Suggested solution to the final exam in Welltest Analysis, May 18, 2009

Problem 1

a) Two flow regimes appear to be evident in the data, with early data dominated by wellbore storage and late data exhibiting a simple radial flow response. A key parameter for the first period is the storage constant *C*, and for the radial flow period the flow capacity *kh*. If we use the shut-in pressure (from Table 1) and the first point from Table 2 we get the storage constant

$$C = \frac{qB}{24}\frac{\Delta t}{\Delta p} = \frac{(5200)(1.45)(0.001)}{(24)(5470.5-5466.3)} = 0.0748 \text{ RB/psi.}$$

To determine *kh* by a similar approach we can assume that the last part of the data represents radial flow with derivative value $d\Delta p / d\ln\Delta t = m\, d\log\Delta t / d\ln\Delta t = m/\ln 10 = m/2.3026$. From Fig. 1 it follows that points near 8 hrs can be picked to determine the slope

$$m = 2.3026\frac{d\Delta p}{d\ln\Delta t} = 2.3026\frac{5949.5-5940.9}{\ln(10.0982)-\ln(6.3715)} = 2.3026\frac{8.6}{0.4605} = 43.002 \text{ psi/log-cycle,}$$

and hence

$$kh = \frac{162.6qB\mu}{m} = \frac{(162.6)(5200)(1.45)(0.84)}{43.002} = 23949 \text{ md}\cdot\text{ft.}$$

Note that we do not need to use equivalent time due to the long producing time.

b) We can use the same data points chosen above, i.e., at the shut-in times 6.3715 and 10.0982 hrs. With the producing time $300\cdot 24 = 7200$ hrs prior to shut-in we then get

$$m = \frac{5949.5-5940.9}{\left|\log\left[10.0982/(7200+10.0982)\right]-\log\left[6.3715/(7200+6.3715)\right]\right|} = \frac{8.6}{0.19978} = 43.047$$

psi/log-cycle. The pressure p_{1hr} at $\Delta t = 1$ hr can be determined by extrapolation from the pressure $p_{ws} = 5949.5$ psi at $\Delta t = 10.0982$ hrs as follows:

$$p_{1hr} = 5949.5 + m\left\{\left[\log 1/(7200+1)\right]-\log\left[10.0982/(7200+10.0982)\right]\right\}$$

$$= 5949.5 + 43.047(-3.8574+2.8537) = 5949.5-43.2 = 5906.3 \text{ psi.}$$

From the slope above we also get

$$kh = \frac{162.6qB\mu}{m} = \frac{(162.6)(5200)(1.45)(0.84)}{43.047} = 23924 \text{ md}\cdot\text{ft}$$

and

$$k = \frac{kh}{h} = \frac{23924}{95} = 251.8 \text{ md.}$$

The skin value can be determined from the formula

$$S = 1.151\left(\frac{p_{1hr} - p_{wf,s}}{m} - \log\frac{t}{t+1} - \log\frac{k}{\phi\mu c_t r_w^2} + 3.23 \right)$$

$$= 1.151\left[\frac{5906.3 - 5466.3}{43.047} - \log\frac{7200}{7200+1} - \log\frac{251.8}{(0.19)(0.84)(2.14\times10^{-5})(0.354)^2} + 3.23 \right]$$

$$= 1.151(10.2214 + 0.00006 - 8.7696 + 3.23) = 5.39\,.$$

The added pressure drop at the wellbore can now also be computed as

$$\Delta p_S = \frac{m}{1.151} S = \frac{43.047}{1.151}(5.39) = 201.6 \text{ psi.}$$

The extrapolated pressure $p*$ at infinite shut-in can be obtained by extrapolating from the pressure at 10.0982 hrs with the result

$$p* = 5949.5 + m\left\{\log 1 - \log\left[10.0982/(7200 + 10.0982)\right]\right\}$$

$$= 5949.5 + 43.047(0 + 2.8537) = 5949.5 + 122.8 = 6072.3 \text{ psi.}$$

c) The extrapolated pressure $p*$ can only be used to estimate the (current) average pressure if the flow behavior is still in or close to infinite acting at shut-in. This in turn would imply that the external radius has to be similar to or larger than the radius of investigation at shut-in, in other words

$$r_{inv} = 0.0246\sqrt{\frac{kt}{\phi\mu c_t}} = 0.0246\sqrt{\frac{(251.8)(7200)}{(0.19)(0.84)(2.14\times10^{-5})}} = 17923 \text{ ft.}$$

This is not impossible, but probably not likely.
All standard techniques involving depletion at shut-in require knowledge of the drainage area to estimate the average pressure at shut-in.

d) The Horner straight line can be extrapolated directly to the average pressure if pseudosteady state is reached prior to shut-in, which is clearly the case here since the radius of investigation at shut-in is more than 4 times the assumed external radius. We can therefore read off the average pressure directly based on the identity

$$p_{ws}(\Delta t) = \bar{p} \quad \text{when} \quad \Delta t_e = \frac{t\cdot\Delta t}{t+\Delta t} = \frac{\phi\mu c_t A}{0.000264 k C_A},$$

in other words when

$$\frac{t+\Delta t}{\Delta t}=\frac{0.000264ktC_A}{\phi\mu c_t A}=\frac{(0.000264)(251.8)(7200)(31.62)}{(0.19)(0.84)(2.14\times10^{-5})\pi(4100)^2}=83.905.$$

We can therefore again extrapolate from the pressure at 10.0982 hrs to obtain the result

$$\bar{p}=5949.5+m\left\{\log 1/83.905-\log\left[10.0982/(7200+10.0982)\right]\right\}$$

$$=5949.5+43.047(-1.9238+2.8537)=5949.5+40.0=5989.5 \text{ psi.}$$

Note: The permeability *k* was missing in the formula listed for the analysis above!

From the identity

$$p_i-\bar{p}=\frac{m}{1.151}2\pi t_{DA}$$

we can determine the initial pressure through the computations

$$p_i=\bar{p}+\frac{m}{1.151}2\pi t_{DA}=5989.5+\frac{43.047}{1.151}2\pi\frac{0.000264kt}{\phi\mu c_t A}$$

$$=5989.5+\frac{43.047}{1.151}\frac{2(0.000264)(251.8)(7200)}{(0.19)(0.84)(2.14\times10^{-5})(4100)^2}=5989.5+623.5=6613 \text{ psi.}$$

e) The radius of investigation at the end of the buildup is

$$r_{inv}=0.0246\sqrt{\frac{kt}{\phi\mu c_t}}=0.0246\sqrt{\frac{(251.8)(12)}{(0.19)(0.84)(2.14\times10^{-5})}}=732 \text{ ft.}$$

A boundary closer than this should be seen in the data.

f) The storage constant can be determined from the slope of a line through the early data. Consistency of the data can be determined by extrapolating this line to $\Delta t=0$ hrs and compare with the shut-in pressure $p_{wf,s}=5466.3$ psi. If we now use the first two points from Table 2 we get the slope

$$m'=\frac{qB}{24C}=\frac{5474.6-5470.5}{0.002-0.001}=\frac{4.1}{0.001}=4100 \text{ psi/hr,}$$

and hence the storage constant

$$C = \frac{qB}{24m'} = \frac{(5200)(1.45)}{(24)(4100)} = 0.0766 \ \text{RB/psi.}$$

The corresponding dimensionless wellbore storage then takes the value

$$C_D = \frac{5.615C}{2\pi\phi h c_t r_w^2} = \frac{(5.615)(0.0766)}{(6.2832)(0.19)(95)(2.14\times10^{-5})(0.354)^2} = 1414$$

If we extrapolate the straight line from the first point to $\Delta t = 0$ we get

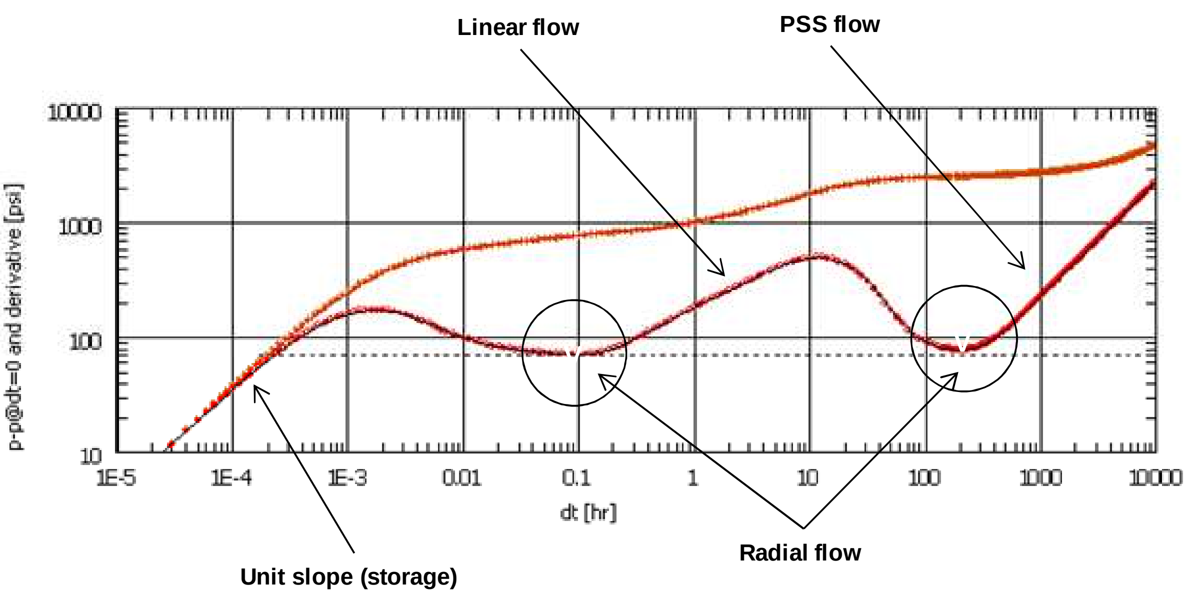
$$p_0 = 5470.5 - m'\Delta t = 5470.5 - (4100)(0.001) = 5470.5 - 4.1 = 5466.4 \ \text{psi,}$$

which is very close to the shut-in pressure in view of the accuracy of the data (one decimal place reported).

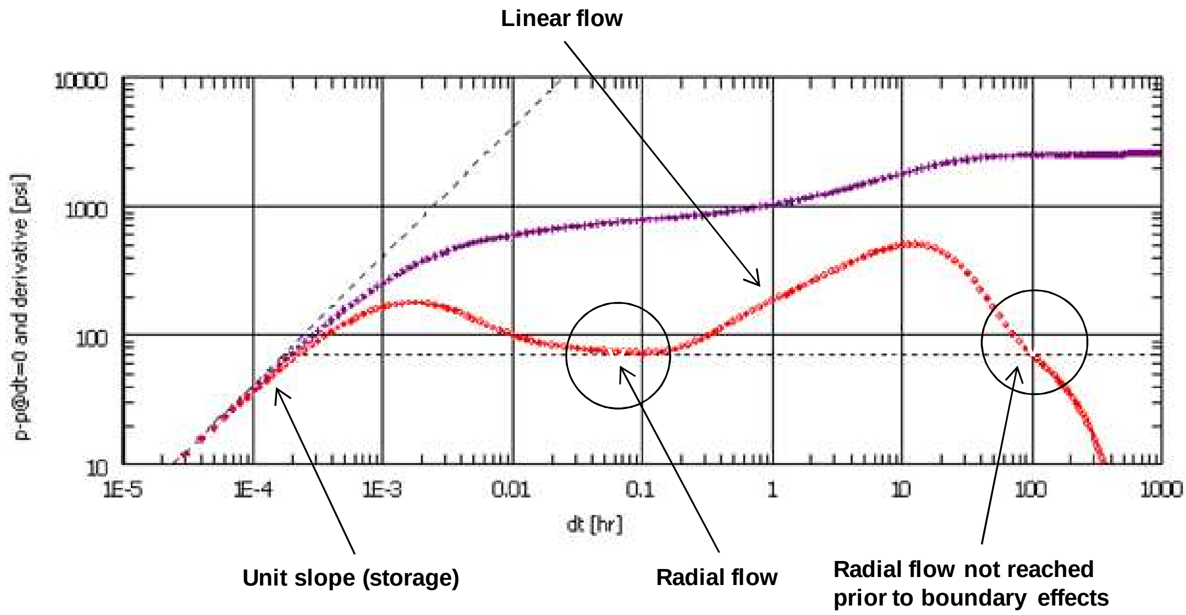
Problem 2

a) We can at the most expect to see periods dominated by wellbore storage (unit slope) , radial flow, linear flow (half slope), radial flow, and pseudosteady-state flow (unit slope).

b) The following generated data represents a possible outcome for a very long flow period at constant rate:



c) The following generated data represents a possible outcome for a very long shut-in period following a very long producing period:



Problem 3

a) The pressures are less than 2000 psia, so we should use a p^2 formulation. Since we only have stabilized data, we can use the first and last points to determine the values

$$\frac{\Delta p^2}{q} = \frac{1881^2 - 1797^2}{12.5} = 24716.2 \quad \text{and} \quad \frac{\Delta p^2}{q} = \frac{1881^2 - 1639^2}{22.7} = 37526.0\,.$$

From these we get the slope

$$b = \frac{37526.0 - 24716.2}{22.7 - 12.5} = 1229.4\,.$$

From the first we can also determine the value

$$a = \frac{1881^2 - 1797^2}{12.5} - (1229.4)(12.5) = 24716.2 - 15367.5 = 9348.7$$

The deliverability of the well will therefore be given by the identity

$$\overline{p}^2 - p_{wf}^2 = aq + bq^2 = 9348.7q + 1229.4q^2\,.$$

Furthermore we get

$$\text{AOF} = \frac{1}{(2)(1229.4)}\left[-9348.7 + \sqrt{9348.7^2 + (4)(1229.4)(1881^2)}\right] = 49.98 \text{ MMscf/d}$$

b) The same points give us

$\Delta p_1^2 = 1881^2 - 1797^2 = 308952 \text{ psi}^2$ at $q_1 = 12.5$ MMscf/d

and

$\Delta p_2^2 = 1881^2 - 1639^2 = 851840 \text{ psi}^2$ at $q_2 = 22.7$ MMscf/d.

From these points we get the slope

$$\frac{1}{n} = \frac{\log \Delta p_2^2 - \log \Delta p_1^2}{\log q_2 - \log q_1} = \frac{\log(851840) - \log(308952)}{\log(22.7) - \log(12.5)} = 1.7,$$

and hence the exponent $n = 0.588$ for the back-pressure equation $q = C(\bar{p}^2 - p_{wf}^2)^n$. Using the first point we next get

$12.5 = C(1881^2 - 1797^2)^{0.588} = C(1690.7)$, and therefore $C = 0.00739$ with

$AOF = C(\bar{p}^2)^n = (0.00739)(1881^2)^{0.588} = 52.40$ MMscf/d.