Suggested solution to the re-sit exam in Well-Test Analysis, March 3, 2015

Problem 1

a) Three flow regimes are evident in the data: (1) Wellbore storage dominated early data, from the beginning to about 0.001 hrs, (2) radial-flow data in the range 0.1-1 hrs, (3) hemi-radial data caused by a single no-flow boundary in the range 20-150 hrs, and additional boundary effects at the end, apparently from linear flow, e.g., between parallel boundaries. Data from the first can be used to determine the wellbore storage constant (*C*).

The storage constant can be determined through the steps

$$C = \frac{qB}{24}\frac{\Delta t}{\Delta p} = \frac{(3190)(1.17)}{24}\frac{0.0002}{8300-8272.65} = \frac{(3190)(1.17)(0.0002)}{(24)(27.35)} = 0.001137 \text{ RB/psi}$$

by using the first entry in Table 2 and the initial pressure. The corresponding dimensionless value will then be given by

$$C_D = \frac{5.615C}{2\pi\varphi h c_t r_w^2} = \frac{(5.615)(0.001137)}{(2\pi)(0.18)(78)(1.2\text{E-}5)(0.354)^2} = 48.13$$

b) Since we have radial-flow data between 0.1 and 1 hr, we can use $p_{wf} = 7502.84$ psia at $\Delta t = 0.20196$ hrs and $p_{wf} = 7441.08$ psia at $\Delta t = 0.80403$ hrs to determine the semi-log slope

$$m = \frac{|7441.08-7502.84|}{\log(0.80403)-\log(0.20196)} = \frac{61.76}{0.600007} = 102.932 \text{ psi/log-cycle.}$$

From the slope we next get

$$kh = \frac{162.6qB\mu}{m} = \frac{(162.6)(3190)(1.17)(3.4)}{102.932} = 20045.9 \text{ md·ft}$$

and therefore

$$k = \frac{kh}{h} = \frac{20045.9}{78} = 257 \text{ md.}$$

The pressure at 1 hour can be determined by extrapolation from either of the two points used to determine the slope *m*, for instance in the form

$$p_{1hr} = 7441.08 - m\left[\log 1 - \log(0.80403)\right] = 7441.08 + 102.932\left[\log(0.80403)\right]$$

$$= 7441.08 + 102.932(-0.09473) = 7441.08 - 9.75 = 7431.33 \text{ psi,}$$

where the fact that the actual slope is negative has been used.

The skin value can next be determined from the formula

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

$$= 1.151\left[\frac{8300 - 7431.33}{102.932} - \log \frac{257}{(0.18)(3.4)(1.2 \times 10^{-5})(0.354)^2} + 3.23 \right]$$

$$= 1.151(8.43926 - 8.44599 + 3.23) = 3.71.$$

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

$$\Delta p_S = \frac{m}{1.151} S = \frac{102.932}{1.151}(3.71) = 331.78 \text{ psi.}$$

c) The easiest is to use the radius of investigation at the end of simple radial flow, roughly at $\Delta t = 1.1$ hrs in view of the plot in Fig. 1, to estimate the distance to the nearest boundary. To this end we can use the result

$$r_{inv} = 0.0246\sqrt{\frac{k\Delta t}{\phi \mu c_t}} = 0.0246\sqrt{\frac{(257)(1.1)}{(0.18)(3.4)(1.2 \times 10^{-5})}} = 152.6 \text{ ft}$$

as estimated distance to the first boundary.

With the same approach we can assume the onset of effects from the next boundary to happen at 120 hours, and use this to estimate the second distance by the value

$$r_{inv} = 0.0246\sqrt{\frac{k\Delta t}{\phi \mu c_t}} = 0.0246\sqrt{\frac{(257)(120)}{(0.18)(3.4)(1.2 \times 10^{-5})}} = 1594 \text{ ft.}$$

For the first boundary we can also attempt to determine when the first and second straight lines intersect in Fig. 2, and use this time in the equation for the distance-t-boundary analysis. This happens roughly at

$$\log(\Delta t) = 0.5,$$

which corresponds to the time

$$\Delta t = 10^{0.5} = \sqrt{10} = 3.1623 \text{ hrs.}$$

From this value we get the estimated distance

$$d = 0.01217\sqrt{\frac{kt}{\phi \mu c_t}} = 0.01217\sqrt{\frac{(257)(3.1623)}{(0.18)(3.4)(1.2 \times 10^{-5})}} = 128 \text{ ft.}$$

d) The minimal distance to the two most distant boundaries can be estimated with the radius of investigation at 30 days = 720 hours, i.e., with the distance

$$r_{inv} = 0.0246\sqrt{\frac{k\Delta t}{\phi\mu c_t}} = 0.0246\sqrt{\frac{(257)(720)}{(0.18)(3.4)(1.2\times10^{-5})}} = 3905 \text{ ft.}$$

Since we do not know whether the first two boundaries are parallel or forming a corner of the rectangle, there are two possibilities

$$A_1 = (152.6 + 1594)(r_{inv} + r_{inv}) = (1746.6)(2\times3905) = 1.36\text{E}7 \text{ sqft}$$

if the first two are parallel, and

$$A_1 = (152.6 + r_{inv})(1594 + r_{inv}) = (152.6 + 3905)(1594 + 3905) = 2.23\text{E}7 \text{ sqft}$$

if the first two form a right angle, with both based on longest estimate to the first boundary. The smaller of the two areas above should be chosen, perhaps with 152.6 replaced by 128 ft for an even smaller estimate.

e) We clearly have storage dominated data in the beginning of the drawdown, and hence can use the first two points from Table 2 to determine the slope

$$m' = \frac{|8246.75 - 8272.65|}{0.0004 - 0.0002} = \frac{25.9}{0.0002} = 129500 \text{ psi/hr,}$$

which in turn yields the storage constant

$$C = \frac{qB}{24m'} = \frac{(3190)(1.17)}{(24)(129500)} = 0.0012 \text{ RB/psi,}$$

corresponding to the dimensionless value

$$C_D = \frac{5.615C}{2\pi\varphi h c_t r_w^2} = \frac{(5.615)(0.0012)}{(2\pi)(0.18)(78)(1.2\text{E-}5)(0.354)^2} = 50.79$$

Problem 2

a) The key parameters are the vertical permeability and vertical distance. If we now set

$$r_{inv} = 7 = 0.0286\sqrt{\frac{k_V\Delta t}{\phi\mu c_t}} = 0.0286\sqrt{\frac{(0.92)\Delta t}{(0.09)(1.11)(2.3\times10^{-4})}} = 5.7229\sqrt{\Delta t}\ ,$$

then we can solve for the time

$$\Delta t = \left(\frac{7}{5.7229} \right)^2 = 1.5 \text{ hrs}$$

as an estimate of the time to the end of early radial flow period.

b) We can use the linear flow equation in the form

$$m' = \frac{0.6236qB}{h(L_w / 2)} \sqrt{\frac{\mu}{k\phi c_t}} \ ,$$

and hence derive the slope

$$m' = \frac{(0.6236)(850)(1.23)}{(14)(1100/2)} \sqrt{\frac{1.11}{(9.2)(0.09)(2.3\times10^{-4})}} = 6.464 \text{ bar}/\sqrt{\text{hr}} \ .$$

Problem 3

a) Since the pressures are high we should use a direct pressure formulation. Therefore, if we use the first and the last of the transient points we get

$$\frac{\Delta p}{q} = \frac{5034.5 - 4927.4}{8200} = 0.01306$$

and

$$\frac{\Delta p}{q} = \frac{5034.5 - 4598.3}{18700} = 0.02333 .$$

From these we get the slope

$$b = \frac{0.02333 - 0.01306}{18700 - 8200} = 9.781\text{E} - 7 .$$

From the last point (the stable point) we get

$$\frac{\Delta p}{q} = \frac{5034.5 - 4582.6}{16100} = 0.02807 ,$$

and hence

$$a = \frac{\Delta p}{q} - bq = 0.02807 - (9.781\text{E}-7)(16100) = 0.01232 .$$

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

$$\bar{p} - p_{wf} = aq + bq^2 = 0.01232q + (9.781\text{E}-7)q^2 .$$

We furthermore get the open flow potential

$$\text{AOF} = \frac{1}{(2)(9.781\text{E}-7)}\left[-0.01232 + \sqrt{0.01232^2 + (4)(9.781\text{E}-7)(5034.5)}\right]$$

$$= 65722 \text{ Mscf/d.}$$

b) The transient points used above can be re-used here, with

$$\Delta p = 5034.5 - 4927.4 = 107.1 \text{ psi}$$

and

$$\Delta p = 5034.5 - 4598.3 = 436.2 \text{ psi}$$

to determine the slope

$$\frac{1}{n} = \frac{\log(436.2) - \log(107.1)}{\log(18700) - \log(8200)} = 1.7035 ,$$

and hence the exponent $n = 0.587$ for the back-pressure equation $q = C(\bar{p} - p_{wf})^n$. Using the last point (the stable point) we next get

$16100 = C(5034.5 - 4582.6)^{0.587} = C(36.183)$, and therefore $C = 445$ with

$$AOF = C(\bar{p}^2)^n = (445)(5034.5)^{0.587} = 66284 \text{ Mscf/d.}$$

Note: For this point we could also use the expression $q = C(\bar{p}^2 - p_{wf}^2)^n$ to carry out the analysis and determine the deliverability of the well.