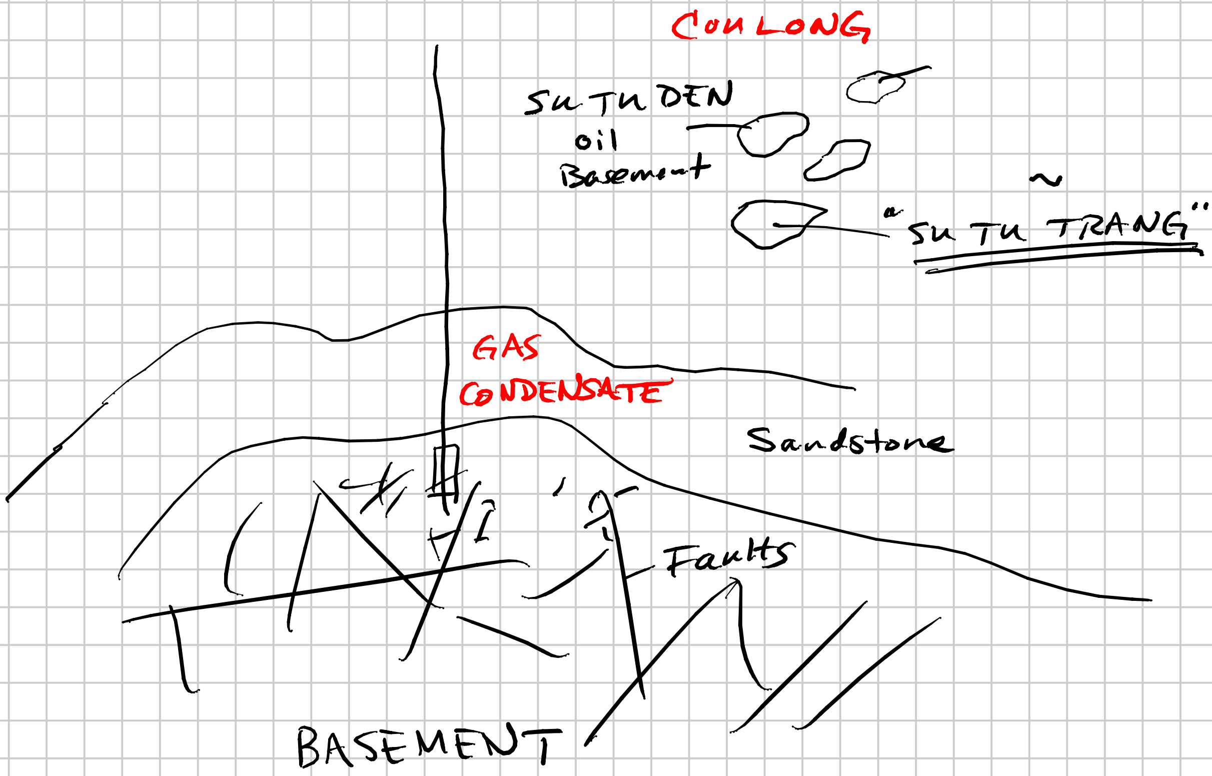
Note Title 11/6/2007



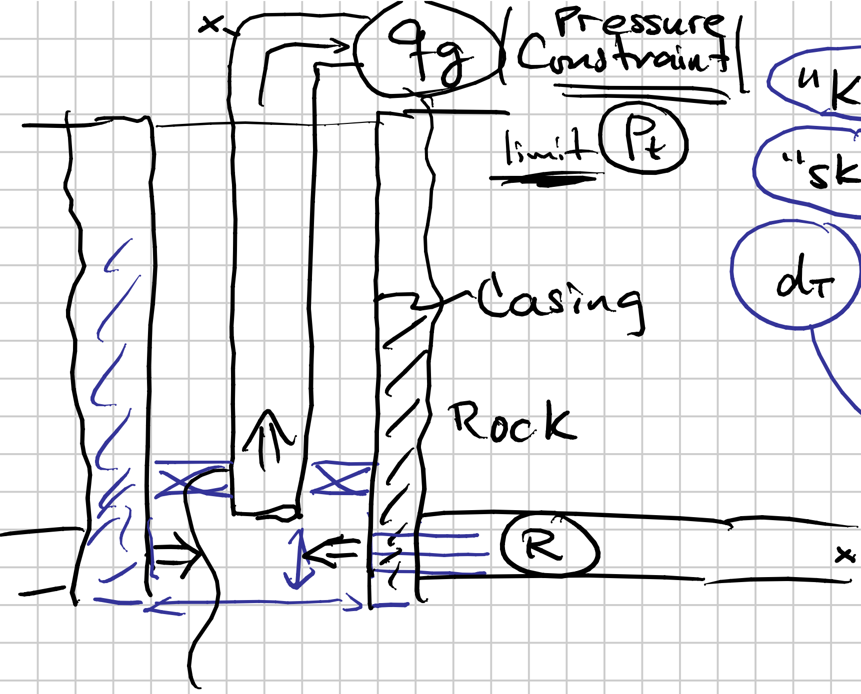
Final Topics (Next Three Weeks)

① Gas Rate Equation (Reservoir / Tubing)

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

T
- Tubing Flow
  - "Vertical Lift Curve" (VLC)
- Composite R+T
  - "Wellhead Backpressure Equation" 0.5–1

$$(q_g)_{well} = C_{WH} \left(p_c^2 - p_t^2\right)^{n_{WH}}$$



"kh"

"skin"

d_T

Wellhead Shutin Pressure

Mother Nature

Wellhead "Tubing" Flowing Pressure

WE CONTROL

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

d_t We control

Baku
"Old Technology"
→ – Casing
– Haning Tubing } ?

RESERVOIR RATE EQUATION

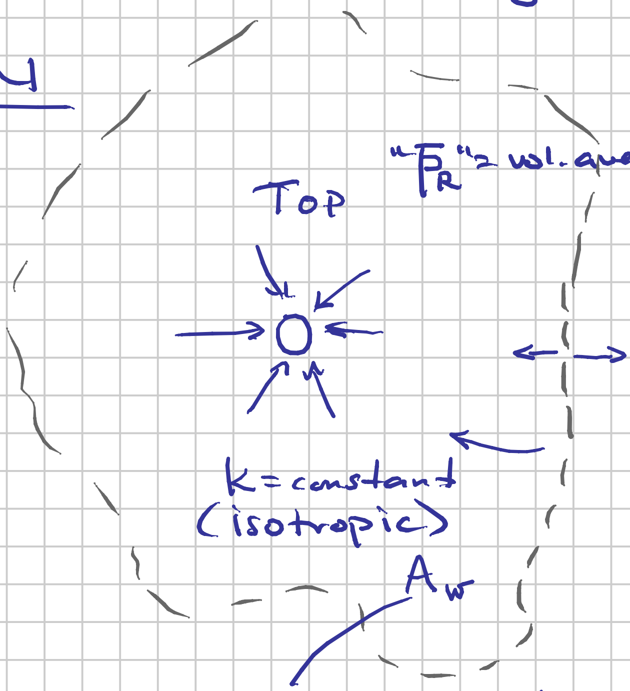
Darcy's Law:

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

Darcy Velocity
$\neq$
Pore Velocity

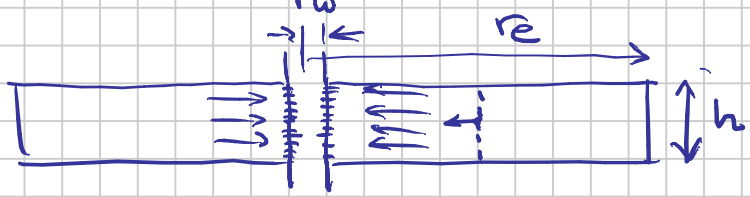
$$q_{fR}\left[\frac{m^3}{s}\right] = v \cdot \underbrace{\underbrace{2\pi r h}_{A_\perp}}$$

= volumetric rate @ p at r ("reservoir" rate)

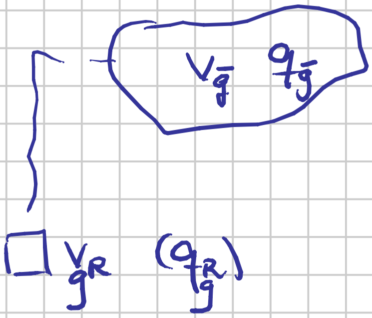


Drainage Outer Area (shape – don't worry)

$$A_w = \pi r_e^2$$



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



$$B_g \equiv \frac{V_{gR}}{V_{\bar{g}}} = \frac{q_{gR}}{q_{\bar{g}}}$$

$$q_{\bar{g}} = q_{gR} \cdot B_g^{-1} \; ; \; B_g = \frac{p_{sc}}{T_{sc}} \cdot \frac{ZT_R}{p}$$

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

Darcy's Law

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

Constant Rate Assumption (Steady-State)

p-dependent	r-dependent
μ_g, B_g	r

"$q_{\bar{g}}$" $\frac{\text{moles}}{\text{day}}$ = constant at ALL r

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

$$\ln \frac{r_e}{r_w} = \frac{2\pi k h}{q_{\bar{g}}} \int$$

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

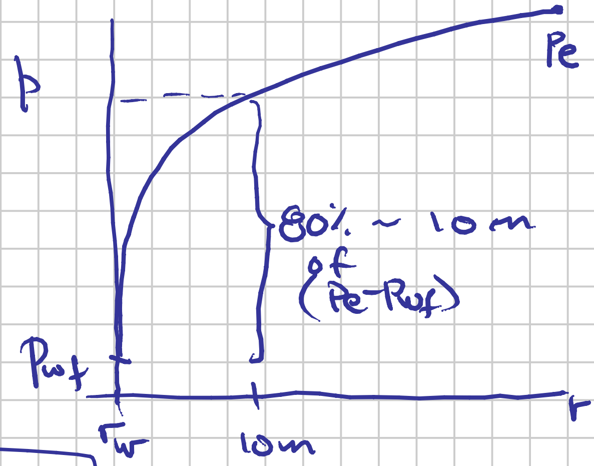
Can't measure

$$\boxed{q_{\bar{g}} = \frac{2\pi k h}{\ln \frac{r_e}{r_w}} \cdot \int_{p_{wf}}^{p_e} \frac{1}{\mu_g B_g} dp}$$

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

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

Solve for r^*



You (or me) or someone else can show that $\boxed{\bar{P}_R \ @ \ p(r = 0.472 r_e)}$

"½"

$$\boxed{q_g = \frac{2\pi kh}{\ln \frac{0.472 r_e}{r_w}} \cdot \int_{P_{wf}}^{\bar{P}_R} \frac{1}{\mu_g B_g} dp}$$

Reservoir Steady State Rate Equation

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

Pressure Integral

"gas mobility term" λ_g

SPE

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

Sometimes: $B_g = \frac{P_{sc}}{T_{sc}} \frac{Z T_R}{P}$

$$P_p \equiv (\quad) 2 \int_0^p \frac{p}{\mu_g Z} dp$$

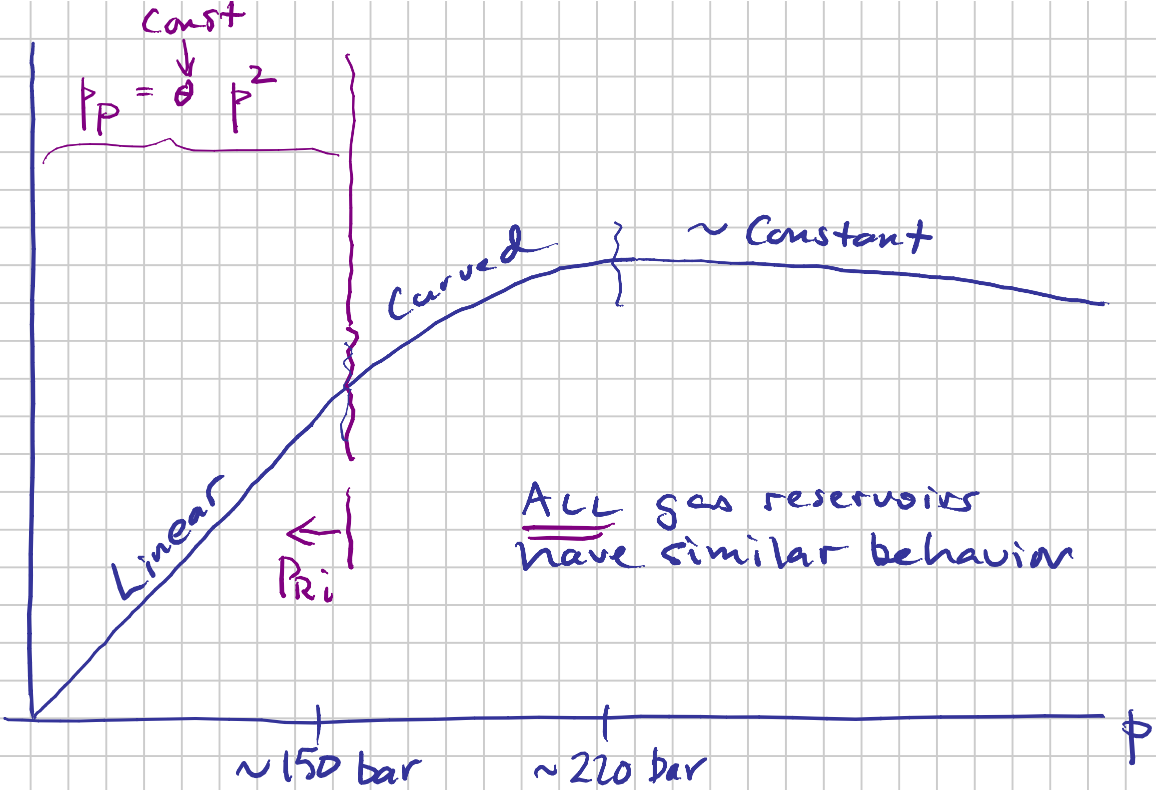
$$\frac{1}{2} \cdot \left(\frac{T_{sc}}{P_{sc} \quad T_R}\right)$$

Original Form (Al-Hussainy, Ramey, Crawford)

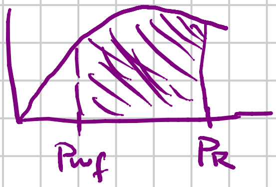
$$\lambda_g = \frac{1}{\mu_g B_g}$$

(OR)

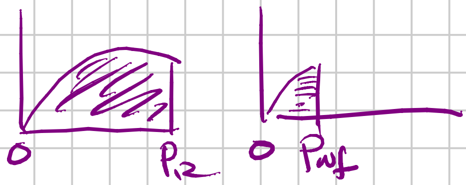
$$\frac{p}{\mu Z}$$



Calculus memory lane



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



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

$p_R < 2500$ psia (130 bar) $\Rightarrow p_p = p^2$

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

low-pressure approximation

Non-Ideal Flow Conditions

(Concept : SKIN)

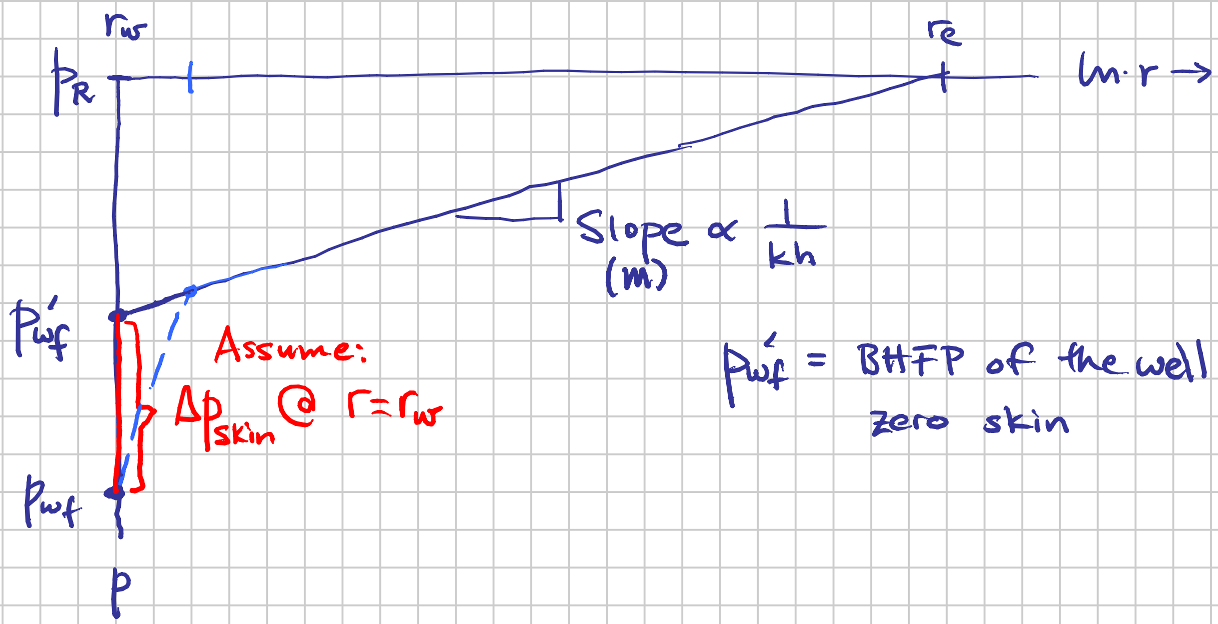
$$q_g = \frac{2\pi k h\,(p_{pR} - p_{pwf})}{\ln\frac{r_e}{r_w} - \frac{3}{4} + s}$$

"lower case" s (SKIN)

"dimensionless pressure drop"

1. "damaged"

$k_d < k$



p'_{wf} = BHFP of the well with zero skin

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

Solve rate eq.

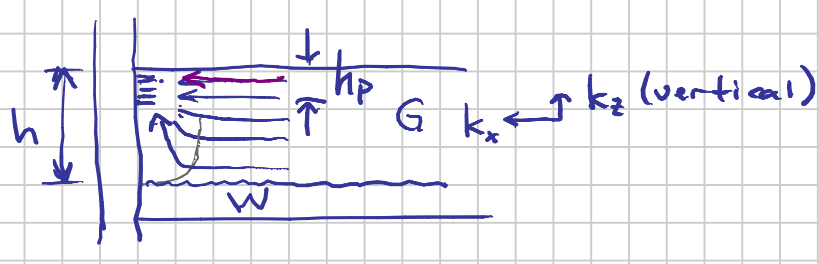
$$\Delta p_{pR} = p_{pR} - p_{pwf}' = \underbrace{\frac{q_g}{2\pi k h}}_{\parallel} \cdot \underbrace{\ln(r_e/r_w) - 3/4}_{\text{dimensionless}}$$

$$\Delta p_{pskin} = p'_{pwf} - p_{pwf} = \underbrace{\left(\frac{q_g}{2\pi k h}\right)}_{\text{slope}} \cdot s$$

s: dimensionless Δp_{skin}

2. Partial Penetration

$\boxed{S_p} > 0$

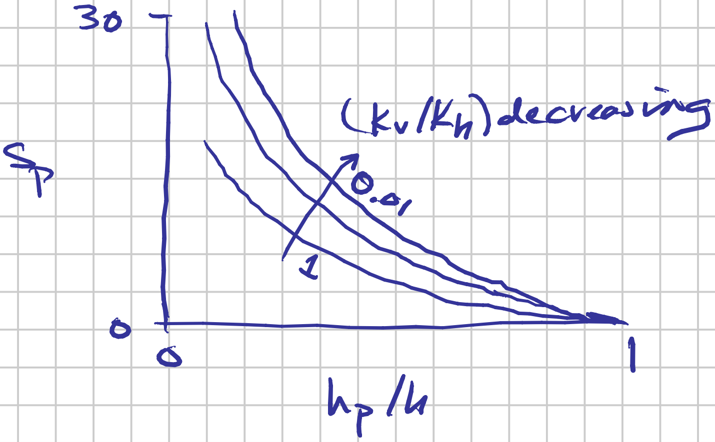


$\uparrow S_p \left(\underbrace{h_p/h}_{\downarrow}, \underbrace{k_v/k_x}_{\downarrow} \right)$

$\uparrow$

(3) .... (12) .... (15)

Skin Effects



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

$\Bigg\}$ $\underbrace{\text{Darcy's}}_{\text{"Laminar" Like Pore Flow}}$ Law isn't good enough

$$\left.\begin{Bmatrix} (kh) \\ s \\ D \\ P_R \end{Bmatrix}\right\} q_g(p_{wf})$$

"IPR"

Forcheimmer

Rock (like k)

NEW

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

PVT

You ...

$$\boxed{q_g = \frac{2\pi kh (p_{pR} - p_{pwf})}{\ln \frac{r_e}{r_w} - \frac{3}{4} + \left[s + \{ D q_g \} \right]}}$$

Damage, PP, ...

FINAL GENERAL RESERVOIR RATE EQ.

Total Skin s_t

$$s_t = s + D q_g$$

Rate-Dependent Skin

$D = \_\_\_ \cdot \beta$

?

- Correlations $\beta \propto \frac{1}{k}$
- Well Tests (Special)

OR

$$A q_g^2 + B q_g - \underbrace{(p_{pR} - p_{pwf})}_{} = 0$$

Quadric Equation

$q_g(\Delta p_p)$

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

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

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

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

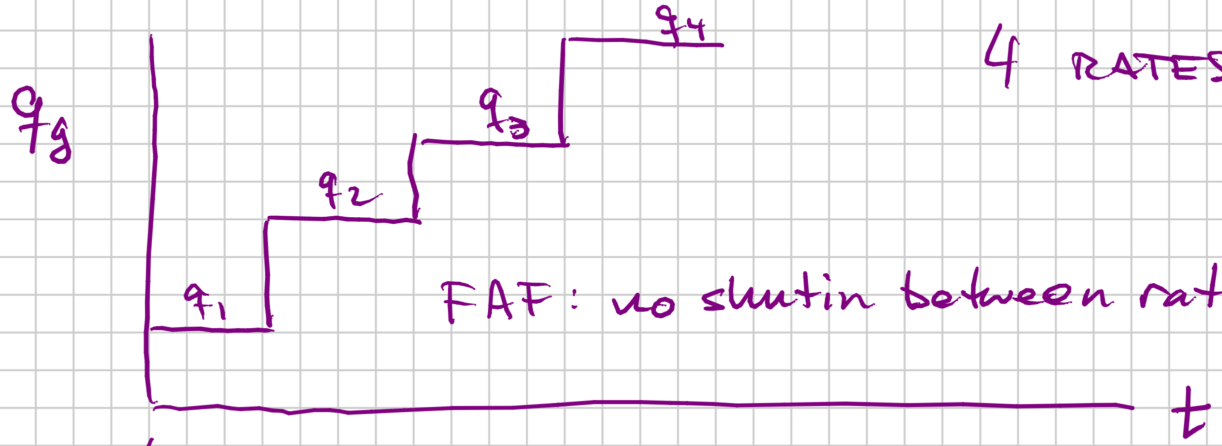
Normally you have an estimate of kh < Core / Log ; PTA (Well Testing)

Special Well Tests $\Rightarrow$ β, D

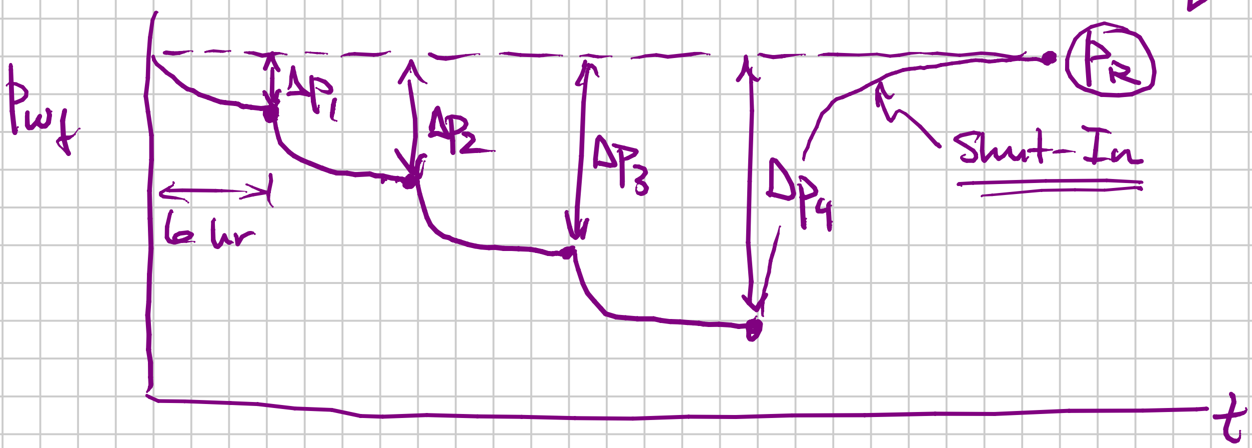
Multi-Rate Flow-After-Flow (FAF) or Isochronal

- SI between each rate
- Δt_p each rate

4 RATES

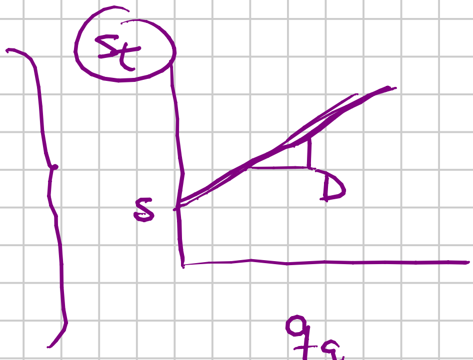


FAF: no shutin between rates



Best-Fit $\Rightarrow$ A, B

$\begin{pmatrix} kh \\ s \end{pmatrix}$, $D(\beta)$



Multi-Rate Test

From Shut-In: $p_R = \boxed{}$

2007.11.07

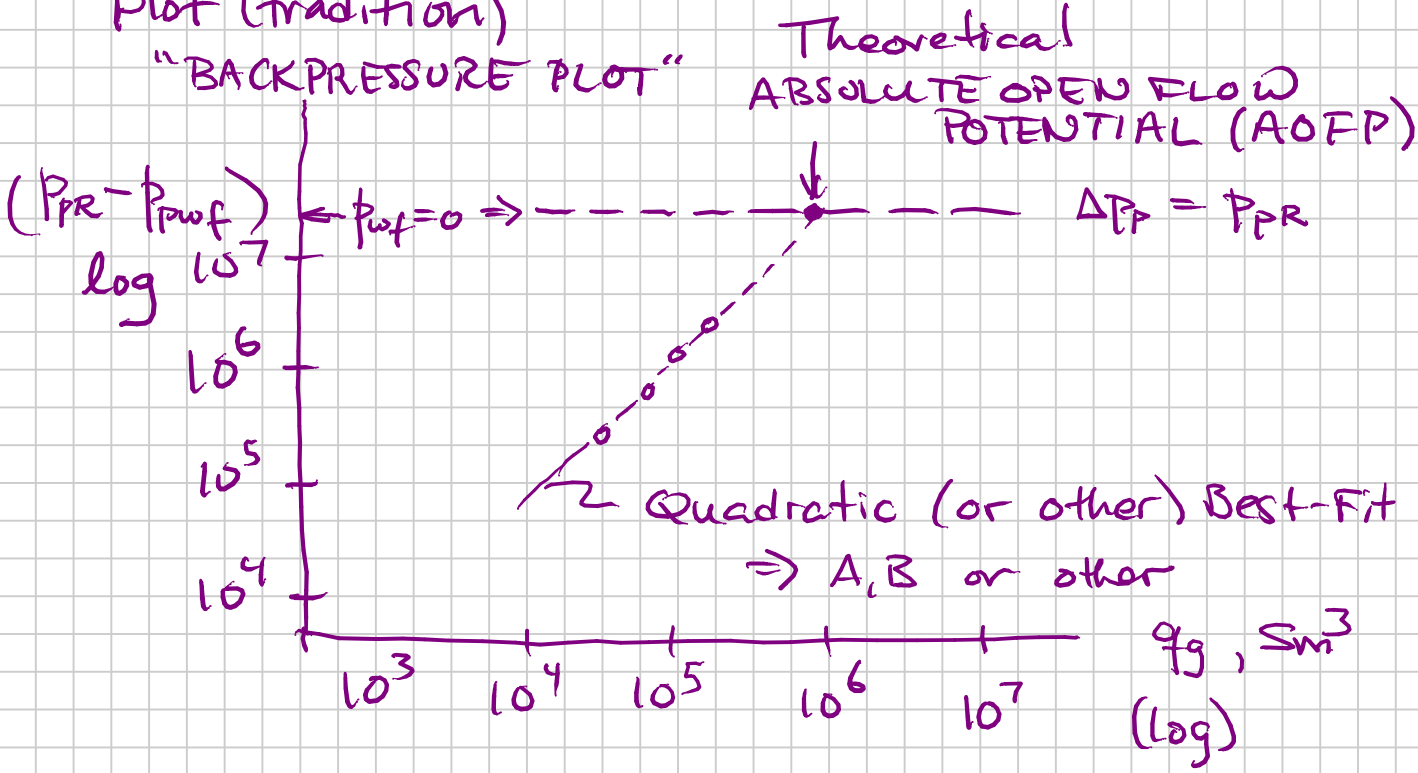
Rate #	$\boxed{q_g}$	$\boxed{p_{wf}}^{*}$	$\Rightarrow \int \Rightarrow$ p_{pwf}	$p_{pR} - p_{pwf}$
1				
2				
3				
4				

$\boxed{}$ Measured

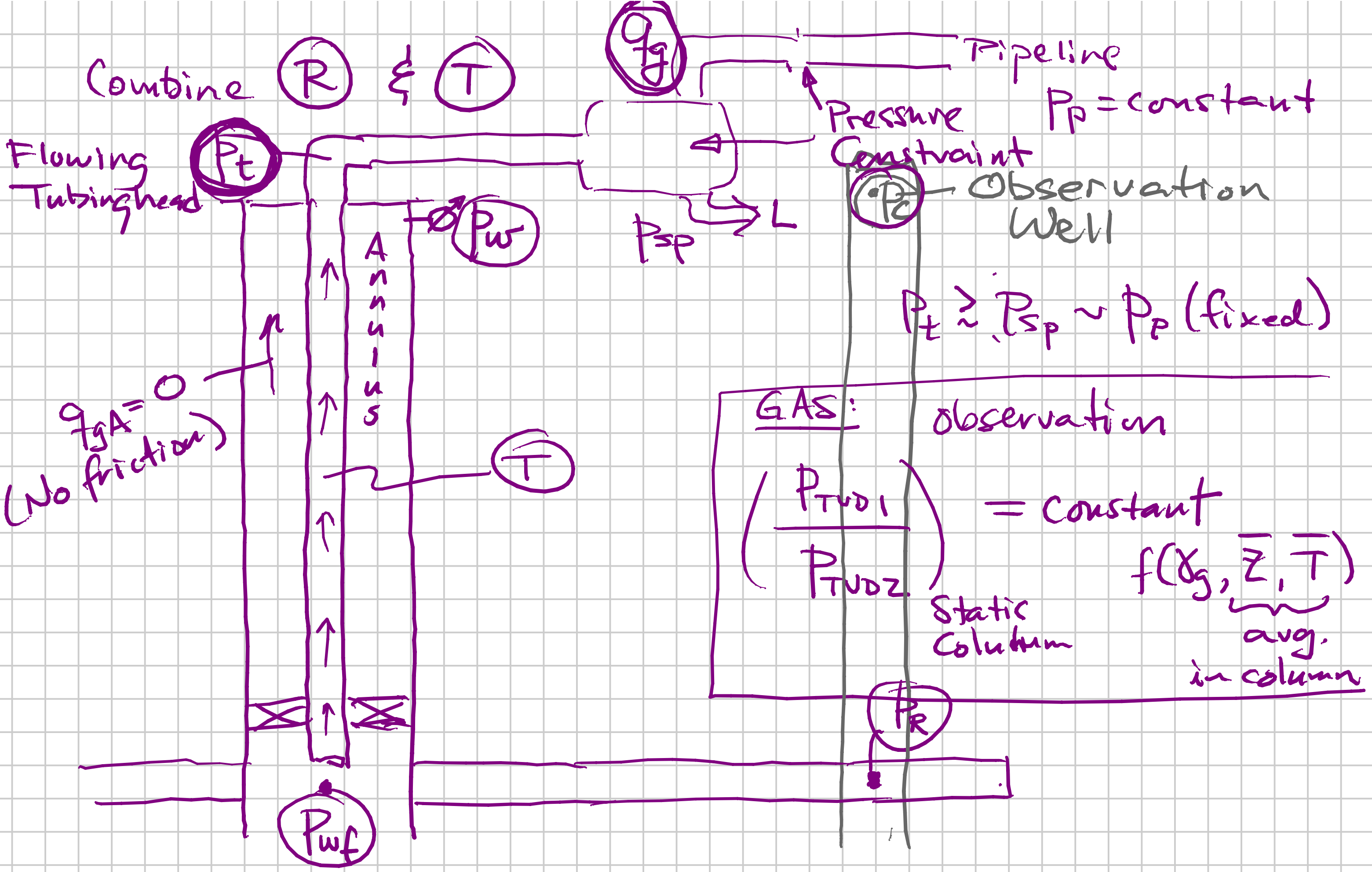
* (a) Wireline-hung or permanent BH pressure gauge

(b) Surface pressures ⟶ Converted Accurately ⟶ BHP's

Plot (tradition)
"BACKPRESSURE PLOT"



Combine R & T



$$P_t \gtrsim P_{sp} \sim P_p \text{ (fixed)}$$

GAS: observation

$$\left(\frac{P_{TVD1}}{P_{TVD2}}\right) = \text{constant}$$

Static Column

$f(\gamma_g, \underbrace{\bar{Z}, \bar{T}}_{\text{avg. in column}})$

Tubing Flows:

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

$$\rho = \frac{pM}{ZRT} \sim (\ ) p$$

$$q_g = C_T \left(p_w^2 - P_t^2\right)^{0.5}$$

Constant

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

Tubing Diameter — Length of Tubing — M_g (γ_g), Gas Gravity — True Vertical Depth

Bring R pressures to a surface datum:

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

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

$$\left(\frac{p_R}{p_c}\right) = \left(\frac{p_{wf}}{p_w}\right) = e^{S/2} = \text{constant} \quad (1.32)$$

1.16

1.42

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

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

$$A q^2 + B q = p_c^2 \cdot e^S - p_w^2 e^S$$

$$A' q^2 + B' q = p_c^2 - p_w^2 \qquad R$$

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

$$\left(\frac{1}{C_T}\right)^2 q_g^2 = p_w^2 - p_t^2 \qquad T$$

1st order accurate

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

"p_R"

Wellhead Backpressure Eq. (Fetkovich)

At a given time:

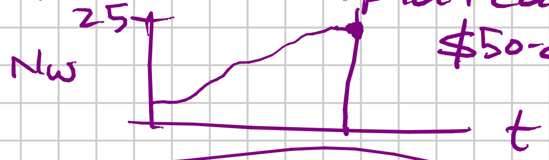
$\downarrow p_R(G_p)(t)$ — Material Balance

- Say let's set p_t = minimum (constraint)

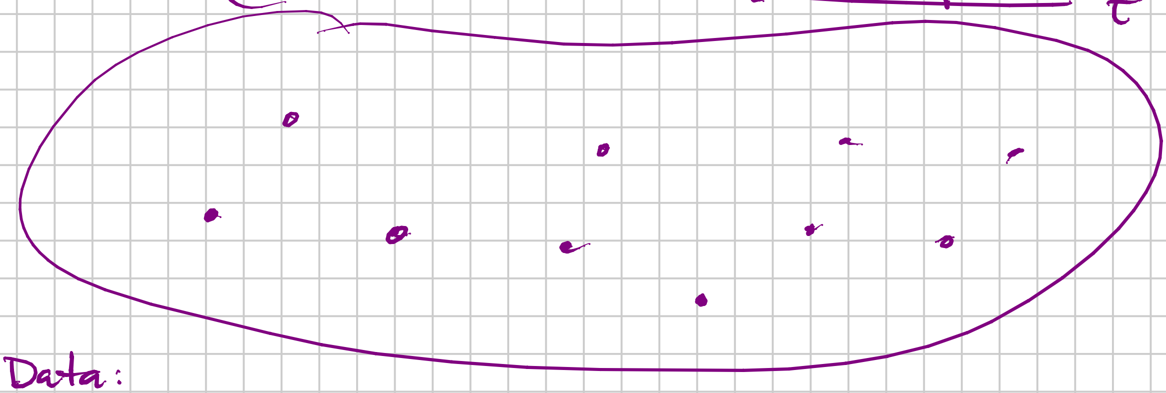
  $\Rightarrow q_{g\,max,well}$ ✓

  $\Rightarrow q_{gField}$ = constant $t_{plateau}$

  $N_w(t)$

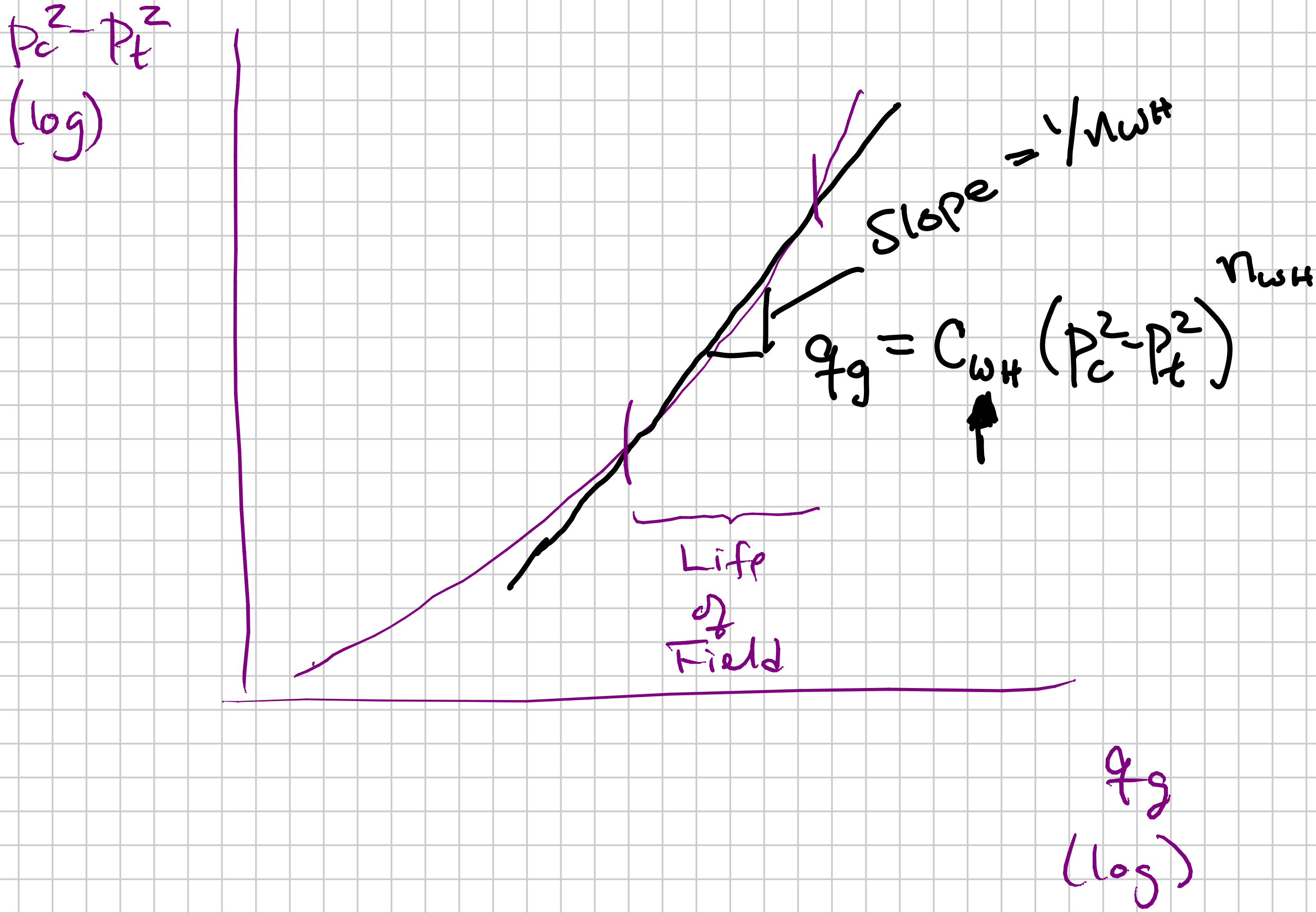


\$50-80 mUSD/well



Key Data:

- IGIP (tank)
- All wells are identical ✓
- q_{gField} / year



$p_c^2 - p_t^2$
(log)
Slope = $1/n_{wH}$
$q_g = C_{wH}\left(p_c^2 - p_t^2\right)^{n_{wH}}$
Life of Field
q_g
(log)

GAS MATERIAL BALANCE

Note Title 11/13/2007

GAS PVT EQ. – REAL GAS LAW

$$pV = nRTZ$$

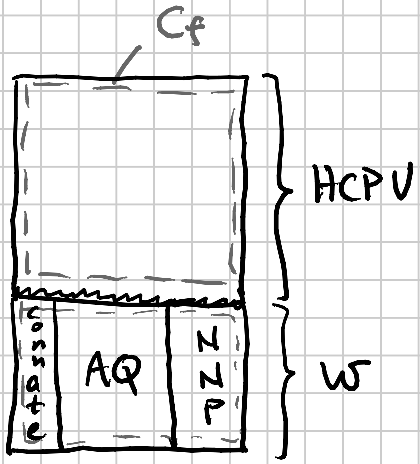
Assumptions:

$V = HCPV = \text{constant}$ ⊛

$Z = f(p, T)$

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

$n_R = n_i - n_p$



"Pot Aquifer"
Small AQ
High K

Introduce: Surface Gas Volumes

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

379 scf/lbmol

23.64 Sm^3/kgmol

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

(G) IGIP $= n_i \cdot 379$

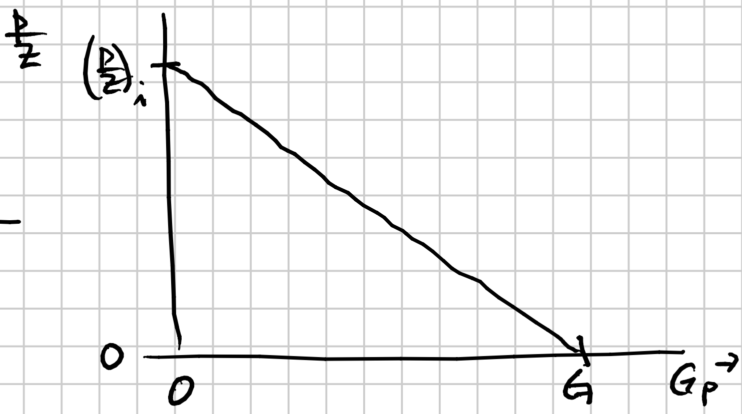
(G_p) Cum. Gas Prod. $= n_p \cdot 379$

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

⇒ Straight-Line Gas. M.B

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

RF



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

Pot Aquifer Model

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

(AQ + NNP)

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

$S_{wc} \sim 0.25$

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

$M \equiv \frac{V_{AQ}}{V_{PR}} \sim 1-5$ (Pot Aq.)

V_{PR} ← Containing HC

} $c_e =$

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

NNP: Non-Net Pay — Water-bearing "dirty" sand

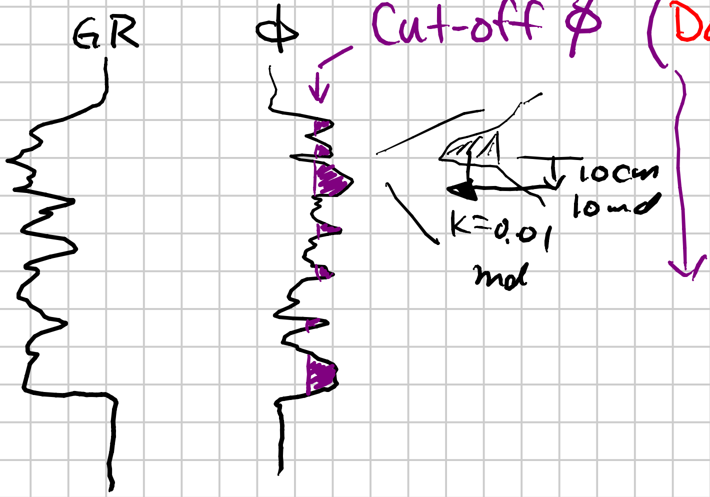
$\Delta z \sim 10-100$ cm

(1) Interbedded shales

(2) "Low-ϕ" (low-k) 'sand'

Additional "interbedded" water

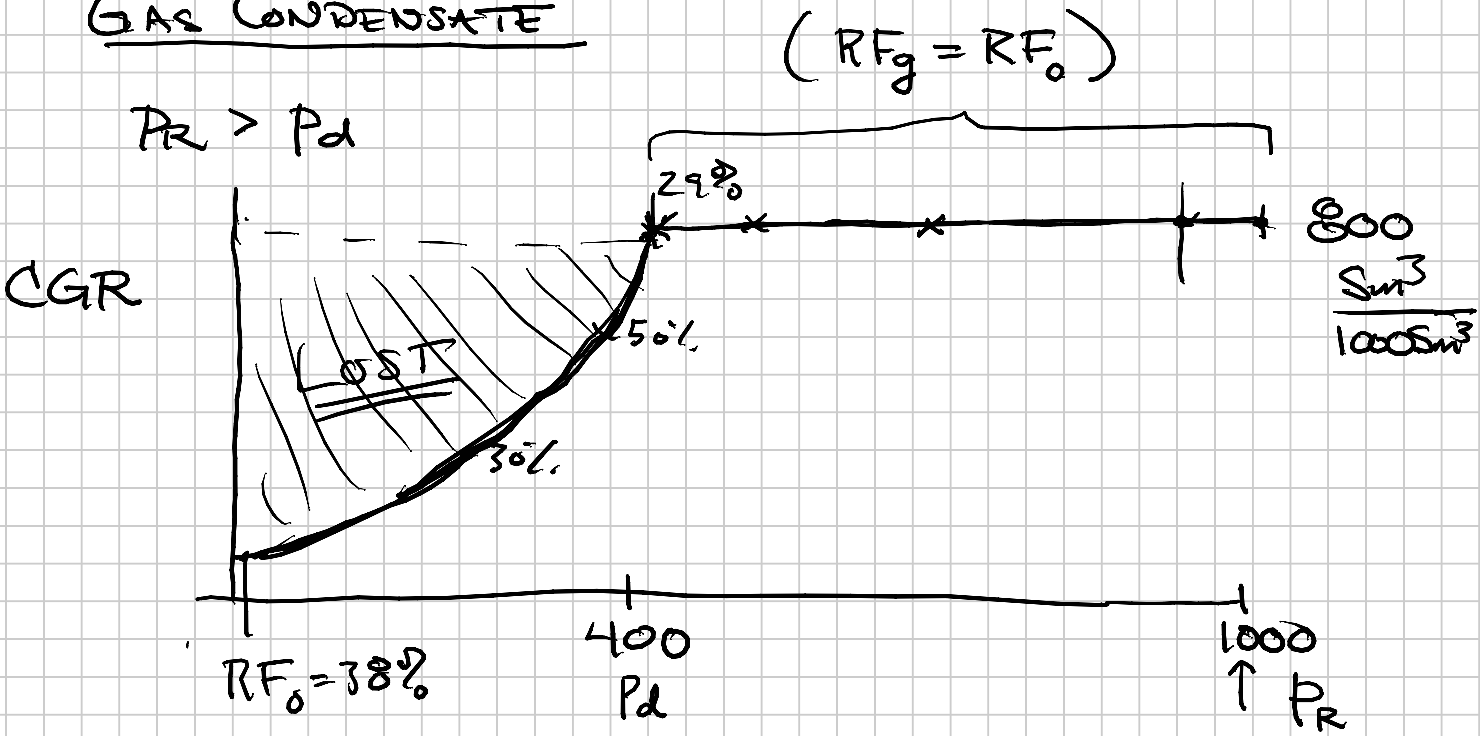
Cut-off ϕ (DON'T USE... particularly for Gas Reservoirs)



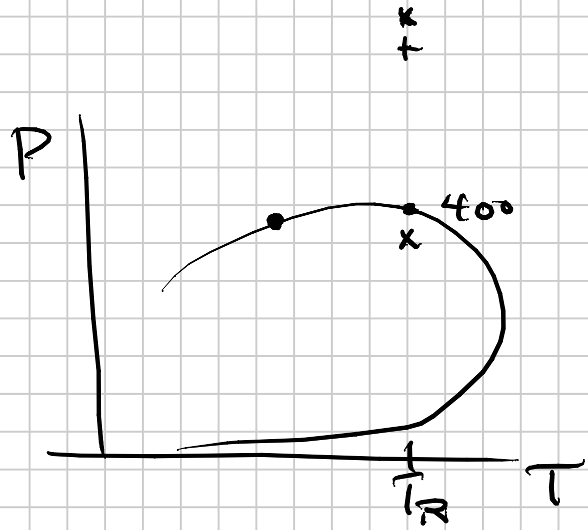
$$\underline{\underline{M}} = \{ M_{AQ} + M_{NNP} \}$$

Gas Condensate

$P_R > P_d$



PVT

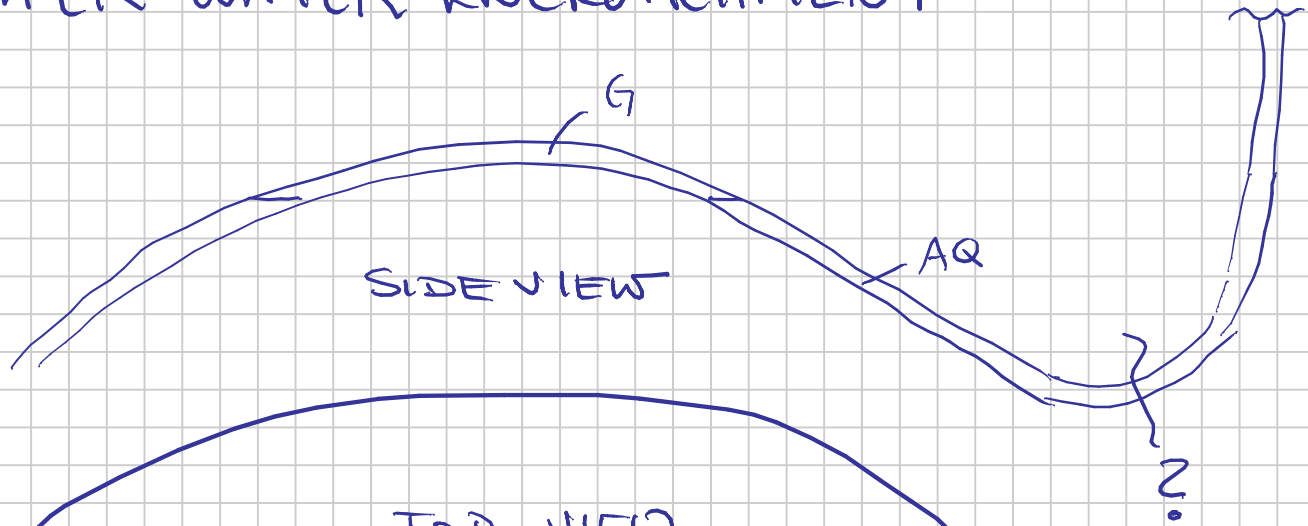


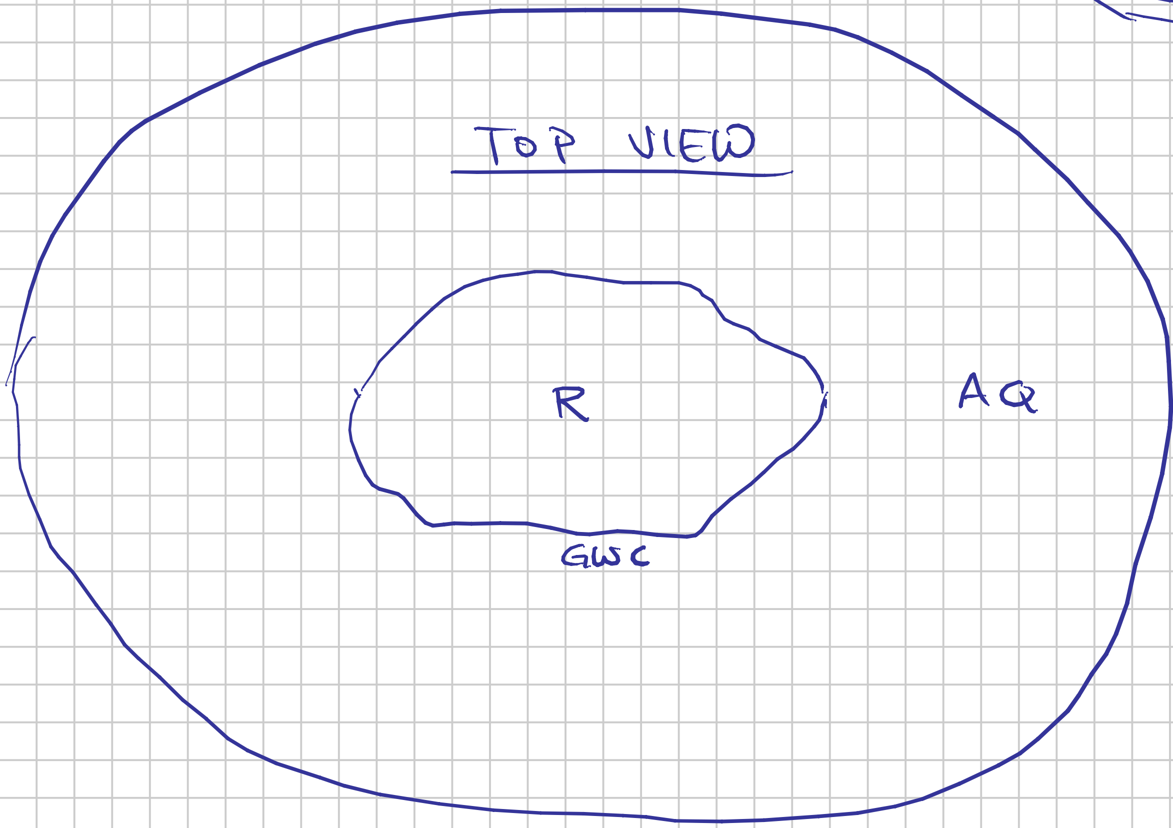
Limited pressure

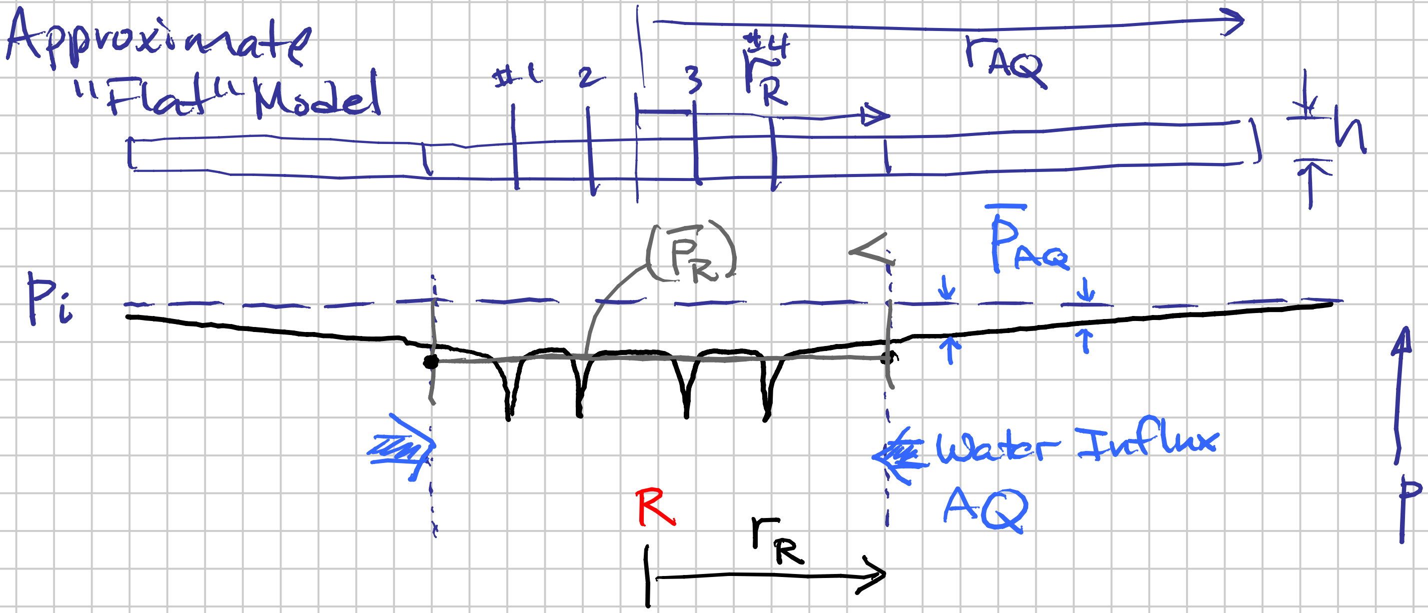
bbl RB STB

5.615 ft^3

AQUIFER WATER ENCROACHMENT







$$q_g = \frac{2\pi k h (P_r - P_{wf})}{\ln r/r_w}$$

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

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

(• p_{G-W} @ r_R changes in time)

(according to the rate of gas production)

Flow in the aquifer $r_R < r < r_{AQ}$

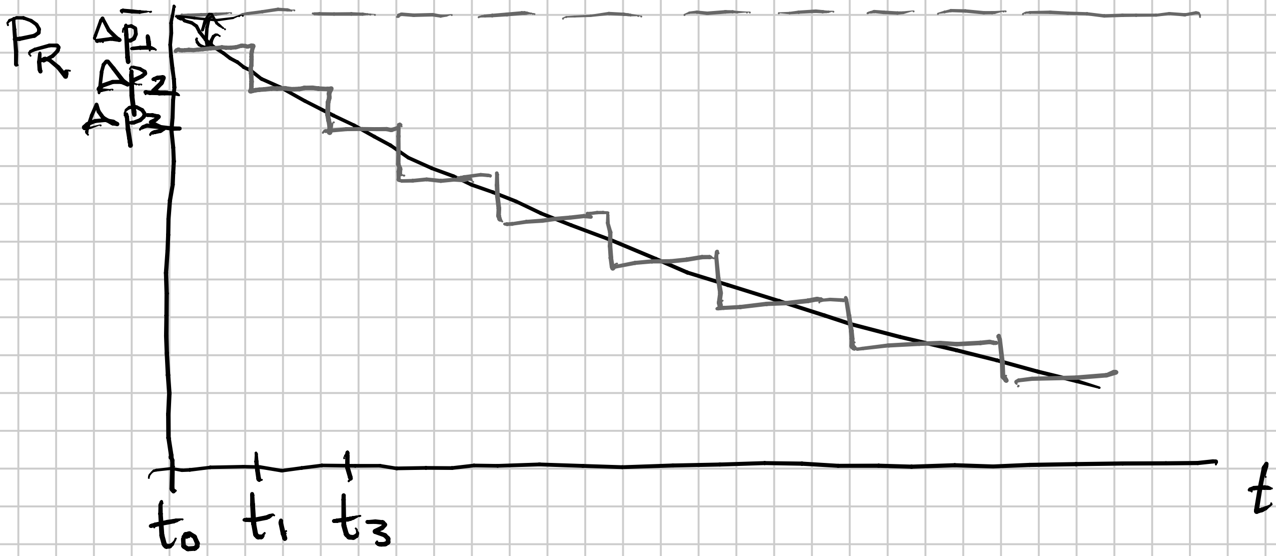
single-phase water flow

$p_R(t)$ boundary condition

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

- van Everdingen-Hurst general solution
- Fetkovich PSS Approximation

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



$$\boxed{q_w(t) \neq} \quad \sum \Delta q_w (\Delta p)_{\Delta t}$$

Δp_1 starts at $t_0 \rightarrow t$

Δp_2 starts at $t_1 \rightarrow t$

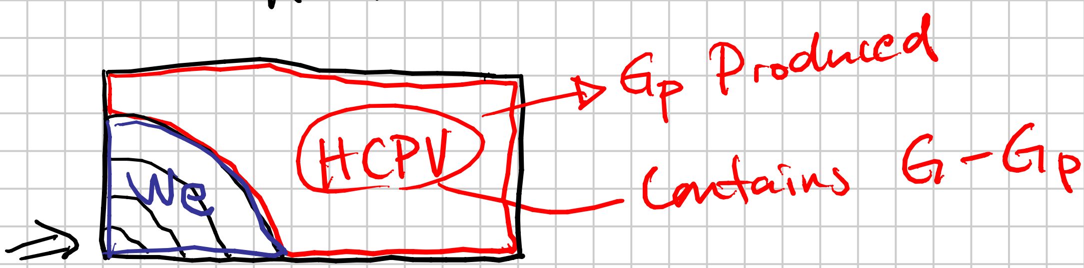
$\vdots$

Cumulative Water Encroachment

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

Filling the Gas R PV

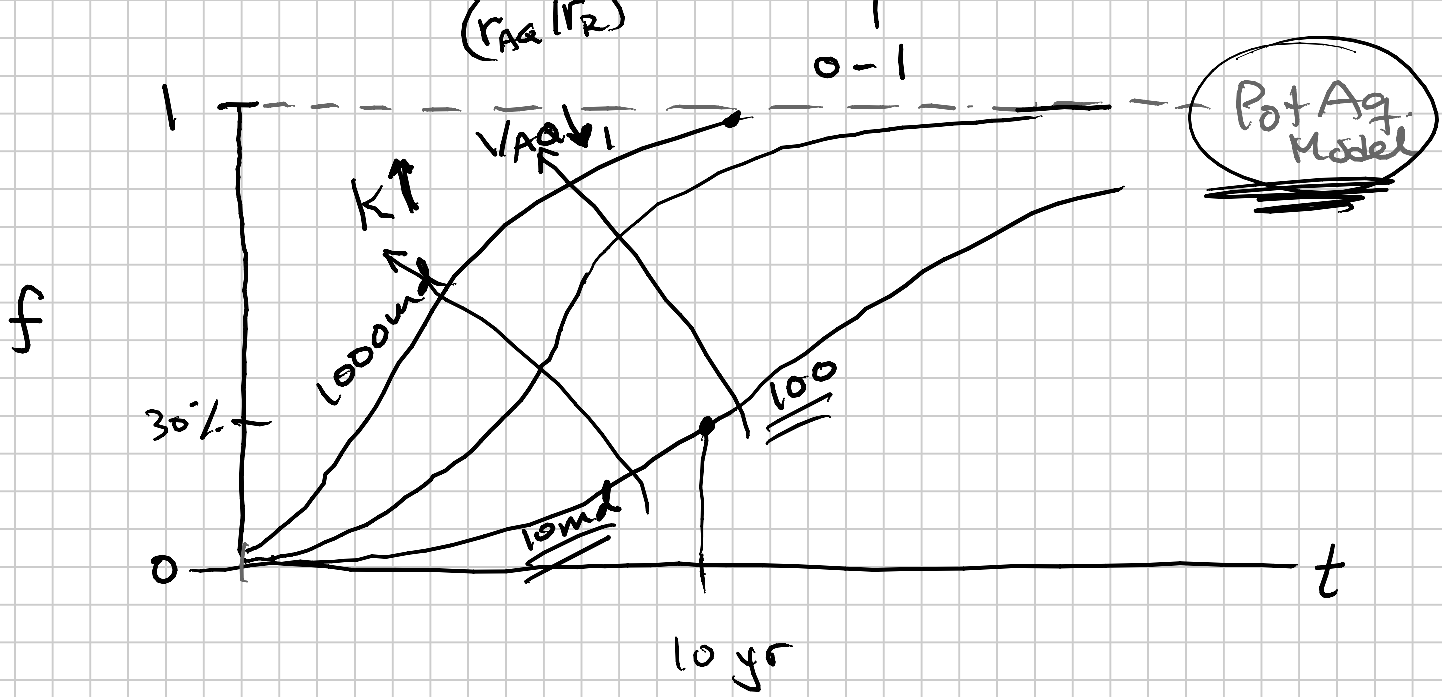
HCPV decreases



Pot Aq. Model gives the maximum encroachment

$$W_{e\,max} = V_{AQ} \cdot (c_w + c_f) \underbrace{(P_i - P_R)}_{\text{total } \Delta P}$$

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



k ≲ 1 md : Little-no aquifer support in a normal 10-20 yr depletion life

PRi HP reservoirs (> 500 bar)

even "small" water volumes can become important