Suggested solution to the final exam.
PART B: Well Testing (50 pt), PET670, February 15, 2019.

Problem 1 (26 pt)

a) Three flow regimes may be identified in the data:
1. Wellbore storage (and skin): from the beginning until 0.5 hr (or slightly longer);
2. Radial flow regime: approximately from 0.5 until 1.2 hr (not well established);
3. Hemi-radial flow regime governed by the sealing fault: approximately from 20 hr and to the end.

(2 + 2 + 2 pt)

b) With radial-flow data in the period of 0.5 - 1 hr, we can use the points p_{wf} = 3970.949 psia at t = 0.504 hr and p_{wf} = 3968.930 psia at t = 1.005 hr to determine the semi-log slope. For this drawdown data semi-log analysis with log t may be used to get the slope, m, psi/log-cycle

$$m = -\frac{3968.930 - 3970.949}{\log(1.005) - \log(0.504)} = \frac{2.019}{0.3} = 6.74.$$

(2 pt)

From the slope we next get flow capacity, kh, md·ft

$$kh = \frac{162.6qB\mu}{m} = -\frac{(162.6)(200)(1.03)(0.65)}{6.74} = \frac{21772.1}{6.74} = 3230.3,$$

and therefore permeability, k, md

$$k = \frac{kh}{h} = \frac{3230.3}{300} = 10.8.$$

(2 pt)

Radial flow regime is identified to last approximately from 0.5 until 1.2 hr, meaning that the pressure at 1 hour can be used from the data set:

$$p_{1hr} \approx p(1.005) = 3968.930.$$

or may be calculated with more precision as:

$$p_{1hr} = 3968.930 - m[\log(1) - \log(1.005)] =$$
$$= 3968.930 - 6.74[0 - 0.002] = 3968.944.$$

(2 pt)

Then, hydraulic diffusivity may be computed as

$$\frac{k}{\phi\mu c_t r_w^2} = \frac{10.8}{(0.3)(0.65)(7.5 \cdot 10^{-6})(0.3 \cdot 0.3)} = \frac{10.8}{1.32 \cdot 10^{-7}} = 8.18 \cdot 10^7.$$

The skin value can next be determined from the formula

$$S = 1.151\left(\frac{p_i - p_{1hr}}{m} - \log\frac{k}{\phi\mu c_t r_w^2} + 3.228\right),$$

$$S = 1.151\left(\frac{4000.0 - 3968.930}{6.74} - \log(8.18 \cdot 10^7) + 3.228\right) =$$

$$= 1.151(4.610 - 7.913 + 3.228) = -0.09.$$

Using $p_{1hr} = 3968.944$ psi (with more precision), gives the same skin (at given precision).

(2 pt)

c) Distance to the sealing fault may be evaluated based on straight-lines with slopes characteristic for the radial and hemi-radial flow regimes in Fig. 2. Intersection of these straight-lines indicates time, which may be used to compute approximate distance to the sealing fault. In our case such a time may be estimated as 8 hr, and the distance, *d*, ft then

$$d = 0.0122\sqrt{\frac{kt}{\phi\mu c_t}} = 0.0122\sqrt{\frac{(10.8)(8)}{(0.3)(0.65)(7.5 \cdot 10^{-6})}} = 93.8.$$

(2 pt)

d) Assuming no data available before 10 hr and without any knowledge about sealing fault nearby the well, the derivative stabilization after 10 hr in the log-log plot (Fig. 1) may be interpreted as initiation of radial flow regime.

With such a radial-flow regime in the period of 20 hr until the end of the drawdown, we can use the points p_{wf} = 3957.312 psia at t = 20 hr and p_{wf} = 3952.943 psia at t = 48 hr to determine the semi-log slope. For this drawdown data semi-log analysis with log t may be used to get the slope, *m*, psi/log-cycle

$$m = -\frac{3952.943 - 3957.312}{\log(48) - \log(20)} = \frac{4.369}{0.38} = 11.5.$$

(2 pt)

From the slope we next get flow capacity, *kh*, md·ft

$$kh = \frac{162.6qB\mu}{m} = -\frac{(162.6)(200)(1.03)(0.65)}{11.5} = \frac{21772.1}{11.5} = 1893.2,$$

and therefore permeability, *k*, md

$$k = \frac{kh}{h} = \frac{1893.2}{300} = 6.3.$$

(2 pt)

The pressure at 1 hour can be determined by extrapolation from either of the two points used to determine the slope m. We can therefore set p_{1hr}, psia

$$p_{1hr} = 3957.312 - m[\log(1) - \log(20)] =$$
$$= 3957.312 - 11.5[0 - 1.3] = 3972.262.$$

(2 pt)

Then, hydraulic diffusivity may be computed as

$$\frac{k}{\phi \mu c_t r_w^2} = \frac{6.3}{(0.3)(0.65)(7.5 \cdot 10^{-6})(0.3 \cdot 0.3)} = \frac{6.3}{1.317 \cdot 10^{-7}} = 4.77 \cdot 10^7.$$

The skin value can next be determined from the formula

$$S = 1.151 \left(\frac{p_i - p_{1hr}}{m} - \log \frac{k}{\phi \mu c_t r_w^2} + 3.228 \right),$$
$$S = 1.151 \left(\frac{4000.0 - 3972.262}{11.5} - \log(4.77 \cdot 10^7) + 3.228 \right) =$$
$$= 1.151(2.412 - 7.679 + 3.228) = -2.35.$$

(2 pt)

e) The permeabilities calculated in the tasks b) and d) are 10.8 and 6.3 mD; skin factors are 0.09 and -2.35. According to the theory, the radial flow permeability estimate (the semi-log slop) for hemi-radial regime should be double of the estimate from radial flow regime.

The radial flow regime looks not to be well established comparing to the hemi-radial flow regime (Fig. 1). Taking this observation into account, the permeability estimation may be improved with a value of 12.6 mD by doubling the permeability value of 6.3 mD.

The skin value estimation depends on correct permeability for radial flow regime. Therefore, the skin of -0.09 should be the only valid estimation.

(2 pt)

Problem 2 (24 pt)

a) There are two flow regimes evident in the data:
   1. Early linear flow with half-slope data from the beginning until 0.3 hr (or slightly longer);
   2. Radial flow from 20 hr (or slightly earlier) and to the end.

(2 + 2 pt)

b) With radial flow data from 20 hr to the end, we can use the points p_{ws} = 5485.281 psia at Δt = 20 hr and p_{ws} = 5492.968 psia at Δt = 48 hr to determine the semi-log slope. For this build-up data semi-log analysis with Horner time, $\Delta t/(t+\Delta t)$, may be used to get the slope, *m*, psi/log-cycle

$$m = \frac{5492.968 - 5485.281}{\log\left(\frac{48}{12+48}\right) - \log\left(\frac{20}{12+20}\right)} = \frac{7.687}{0.11} = 69.88.$$

(2 pt)

From the slope we next get flow capacity, *kh*, md·ft

$$kh = \frac{162.6qB\mu}{m} = \frac{(162.6)(500)(1.03)(0.65)}{69.88} = \frac{54430.4}{69.88} = 778.9,$$

and therefore permeability, *k*, md

$$k = \frac{kh}{h} = \frac{778.9}{300} = 2.6.$$

(2 pt)

The pressure at Δt = 1 hour can be determined by extrapolation from either of the two points used to determine the slope *m*. We can therefore set p_{1hr}, psia

$$p_{1hr} = 5485.281 + m[\log(1/(12+1)) - \log(20/(12+20))] =$$
$$= 5485.281 + 69.88[-1.114 + 0.204] = 5485.281 - 63.591 = 5421.69.$$

(2 pt)

Then, hydraulic diffusivity may be computed

$$\frac{k}{\phi\mu c_t r_w^2} = \frac{2.6}{(0.3)(0.65)(7.5\cdot 10^{-6})(0.3\cdot 0.3)} = \frac{2.6}{1.317\cdot 10^{-7}} = 1.97\cdot 10^7.$$

The skin value can next be determined from the formula

$$S = 1.151\left(\frac{p_{1hr} - p_{wf,s}}{m} - \log\frac{t}{t+1} - \log\frac{k}{\phi\mu c_t r_w^2} + 3.228\right),$$

$$S = 1.151\left(\frac{5421.69 - 5371.712}{69.88} - \log(0.92) - \log(1.97\cdot 10^7) + 3.228\right) =$$

$$= 1.151(0.715 + 0.036 - 7.294 + 3.228) = 1.151(-3.315) = -3.82.$$

(2 pt)

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

$$\Delta p_S = \frac{m}{1.151} S = \frac{69.88}{1.151}(-3.82) = -231.921.$$

(2 pt)

c) We can for instance use the points p_{ws} = 5377.654 psia at Δt = 0.01 hr and p_{ws} = 5390.325 psia at Δt = 0.1 hr to determine the slope, m', psi/$\sqrt{\text{hr}}$

$$m' = \frac{5390.325 - 5377.654}{\sqrt{0.1} - \sqrt{0.01}} = \frac{16.733}{0.316 - 0.1} = 58.66,$$

(2 pt)

for the linear-flow analysis. From this slope we get the half-length, x_f, ft

$$x_f = \frac{4.064qB}{hm'}\sqrt{\frac{\mu}{k\phi c_t}} = \frac{(4.064)(500)(1.03)}{(300)(58.66)}\sqrt{\frac{0.65}{(2.6)(0.3)(7.5 \cdot 10^{-6})}} =$$

$$= \frac{2092.96}{17598}\sqrt{\frac{0.65}{5.9 \cdot 10^{-6}}} = (0.12)(331.92) = 39.8.$$

(2 pt)

If the fracture has infinite conductivity, then we get the skin value

$$S = \ln\frac{2r_w}{x_f} = \ln\frac{(2)(0.3)}{39.8} = \ln(0.0151) = -4.19.$$

If the fracture has uniform flux, then we get

$$S = \ln\frac{er_w}{x_f} = \ln\frac{(2.718)(0.3)}{39.8} = \ln(0.0205) = -3.89.$$

The value from the semi-log analysis is closer to the uniform flux result.
(2 pt)

d) With short flow prior to shut-in and no boundary effects seen in buildup data we can use p^* as an estimate of the formation pressure. We can again extrapolate the semi-log straight line from the first data point used above and get p^*, psia

$$p_i = p^* = 5485.281 + m\left[\log(1) - \log\left(\frac{20}{12 + 20}\right)\right] =$$

$$= 5485.281 + 69.88(0.204) = 5499.54.$$

(2 pt)

With flow at the same constant rate of 500 STB/D, we can compute drawdown (flowing) pressure after 48 hours using

$$p_{wf}(t) = p_i - m\left(\log t + \log\frac{k}{\phi\mu c_t r_w^2} - 3.228 + \frac{S}{1.151}\right),$$

$$p_{wf}(48) = 5499.54 - 69.88(\log(48) + \log(1.97 \cdot 10^7) - 3.228 - 3.82/1.151) =$$

$$= 5499.54 - 69.88(1.68 + 7.294 - 3.228 - 3.32) = 5499.54 - 69.88(2.426) =$$

$$= 5499.54 - 169.529 = 5330.011.$$

where pressure drawdown, psi

$$p_i - p_{wf} = 169.529.$$

(2 pt) Comment: Computed pressure drawdown or flowing pressure (alone) is considered as sufficient result.

General comments: in a 2-point task, 2 points are given if both equation used and computed result are correct; 1 point if only equation used is correct. An incorrect result of preceding calculations (used in current task) does not change grading of the current task.

STANDARD EQUATIONS WELL TESTING

$p_D = \frac{kh}{18.66 qB\mu} \Delta p$	(SI units, oil; field units: 18.66 → 141.2)
$t_D = \frac{0.000355k}{\phi \mu c_t r_w^2} t$	(SI units, oil and gas; field units: 0.000355 → 0.000264)
$m = \frac{21.49 qB\mu}{kh}$	(SI units; field units: 21.49 → 162.6)
$p_{wf}(t) = p_i - m\left(\log t + \log \frac{k}{\phi \mu c_t r_w^2} - 3.098 + \frac{S}{1.151}\right)$	(SI units, DD data; field units: 3.098 → 3.228)
$S = 1.151\left(\frac{p_i - p_{1hr}}{m} - \log \frac{k}{\phi \mu c_t r_w^2} + 3.098\right)$	(SI units, DD data; field units: 3.098 → 3.228)
$p_{ws}(\Delta t) = p_{wf,s} + m\left(\log \frac{\Delta t}{t + \Delta t} + \log t + \log \frac{k}{\phi \mu c_t r_w^2} - 3.098 + \frac{S}{1.151}\right)$	(SI units, BU data; field units: 3.098 → 3.228)
$S = 1.151\left(\frac{p_{1hr} - p_{wf,s}}{m} - \log \frac{t}{t+1} - \log \frac{k}{\phi \mu c_t r_w^2} + 3.098\right)$	(SI units, BU data; field units: 3.098 → 3.228)
$\Delta p_S = \frac{m}{1.151} S$	
$r_{inv} = 0.0286 \sqrt{\frac{kt}{\phi \mu c_t}}$	(SI units; field units: 0.0286 → 0.0246)
$d = 0.0141 \sqrt{\frac{kt}{\phi \mu c_t}}$	(SI units; field units: 0.0141 → 0.0122)

Fractured wells:

$m' = \frac{0.624 qB}{h x_f} \sqrt{\frac{\mu}{k \phi c_t}}$	(SI units; field units: 0.624 → 4.064)
$S = \ln \frac{2 r_w}{x_f}$	(fracture with infinite conductivity)
$S = \ln \frac{e r_w}{x_f} = \ln \frac{2.718 r_w}{x_f}$	(fracture with uniform flux)

Gas tests:

$q_{sc} = C\left(\bar{p}^2 - p_{wf}^2\right)^n$	(simplified deliverability, p^2 formulation)
$\bar{p}^2 - p_{wf}^2 = a q_{sc} + b q_{sc}^2$	(LIT based deliverability, p^2 formulation)
$AOF = \frac{1}{2b}\left(-a + \sqrt{a^2 + 4b\bar{p}^2}\right)$	(LIT based AOF, p^2 formulation)