Lecture Three

Standing's Method

Standing (1970) essentially extended the application of Vogel's to predict future inflow performance relationship of a well as a function of reservoir pressure. He noted that Vogel's equation: Equation 2-9 can be rearranged as:

$$\frac{Q_o}{(Q_o)\max} = \left(1 - \frac{P_{wf}}{\bar{P}_r}\right)\left[1 + 0.8\left(\frac{P_{wf}}{\bar{P}_r}\right)\right] \quad \text{.......... (2.13)}$$

Standing introduced the productivity index J as defined by Equation 2-1 into Equation 2-13 to yield:

$$J = \frac{(Q_o)_{max}}{\bar{P}_r}\left[1 + 0.8\left(\frac{P_{wf}}{\bar{P}_r}\right)\right] \quad \text{................. (2-14)}$$

Standing then defined the present (current) zero drawdown productivity index as:

$$J_p^* = 1.8\left[\frac{(Q_o)_{max}}{\bar{P}_r}\right] \quad \text{................. (2-15)}$$

Where Jp^* is Standing's zero-drawdown productivity index. The Jp^* is related to the productivity index J by:

$$\frac{J}{J_p^*} = \frac{1}{1.8}\left[1 + 0.8\left(\frac{P_{wf}}{\bar{P}_r}\right)\right] \quad \text{................ (2-16)}$$

Equation 2-1 permits the calculation of Jp from a measured value of J.

To arrive at the final expression for predicting the desired IPR expression, Standing combines Equation 2-15 with Equation 2-13 to eliminate $(Qo)_{max}$ to give:

$$Q_o = \left[\frac{J_f^*(\overline{p}_r)_f}{1.8}\right]\left\{1 - 0.2\left[\frac{p_{wf}}{(\overline{p}_r)_f}\right] - 0.8\left[\frac{p_{wf}}{(\overline{p}_r)_f}\right]^2\right\} \quad \text{.......... (2-17)}$$

Where the subscript f refers to future condition,

Standing suggested that Jf^* can be estimated from the present value of Jp^* by the following expression:

$$J_f^* = J_p^*\left(\frac{k_{ro}}{\mu_o B_o}\right)_f \Big/ \left(\frac{k_{ro}}{\mu_o B_o}\right)_p \quad \text{............ (2-18)}$$

Where the subscript p refers to the present condition,

If the relative permeability data are not available, Jf^* can be roughly estimated from:

$$J_f^* = J_p^*\left[(\overline{p}_r)_f/(\overline{p}_r)_p\right]^2 \quad \text{........... (2-19)}$$

Standing's methodology for predicting a future IPR is summarized in the following steps:

Step 1: Using the current time condition and the available flow test data, calculate $(Qo)_{max}$ from Equation 2-9 or Equation 2-13.

Step 2: Calculate J* at the present condition, i.e., Jp^*, by using Equation 2-15.

Notice that other combinations of Equations 2-13 through 2-16 can be used to estimate Jp*.

Step 3: Using fluid property, saturation, and relative permeability data, calculate both $(kro/\mu oBo)_p$ and $(kro/\mu oBo)_f$.

Step 4: Calculate Jf* by using Equation 2-18. Use Equation 2-19 if the oil relative permeability data are not available.

Step 5: Generate the future IPR by applying Equation 2-17.

Example 2-5:

A well is producing from a saturated oil reservoir that exists at its saturation pressure of 4000 psia. The well is flowing at a stabilized rate of 600 STB/day and a p_{wf} of 3200 psia. Material balance calculations provide the following current and future predictions for oil saturation and PVT properties.

	Present	Future
$\bar{p}_r$	4000	3000
μ_o, cp	2.40	2.20
B_o, bb1/STB	1.20	1.15
k_{ro}	1.00	0.66

Generate the future IPR for the well at 3000 psig by using Standing's method.

Solution:

Step 1: Calculate the current $(Qo)_{max}$ from Equation 2-13.

$$(Q_o)_{max} = 600/\left[\left(1-\frac{3200}{4000}\right)(1+0.8)\left(\frac{3200}{4000}\right)\right] = 1829 \text{ STB/day}$$

Step 2: Calculate Jp* by using Equation 2-15.

$$J_p^* = 1.8\left[\frac{1829}{4000}\right] = 0.823$$

Step 3: Calculate the following pressure-function:

$$\left(\frac{k_{ro}}{\mu_o B_o}\right)_D = \frac{1}{(2.4)(1.20)} = 0.3472$$

$$\left(\frac{k_{ro}}{\mu_o B_o}\right)_f = \frac{0.66}{(2.2)(1.15)} = 0.2609$$

Step 4: Calculate Jf∗ by applying Equation 2-18.

$$J_f^* = 0.823\left(\frac{0.2609}{0.3472}\right) = 0.618$$

Step 5: Generate the IPR by using Equation 2-17.

p_{wf}	Q_o, STB/day
3000	0
2000	527
1500	721
1000	870
500	973
0	1030

It should be noted that one of the main disadvantages of Standing's methodology is that it requires reliable permeability information; in addition, it also requires material balance calculations to predict oil saturations at future average reservoir pressures.

Fetkovich's Method

Muskat and Evinger (1942) attempted to account for the observed nonlinear flow behavior (i.e., IPR) of wells by calculating a theoretical productivity index from the pseudosteady-state flow equation. They expressed Darcy's equation as:

$$Q_o = \frac{0.00708kh}{\left[\ln\frac{r_e}{r_w} - 0.75 + s\right]} \int_{p_{wf}}^{\bar{p}_r} f(p)dp \quad \text{......... (2-20)}$$

Where the pressure function f (p) is defined by:

$$f(p) = \frac{k_{ro}}{\mu_o B_o} \quad \text{............ (2-21)}$$

Where:

kro = oil relative permeability

k = absolute permeability, md

Bo = oil formation volume factor

μo = oil viscosity, cp

Fetkovich (1973) suggests that the pressure function f (p) can basically fall into one of the following two regions:

Region 1: Undersaturated Region

The pressure function f (p) falls into this region if p > pb. Since oil relative permeability in this region equals unity (i.e., kro = 1), then:

$$f(p) = \left(\frac{1}{\mu_o B_o}\right)_p \quad \ldots\ldots\ldots\ldots\ldots\ (2\text{-}22)$$

Fetkovich observed that the variation in f (p) is only slight and the pressure function is considered constant as shown in Figure 2-9.

Region 2: Saturated Region

In the saturated region where p < pb, Fetkovich shows that the ($k_{ro}/\mu_o B_o$) changes linearly with pressure and that the straight line passes through the origin. This linear is shown schematically in Figure 2-9 can be expressed mathematically as:

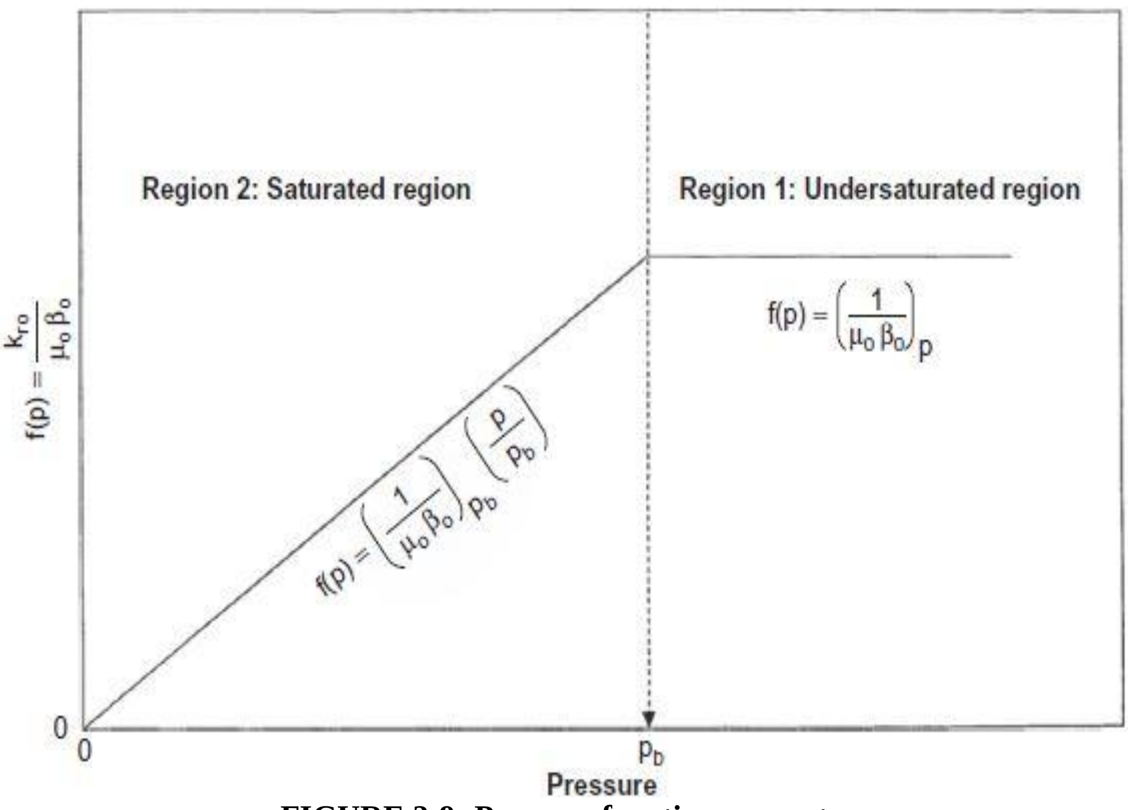

FIGURE 2-9: Pressure function concept.

$$f(p) = \left(\frac{1}{\mu_o B_o}\right)_{p_b} \left(\frac{p}{p_b}\right) \quad \ldots\ldots\ldots\ldots\ldots\ (2\text{-}23)$$

Where μo and Bo are evaluated at the bubble-point pressure,

In the application of the straight-line pressure function, there are three cases that must be considered:

- Pr and pwf > pb
- Pr and pwf < Pb
- Pr > pb and pwf < Pb

All three cases are presented below.

Case 1: Pr and Pwf > Pb

This is the case of a well producing from an undersaturated oil reservoir where both P_{wf} and P_r are greater than the bubble-point pressure. The pressure function f (p) in this case is described by Equation 2-22. Substituting Equation 2-22 into Equation 2-20 gives:

$$Q_o = \frac{0.00708kh}{\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s} \int_{pwf}^{\overline{p}_r} \left(\frac{1}{\mu_o B_o}\right) dp$$

Since (1/μoBo) is constant, then:

$$Q_o = \frac{0.00708kh}{\mu_o B_o \left[\ln\left(\frac{r_e}{r_w}\right) -0.75+ \ S\right]} (\overline{p}_r - p_{wf}) \quad \ldots\ldots\ldots\ (2\text{-}24)$$

Or

$$Q_o = J(\overline{p}_r - p_{wf}) \quad \ldots\ldots\ldots\ldots\ (2\text{-}25)$$

The productivity index is defined in terms of the reservoir parameters as:

$$J = \frac{0.00708\,kh}{\mu_o B_o \left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right]} \quad \ldots\ldots\ldots\ (2\text{-}26)$$

Where Bo and μo are evaluated at (pr +pwf)/2,

Example 2-6:

A well is producing from an undersaturated-oil reservoir that exists at an average reservoir pressure of 3000 psi. The bubble-point pressure is recorded as 1500 psi at 150°F. The following additional data are available:

- stabilized flow rate = 280 STB/day
- stabilized wellbore pressure = 2200 psi
- h = 200' rw = 0.30' re = 6600' S = –0.5
- k =65 md
- μo at 2600 psi = 2.4 cp
- Bo at 2600 psi = 1.4 bbl/STB

Calculate the productivity index by using both the reservoir properties (i.e., Equation 2-26) and flow test data (i.e., Equation 2-25).

Solution:

- From Equation 2-26

$$J = \frac{0.00708(65)(20)}{(2.4)(1.4)\left[\ln\left(\frac{660}{0.3}\right) - 0.75 - 0.5\right]} = 0.42 \text{ STB/day/psi}$$

- From production data:

$$J = \frac{280}{3000 - 2200} = 0.35 \text{ STB/day/psi}$$

Results show a reasonable match between the two approaches. It should be noted, however, that there are several uncertainties in the values of the parameters used in Equation 2-26 to determine the productivity index. For example, changes in the skin factor S or drainage area would change the calculated value of J.

Case 2: P_r and P_{wf} < P_b

When the reservoir pressure Pr and bottom-hole flowing pressure Pwf are both below the bubble-point pressure Pb, the pressure function f (p) is represented by the straight line relationship as expressed by Equation 2-23. Combining Equation 2-23 with Equation 2-20 gives:

$$Qo = \left[\frac{0.00708kh}{\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s}\right] \int_{P_{wf}}^{\bar{P}_r} \frac{1}{(\mu_o B_o)} \left(\frac{p}{p_b}\right) dp$$

Since the term $\left[\left(\frac{1}{\mu_o B_o}\right)_{pb} \left(\frac{1}{p_b}\right)\right]$ is constant, then:

$$Q_o = \left[\frac{0.00708\,kh}{\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s}\right] \frac{1}{(\mu_o B_o)_{pb}} \left(\frac{1}{p_b}\right) \int_{P_{wf}}^{\bar{P}_r} p\,dp$$

Integrating gives:

$$Q_o = \frac{0.00708\,kh}{(\mu_o B_o)_{pb}\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right]} \left(\frac{1}{2p_b}\right) (\bar{p}_r^{2} - p_{wf}^{w}) \quad \text{....... (2-27)}$$

Introducing the productivity index into the above equation gives:

$$Q_o = J\left(\frac{1}{2p_b}\right)(\bar{p}_r^{2} - p_{wf}^2) \quad \text{............. (2-28)}$$

The term (J / 2Pb) is commonly referred to as the performance coefficient C, or:

$$Q_o = C(\bar{p}_r^{2} - p_{wf}^2) \quad \text{........ (2-29)}$$

To account for the possibility of non-Darcy flow (turbulent flow) in oil wells, Fetkovich introduced the exponent n in Equation 2-30 to yield:

$$Q_o = C(\bar{p}_r^{2} - p_{wf}^2)^n \quad \text{.................. (2-30)}$$

The value of n ranges from 1.00 for a complete laminar flow to 0.5 for highly turbulent flow,

There are two unknowns in Equation 2-30: the performance coefficient C and the exponent n. At least two tests are required to evaluate these two parameters, assuming Pr is known:

By taking the log of both sides of Equation 2-30 and solving for log (pr^2 - p_{wf}^2) the expression can be written as:

$$\log\left(\bar{p}_r^{2} - p_{wf}^{2}\right) = \frac{1}{n}\log Q_o - \frac{1}{n}\log C$$

A plot of (p_r^2 – p_{wf}^2) versus Qo on log-log scales will result in a straight line having a slope of 1/n and an intercept of C at $p_r^2 - p_{wf}^2 = 1$. The value of C can also be calculated using any point on the linear plot once n has been determined to give:

$$C = \frac{Q_o}{[p_r^2 - p_{wf}^2]^n}$$

Once the values of C and n are determined from test data, Equation 2-30 can be used to generate a complete IPR.

To construct the future IPR when the average reservoir pressure declines to $(\overline{pr})_f$, Fetkovich assumes that the performance coefficient C is a linear function of the average reservoir pressure and, therefore, the value of C can be adjusted as:

$$(C)_f = (C)_p \left[(\bar{p}_r)_f / (\bar{p}_r)_p\right] \quad \text{……….. (2-31)}$$

Where the subscripts f and p represent the future and present conditions,

Fetkovich assumes that the value of the exponent n would not change as the reservoir pressure declines. Beggs (1991) presented an excellent and comprehensive discussion of the different methodologies used in constructing the IPR curves for oil and gas wells.

The following example was used by Beggs (1991) to illustrate Fetkovich's method for generating the current and future IPR.

Example 2-7:

A four-point stabilized flow test was conducted on a well producing from a saturated reservoir that exists at an average pressure of 3600 psi.

Q_o, STB/day	p_{wf}, psi
263	3170
383	2890
497	2440
640	2150

a. Construct a complete IPR by using Fetkovich's method.

b. Construct the IPR when the reservoir pressure declines to 2000 psi.

Solution:

Part A

Step 1: Construct the following table:

Q_o, STB/day	p_{wf}, psi	$(\bar{p}_r^2 - p_{wf}^2) \times 10^{-6}$, psi^2
263	3170	2.911
383	2890	4.567
497	2440	7.006
640	2150	8.338

Step 2: Plot $(p_r^2 - p_{wf}^2)$ verses Qo on log-log paper as shown in Figure 2-11 and determine the exponent n, or:

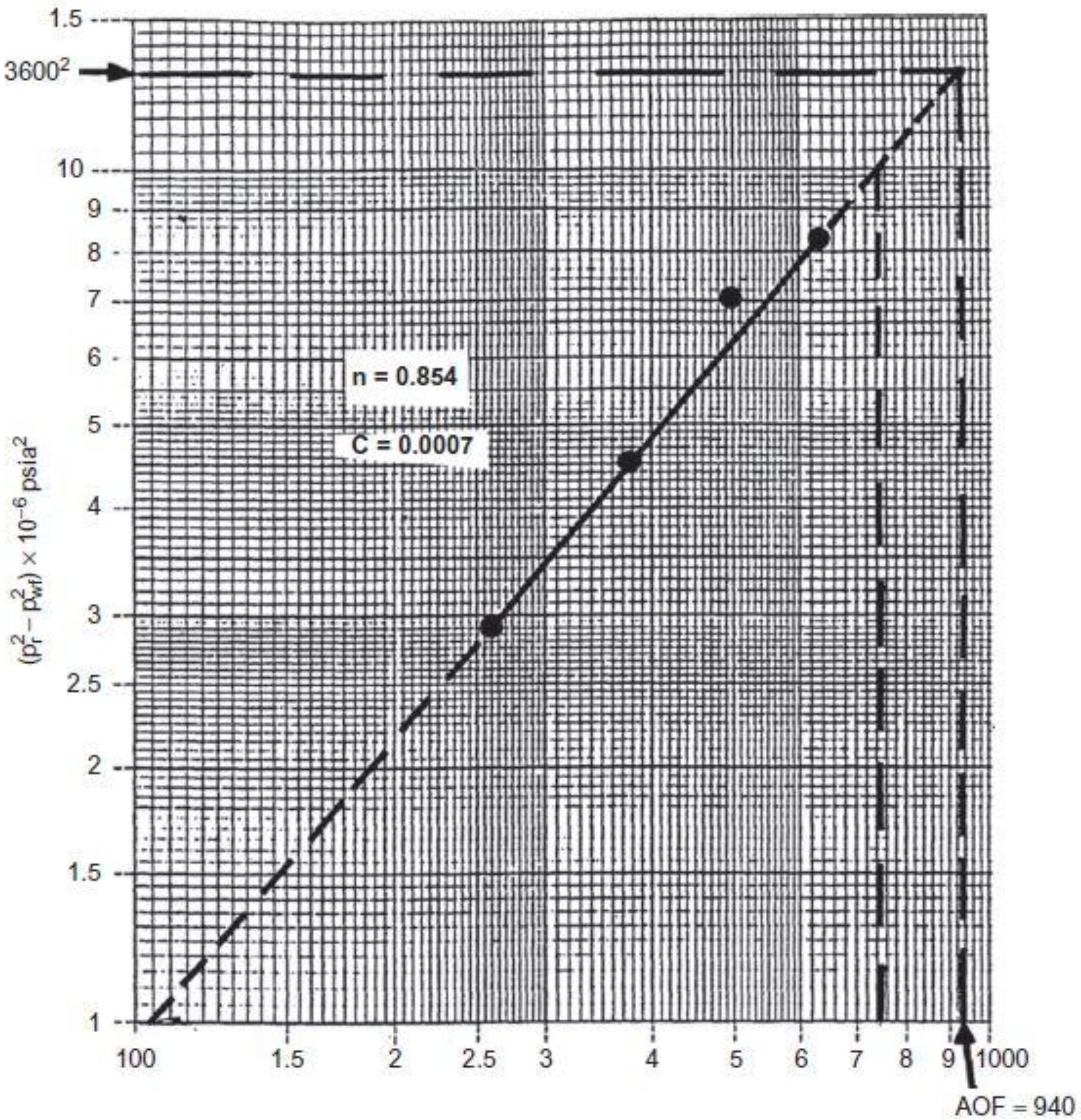

FIGURE 2-10: Flow-after-flow data for example 2-7

$$Q_o = 0.00079\,(3600^2 - p_{wf}^2)^{0.854}$$

Step 3: Solve for the performance coefficient C:

$$C = 0.00079$$

Step 4: Generate the IPR by assuming various values for p_{wf} and calculating the corresponding flow rate from Equation 2-20:

$$Q_o = 0.00079\,(3600^2 - p_{wf}^2)^{0.854}$$

p_{wf}	Q_o, STB/day
3600	0
3000	340
2500	503
2000	684
1500	796
1000	875
500	922
0	937

The IPR curve is shown in Figure 2-11. Notice that the AOF, i.e., $(Qo)_{max}$, is 937 STB/day.

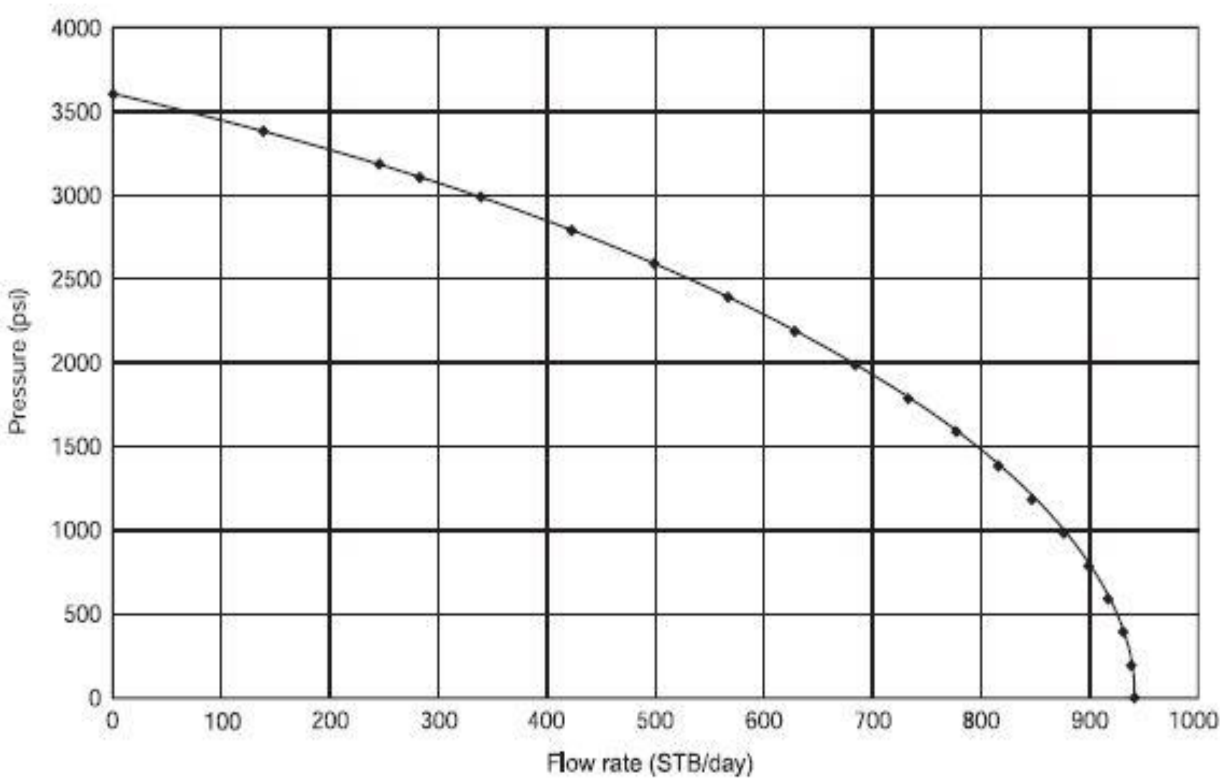

FIGURE 2-11: IPR using Fetkovich method.

Part B

Step 1: Calculate future C by applying Equation 2-31

$$(C)_f = 0.00079\left(\frac{2000}{3600}\right) = 0.000439$$

Step 2: Construct the new IPR curve at 2000 psi by using the new calculated C and applying the inflow equation.

$$Q_o = 0.000439\left(20002 - p_{wf}^2\right)^{0.854}$$

p_{wf}	Q_o
2000	0
1500	94
1000	150
500	181
0	191

Both the present time and future IPRs are plotted in Figure 2-12.

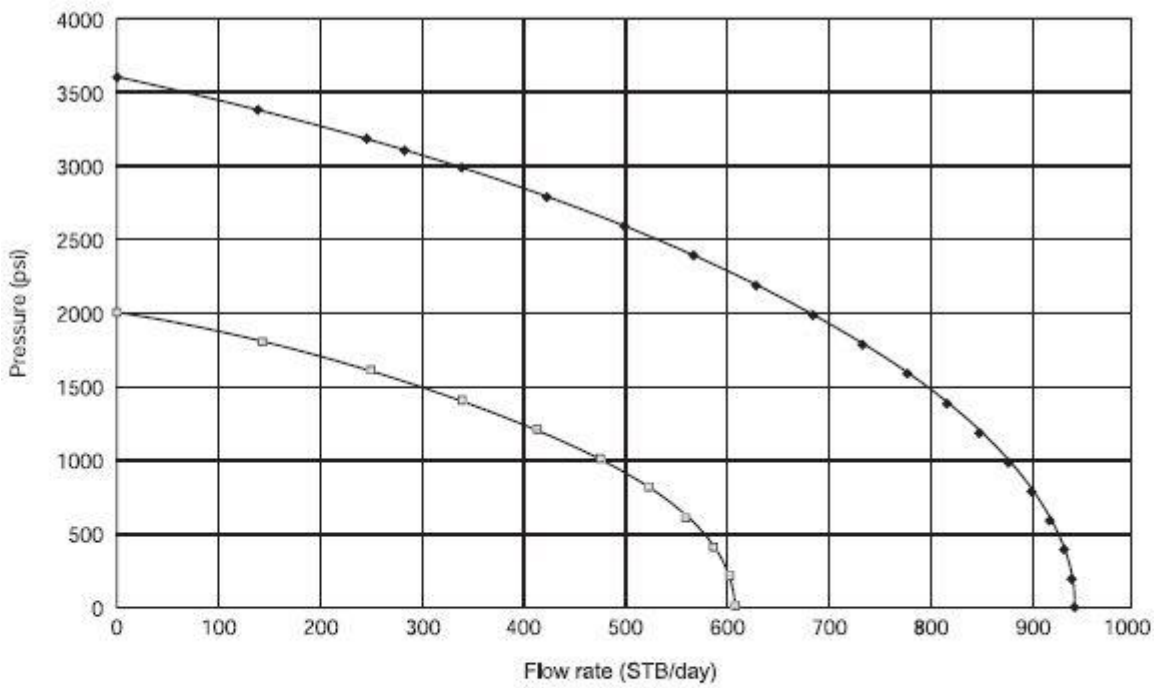

FIGURE 2-12: Future IPR at 2000 psi.

Case 3: Pr > Pb and Pwf < Pb

Figure 2-13 shows a schematic illustration of Case 3 in which it is assumed that pwf < pb and pr >pb. The integral in Equation 2-20 can be expanded and written as:

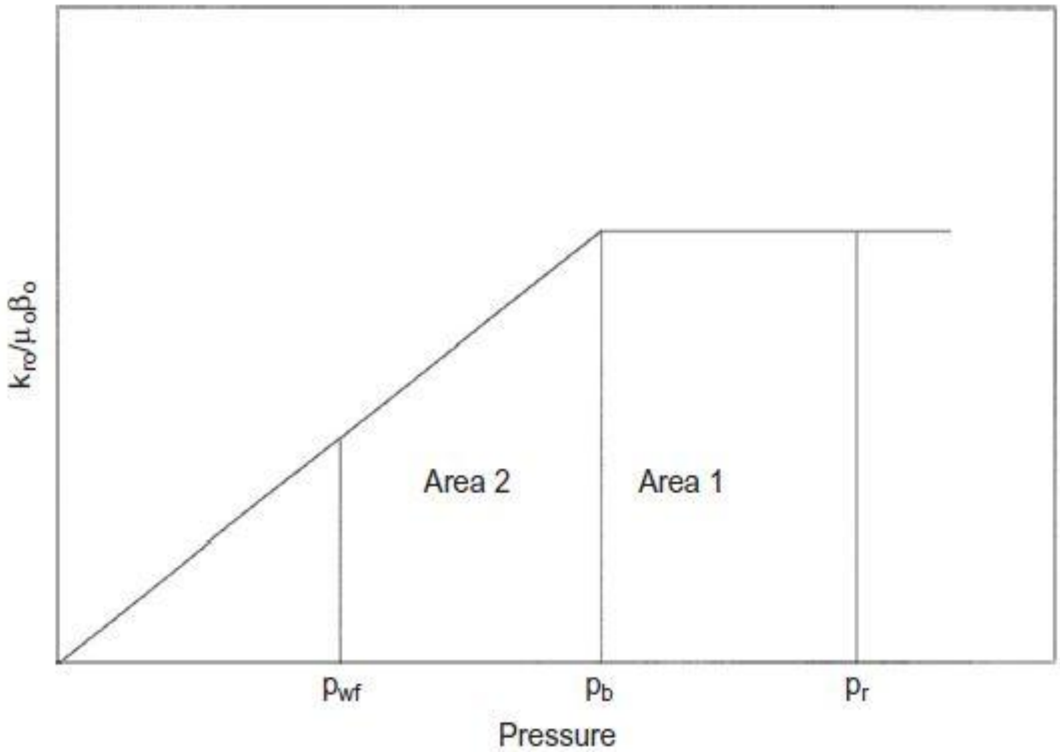

FIGURE 2-13: (kro/μoBo) vs. pressure for Case #3.

$$Q_o = \frac{0.00708\,kh}{\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s}\left[\int_{p_{wf}}^{p_b} f(p)\,dp + pb\int_{pb}^{\bar{p}r} f(p)\,dp\right]$$

Substituting Equations 2-22 and 2-13 into the above expression gives:

$$Q_o = \frac{0.00708\,kh}{\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s}\left[\int_{p_{wf}}^{p_b}\left(\frac{1}{\mu_o B_o}\right)\left(\frac{p}{p_b}\right)dp + \int_{p_b}^{\bar{p}_r}\left(\frac{1}{\mu_o B_o}\right)dp\right]$$

Where μo and Bo are evaluated at the bubble-point pressure pb. Arranging the above expression gives:

$$Q_o = \frac{0.00708\,kh}{\mu_o B_o\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right]}\left[\frac{1}{p_b}\int_{p_{wf}}^{p_b} p\,dp + \int_{p_b}^{\bar{p}r} dp\right]$$

Integrating and introducing the productivity index J into the above relationship gives:

$$Q_o = J\left[\frac{1}{2p_b}(p_b^2 - p_{wf}^2) + (\bar{p}_r - p_b)\right]$$

or ………… (2-32)

$$Q_o = J\left[(\bar{p}_r - p_b) + \frac{1}{2p_b}(p_b^2 - p_{wf}^2)\right]$$

Example 2-8:

The following reservoir and flow-test data are available on an oil well:

- Pressure data: pr = 4000 psi pb = 3600 psi
- Flow test data: pwf = 3200 psi Qo = 280 STB/day

Generate the IPR data of the well.

Solution:

Step 1: Calculate the productivity index from the flow-test data.

$$J = \frac{280}{4000 - 3200} = 0.7 \text{ STB/day/psi}$$

Step 2: Generate the IPR data by applying Equation 2-25 when the assumed pwf > pb and using Equation 2-32 when pwf < pb.

P_{wf}	Equation	Q_o
4000	(2-25)	0
3800	(2-25)	140
3600	(2-25)	280
3200	(2-25)	560
3000	(2-32)	696
2600	(2-32)	941
2200	(2-32)	1151
2000	(2-32)	1243
1000	(2-32)	1571

500	(2-32)	1653
0	(2-32)	1680

Results of the calculations are shown graphically in Figure 2-14.

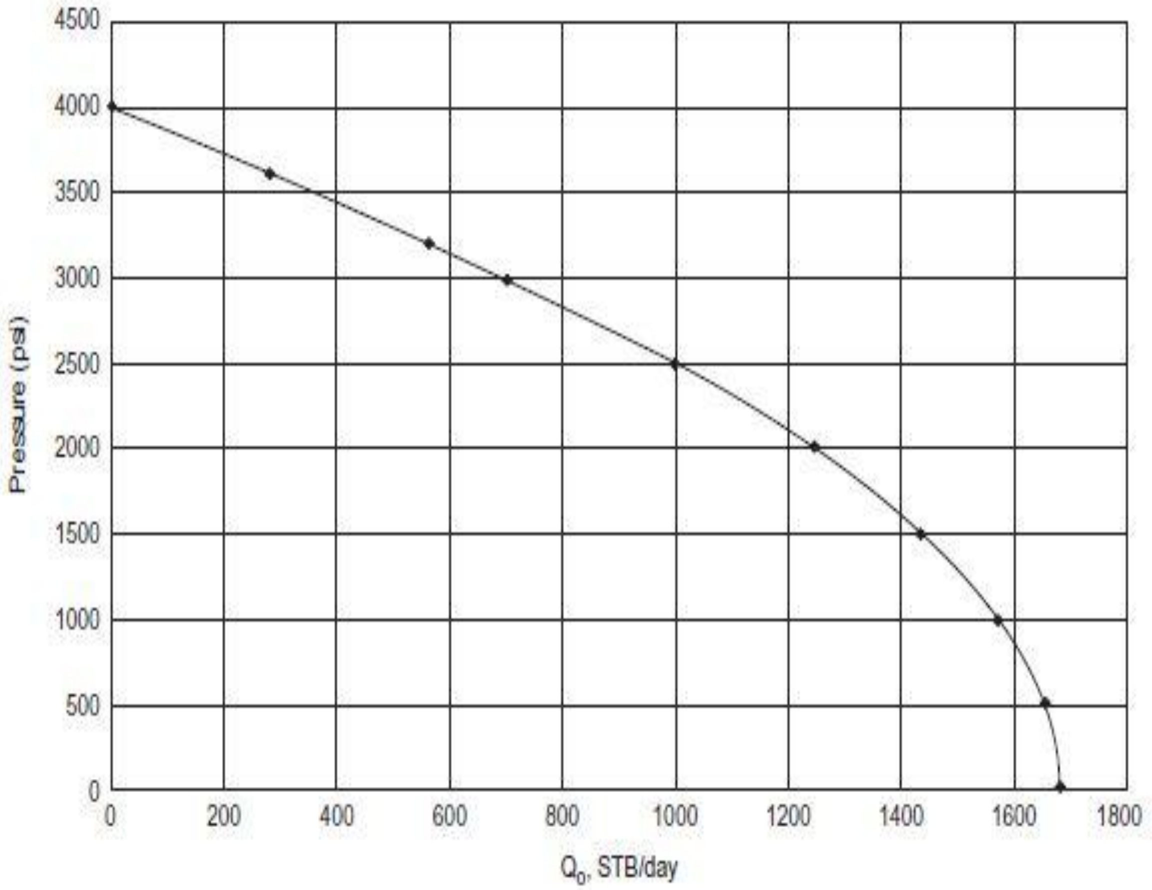

FIGURE 2-14: IPR using the Fetkovich method.

It should be pointed out Fetkovich's method has the advantage over Standing's methodology in that it does not require the tedious material balance calculations to predict oil saturations at future average reservoir pressures.