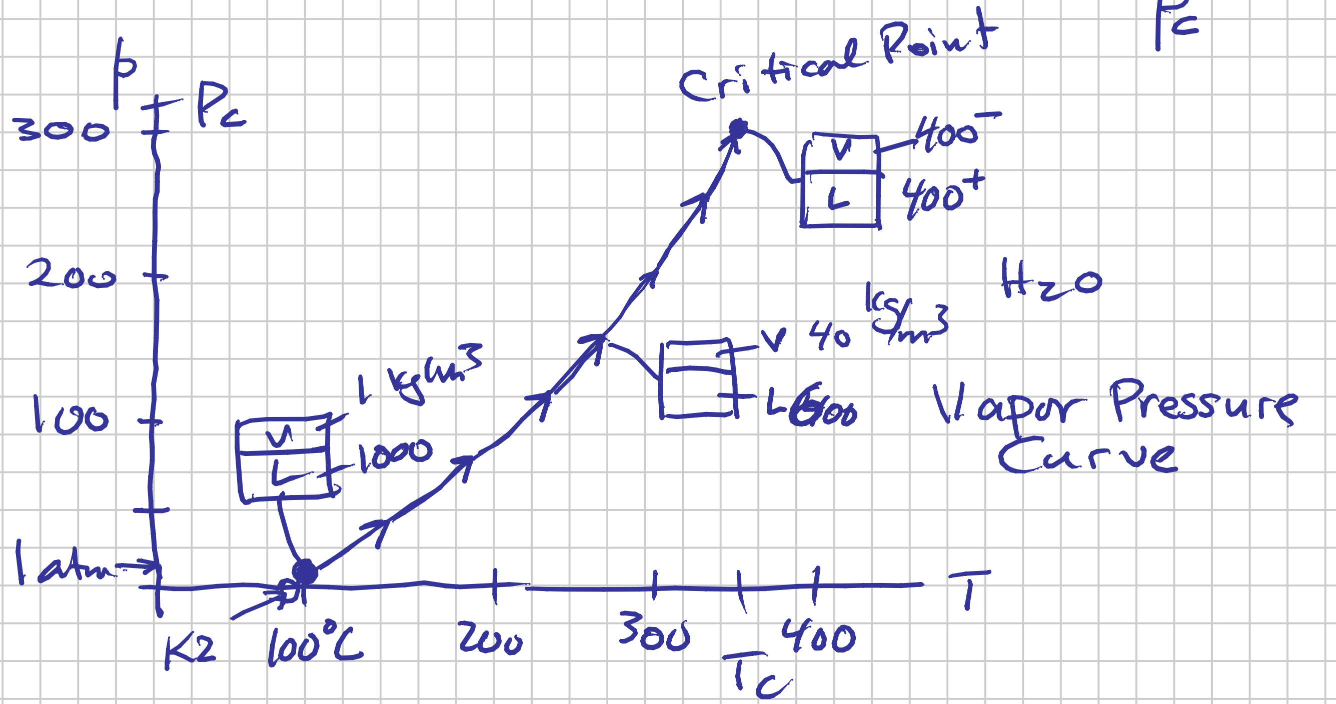
1. PhD student Marshall B. Standing "Muz"

⇒ Publication ~ 1941



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

Review: (p_c, T_c) "Critical Point"



Gas Specific Gravity $\boxed{\gamma_g} \equiv \frac{\rho_{g,sc}}{\rho_{air,sc}} = \frac{M_g}{M_{air}}$

est. T_c, P_c

$Z_{sc} = 1$

28.97

Methane: $M = 16 \Rightarrow \gamma_g = \underline{0.55}$ (air = 1)

Reservoir Gases: $\gamma_g \sim 0.55 \to 1.5$ (2)

Calculating Z

(1) Fetch p, T

(2) Get P_c, T_c

Mixtures

$$P_{pc} \cong \sum_i y_i P_{ci}$$

Gas mole fraction

$\gtrsim (P_c)_{C_1}$

$$T_{pc} = \sum_i y_i T_{ci}$$

$\gtrsim (T_c)_{C_1}$

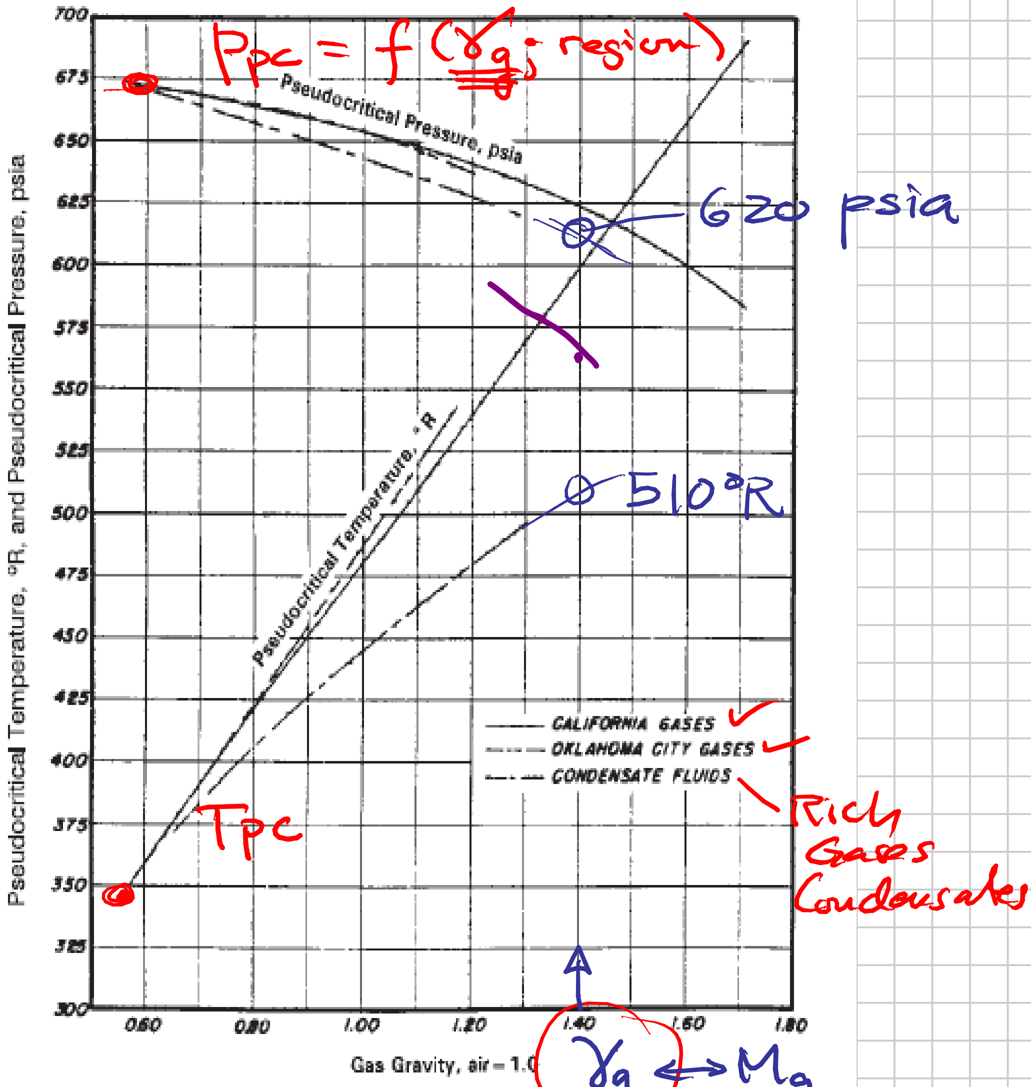


Fig. 3.7—Gas pseudocritical properties as functions of specific gravity.

(3) $T_{pr} \equiv \dfrac{T}{T_{pc}}$

$P_{pr} \equiv \dfrac{P}{P_{pc}}$

(4) SK Chart $\Rightarrow$ Z, at (p, T)

Kristin:

$P_{Ri} = 900$ bara

$T_R = 170\,°C$

$\gamma_g = 1.4$

$P_{pc} = 620$ psia

$T_{pc} = 510\ °R$

$$T_{pr} = \frac{T(K)}{T_c(K)} = \frac{170+273}{(510/1.8)}$$

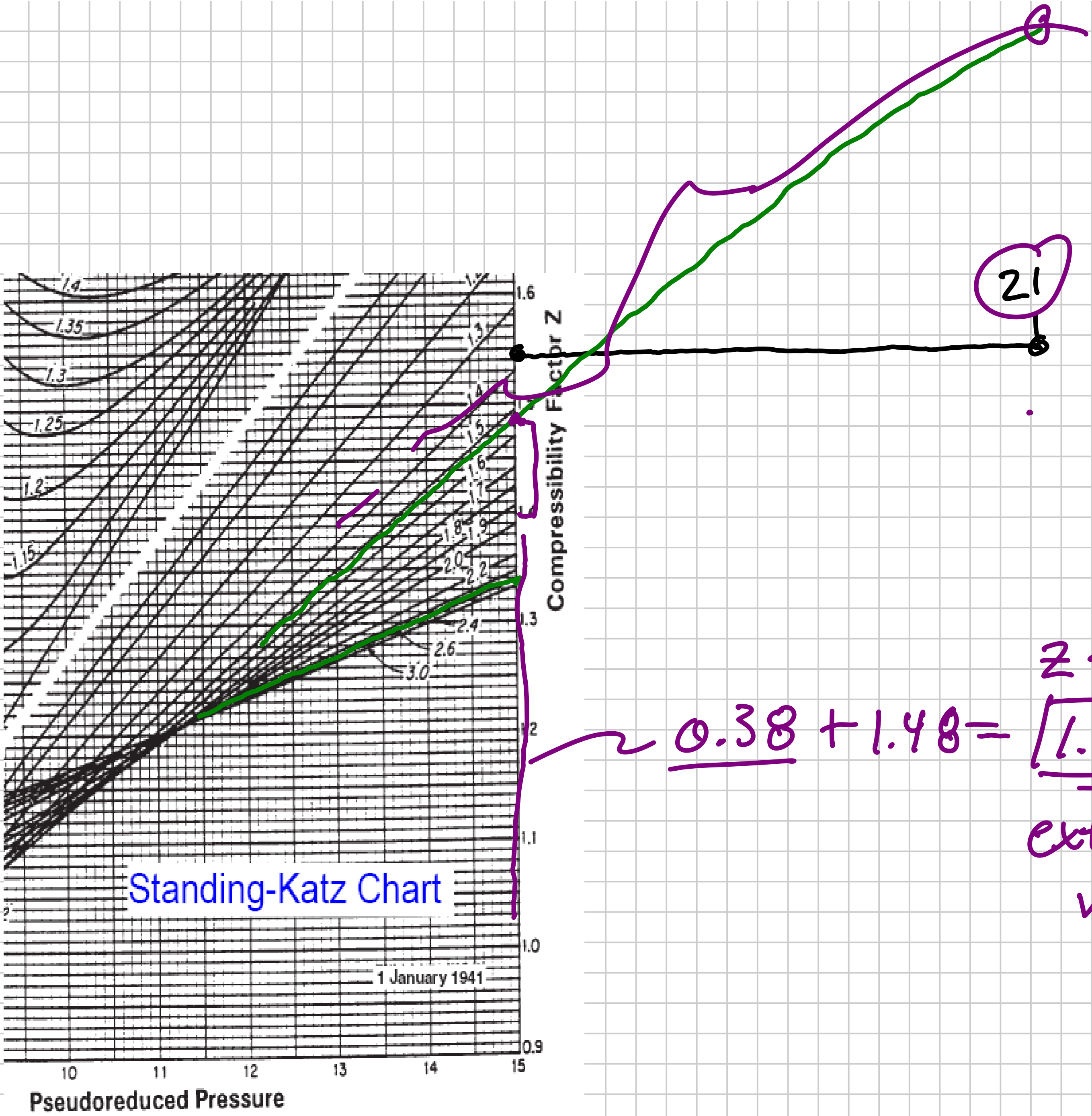
$$= 1.56$$

$$P_{pr} = \frac{900 \text{ bara}}{620 \text{ psia} \cdot \frac{1 \text{ bara}}{14.5 \text{ psia}}}$$

$P_{pr} = 21.0$

(off the chart)

$\cancel{\therefore Z \approx 1.55}$

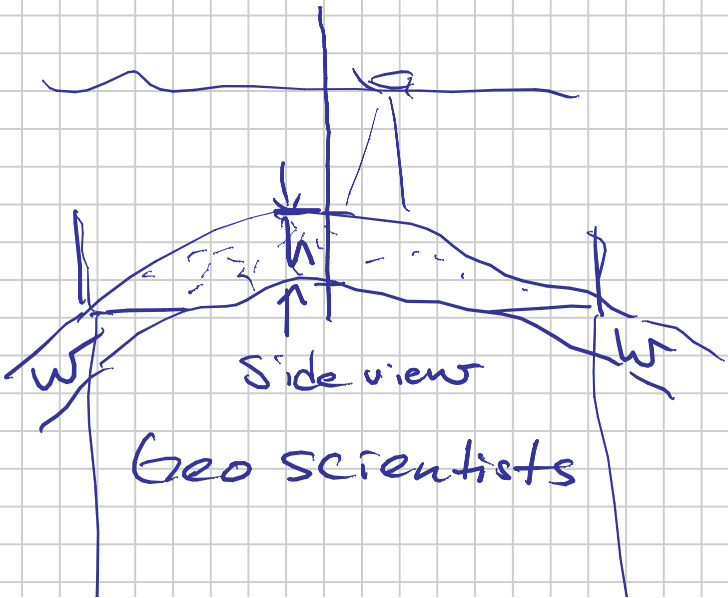


$Z \sim$

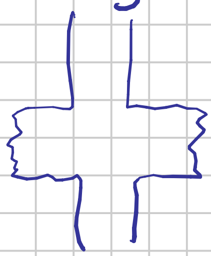
$\underline{0.38} + 1.48 = \boxed{1.86}$

extrap ✓

What & How do we use $Z(p)$



Log

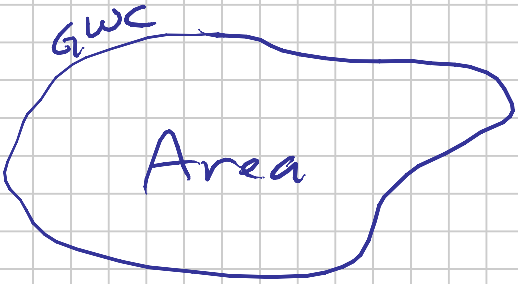


$\Rightarrow$ GAS Hydrocarbon estimate ~~Bulk~~ Pore Volume

$\bar{A} \times \bar{h}$

$\times \bar{\phi}_{\substack{logs \\ cores}} \times (1-\bar{S}_w)$ Gas

Top



$\underline{\underline{V_{gR}}} = \bar{A}\,\bar{h}\,\bar{\phi}(1-\bar{S}_w)$

We don't sell the Germans gas "down there"

$\sim 10^+ \ \$/Mscf$

$V_{gR} \rightarrow$ Sellable (s.c.) Gas Volume

$= 100 \cdot 10^9 \ m^3$

@ Kristin conditions

$$P_R V_{gR} = n R T_R Z_R$$

2

$$n_{gi} = \frac{pV}{RTZ} \quad \text{kg-mole}$$

3%

± 0.03

$$= \frac{900(1 \cdot 10^9)}{(0.08314)(170+273)(2)}$$

$$= 1.22 \cdot 10^{10} \ \underline{\text{kg-mole}} \times 23.68 \ \frac{Sm^3}{\text{kg-mole}}$$

$$= 2.9 \cdot 10^{11} \quad Sm^3$$

$$290 \cdot 10^9 \ Sm^3 \times 35.31 \ \frac{scf}{Sm^3}$$

$$10 \cdot 10^{12} \text{ scf} \times \underbrace{\text{USD} \frac{10}{1000\text{ scf}}}_{\sim \text{Price}}$$

$$= 100 \cdot 10^{9} \text{ USD}$$

Note Title 9/3/2008

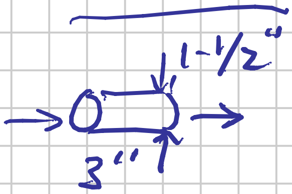
Introduce the Real Gas Law $pV = nRT\boxed{Z}$ $Z(p,T)$

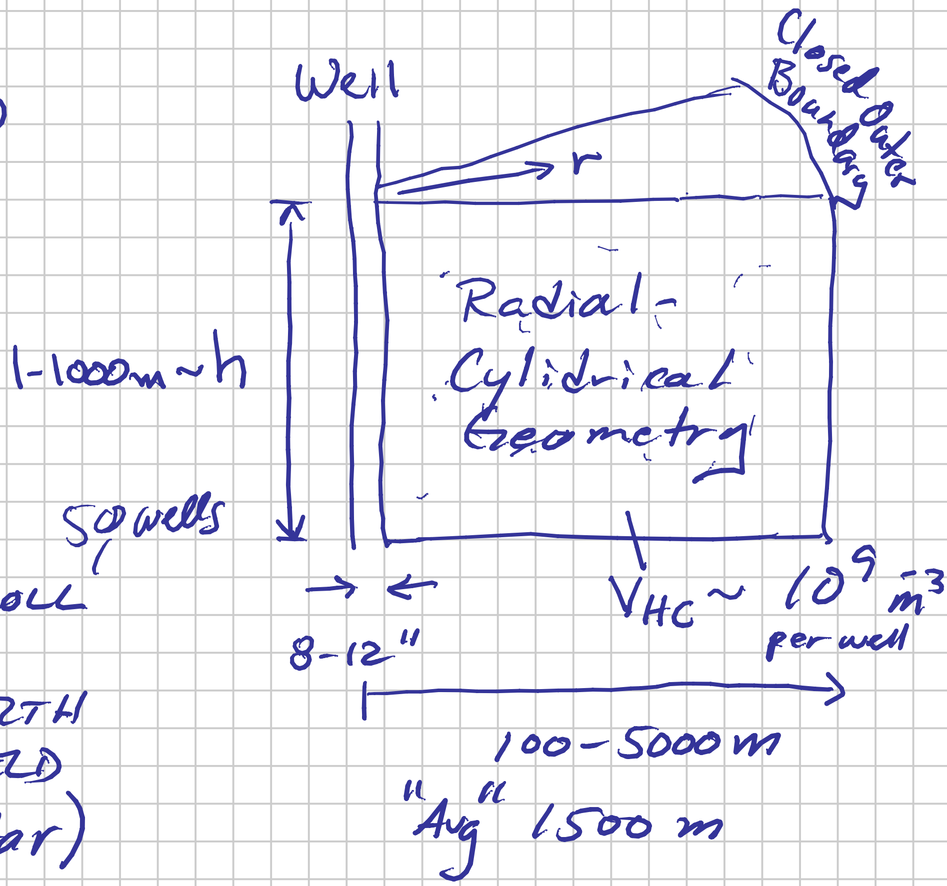
into $\underbrace{\text{Darcy Eq}}$ & Gas "Material Balance" (MB)

⇓

"Rate Eq"

Realistic Flow Geometry





$45 \cdot 10^{12}$ scf TROLL 50 wells

$\underbrace{900 \cdot 10^{12}\ \text{scf}}_{\text{Tcf}}$ NORTH FIELD (Qatar) 250 wells

\$0.5m

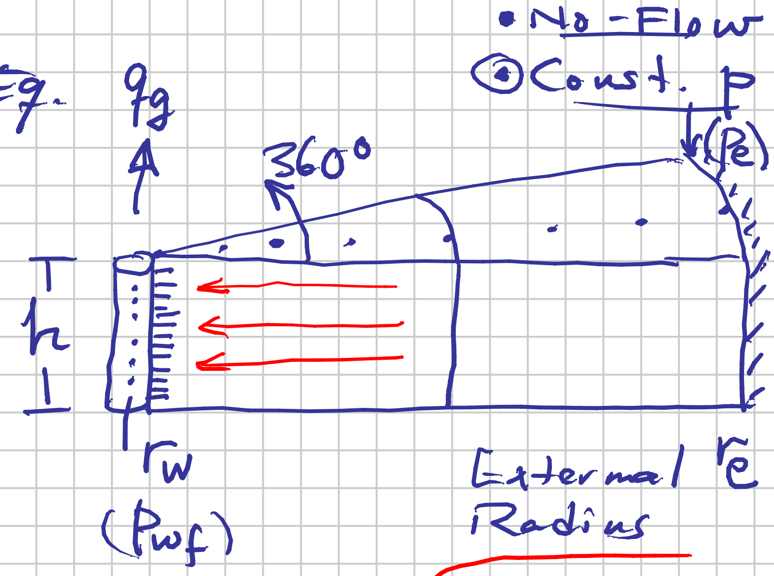
\$5B

By Well IGIP ~ $50 \cdot 10^{6}$ scf → $1\text{-}2 \cdot 10^{12}$ scf

Initial Gas In Place

S.Ci

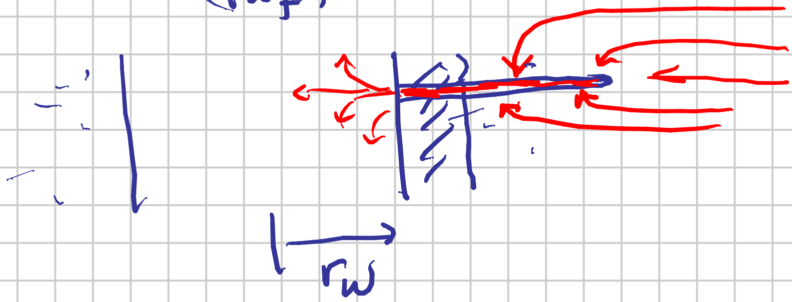
Develop the Gas Rate Eq.



⊙ $p @ r_e = \text{const}$

⊙ Steady State Flow:

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



q_g = surface gas volumetric rate at S.C. 1atm, 60°F

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

$$\rho = \frac{M}{RT}\cdot\left(\frac{p}{Z}\right)$$

Mass Flow Rate at Surface | Mass Flow Rate at any r

Given:

$$q_g \cdot (\rho_g)_{sc} = \underbrace{v_g \cdot A_\perp}_{q_{gR}} \cdot \rho_g$$

$[Sm^3/s]\ [kg/Sm^3]$ $\qquad$ $[m^3/s]\ [kg/m^3]$

$$\underset{\uparrow\ \text{Given}}{q_g} \cdot \frac{\cancel{M}\, p_{sc}}{\cancel{R}T_{sc}} = \underbrace{\frac{k}{\mu_g}\frac{dp}{dr}}_{=v_g} \cdot 2\pi r h \cdot \frac{\cancel{M}}{\cancel{R}T_R}\cdot\frac{p}{Z}$$

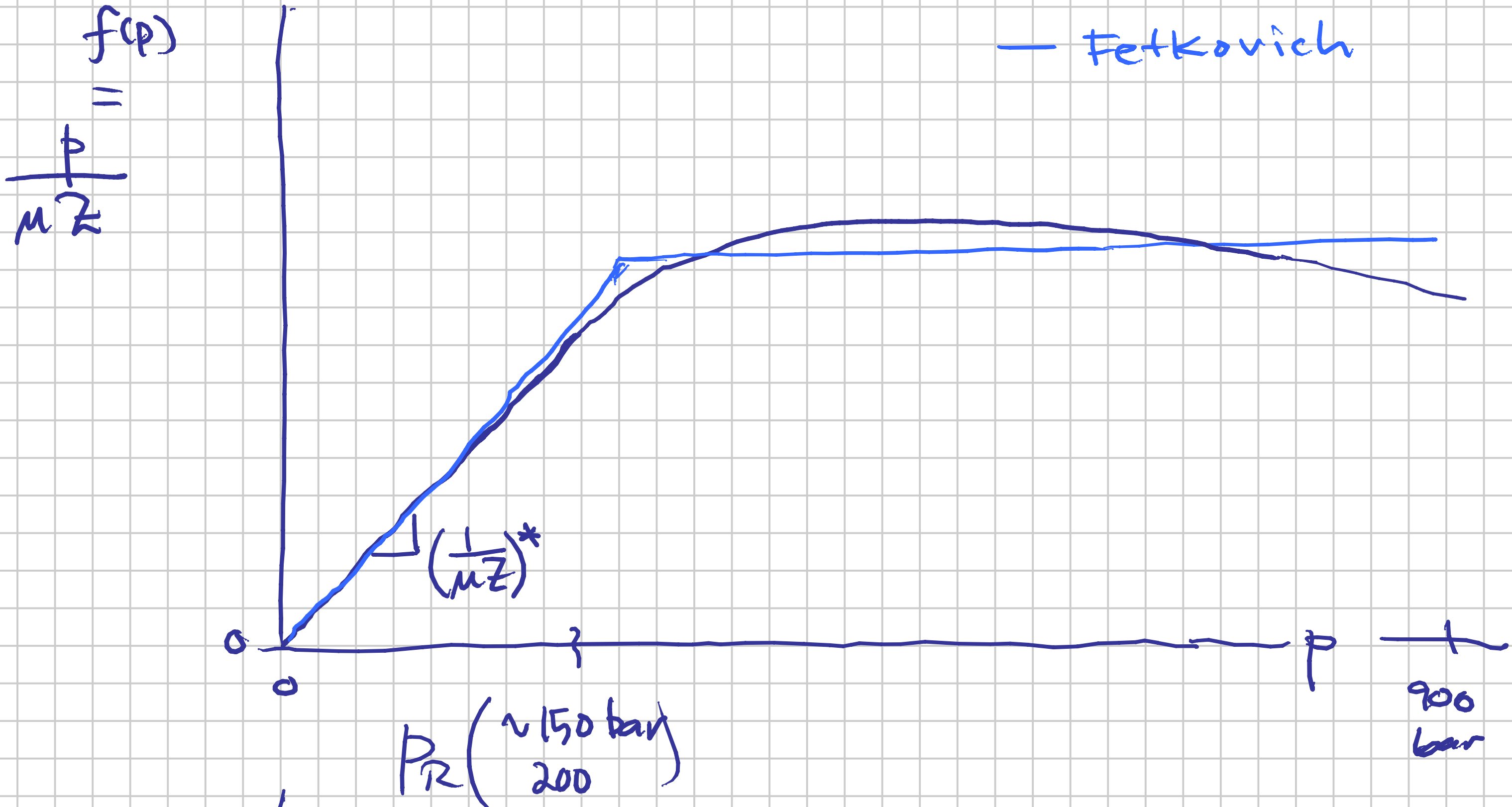
Collect all "constants" on RHS

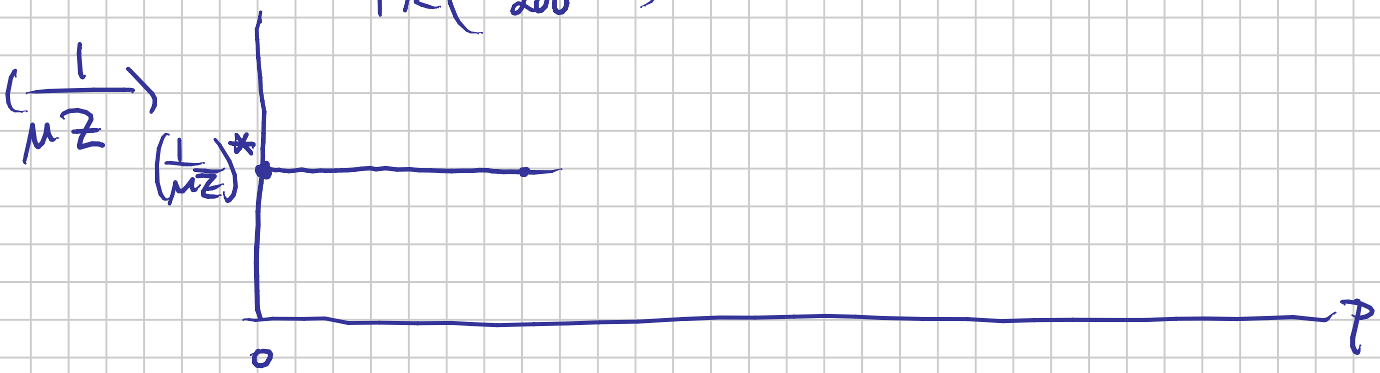
$$q_g = \underbrace{\frac{T_{sc}}{T_R\, p_{sc}} \cdot 2\pi k h}_{\text{constant}} \cdot r \frac{p}{\mu_g Z} \frac{dp}{dr}$$

$$\underset{\uparrow\,\text{Given}}{q_g} \cdot \underbrace{\int_{r_w}^{r_e} \frac{1}{r}\, dr}_{\ln r_e/r_w \;\sim 6-10\; \text{"8"}} = \underbrace{\frac{2\pi k h}{(T_R p_{sc}/T_{sc})}}_{\text{const.}} \int_{p_w}^{p_e} \underbrace{\frac{p}{\mu Z}}_{f(p)}\, dp$$

$$q_g = \underbrace{\frac{2\pi \overline{kh}}{\left(\frac{T_R p_{sc}}{T_{sc}}\right)\left[\ln(r_e/r_w) + \text{"}G\text{"}\right]}}_{\underline{\underline{C}}} \int_{\underset{\uparrow\,\text{flowing}}{p_{wf}}}^{p_e} \underbrace{\frac{p}{\mu Z}}_{f(p)}\, dp$$

"G" ~ 0 non-perfect flow effects in perforations





$$\left(\frac{1}{\mu Z}\right)^* \sim \frac{1}{\mu_g^o}$$ ← Gas Viscosity @ $p \sim 0$ (1 atm) ~ 0.015 cp

{ Low-P $\lesssim$ 200 bara }

$$\int_{p_{wf}}^{p_e} \frac{p}{\mu Z} dp = \frac{1}{2\mu_g^o}(p_e^2 - p_{wf}^2)$$

$$q_g = \frac{2\pi k h}{\left[\left(\frac{T_R p_{sc}}{T_{sc}}\right)\ln\frac{r_e}{r_w} + (\quad)\right]} \cdot \frac{1}{2\mu_g^o} \cdot (p_e^2 - p_{wf}^2)$$

Usually small

$$\underbrace{\qquad\qquad\qquad\qquad}_{C}$$

$$\boxed{q_g = C \cdot (P_e^2 - P_{wf}^2)}$$

Ormen Lange

(1) kh

(2) Geometry terms

1960s : Al-Hussainy, Ramey, Crawford

Defined: Gas Pseudopressure

$$\underset{(p_p)_{>1990}}{m} = 2\int_0^p \frac{p}{\mu Z} \cdot dp$$

	p	μ	Z	$p/\mu Z$	p_p (m)
	50				
P_{wf}	100				
	⋮				
P_e					
	900				

$$\int_{P_{wf}}^{P_e} \frac{p}{\mu Z} dp = \int_0^{P_e} \frac{p}{\mu Z} dp - \int_0^{P_{wf}} \frac{p}{\mu Z} dp$$

$= (P_{pe} - P_{pwf})$

Final General Gas Rate Eq

m^2 m Pa/s

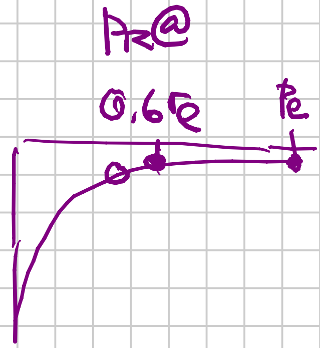
$$q_g = \frac{\pi k h \left(\bar{P}_{PR} - P_{pwf}\right)}{\left(\frac{T_R P_{sc}}{T_{sc}}\right)\left[\underbrace{\ln\frac{r_e}{r_w}}_{\sim 8} - 0.75\right]}$$

$\frac{K}{K}$ Pa

Sm^3/s

No-Flow @ r_e

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



Use $\bar{P}_R$ = vol. avg. p of drainage volume

instead of P_e

$$\ln\frac{0.6 r_e}{r_w} = \ln\frac{r_e}{r_w} - 0.5$$

Note Title 9/4/2008

GAS RATE EQ

$$\underline{\underline{q_g}} = \frac{10^6\,(\bar{k}h)^{\text{same}}}{\underbrace{\left(\frac{T_R\, p_{sc}}{T_{sc}}\right)_{\text{same}} \left[\underbrace{\ln\frac{r_e}{r_w}}_{\sim 8} - \underbrace{\frac{3}{4}}_{\text{No-Flow O.B.}} + s\right]}_{\text{"Constant" for a given well with a given } \bar{kh} \text{ and a given well geometry}}} \; \underbrace{2\int_{p_{wf}\;250}^{\bar{p}_R\;300} \frac{p}{\mu z}\, dp}_{(p_{pR} - p_{pwf})}$$

Vol. Avg. Res Press

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

"s" ("Skin")

Non-idealities ⇒ deviation from our simple geometric mode 

and $k(r, z, \theta) = \text{constant}$

$\bar{k} = 100$ md ↕ 2–5 orders of magnitude

Exception:
low $k(r \sim r_w)$

1) Damage

$$S_d = \left(\frac{\bar{k}}{k_d} - 1\right) \cdot \ln\frac{r_d}{r_w}$$

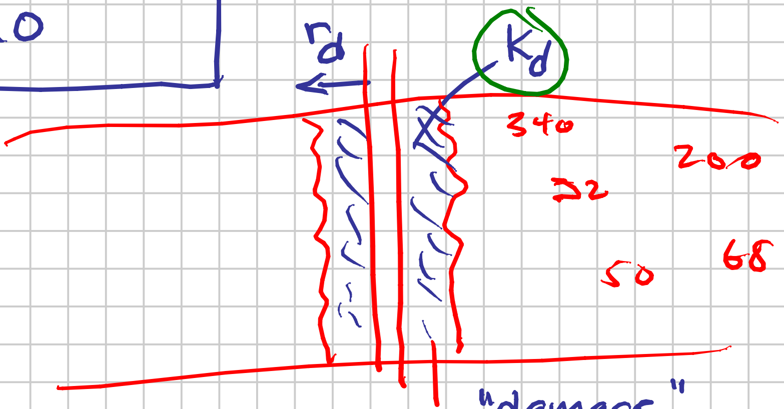
$\bar{k} = 100$ md

$k_d = 1$ md

$r_d = 2$ ft (0.7 m)

$r_w = 8$ in (0.2 m)

$\boxed{S_d = +120}$



"damage"

$K = 1$ md
$\downarrow$
0.1 md

No damage

$q_g = 10^6 \; Sm^3/d$

for same p_{wf}

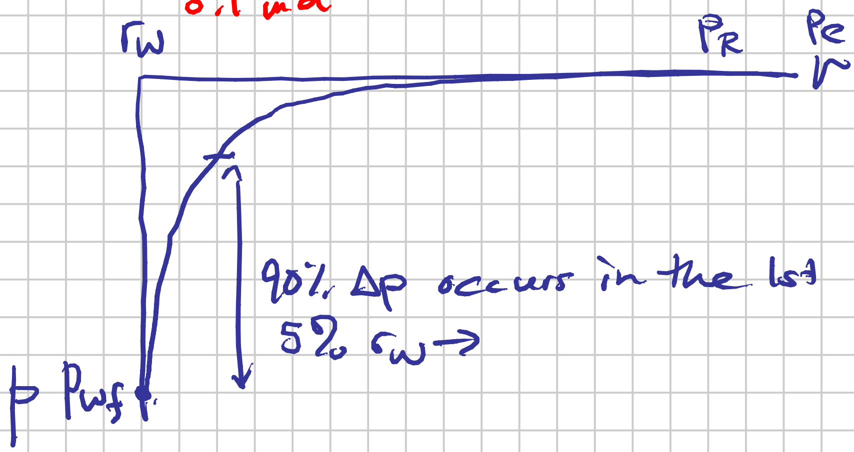
$p_R = 300$ bar

$p_{wf} = 250$ bar

SAME

$q_g = ?$

$S_d = +120$



$p \propto \ln r$

$$\left(\ln \frac{r_e}{r_w} - \frac{3}{4}\right) = 8$$

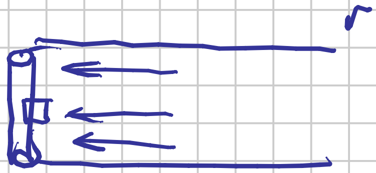
$$\frac{q_s}{q_{s=0}} = \frac{(\ln r_e/r_w + 0)}{(\ln r_e/r_w + S)}$$

$$= \frac{8}{8+120}$$

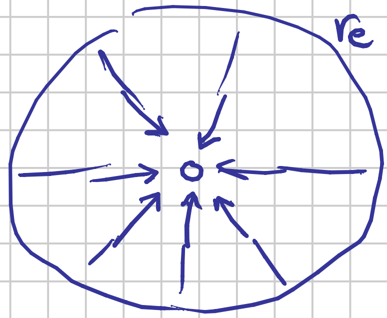
$$(q_g)_{s=120} = \underset{10^6}{(q_g)_{s=0}} \cdot \frac{8}{128} = \underline{62500 \; \frac{Sm^3}{d}}$$

- Flow Geometric Skin

Ideal:



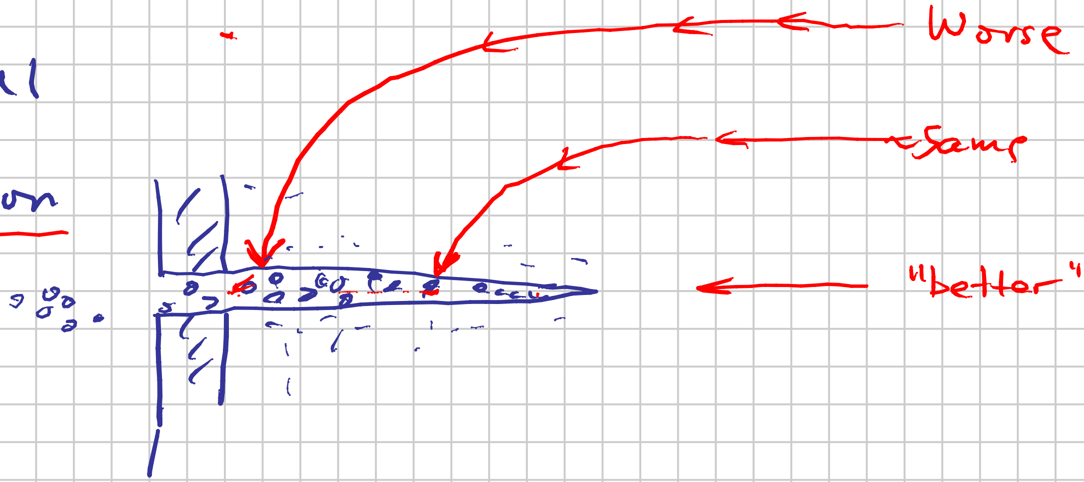
Side



Top

Non-Ideal

- Perforation



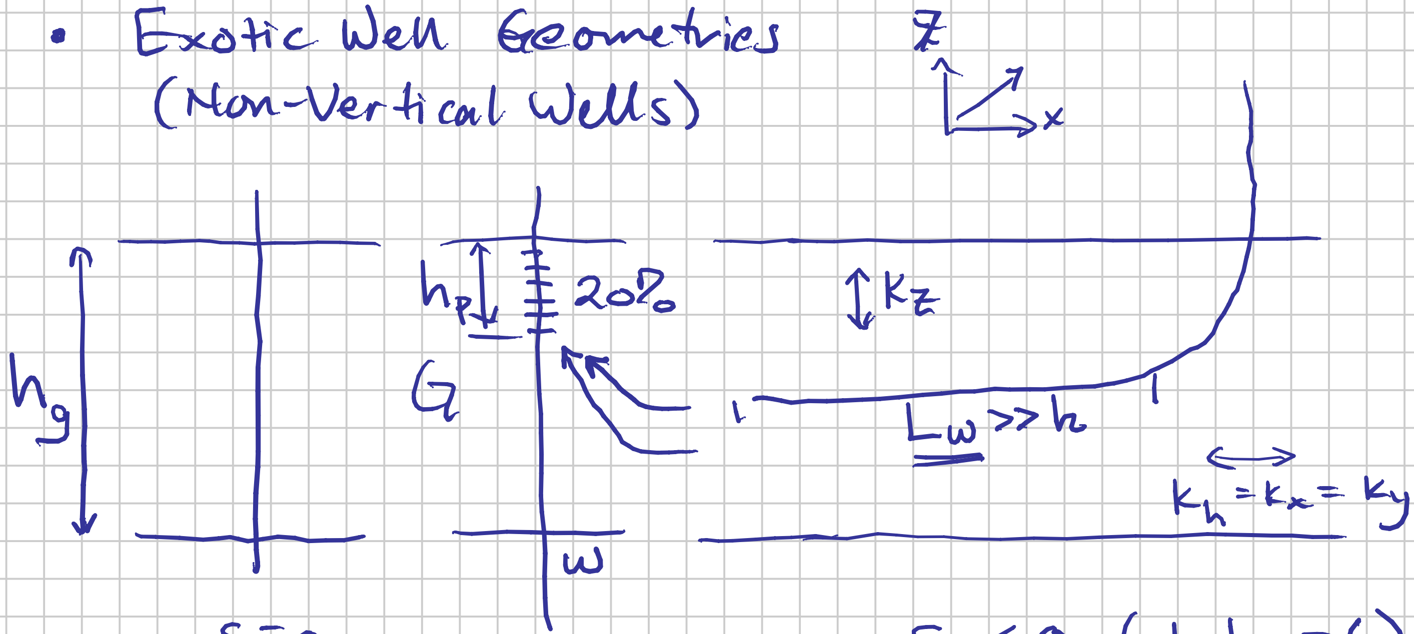
Casing

+0.5 ish

$\boxed{S_{perf} \sim 0}$

−0.5 ish

- Exotic Well Geometries
  (Non-Vertical Wells)



$s = 0$

$S_{pp} > 0$

$S_G < 0$ $(\underbrace{-1 \text{ to } -6}_{})$

$$S_{pp} = f\left(\frac{h_p}{h}, \sqrt{\frac{k_v}{k_h}}\right)$$

$$\underbrace{0.1-1 \qquad \frac{1}{3}-\frac{1}{10}}_{+1 \text{ to } +50}$$

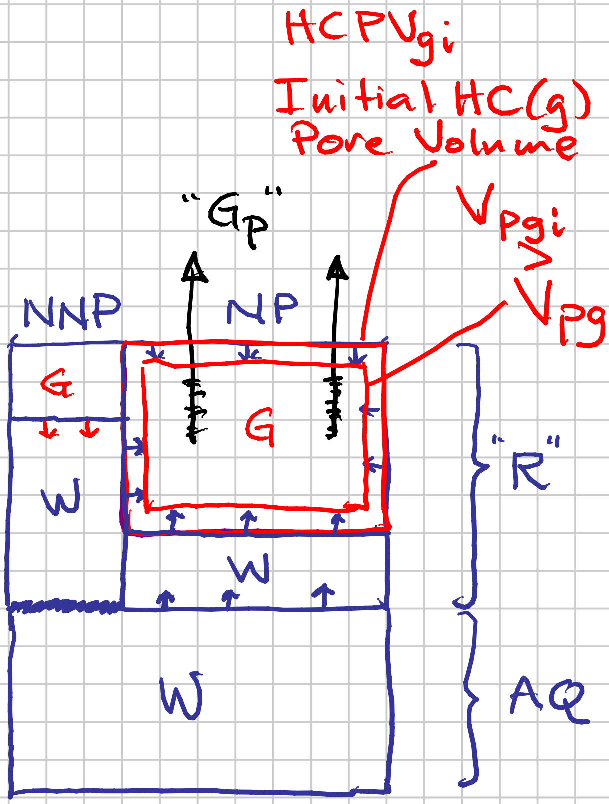
Generalized & Realistic Gas Material Balance (MB)

MB: $\bar{p}_R \sim G_p \leftrightarrow n_p$

G_p: Cumulate Surface Gas Volume Produced

Real Gas Law:

$$pV = nRTZ$$



$\boxed{\text{"Simplified" Gas MB}}$

V_{pgi} = constant

"R": Rock containing pores containing gas

"AQ" Rock "connected" (flow) to R but Containing only Water (Aquifer)

R: (1) NP - Net Pay ("good k"; significant flow of gas)

W: Connate Water

5% - 50% $k_w \sim 0$

(2) NNP   Non-Net Pay $k_g \sim 0$

$S_w \sim 50\text{-}100\%$

Often Interspersed between NP rock
- Shale
- "Dirty" (low k) sandstone / carbonate

V_{pgi} = constant

$pV = nRT_R Z$

$$V_{pgi} = n_{Ri} \cancel{R} \cancel{T_R} (Z_{Ri} / P_{Ri})$$

$$V_{pg} = n_R \cancel{R} \cancel{T_R} (Z_R / P_R) =$$

$$n_R = n_{Ri} - n_p$$

$$n_{Ri} (Z_{Ri} / P_{Ri}) = (n_{Ri} - n_p)(Z_R / P_R)$$

$$\frac{P_R}{Z_R} = \left(\frac{P_{Ri}}{Z_{Ri}}\right) \cdot \left(1 - \frac{n_p}{n_{Ri}}\right)$$

Cum. Produced Surface Gas Volume $\quad G_p = n_p \cdot \cancel{\frac{RT_{sc}}{P_{sc}}}$

Initial -" in Place $\quad G = n_{Ri} \cancel{\frac{RT_{sc}}{P_{sc}}}$

$$\boxed{\frac{p_R}{Z_R} = \left(\frac{p_{Ri}}{Z_{Ri}}\right) \cdot \left(1 - \frac{G_p}{G}\right)}$$

Kristin Field

$p_{Ri} = 900$ bara $\quad Z_{Ri} = 1.7$

$p_R = 450$ bara $\quad Z_R = 1.15$

Recovery Factor RF_g (G_p/G)

at 450 bara $= p_R$?

$$\frac{G_p}{G} = 1 - \frac{(p/Z)}{(p/Z)_i} = 1 - \frac{(450/1.15)}{(900/1.7)}$$

$$= 0.26 \qquad \underline{\underline{25\%}}$$

vs "intuitive" (ideal gas) 50% RF

Include the change in V_{pg} (p_R) due to

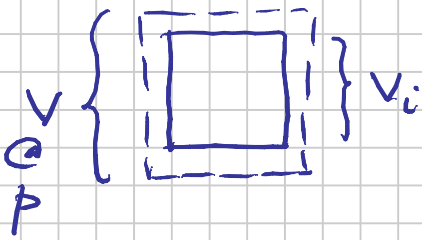
(1) AQ water expanding
(2) Connate water NP expanding
(3) — " — NNP — " —
(4) Pore Volume reduction

Two Physical Properties

(1) c_w ⇒ water expansion
(2) c_f c_r ⇒ pore volume change

Isothermal Compressibility

$$c \equiv -\frac{1}{V_i}\frac{dV}{dp}$$



p_i
↓ Δp -ve
p

Instantaneous compressibility

$V_i \rightarrow V$
$p_i \rightarrow p$
requires integrating this equation

e.g. assume c = const.
⇒

Use a concept of "cumulative compressibility"

$$\bar{c} = -\frac{1}{V_i}\cdot\frac{\Delta V}{\Delta p}$$

any Δp change

$V_{pgi} \rightarrow V_{pg}$ Volume of R gas $\Rightarrow$ Gas Law

$$V_{pgi} - V_{pg} = \Big\{ \underbrace{\underset{\substack{\text{rock}\\ \text{comp.}}}{\Delta V_{pg}} + \underset{\substack{\text{water}\\ \text{entering}}}{\Delta V_{pg}}} \Big\}$$

$$\left\{ \begin{array}{ll} c_w & V_w \\ c_f & V_p \end{array} \right\}$$

(MP + NNP + Aq)

Composite all of these effects into a single

Total Cumulative Effective Compressibility $\boxed{\bar{c}_t}$ est.

$$\bar{c}_t = \frac{1}{V_{pgi}} \cdot \frac{\Delta V_{pg}}{\Delta p}$$

Est.

Solve for V_{pg}

$$\Delta V_{gp} = - V_{pgi} \cdot \bar{c}_t \, \Delta p$$

$$V_{gpi} - V_{pg} =$$

$$\therefore V_{pg} = V_{pgi} (1 - \bar{c}_t \Delta p)$$

Real Gas Law:

$$pV = nRTZ$$

$$V = V_{pg}$$

$$n = n_R = n_{Ri} - n_p$$

$$p_R \cdot V_{pgi} (1 - \bar{c}_t \Delta p) = (n_{Ri} - n_p) R T Z_R$$

$$V_{pgi} = \frac{n_{Ri} R T Z_{Ri}}{p_{Ri}}$$

$\Delta p = p_{Ri} - p_R$

$$\frac{p_R}{Z_R}\left(1 - \bar{C}_t \Delta p\right) = \left(\frac{p_{Ri}}{Z_{Ri}}\right)\left(1 - \frac{n_p}{n_{Ri}}\right)$$

G_p/G

POT AQUIFER MODEL

$$\boxed{\frac{p_R}{Z_R}\left(1 - \bar{C}_t \Delta p\right) = \left(\frac{p_{Ri}}{Z_{Ri}}\right)\left(1 - \frac{G_p}{G}\right)}$$

Recovery Factor

Traditional Simplified MB

$\Delta p\, C_t = 0$

$V_{pg} = V_{pgi}$

SPE 22921

Fetkovich et al.

$\bar{C}_t = \bar{C}_e$: V_{AQ}, V_{pR}, C_w, C_f

G

High-p Reservoir

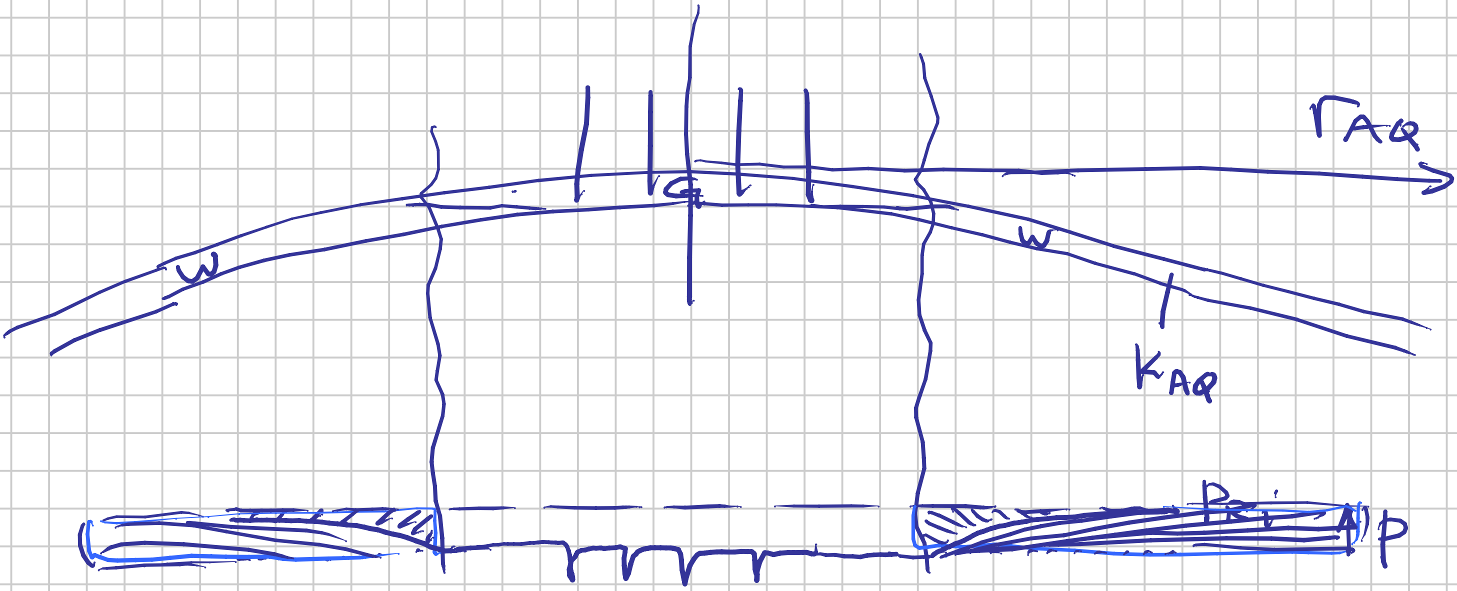
$c_w(p)$
$c_f(p)$

$$M \equiv \frac{V_{AQ}}{V_{pR}} \qquad 0.1 - 10^{+}$$

MOST GENERAL GAS M.B.

– Takes into account

$$\bar{p}_{AQ} \underset{(>)}{\neq} \bar{p}_R$$



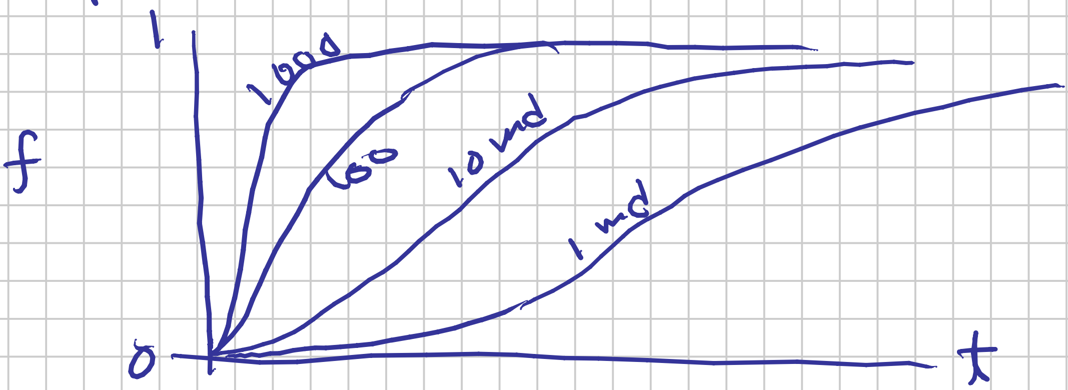
Max Water Volume Encroachment

$$\underbrace{f(t)}_{0-1} \; V_{AQ} \cdot c_{AQ} \cdot (p_{Ri} - p_R)$$

Superposition
Van Everdingen
Hurst

Fetkovich
Simplified

⋮

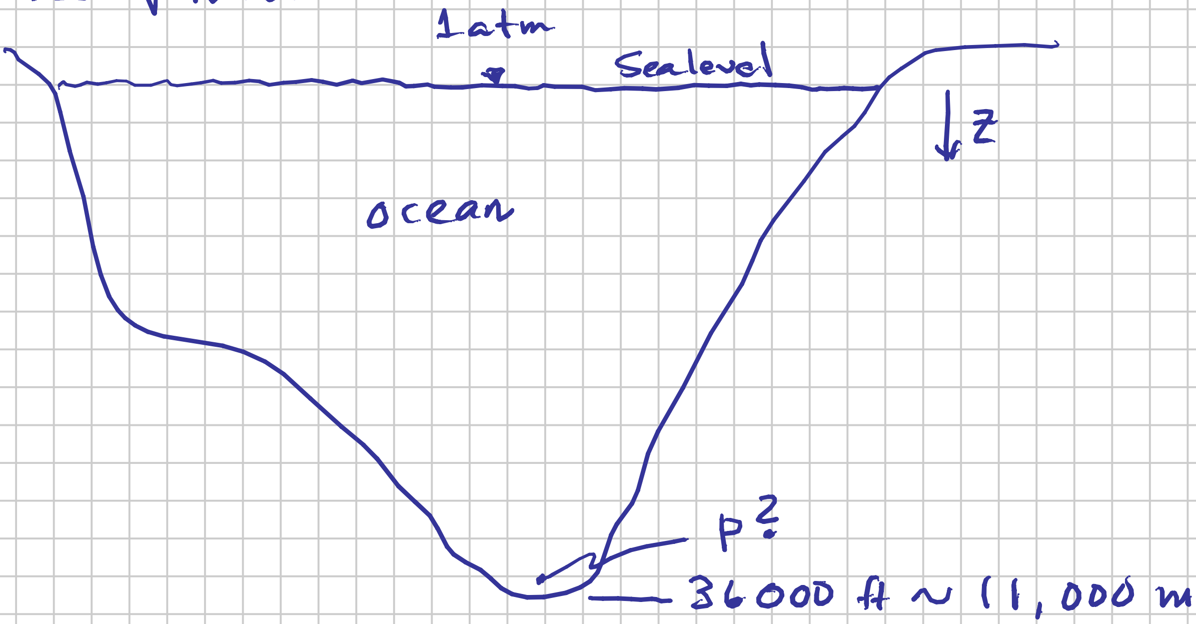


Note Title 9/10/2008

TODAY : QUIZ

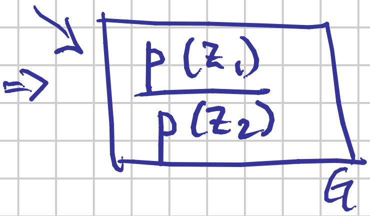
Simple PVT Models to estimate the pressure-vs-depth relationship of {Gas, Oil, Water} in a "static column" of fluid

Assumptions:



- $T(z)$ = constant

- Static : $\dfrac{dp}{dz} = \rho g$



$z_1 > z_2$

$p(z_1) > p(z_2)$

Water : $c_w \equiv -\dfrac{1}{V}\left(\dfrac{dV}{dp}\right)_T$ = constant

(ρ_w^o) at 1atm
e.g. 1025 kg/m^3
Seawater

Oil : c_o = const ~~$c_o(p)$~~ ....

Gas : $pV = nRTZ$

$$\Rightarrow \rho_g = \frac{m}{V} = \frac{nM}{V} = \frac{pM}{RTZ} \simeq \frac{pM}{RT\bar{Z}}$$

$Z_1(p)$ complex

Assumption: $\underbrace{\underset{\text{depth } z}{\underset{\uparrow}{p(z_2)}} \rightarrow \underset{\text{depth}}{\underset{\uparrow}{p(z_1)}}}_{\bar{Z} \text{ at } \frac{p_1+p_2}{2}}$

Quiz:

(1) p at deepest ocean depth*

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

(2) $\frac{p(z_1)}{p(z_2)}$ for gas

* c_w? Ch. 9, $\sim 2.5 \cdot 10^{-6}$ $\cancel{\frac{vol}{vol}} \cdot \frac{1}{psi} \times \frac{14.5\ psi}{bar}$

$= 36 \cdot 10^{-6}$ 1/bar

Ignore c

$\rho_w = \rho_w^\circ = 1025\ kg/m^3$

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

$$p_2 - p_1 = \rho g (z_2 - z_1)$$

$p_1 = 1$ atm ~ 1 bar

$\rho = 1025\ kg/m^3$

$g = 9.8\ m/s^2$

$z_1 = 0$

$z_2 = 11\,000$ m

$$p_2 = p_1 + \underbrace{\overset{10^4}{(1025)(9.8)}(11000)}_{Pa}$$

$$= 10^5 +$$

$$= 10^5 + 1.1 \cdot 10^8$$

$$= 1.1\ldots \cdot 10^8$$

$$= 1100 \text{ bar}$$

$$c = -\frac{1}{V}\frac{dV}{dp}$$

$$c\int_{p_1}^{p_2} dp = -\int_{V_1}^{V_2} \frac{1}{V}\, dV$$

$$c(p_2 - p_1) = \ln V_1/V_2$$

$$V_2 = V_1 e^{-c\Delta p}$$

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

$$\rho_2 = \rho_1 e^{c\Delta p}$$

$$\boxed{\rho = \rho_0 \cdot \exp(c\,\Delta p)}$$

$$1025 \cdot \exp\Big(\underbrace{36 \cdot 10^{-6}}_{\frac{1}{bar}} \cdot \underbrace{1100}_{bar}\Big)$$

$$= 1025 \cdot 1.$$

$$= 1066 \text{ kg/m}^3$$

$$p_{bottom} = 1100^{+} \text{ bar}$$

Gas:

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

$$\rho = \frac{pM}{RTZ} \simeq \underbrace{\left(\frac{M}{RTZ}\right)}_{const.} \cdot p$$

$$\int \frac{1}{p}\, dp = (\quad)\int dz$$

$$\ln p_2/p_1 = \left(\frac{M}{RTZ}\right)(z_2 - z_1)$$

$\downarrow z$

$$\boxed{\frac{p_2}{p_1} = \exp\left\{\left(\frac{Mg}{RT\bar{Z}}\right)(z_2 - z_1)\right\}}$$

True Vertical Depth TVD

$z_1 > z_2$

Bottomhole → P_1

Surface → P_2

$$\frac{P_1}{P_2} = \underbrace{\exp\left\{\underbrace{\left(\frac{Mg}{RT\bar{Z}}\right)}_{>0}\underbrace{(z_1 - z_2)}_{>0}\right\}}_{\underbrace{>0}_{\sim\text{constant}}}$$

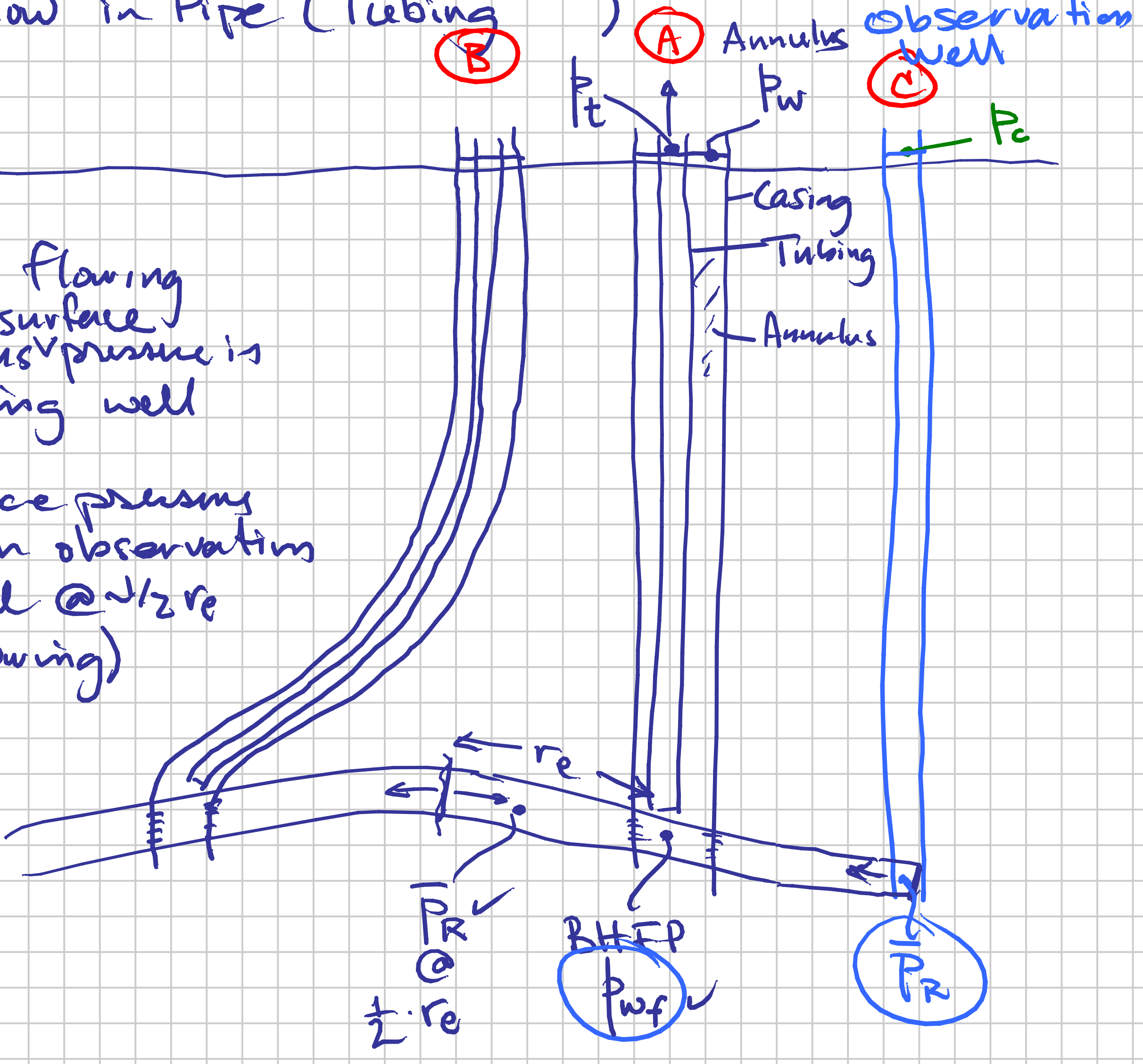
1.1 – 1.25

Gas Flow in Pipe (Tubing)

P_t = tubing flowing surface

P_W = annulus pressure in a flowing well

P_c = surface pressure of an observation well @ ~½ r_e (not flowing)



$$\exp\left\{\frac{Mg}{RT\,\bar{Z}}\right\} = 1.1$$

Observed Surface Pressure bara	A	B	C
	220	170	380

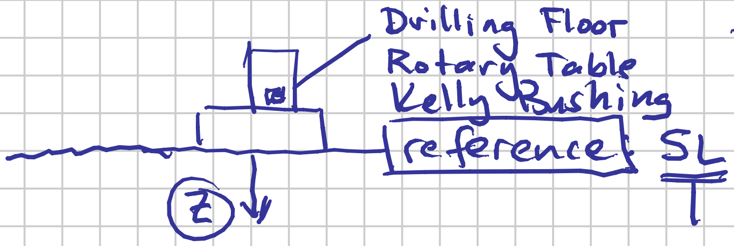
Calculate: $(p_{wf})_A$ $(p_{wf})_B$ p_R

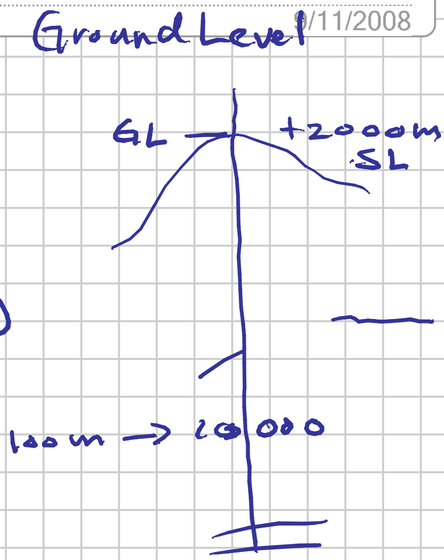
Can I calculate $(p_t)_A$ $(p_t)_B$?

What do I need to calculate ?

Note Title 9/11/2008

Summarize Static Column $p(z)$ Issue





$p(z) \propto \rho$

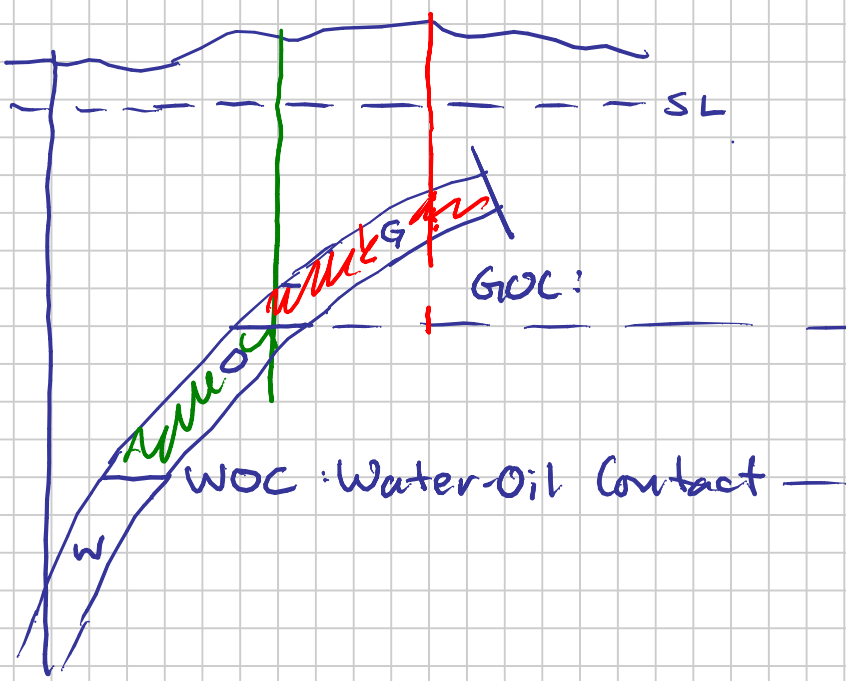
1st Approx: ρ_p = constant

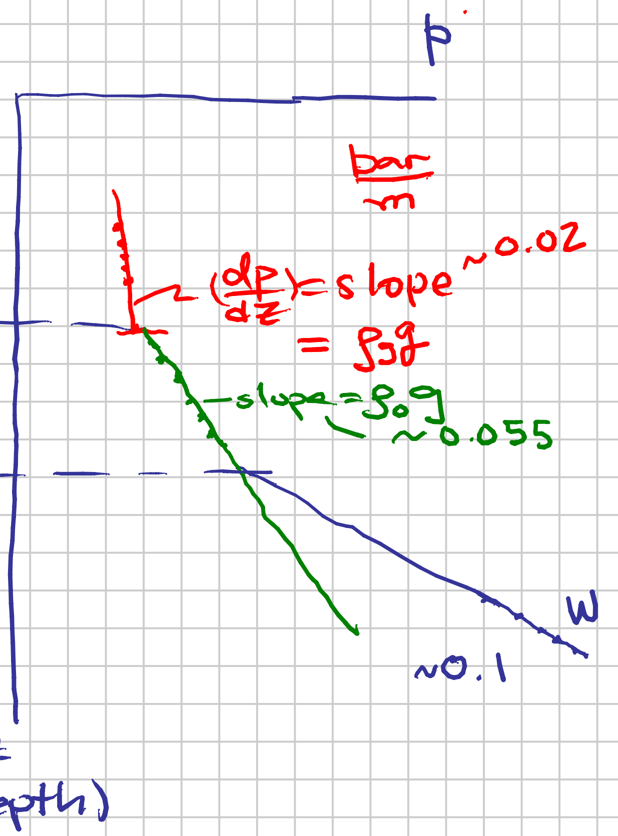
Within the Reservoir: $p \in (g, o, w)$

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

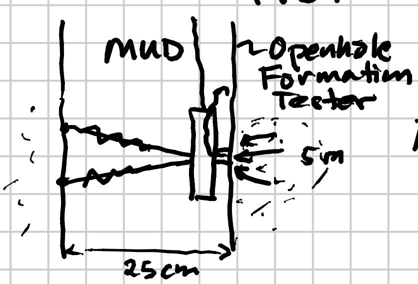
Water Gradients (slope) 0.1 bar/m

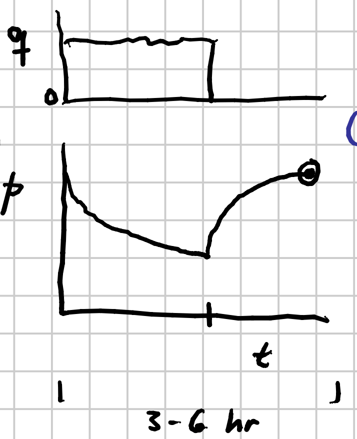
Gas Grad. 0.015–0.035 $\frac{bar}{m}$





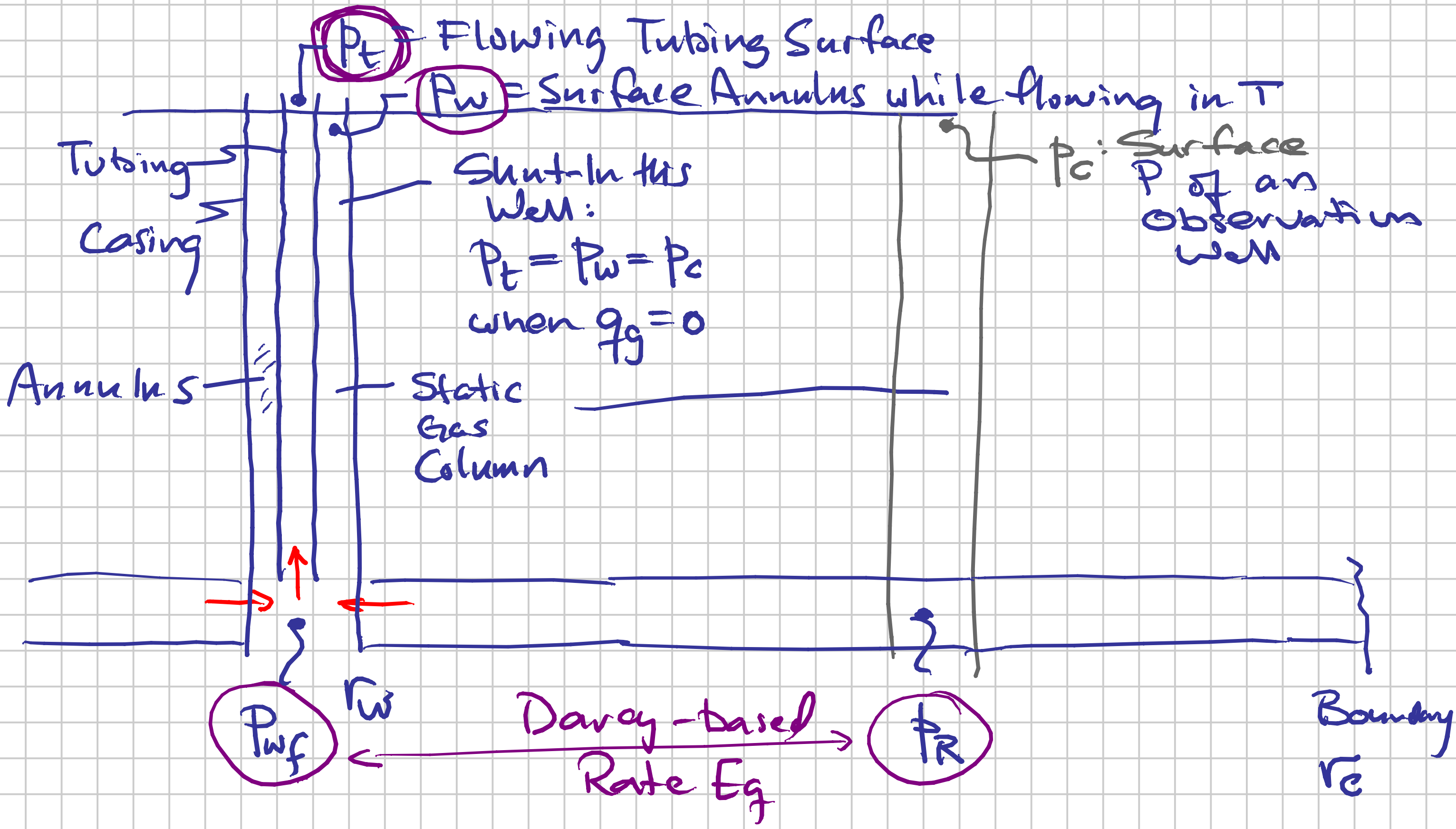
MDT





Gas Reservoirs

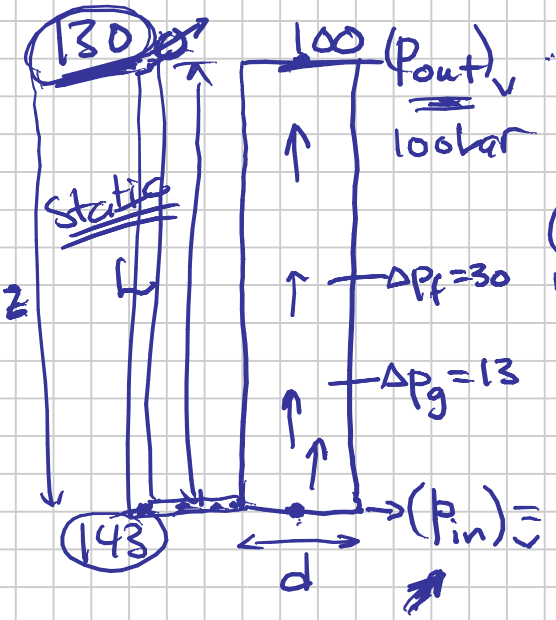
Gas Flow through (Tubing) Pipe



p_t, p_w, p_c all SURFACE elevation pressures

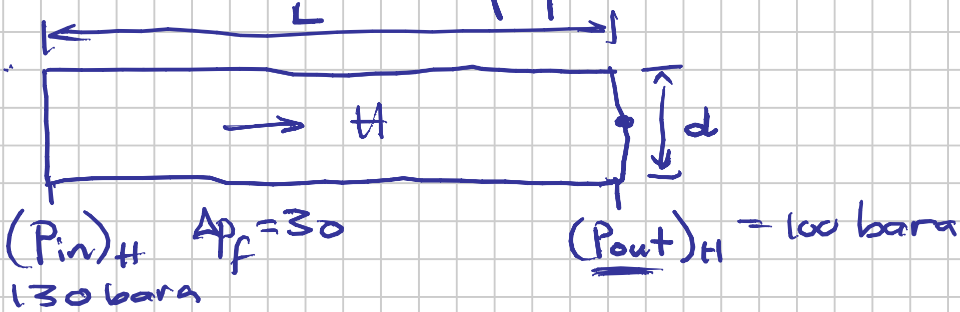
$$\frac{p_{wf}}{p_w} = \frac{p_R}{p_c} = \exp\left\{\frac{Mg}{RT\bar{Z}}\right\}$$

Friction Pressure Losses in pipe:



$(P_{in}) \doteq 130 \cdot \underbrace{\exp\{S/2\}}_{1.1}$

$= 143$



$$(P_{in}^2)_H - (P_{out}^2)_H = \underbrace{\left(\frac{(P_{in})_V}{e^{S/2}}\right)^2}_{\text{Elevation Corrected pressure}} - (P_{out}^2)_V$$

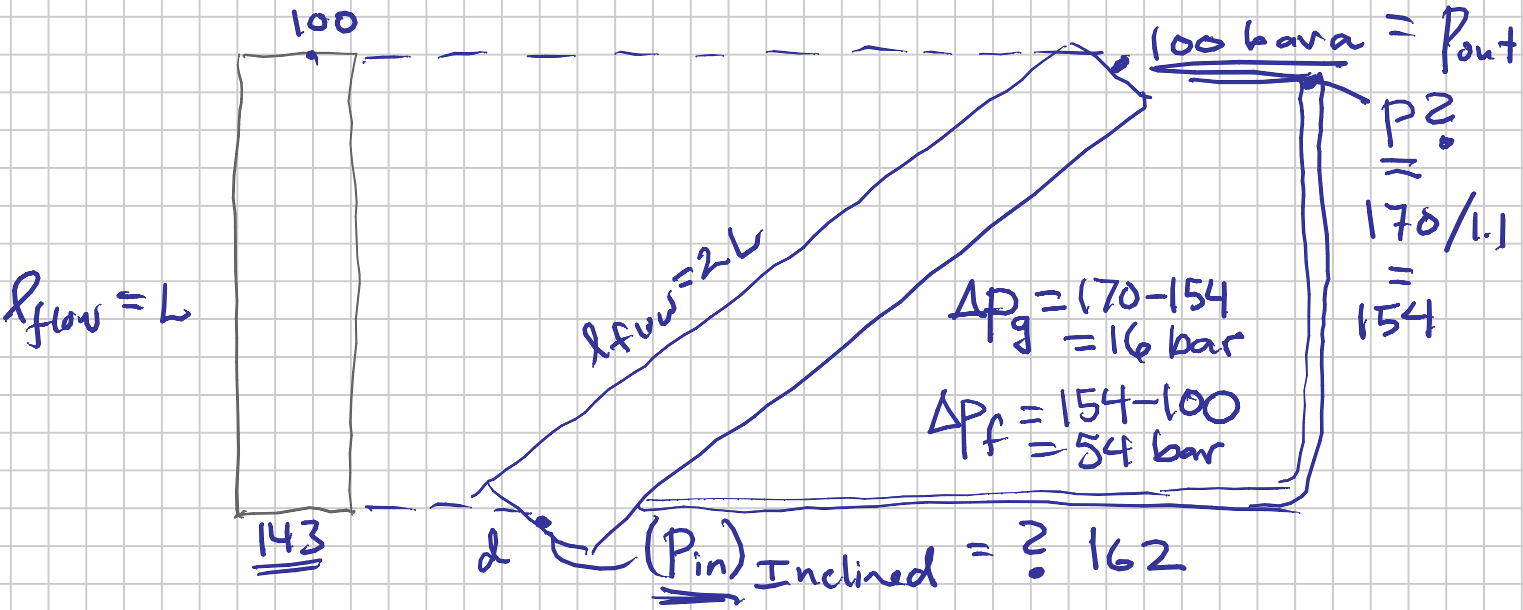
$\rho \underset{\sim}{\propto} p$

TVD

$$S \equiv \frac{2 \cdot Mg}{RTZ} L$$

$$\rightarrow \frac{p_1}{p_2} = \exp\left\{\frac{Mg}{RTZ}\Delta z\right\}$$

$p_1 > p_2 \qquad \Delta z > 0$



$$\underbrace{(\Delta p_f^2)} \propto l_{flow}$$

$$\left(\frac{(P_{in})_I}{1.1}\right)^2 - P_{out}^2 = 2 \cdot \Delta p_f^2 = 2 \cdot \underbrace{(130^2 - 100^2)}$$

$l_{flow} = L \qquad = 13800$

$$\Rightarrow (P_{in})_I = \left[(13800 + 100^2)\right]^{1/2} 1.1$$

$$= 170 \text{ bara}$$

Summary:

$$\dot{m} = a\cdot\left(\tilde{P}_{in}^2 - \tilde{P}_{out}^2\right)^{1/2}$$

Volumetric surface gas rate $q_g = \dot{m}\cdot(\rho_g)_{sc}^{-1}$

$\frac{kg}{s}\cdot\frac{m^3}{kg}$

$$\boxed{q_g = C\left(\tilde{P}_{in}^2 - \tilde{P}_{out}^2\right)^{1/2}}$$

$\tilde{p}$ = equivalent pressure at a common depth reference "datum" @ $\tilde{z}$

Depths

$$\tilde{p}_{(\tilde{z})} = p_{(z)}\cdot\exp\left\{\frac{M_g}{R\bar{T}\bar{Z}_1}\cdot(z-\tilde{z})\right\}$$

Gas Z-factor!

Tubing Flow Constant C_T or "T"

Fetkovich paper

Units, Mair, "Z"

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

and e = natural log

G = gas gravity (γ_g)

H = vertical depth, ft TVD

T_a = average temperature, °R $\bar{T}$

Z_a = gas deviation factor at average pressure $\bar{Z}$

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

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

Q = Mscfd

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

$P_c/P_R = 1/e^{S/2}$; $P_R^2 = P_c^2\cdot\exp\{S_1\}$

q_g Mscf/D = 10^3 scf/D

Tubing Friction Curves

The basic equation relating wellhead static column pressure p_w and the wellhead flowing tubing pressure P_t as given in the IOCC Manual[4] is

$$p_{wf}^2 = e^s\ P_t^2 + \left(\frac{F_r\ Q\ T_a\ Z_a}{31.62}\right)^2 (e^s - 1) \qquad ..(21)$$

where

$$\boxed{F_r = \frac{0.10797}{D^{2.612}}} \qquad \text{with D in inches.}$$

Dividing both sides by e^s, we obtain

$$\frac{p_{wf}^2}{e^s} = P_t^2 + \left(\frac{F_r\ Q\ T_a\ Z_a}{31.62}\right)^2 \frac{(e^s - 1)}{e^s} \qquad ..(22)$$

with $p_{wf}^2/e^s = p^2_w$ we can rearrange and obtain

$$Q = \boxed{\left[\frac{31.62\ e^{s/2}}{\sqrt{(e^s - 1)}\ F_r\ T_a\ Z_a}\right]} (p_w^2 - P_t^2)^{0.5} \qquad ..(23)$$

The general form is simply

$$Q = T\ (P_w^2 - P_t^2)^{0.5} \qquad ..(24)$$

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

$\tilde{p}_{wf}$ corrected to surface datum

$$C_T = \underbrace{\frac{31.62\ e^{s/2}}{\sqrt{e^s - 1}\ \bar{T}\bar{Z}}}_{\text{Given well tubing} \cong \text{constant}} \cdot \left\{\frac{1}{F_r}\right\} = \text{const.} \cdot d_T^{2.6}$$

$$\left\{d_T^{2.6}\right\}$$

Main engineering parameter controlling

ΔP_f

Gas Rate Eq.

Darcy: $q_g = C_R\,(P_R^2 - P_{wf}^2)$ low-p approx.

$$C_R = \frac{kh}{(\quad)\left[\ln\frac{r_e}{r_w} - \frac{3}{4} + S\right]}$$

Tubing

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

Control!

Bring all pressures to surface datum

$P_w,\ P_t$ ✓

$P_c = P_R / e^{S/2}$ $P_R^2 = P_c^2 \cdot e^S$

$P_w = P_{wf} / e^{S/2}$ $P_{wf}^2 = P_w^2 \cdot e^S$

$$q_g = \left\{C_R \cdot e^S\right\}(P_c^2 - P_w^2)$$

$$\left\{\begin{array}{l} q_g = C_R'\,(P_c^2 - P_w^2) \\ q_g = C_T\,(P_w^2 - P_t^2)^{1/2} \end{array}\right\} \text{Combine}$$

"R" Δp $\quad p_c^2 - p_w^2 = \frac{1}{C_R'} q_g$

"T" Δp $\quad p_w^2 - p_t^2 = \frac{1}{C_T^2} q_g^2$

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

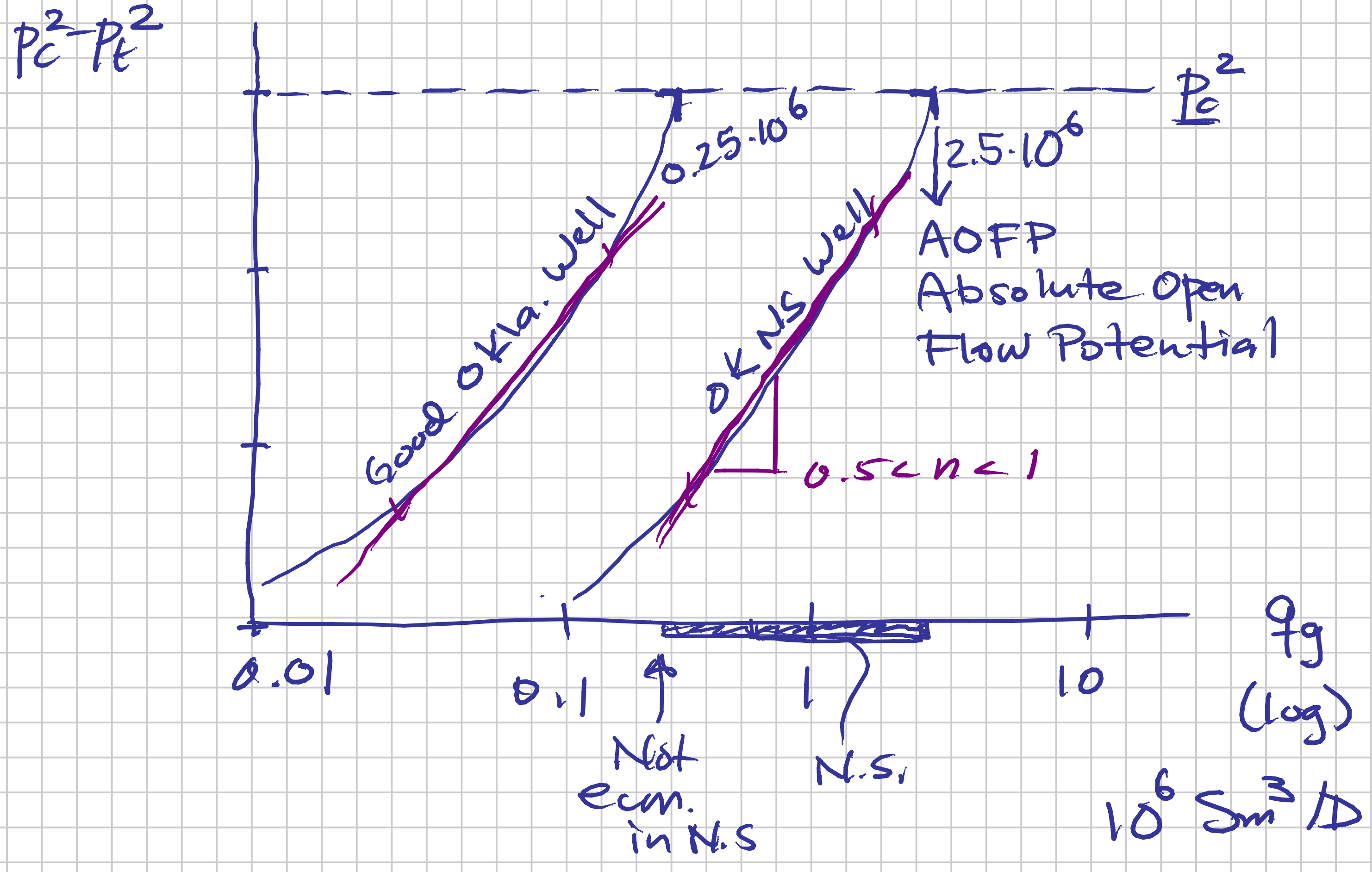
Quadratic Eq q

$$0 = ax^2 + bx + c$$

$$\underline{\underline{q_g}} = \frac{-C_R'^{-1} + \left[C_R'^{-2} - 4\left(\frac{1}{C_T^2}\right)\Delta p^2\right]^{1/2}}{2\left(\frac{1}{C_T^2}\right)}$$

$(p_c^2 - p_t^2) = \Delta p^2$

Wellhead (Tubinghead) Backpressure Eq.



Approximate "Model" Eq.

$$q_g \cong C\,(P_c^2 - P_t^2)^n \quad ; \; n \; 0.5 \to 1$$

Want to know

Control

$$\begin{Bmatrix} C_R \\ C_T \end{Bmatrix}$$

Nature (kh) ... (T, ...)

Us (s) (d_T)

$$\beta \propto \left(\frac{1}{k}\right)$$

Note Title 9/17/2008

Forchheimer 190x — Rock Property — Darcy

$$\underbrace{\frac{dp}{dx}} = \underline{\left(\frac{\mu}{k}\right)v} + \underbrace{\beta \rho v^2}_{*} \qquad \frac{dp}{dx} = \left(\frac{\mu}{k}\right) v$$

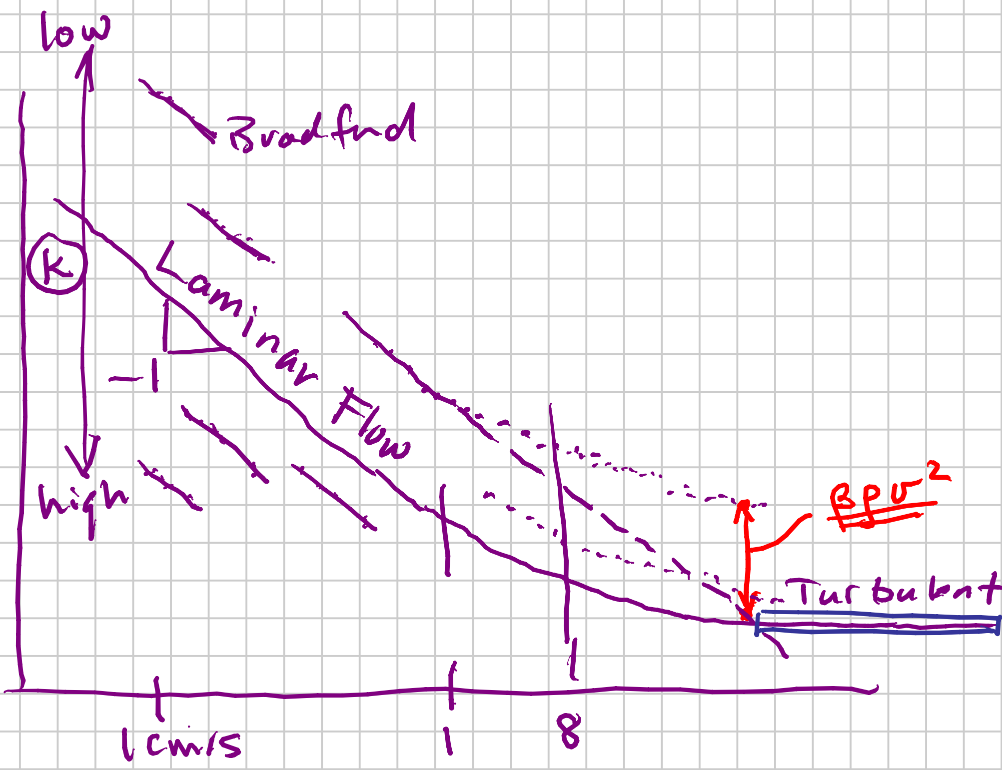
Morris Muskat

1930s

Friction Factor

$$f \sim \frac{\text{"}\Delta p\text{"}}{v^2}$$

(log)



Muskat "Re" ~ "v"

(log)

Gas Flow in Pipe:

$$\boxed{q_g = C_p (P_{in}^2 - P_{out}^2)^{0.5}} \Rightarrow f = \text{constant}$$

"totally" turbulent flow.

$$\Downarrow$$

$$f_g = \frac{\Delta p^2}{q^2} \quad \text{vs} \quad q$$

$q \propto v$

$\frac{\Delta p^2}{v^2}$ vs v

$$q_g = \left\{ \frac{kh}{T_R \left[\underbrace{\ln \frac{r_e}{r_w} - \frac{3}{4}}_{\sim 8} + s \right]} \right\} \underbrace{\int_{p_{wf}}^{p_R} \frac{p}{\mu Z} \, dp}_{}$$

"C"

$$p_{pR} - p_{pwf} = \Delta p_p$$

Forchheimer "Modification"

Constant $\propto \beta$

Total $S_t = s^* + (D q_g) \Rightarrow \left\{ \begin{array}{c} \text{Rate-dependent} \\ \text{Skin} \end{array} \right\}$

Constant:
- Damage
- Flow Geometry

$D q_g \sim 1 \to 100$

(*) Needs to be quantified.

Not to be used $\rightsquigarrow \beta = a k^{b\nu - 1}$ ✗

$\Rightarrow$ Tend to estimate a D value ~ 10 times too small

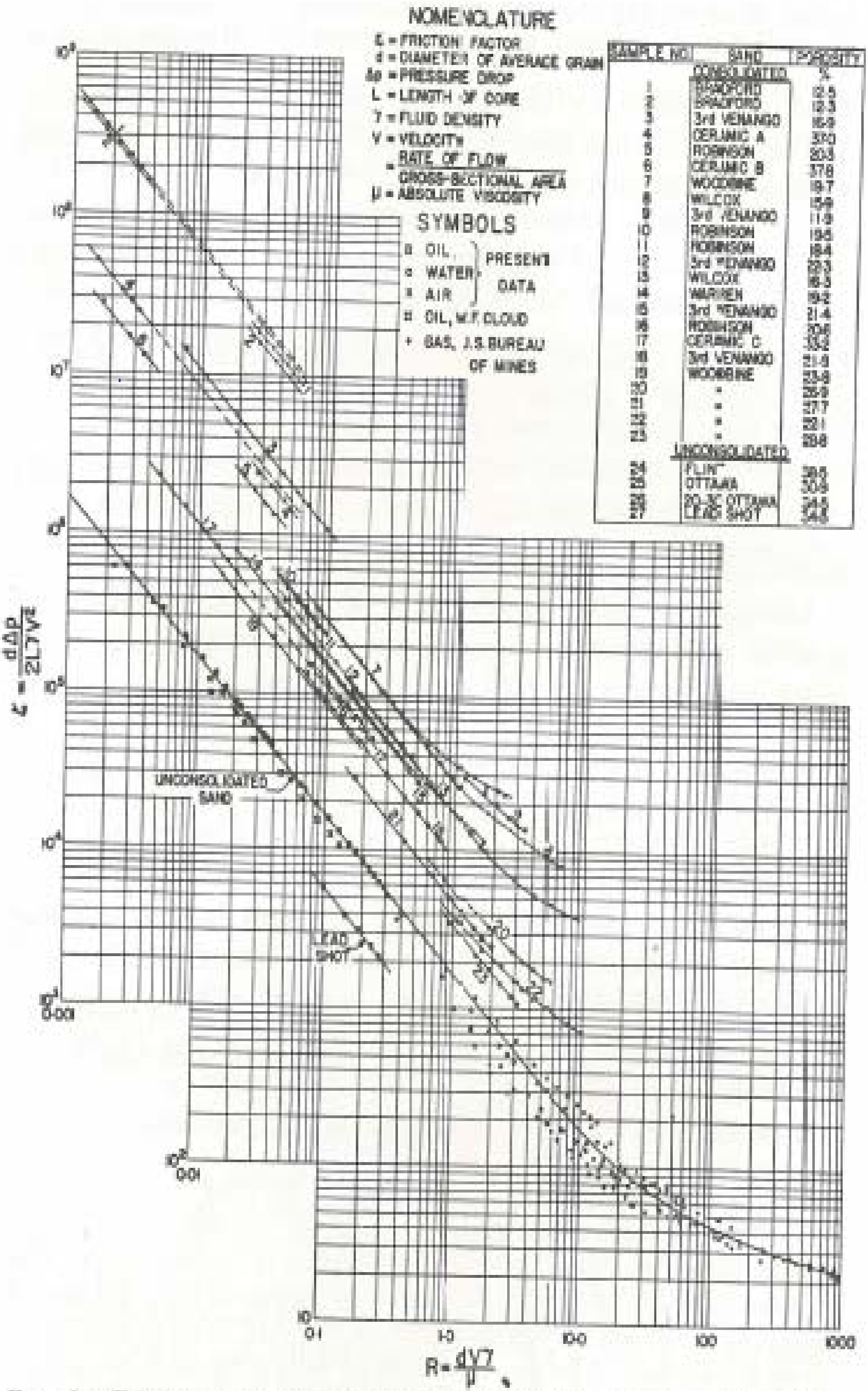


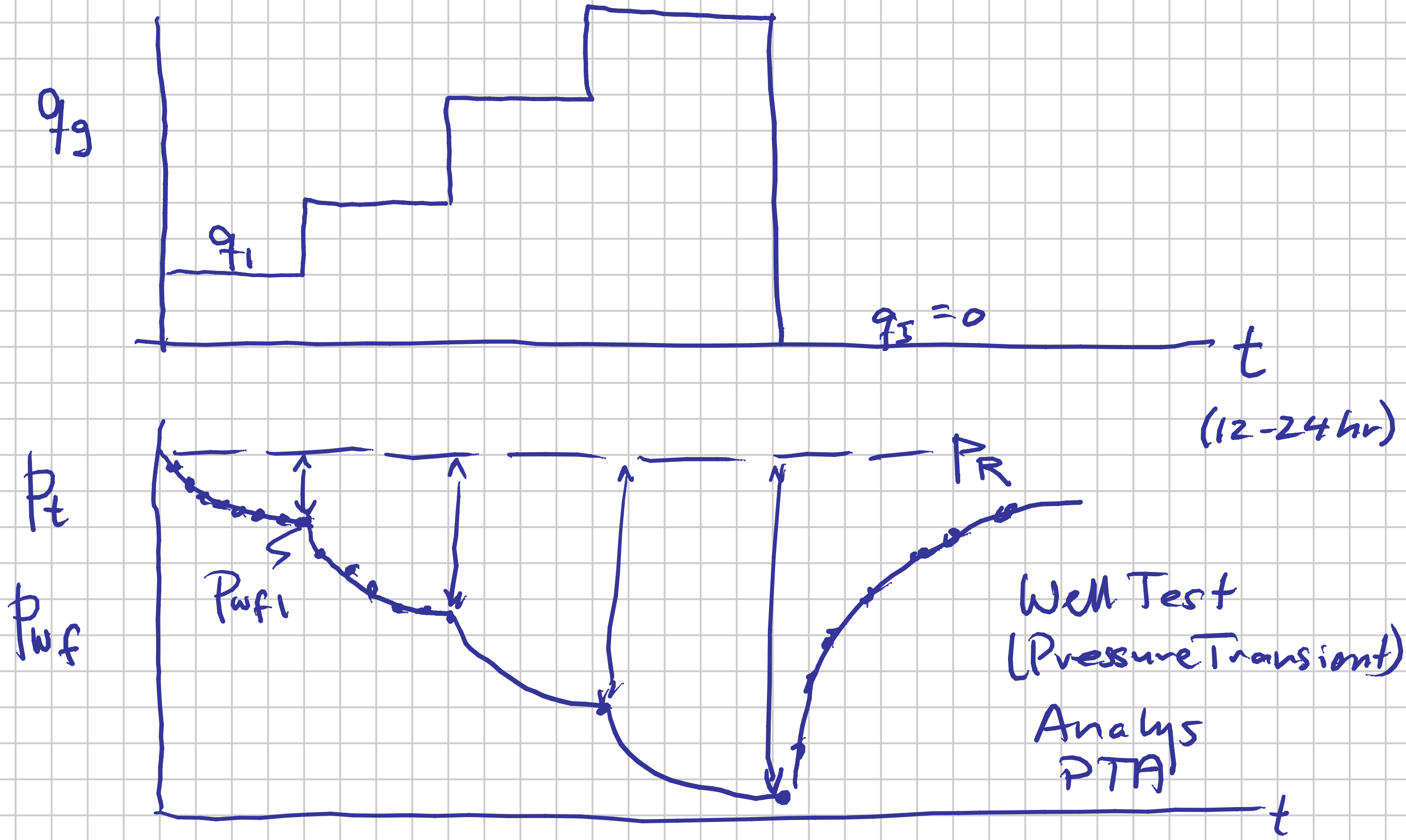
Fig. 8.—Friction-factor chart for the flow of fluids through sands. (*After Fancher, Lewis, and Barnes, Bull. Pa. State Expt. Sta.*)

Need for MULTI-RATE TESTING OF (ALL) GAS WELLS

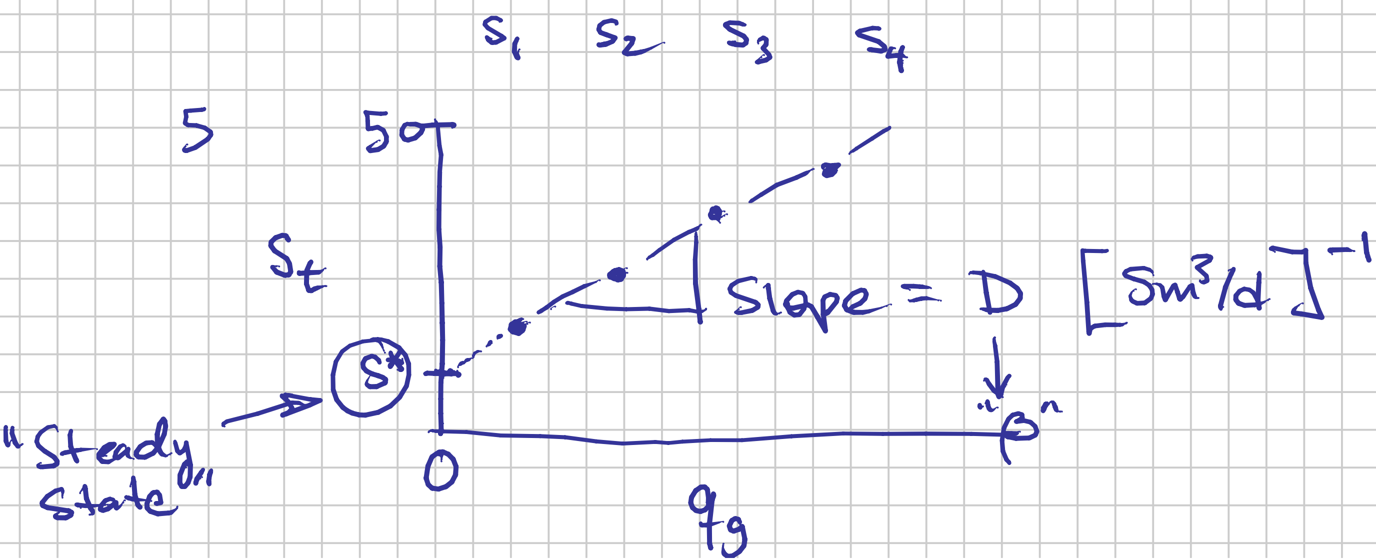
⇒ Fetkovich

Multi-Rate Test Methods :

① Isochronal



know : (kh)



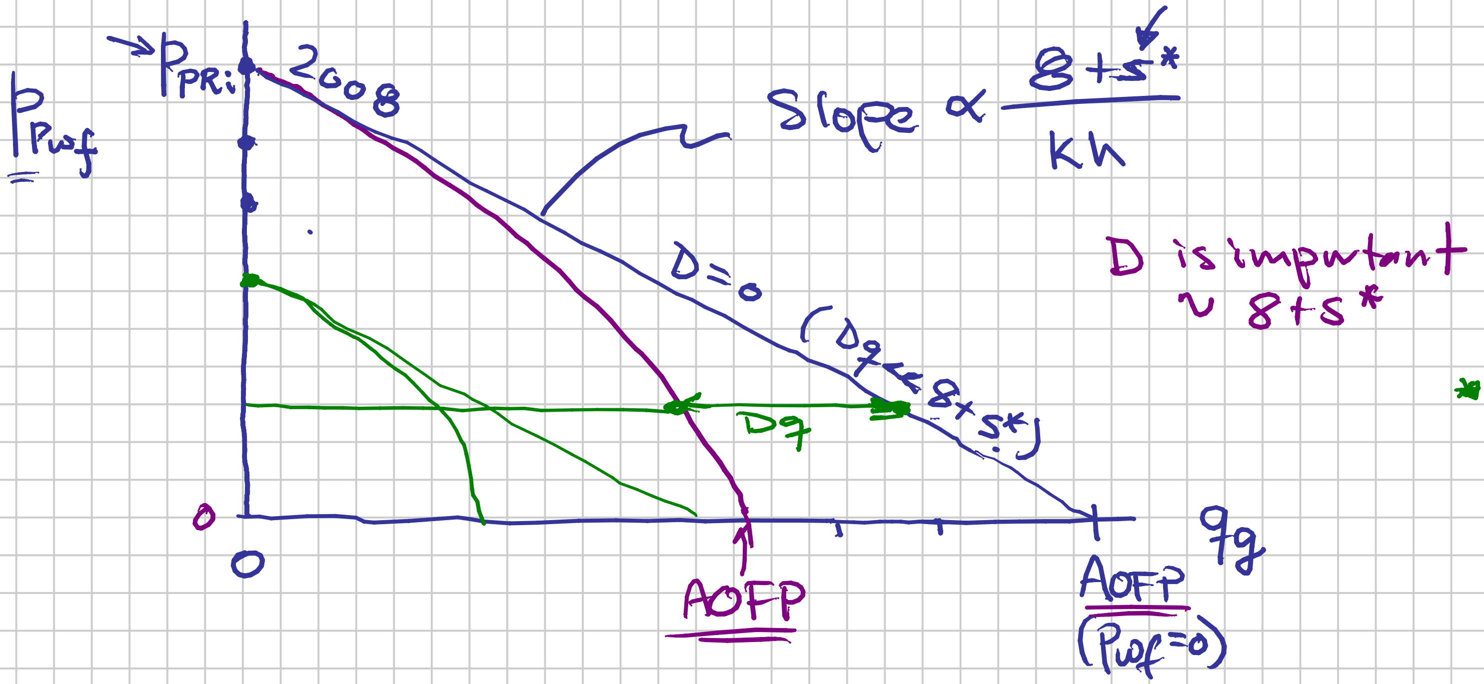
Damage + Flow Geometry

Resolve Rate equation

$$A q_g^2 + B q_g + \Delta P_p = 0$$

Graphical Representation

① Inflow Performance Relation (IPR)



② Backpressure Plot: Fetkovich

Note Title 9/18/2008

Gas Rate Eq.

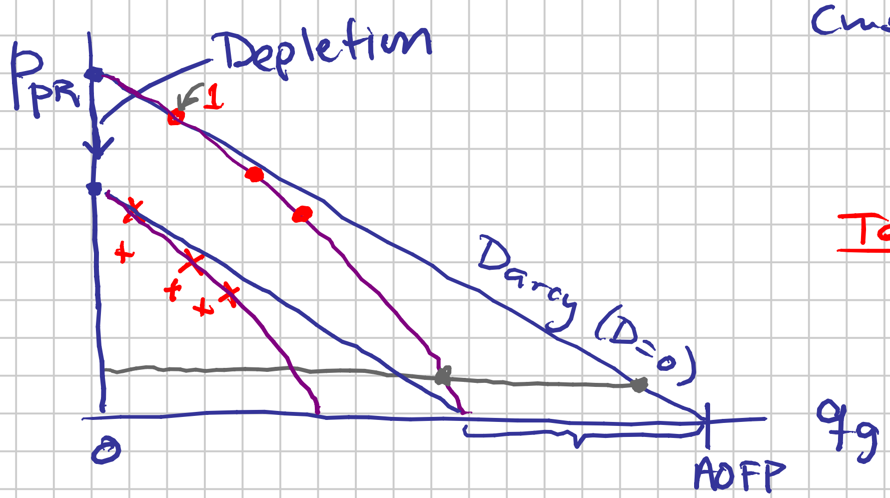
Based on Forchheimer "Law"

Graphical Presentation

$$q_g = \frac{kh\,(P_{pR} - P_{pwf})}{T_R\left[\ln\frac{r_e}{r_w} + s^* + \underbrace{Dq_g}\right]}$$

Const — Rate Dependent

(1) IPR



Test Data

● 2008

× 2010

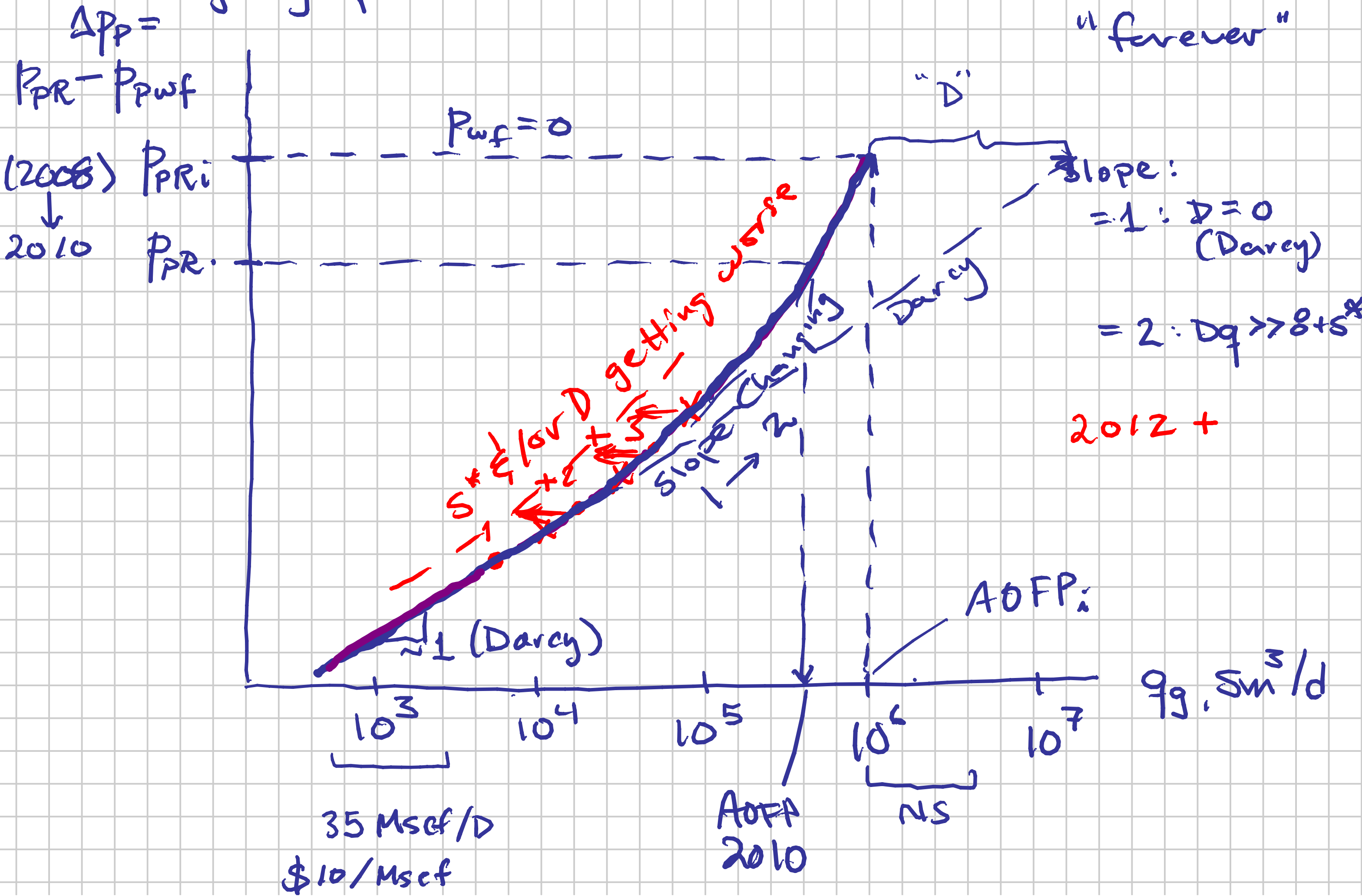
Prosper

(2) Backpressure Plot (Diagnostic)

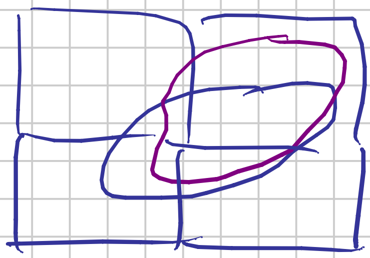
log-log plot

$\underbrace{\bar{kh},\ \underline{s^*},\ D}$

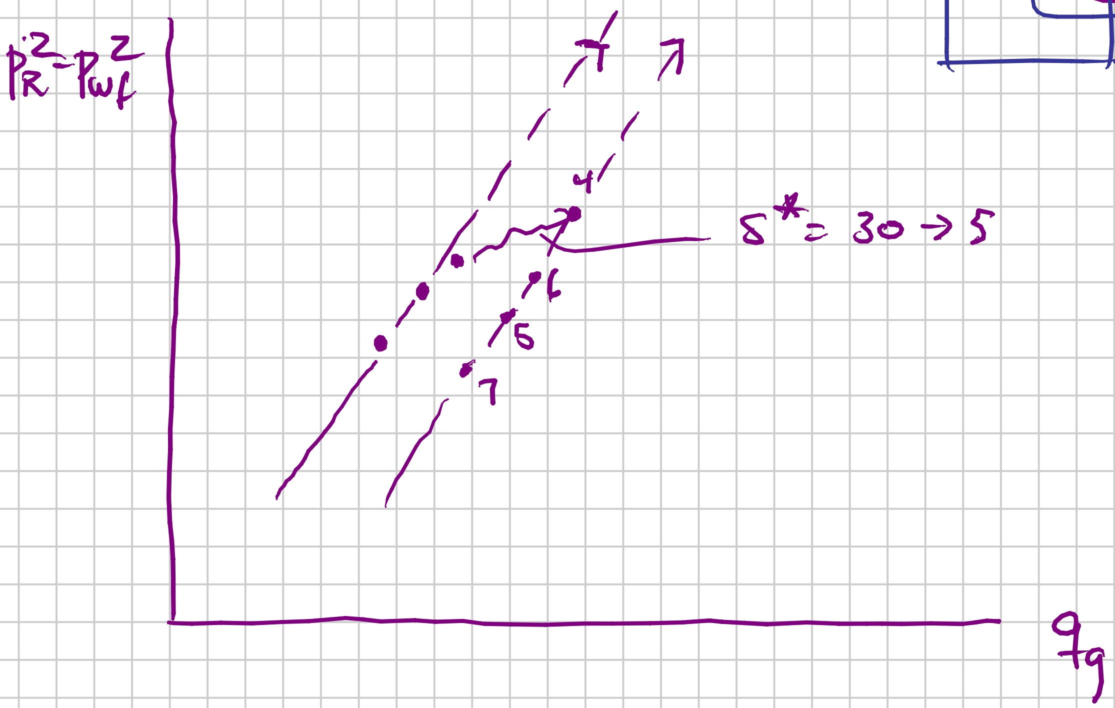
Constants "forever"



Hewett UK NS



Fetters



Combine R + T ⇒

$q_g(p_R, p_t)$

↑
surface
Flowing
Tubing

R : $\bar{p}_R \to p_{wf}$: "Darcy" ⇒ Forchheimer

T : $p_{wf} \to p_t$

p^2 is an ok ~ of p_P p_R (< 200⁺ bar)

$$(p_R^2 - p_{wf}^2) = A'_R q_g + B'_R q_g^2$$ "R"

Darcy

kh, s*

"D"

$$\boxed{p_c^2 - p_w^2 = A_R q_g + B_R q_g^2}$$ "R"

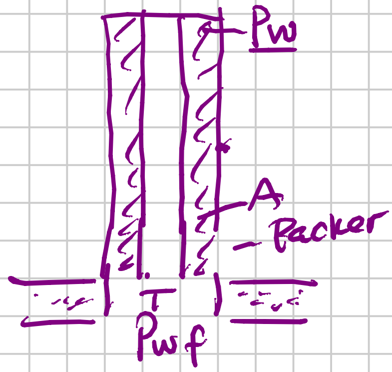
Surface Pressure of an Observating Well

Flowing Annulus Pressure w/NO Packer

$$A_R = A'_R e^{s/2}$$

$$B_R = B'_R e^{s/2}$$

$$\frac{p_R}{p_c} = \underbrace{e^{s/2}}_{} \sim \underbrace{1.x}_{} = \frac{p_{wf}}{p_w}$$



$$\boxed{p_c^2 - p_w^2 = A_R q_g + B_R q_g^2}$$ "R"

$$p_w^2 - p_t^2 = B_T q_g^2$$ "T"

Add

$$(p_c^2 - p_t^2) = A_R q_g + \underbrace{(B_R + B_T)}_{} q_g^2$$

$q_g = C_T (p_w^2 - p_t^2)^{1/2}$

$B_T = \frac{1}{C_T^2}$

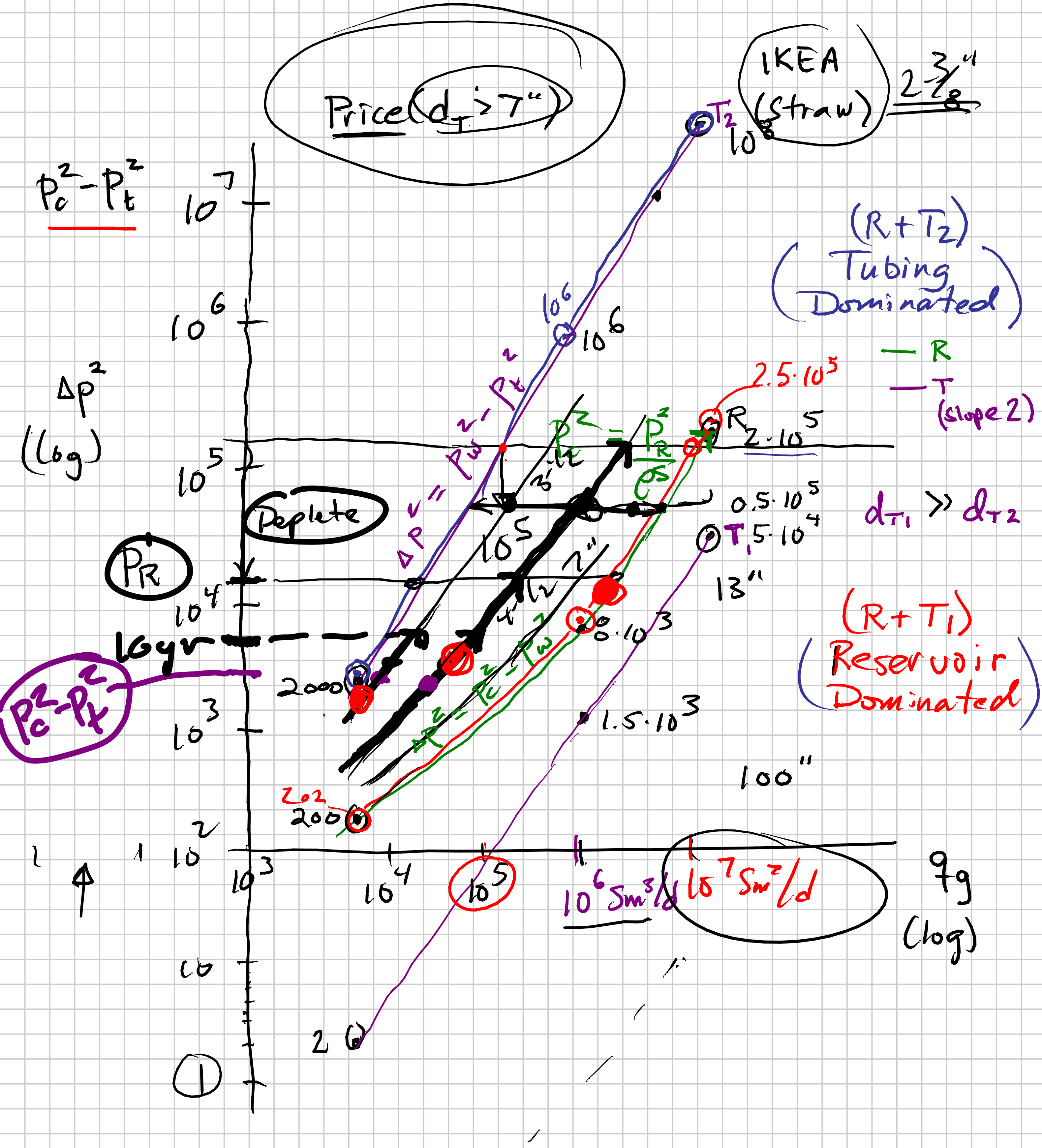
$$\boxed{(p_c^2 - p_t^2) = A_R q_g + B q_g^2}$$

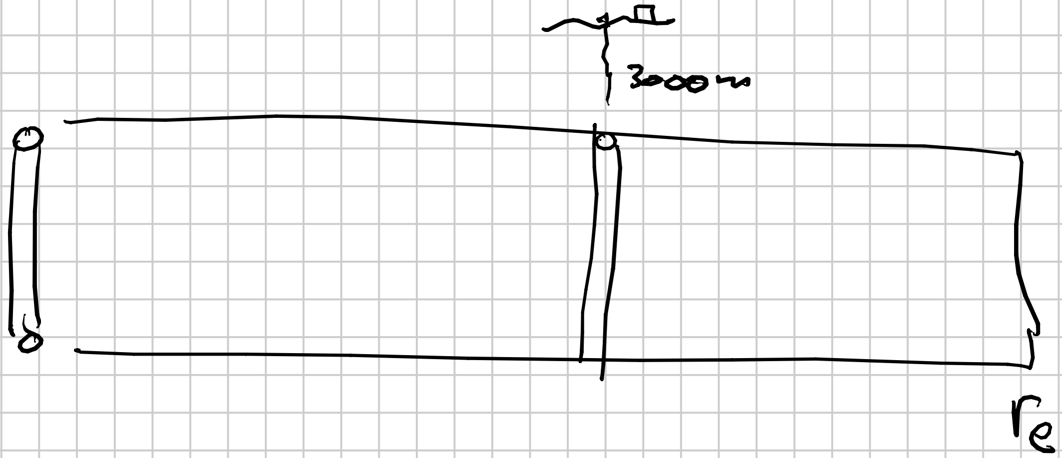
$B_T \propto \left(d_T^{2.6}\right)^2$

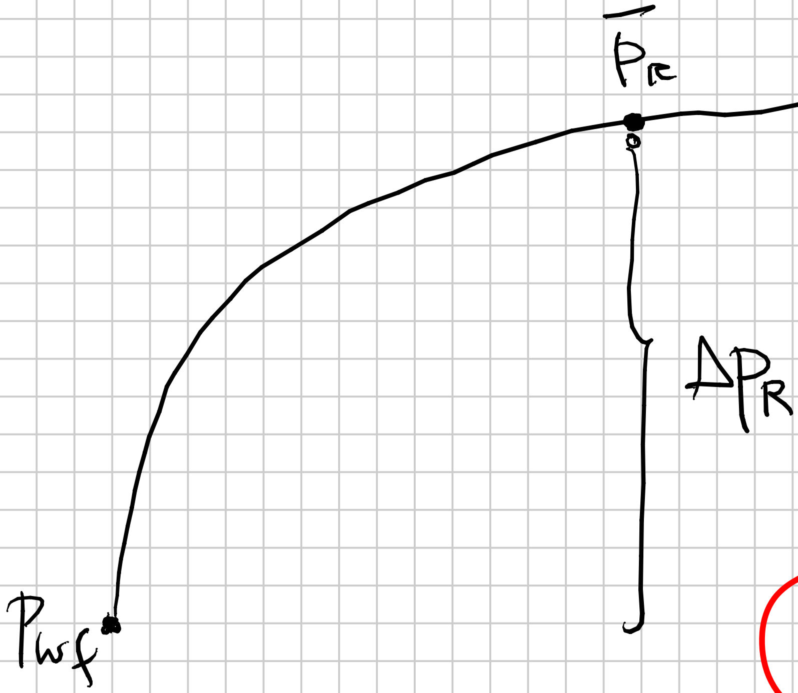
~~Kh~~

s^* ← We Control

Like to have max. q_g for a given p_t

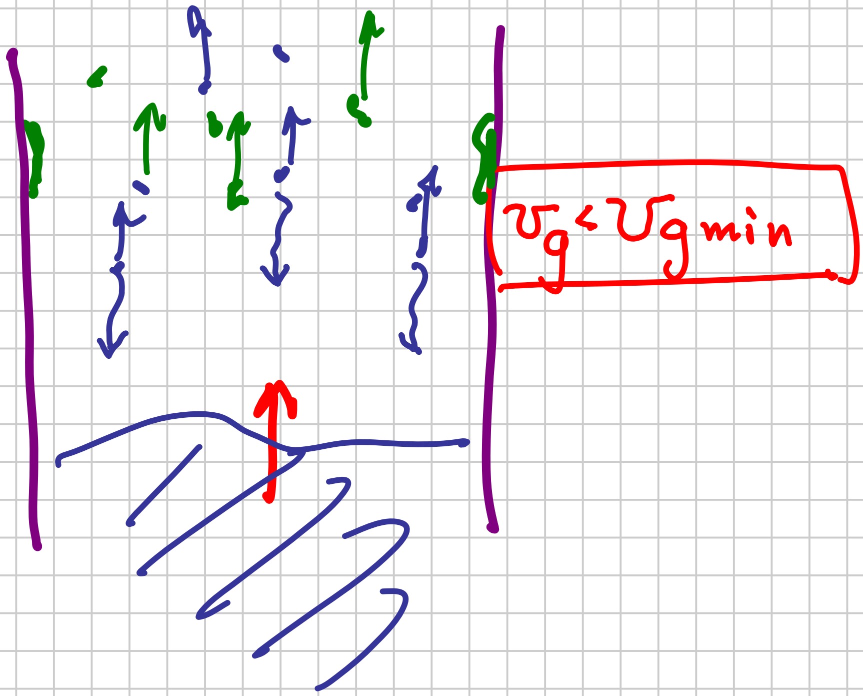






$$v_g = q_g / \pi \left(\frac{d_i}{2}\right)^2$$

Liquid Lifting



Note Title 9/24/2008

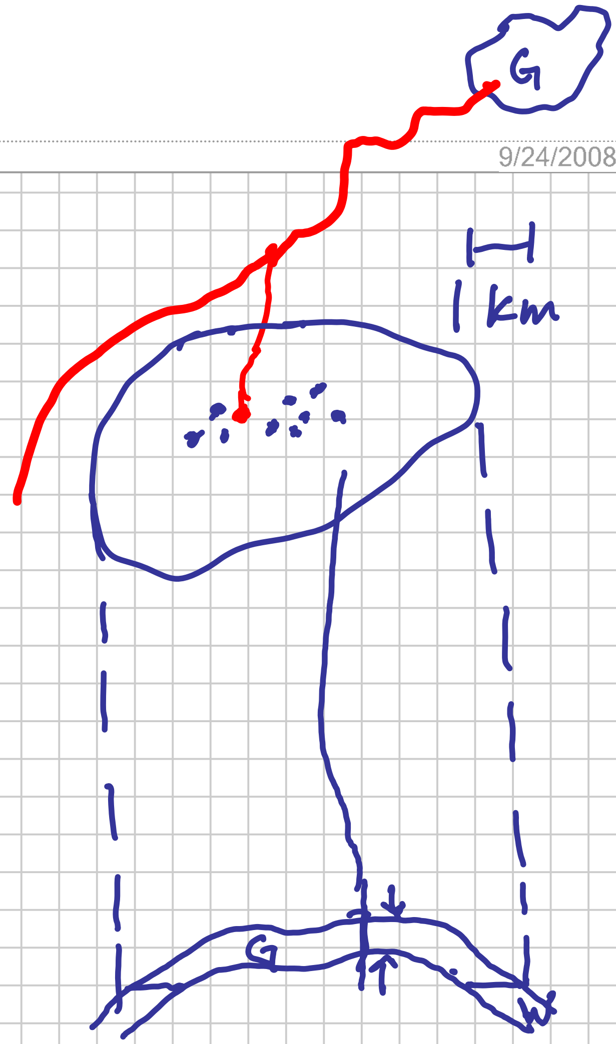
① Estimate Initial Gas in Place (IGIP), G [Sm^3]

- $\bar{A}$, $\bar{h}_g$, $\bar{\phi}$, $\bar{S}_w$

$\underbrace{\bar{A},\ \bar{h}_g,\ \bar{\phi},\ \bar{S}_w}_{\text{Hydrocarbon PV}}$

HCPV

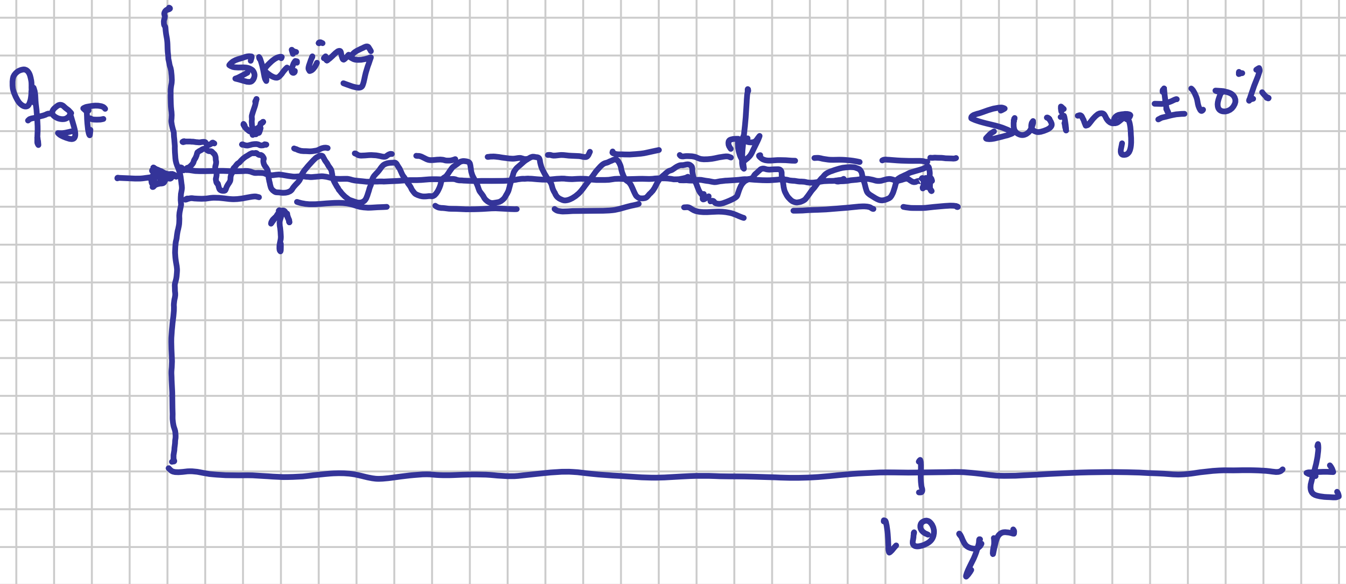
$\underbrace{V_{PR}}_{PV} \cdot \underbrace{(1-\bar{S}_w)}_{HC}$



② Purchaser specifies

$q_{gF} \sim$ % G / year

(3-6) × Contract Period < 50 % G
(Plateau)
(7-15 yr)

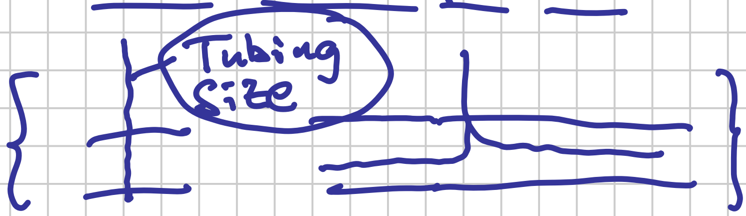


How many wells do we need to satisfy the Gemnas for 10 yr?

$\boxed{N_w}$

Major Cost Variable

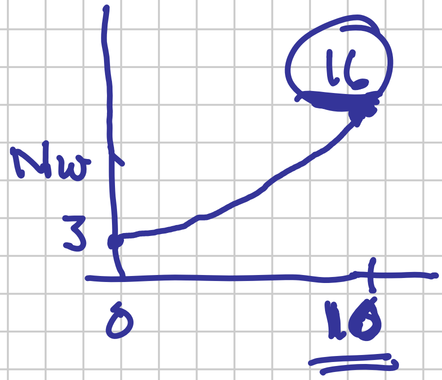
— What kind of wells



How do we do this?

① q_{gF} defined (t)

② $\underbrace{q_{gF}}_{=\text{constant}} = \underbrace{\bar{q}_{gw}(t)} \cdot \underline{N_w}(t)$?



$$q_{gw}(t) = f(A, B, \Delta p^2)$$

$$\Delta p^2 = p_c^2 - \underbrace{p_t^2}$$

Constraint on how low this can be

- Pipeline pressure (no compression)
- Compressor

Well rate expected when delivering against "backpressure"

$$p_c(t) = \frac{\text{"}p_R\text{"}(t)}{[e^{s/2}]}$$

$\boxed{p_{t\,min}}$ = constant

$(B_R + B_T)$ ← Simple eqs.

inlet

$$B \underline{q_{gw}^2} + A \underline{q_{gw}} - \underline{\Delta p^2} = 0$$

"R" "T"   "R"

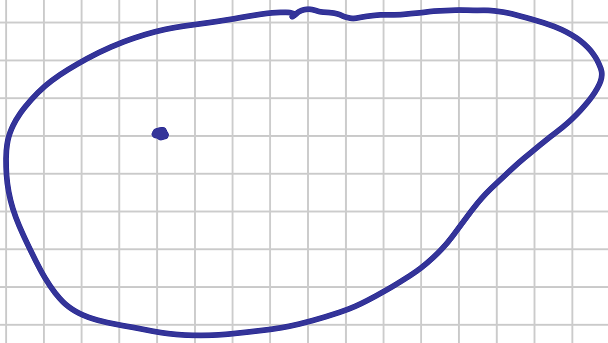
D d_T $\left\{ \begin{matrix} s^* \\ kh \end{matrix} \right\}$

$$A q_{gw} = \Delta p^2$$

Darcy law

$$q_{gw} = \frac{kh\,(p_R^2 - p_{wf}^2)}{\underbrace{\ln\frac{r_e}{r_w} - \frac{3}{4}}_{7-9} + s^*}$$

r_e



$K(x,y,z) \sim \text{const.}$

$$A_w \cong \pi r_e^2$$

$$A_w \cong \frac{A_F}{N_w}$$

PROBLEM DESCRIPTION

- $G = 10$ Tcf ← $\bar{\phi}\ \bar{S}_w\ \bar{h}$ $\qquad 1\text{ Tcf} = 10^{12}$ scf
  ± 2 Tcf $\qquad$ 35.31 scf / Sm^3
  after 1 discovery exploration well

- Germans want to buy 4% G / year, 12 yr
  (you can optionally solve for 10% swing)

- Initial Well Test Results

$q_g = 1.5 \cdot 10^6$ Sm^3/d

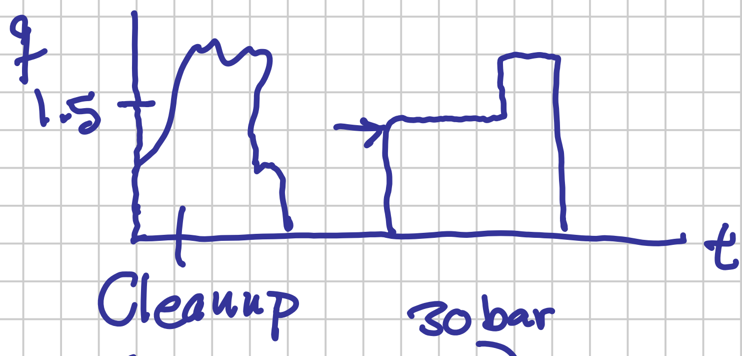
$p_{Ri} = 250$ bara $\quad (T_R = 80\ °C)$

Depth 2500 m bSL $\quad \sim 8000'$

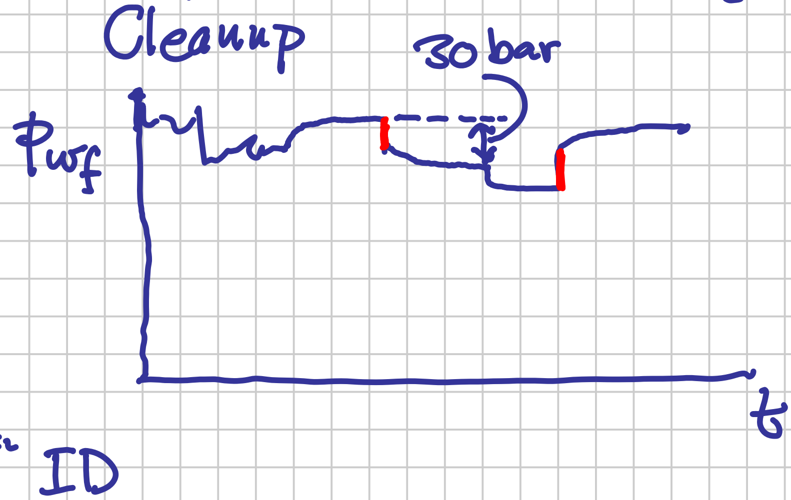
$\Delta p_R = 30$ bar

$\Delta p_{S*} = 15$ bar

$\Delta p_{\text{"D"}} \sim 0$



$\Delta p_T \sim 100$ bar
@ $1.5 \cdot 10^6$ Sm^3/d rate



Test Tubing $d_T = 3.5''$ ID

$h(x,y) \approx \bar{h} = $ constant

$p_{tmin} = 50$ bara

PVT: e-note on gas-pvf

$\bar{\gamma}_g = 0.7$

Tubing: 5-1/2" 7" 9" OD

~5" ~6.5" 8.5" ID ?

$e^{s/2} = 1.2$

Solve:

- Assume Production Wells $s^* = 0$.

- 7" OD tubing as "base" case
- N_w at 12 yr.