Bottom Hole Pressure Analysis–Field Examples

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INTRODUCTION

Bottom hole pressures have been measured for many years in the oil industry under flowing and static conditions. The principal uses were for productivity predictions and for predictions of future reservoir performance. More recently it has been recognized that pressure transients, which result from build-up, draw-down and interference tests, can provide much quantitative information about the well and the reservoir. Utilization of appropriate analysis techniques permits estimations of well damage, static reservoir pressure, permeability, reservoir size and reserves. Also, it is possible to determine the existence of barriers and boundaries, such as faults or fluids contacts, and to estimate the distance to them.

Each year new techniques of analysis of pressure transients and new applications have been published in the literature because of the availability of newer mathematical tools and digital computers. This trend will undoubtedly continue, giving the petroleum engineer in the future more opportunities to make money for his company through application of these techniques. However, it is questionable that existing techniques are being utilized to maximum advantage, possibly because these are viewed by operations personnel as being for laboratory use only. Therefore, several field applications of the use of pressure analysis are presented in this paper. The economic aspects, although not stressed, are quite apparent. A brief review of the theory behind the applied techniques is presented.

PRESSURE ANALYSIS

The diffusivity equation in the form

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} = \frac{\phi \mu c}{k}\frac{\partial p}{\partial t} \qquad [1]$$

describes the pressure, p, at any point, r, in a cylindrical system at a given time, t, when a fluid of slight, but constant, compressibility, c, flows through the porous medium under non-steady state conditions. A solution for the case of the infinite reservoir[1] is

$$p_i - p_{r,t} = -\frac{70.6\, qB\mu}{kh} Ei\left[-\frac{948.2\, \phi \mu c r^2}{kt}\right]$$

$$= -\frac{70.6\, qB\mu}{kh} Ei\left[-\frac{1}{4\, t_D}\right] \qquad [2]$$

where: p_i = pressure at all r before start of production

$p_{r,t}$ = pressure at radius r at time t.

$$Ei(-x) = -\int_x^\infty \left[\frac{e^{-u}}{u}\right] du \qquad [2a]$$

and all quantities are in engineering units as defined in the nomenclature.

When $\left(\frac{948.2\, \phi\mu c r^2}{kt}\right)$ of the Eli integral becomes less than 0.01, Ei(-x) = ln x + .5772 so the equation may be written with close approximation as

$$P_{r,t} = P_i - \frac{70.6\, qB\mu}{kh}\left[\ln\left(\frac{kt}{948.2\, \phi\mu c r^2}\right) - 0.5772\right] \qquad [3]$$

When considering the pressure transient at the well, $P_{r,t}$ becomes P_w at time t and r becomes r_w

PERMEABILITY

Permeability is easily calculated from the non-steady state drawdown pressure in a well producing at a constant rate because pressure is a function of the logarithm of time, Eq. 3. The early transients do not behave logarithmically but these are usually of very short duration. The duration of the non-steady state logarithmic decline is a function of the size of the reservoir.

In this logarithmic decline region, the pressure-time curve on semilog paper is a straight line of slope"m" which is easily determined by taking the pressure decline per log cycle. Eq. 3 can be rearranged, with conversion to base 10 logarithm, to give

$$m = -\frac{(2.303)(70.6)q\mu B}{kh} \quad \frac{162.5\ q\mu B}{kh} \quad \text{or}$$

$$kh = -\frac{162.5\ q\mu B}{m} \qquad [4]$$

From this, permeability can be calculated if the thickness, h, is known. In like manner, build-up pressures can be used from a well that has been produced at a constant rate, q, for a time t_f prior to shut-in by rearranging Eq. 3, through the superposition theorem,

$$P_w = P_i + \frac{162.5 q\mu B}{kh}\left[\log\left(\frac{t_s}{t_s + t_f}\right)\right] \qquad [5]$$

which gives, of course, Eq. 4 with the sign changed for m if m is measured on the straight line portion of the curve on the semi-log plot.

These equations, although derived for slightly compressible fluids, can be applied to gas wells, provided the wells exhibit moderate drawdowns. The gas production rate must be evaluated, however, at average reservoir pressure. Here a plot of the square of well pressure, P_w^2, against logarithm of time, is more realistic for gas wells [2] Eq. 4 becomes

$$kh = 1637 \frac{q_g z T \mu}{\bar{m}} \qquad [6]$$

where q_g = gas production rate, MCFPD at 14.7 psi and 60°F.
$\bar{m}$ = slope, psi^2 per log cycle.

DISTANCE TO A BARRIER

The presence of a barrier close to a well is detected from build-up, drawdown or fall-off tests by a two-fold or greater change in slope of the pressure-time curve. The presence of a linear barrier, such as a fault, located at a distance, d, from the producing well interferes with the pressure transient after some time. Prior to this time, however, the pressure transient acts as if the reservoir is infinite so that the pressure decline (or build-up) with logarithm of time is a straight line of slope, m, as defined by Eq. 3. Then, the pressures vary from this relationship as the pressure transient reflects the presence of the barrier. Eventually, a new straight line decline of slope 2m is established. If the barrier is non-linear, then the slope ratio may be somewhat larger or smaller than 2.

The distance to the barrier can be estimated by use of the dimensionless time equation

$$t_D = \frac{0.000264\ kt}{\phi c \mu r^2} \qquad [7]$$

For the case of a linear barrier, Grady and Hawkins[3] note that extrapolation of the early and late straight line decline portions of the pressure logarithm of time plot results in an intersection at dimensionless time $t_{Dx} = 1.78$. The time t_{fx} in hours after start of flow, where this intersection occurs, is used in Eq. 7 to calculate the distance (r=d) to the barrier.

$$d = \left(\frac{0.000264 k\ t_{fx}}{1.78 \phi \mu c}\right)^{0.5} = \left(\frac{k\ t_{fx}}{6750\ \phi\ \mu\ c}\right)^{0.5} \qquad [7a]$$

The selection of t_{fx}, corresponding to t_{Dx} = 1.78, is illustrated in Fig. 4. For pressure build-up tests the intersection time after shut-in, t_{sx}, obtained from the pressure-log time plot, is used in Eq. 7a for t_{fx}.

Another study by Bixel, et al. [4], indicates that the linear boundary appreciably affects the drawdown curve at dimensionless time $t_D = 0.4$; that is, the pressures begin to deviate from the straight line decline of the early time. The distance can be calculated by rearranging Eq. 7 and substituting $t_D = 0.4$.

$$d = \left(\frac{0.000264\ k\ t_f}{0.4\ \phi\ \mu\ c}\right)^{0.5} \qquad [7b]$$

The selection of the real time t_f corresponding to $t_D = 0.4$ is illustrated in Fig. 4. This also can be used on build-up curves where t_s is the time in hours where the pressures begin to deviate from the straight line relationship.

RESERVOIR VOLUME AND LIMIT

Several methods have been devised to estimate reservoir volume from transient tests. Important limitations to all methods are the assumptions of ideal fluids, homogeneous rock properties and symmetrical drainage boundaries. Since these are rather critical in reservoir limits estimates, results of such tests should be applied with good engineering judgment.

In one method a drawdown test is conducted on the well which is produced continuously at constant rate q until a constant steady state pressure decline with time is reached. The rate of pressure decline dp/dt is measured and the volume estimated by

$$N = \frac{\left(1-S_w\right)q}{c_t \ dp/dt} \qquad [8]$$

where dp/dt - psi/day

q - STB/day

N - Oil in place in stock tank barrels

It is important that the producing rate be kept constant during the test.

Another method utilizes the build-up curve to estimate size from the time required for build-up. The well is produced for a sufficient time to reach steady state and then shut in and allowed to build up to a static value. The build-up curve is plotted and a pressure point, P_w, is determined at time, t_s, on the straight line portion of the curve. The volume may then be calculated for semi-steady state by

$$N = \frac{2.415 \times 10^{-1} \times (1-S_w)\, q\, t_s}{c_t\, m} \cdot e^{2.303\left(\frac{\bar{p}-P_w}{m}\right)} \qquad [9a]$$

or, for steady state, by

$$N = \frac{5.37 \times 10^{-2}\, (1-S_w)\, q\, t_s}{c_t\, m} \cdot e^{2.303\left[\frac{P_e-P_w}{m}\right]} \qquad [9b]$$

Small errors in $\bar{p}$ or p_e can produce large errors in the calculated value of N. Also, Eq. 9 is based on a radial model and non-central location of the producing well can cause large errors because the time required for pressure build-up is related to shape as well as size.

An alternate method to the use of Eq. 9 is to utilize a curve fitting procedure. The dimensionless pressure build-up curves for a radial drainage area with a centrally located well are usually presented in terms of drawdown from $\bar{p}$ or p_e as a function of dimensionless time, Fig. 1. The pressure drawdown at the well as a function of time is converted to dimensionless pressure versus time by

$$\Delta p_{Dw} = \frac{1.15}{m}(\bar{p} - p_{ws}), \text{semisteady state, or}$$

$$\frac{1.15}{m}(p_e - p_{ws}), \text{steady state} \qquad [10]$$

Then plot Δp_{Dw} vs. log t_s, on a sheet of transparent graph paper, using the same scales as the dimensionless pressure curves of Fig. 1. Overlay the actual plot to get a "best fit" match between it and one of the two dimensionless curves. Note the relationship between t_s and t_{Des} for this best fit. Then the volume can be calculated from

$$N = \frac{2.4 \times 10^{-2}\, (1-S_w) q\, t_s}{c\ m\ t_{Des}} \qquad [11]$$

This has the advantages of allowing one to see if the curve shape is correct for the assumption made for reservoir shape and of permitting small errors in final shut-in pressure to be adjusted since the zero drawdown points do not have to coincide if there is good curve fit.

FIELD EXAMPLES

Case I - South Texas Well - Wilcox Formation

The 11,200 ft Wilcox sand was tested with the open hole wireline formation test tool. Two cu ft of gas and 10,000 cc of filtrate were recovered in 10 minutes through 0.020 in. choke at 8100 psi flowing pressure. Final shut-in pressure was 8700 psi in one minute. After setting pipe, the zone was drill stem tested through perforations with the results shown on Fig. 2. The pressure build-up curve from the single shut-in test is plotted also.

The straight line portion of the build-up curve is extrapolated as a short dashed line to infinite shut-in time ($t_s/t_s + t_f = 1$). This gives a static reservoir pressure of 6825 psi. The permeability is estimated by Eq. 6 to be

$$kh = \frac{1637\, q\, \mu\, TZ}{m}$$

$$= \frac{1637 \times 738 \times 0.028 \times 660 \times 1.1}{8 \times 10^6}$$

$$= 3 \text{ md} - \text{ft}$$

The well capacity would be, assuming 320 acre spacing, in the order of

$$q = \frac{0.703\ kh\left(p_e^2 - p_w^2\right)}{1000\,\mu TZ\ \ln\left(0.607\ r_e/r_w\right)}$$

$$= \frac{0.703 \times 3(6825^2 - 2000^2)}{1000 \times 0.028 \times 660 \times 1.1}\ln\left[0.607 \times 0.25\right]$$

$= 525$ MCFPD

Since the initial pressure is known to be approximately 8700 psi from the formation tester, we can infer either that the reservoir is very limited or that the thickness permeability product, kh, somewhat removed from the well bore is much lower than that indicated by the pressure build-up curve. If the latter is the case, the pressure build-up curve would have to extrapolate to the initial shut-in pressure somewhat as shown in Fig. 2. Then the maximum kh at some distance would be

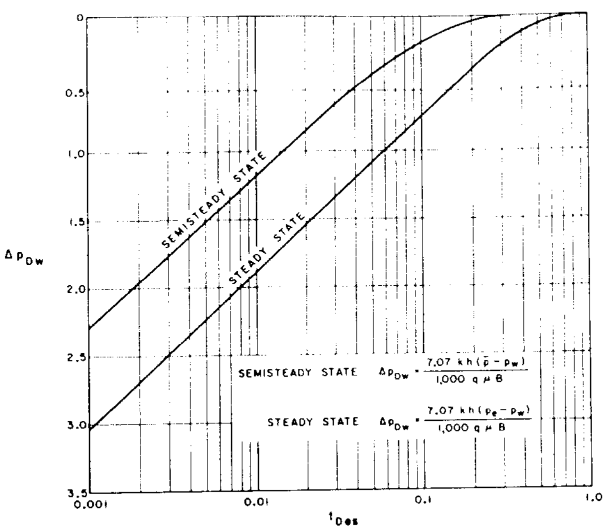

FIGURE 1
DIMENSIONLESS BUILD-UP CURVES FOR CIRCULAR DRAINAGE AREA WITH CENTRALLY LOCATED WELL

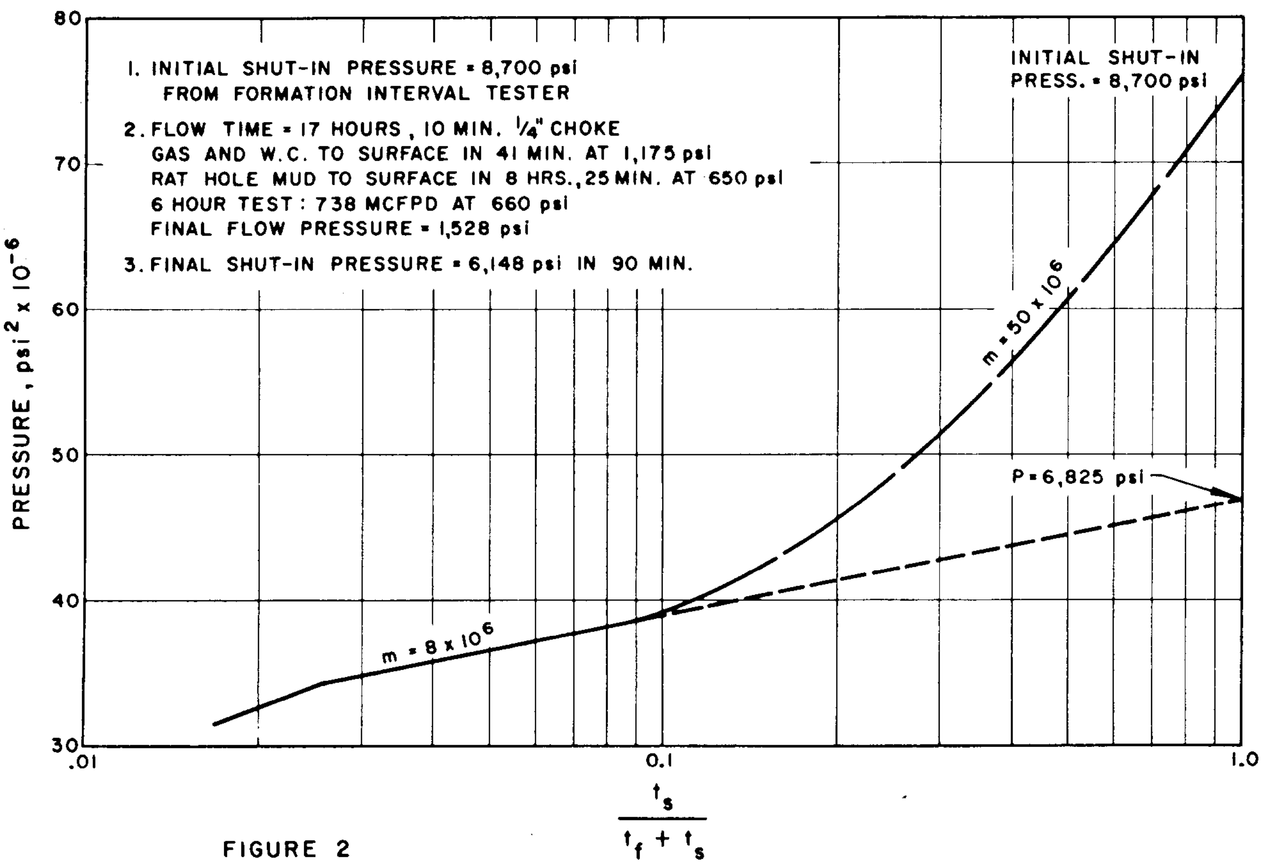

FIGURE 2
CASE I — WILCOX SAND-SOUTH TEXAS

$$kh = 3.0 \times \frac{8 \times 10^6}{50 \times 10^6} = 0.5 \text{ md-ft}$$

The well capacity with no local improvement would be about 90 MCFPD.

The well was shut in for four days after running completion assembly. After four days of production the well made 520 MCFPD at 225 psi tubing pressure. At the end of two weeks, production was 370 MCFPD with 200 psi tubing pressure. The well was then acidized preceded by Diesel oil. The well never cleaned up to the rate just prior to the acid job and was abandoned after a period of time.

Case II - New Mexico Well-Wolfcamp Formation

The Wolfcamp formation was drill stem tested in open hole by the double shut-in method. The test data are listed in Fig. 3 with the pressure build-up curves for initial and final shut-in times. The test shows a very definite indication of reservoir depletion with the extrapolated final shut-in pressure being 393 psi less than the initial shut-in pressure. Also, the final pressure was constant for the last 16 minutes of the 40 minute shut-in period. The best possibility would be a small volume of rock of high permeability surrounded by very tight rock. As in Case I, the slope of the final part would have to be many times that of the early part of the build-up curve in order to extrapolate the pressure curve to original reservoir pressure.

The well was completed in the Wolfcamp with an initial potential of 272 BOPD with a flowing tubing pressure of 1925-1425 psi. The well produced about 2,000 barrels of oil and died. The gas-oil ratio had climbed and the shut-in bottom hole

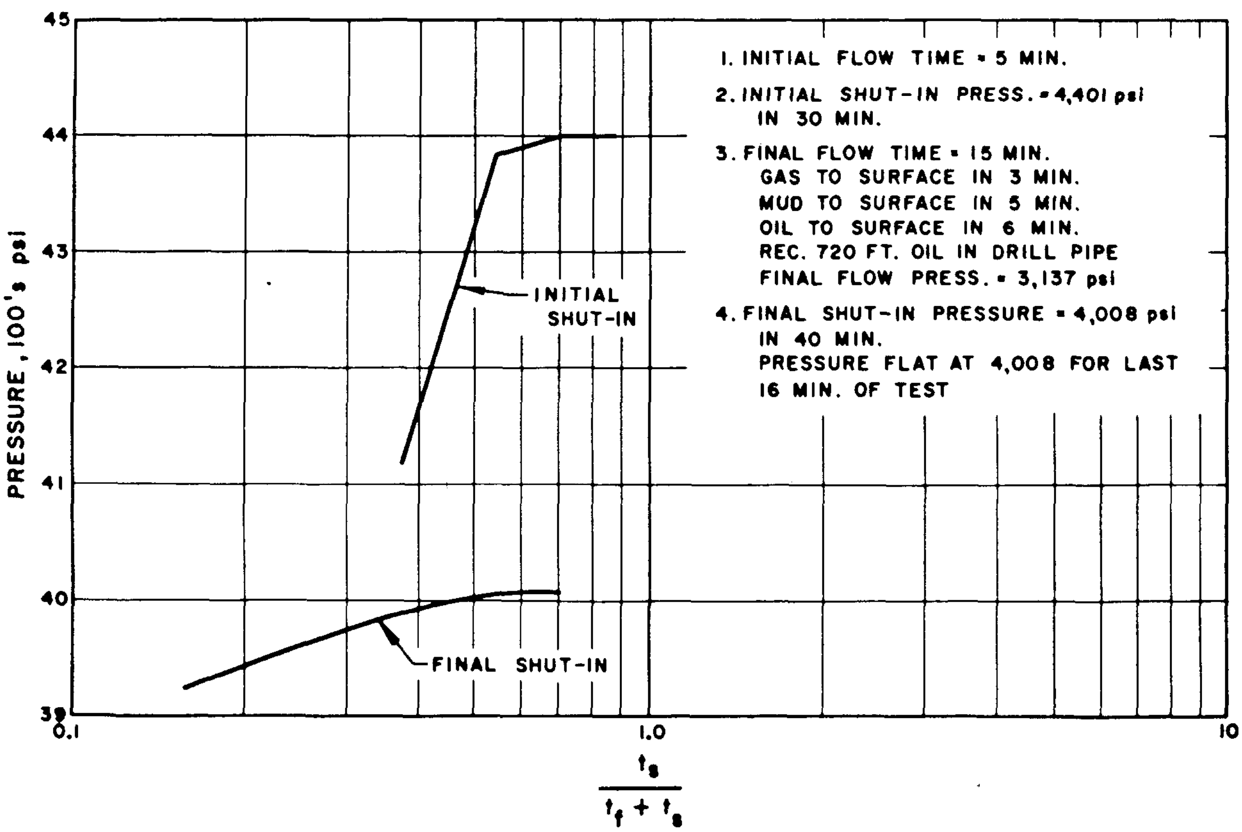

FIGURE 3
CASE 2 — WOLFCAMP FORMATION-NEW MEXICO
OPEN HOLE DRILL STEM TEST

pressure had declined to 600 psi. In fact, the pressures, gas-oil ratios and production closely resembled the classic history of a solution gas drive reservoir.

Case III - Permian Basin Well - Noodle Creek Formation

The Noodle Creek limestone was drill stem tested in this well at the rate of 17 bbls of oil on one hour test for a new field discovery. Official potential was 408 BOPD on June 17, 1963. A three-day flow test was commenced in October followed by a 72 hour shut-in period. The pressure drawdown data are presented in Fig. 4. The large increase in slope between the early ($t_f < 5$ hours) and late periods indicate the presence of a nearby boundary or boundaries. The magnitude of the change suggests that several boundaries are influencing the pressure history. Analysis of the pressue build-up during the 72 hour shut-in period also indicates these points.

Assuming the existence of a boundary, the distance to it is calculated from Eq. 7b by using the time at which the deviation of the drawdown data from the early straight line begins, or t_f = 5.5 hours. This gives:

5. $$d = \left(\frac{0.000264\ k_o\ t_f}{0.4\ \phi\ \mu\ c}\right)^{0.5}$$

$$= \left(\frac{0.000264 \times 1000 \times 5.5}{0.4 \times 0.2 \times 3.1 \times 10 \times 10^{-6}}\right)^{0.5} = 765 \text{ ft}$$

The permeability, k_o was calculated from the build-up curve and other properties from core and fluid analyses.

Pressures taken in the last 12 hours indicate that a flattening of the slope may occur. This could be indicative of the marked change in mobility ratio at a considerable distance from the well.

The slope of the pressure decline curve from 36 to 60 hours (6 psi/day) indicates an oil-in-place volume from Eq. 8 of:

$$N = \frac{(1-S_w)\ q}{c_t\ dp/dt} = \frac{(1-0.25)(89)}{10 \times 10^{-6} \times 6} = 1112 \text{ MSTB}$$

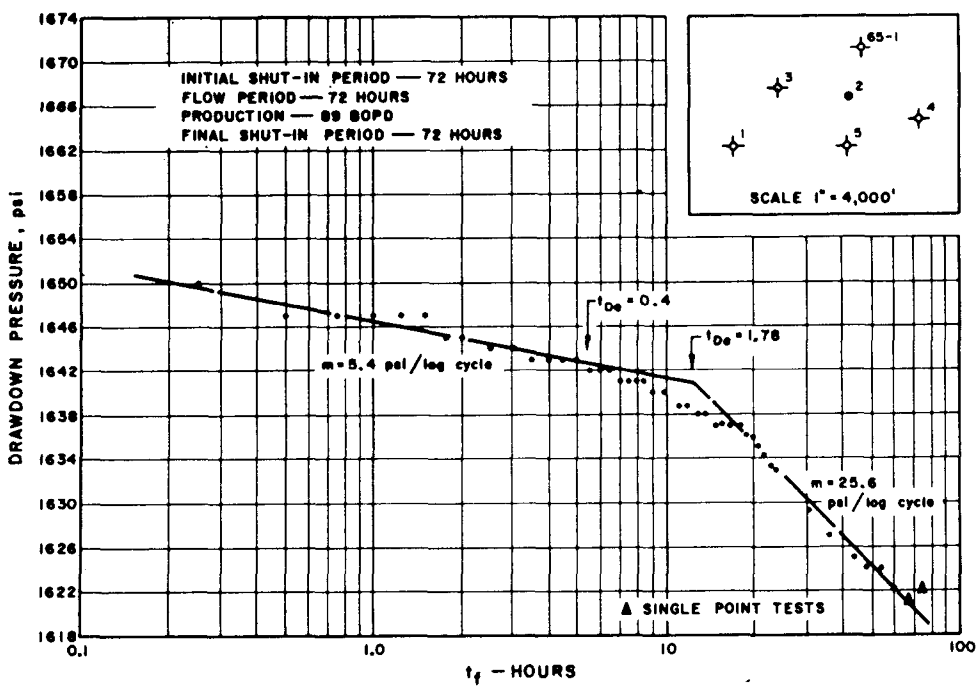

FIGURE 4

CASE 3 — NOODLE CREEK LIME- NORTH PERMIAN PRESSURE DRAWDOWN TEST

Of course, the pressure decline rate may not be stabilizing so the in-place oil could be substantially higher. On the other hand, the leveling may be due to a water drive which would affect the slope used in our calculation. In which case, the reservoir could be smaller than the calculated 1112 MSTB.

Drilling (see Insert, Fig. 4) has proven the reservoir to be of limited extent. Production history indicates that a rather active water drive is present in the reservoir.

Case IV - Amsden Formation - Montana

This well was the discovery well in the Amsden dolomite in this field. The formation was cored from 6068 to 6108 ft. An open hole drill stem test recovered free oil. The well was completed in May, 1955, as a flowing oil well. After cleaning up, the well was produced at the rate of 368 BOPD. The build-up curve is shown in Fig. 5. From this and Eq. 4, the permeability to oil is:

$$k_o = \frac{162.5 \ q \ \mu \ B}{h \ m} = 620 \text{ md}$$

The pressures were converted to dimensionless drawdown pressures by Eq. 10 and are plotted as function of time in Fig. 6. This curve was placed on Fig. 1 where a best fit with the semi-steady state curve was obtained. Indicated on Fig. 6 is the dimensionless time (t_{De}) which matched the time t_s of 10 hours. The volume of the reservoir was estimated from Eq. 11 to be

$$N = \frac{2.4 \times 10^{-2}(1-.25)(368)(10)}{13 \times 10^{-6} \times 14.7 \times 0.051} = 6.8 \times 10^6 \text{ bbl}$$

Subsequent drilling indicated a size of approximately eight million bbl. Later, the reservoir was discovered to have an active water drive.

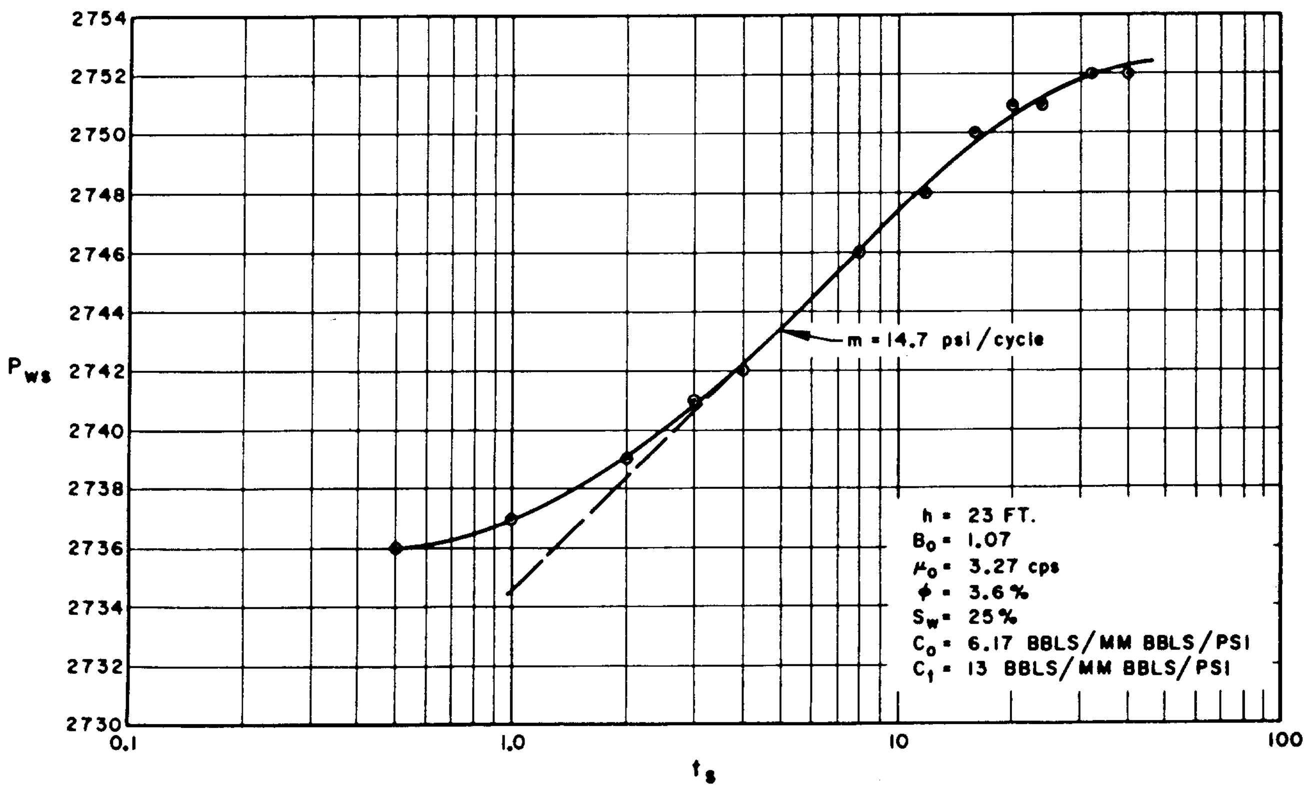

FIGURE 5
CASE 4 — AMSDEN DOLOMITE - MONTANA
PRESSURE BUILD-UP

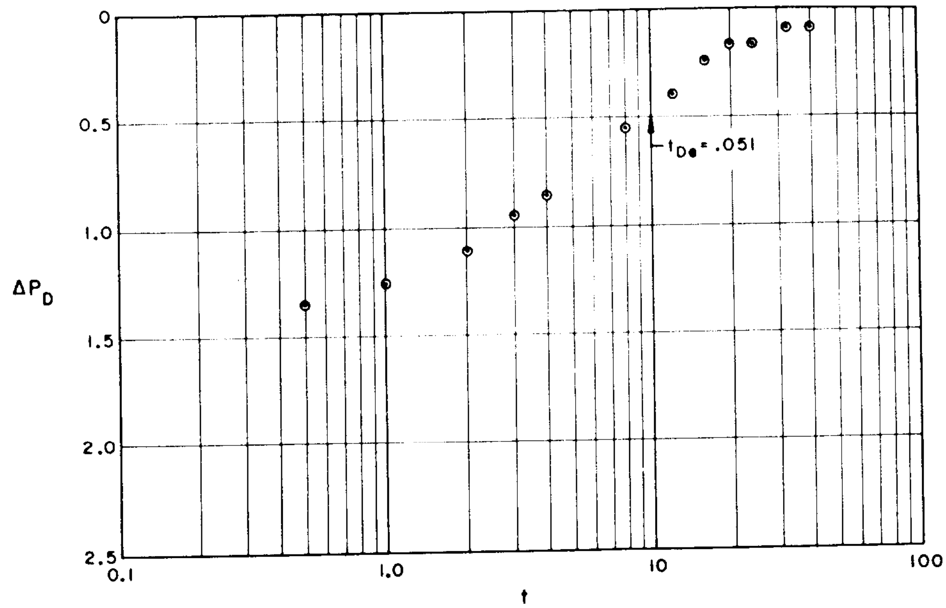

FIGURE 6
CASE 4 — AMSDEN DOLOMITE - MONTANA
DIMENSIONLESS PRESSURE DRAWDOWN

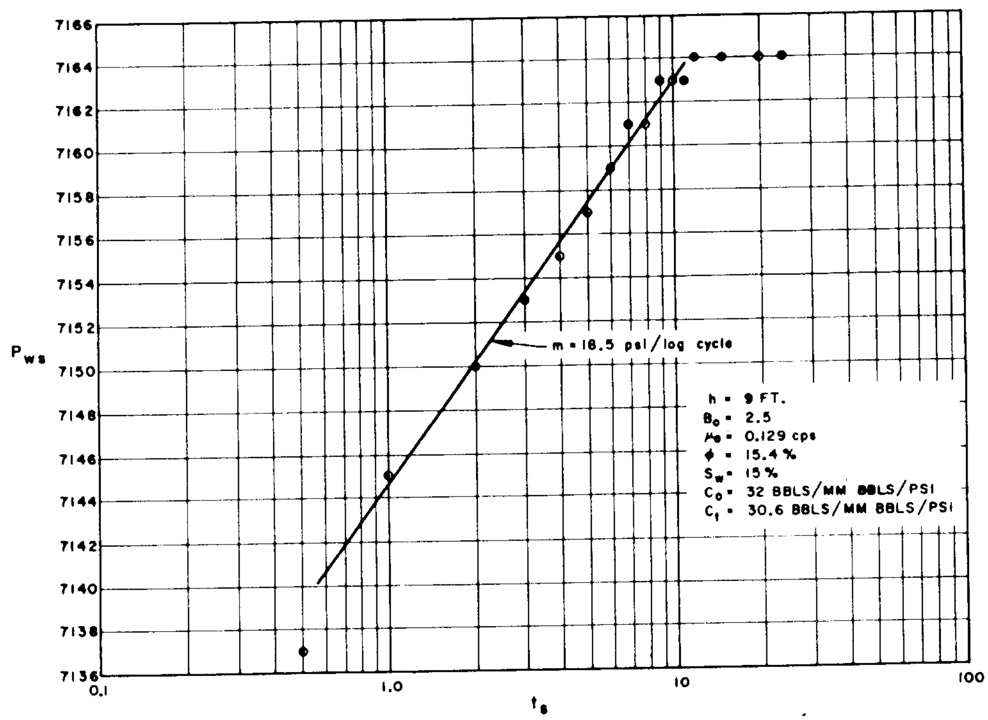

FIGURE 7
CASE 5 — CADEVILLE SAND - NORTH LOUISIANA
PRESSURE BUILD-UP CURVE

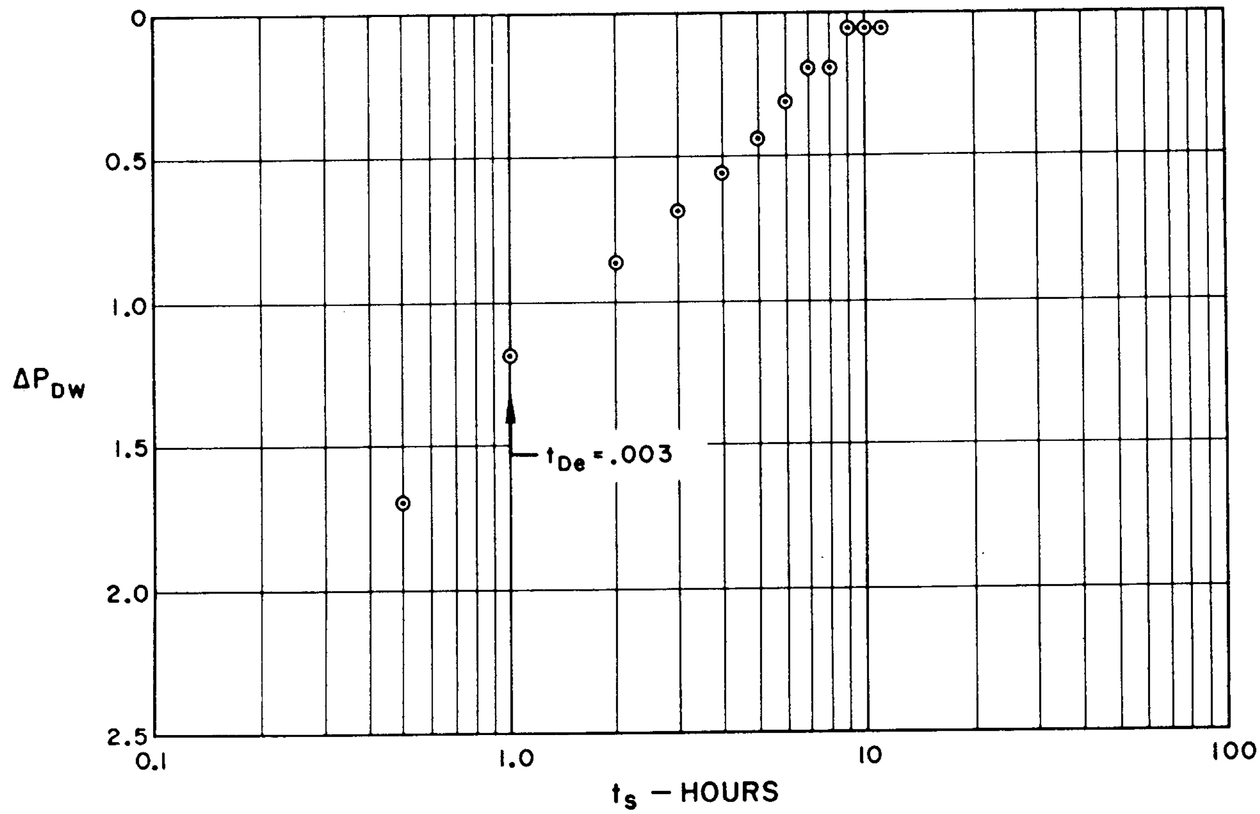

FIGURE 8
CASE 5 — CADEVILLE SAND-NORTH LOUISIANA
DIMENSIONLESS PRESSURE DRAWDOWN

Case V - Cadeville (Cotton Valley) Sand, North Louisiana

This well was the discovery in the Cadeville sand through perforations at 9695-9709 ft in July, 1955. The initial test was conducted at a flow rate of 130 BOPD on same choke size. The pressure build-up is plotted in Fig. 7 with other pertinent data. From Eq. 4,

$$k = \frac{162.5 \times 130 \times 0.129 \times 2.5}{9 \times 18.5} = 41 \text{ md}$$

Dimensionless pressure drawdowns (Δp_D), converted by means of Eq. 10 are plotted as a function of time in Fig. 8. The best fit between Fig. 8 and Fig. 1 was selected for semi-steady state with $t_{De} = 0.003$ for $t_s = 1$ hr which gives an oil-in-place volume from Eq. 11 of

$$N = \frac{2.4 \times 10^{-2} (0.85)(130) \ 1}{30.6 \times 10^{-6} \times 18.5 \times 0.003}$$

$$= 1.56 \times 10^6 \text{ bbl}$$

Subsequent drilling indicated the size to be about 3.2 million bbl.

SUMMARY

Transient pressure analysis is a powerful tool which has become available to petroleum engineers in the last few years. Many applications have been suggested in the literature, but few have been given widespread trials. By presentation of several field examples, it is hoped that many more engineers and managements will utilize pressure analysis.

NOMENCLATURE

μ - viscosity, centipoise

ϕ - porosity

B - formation volume factor

c - compressibility, bbls/bbls/psi

c_t - total compressibility of system, bbls/bbls/psi

h - height of formation, ft

k - permeability, millidarcies

p - pressure, psi

$\bar{p}$ - average pressure, psi

p_e - pressure at radius r_e psi

p_w - pressure at well bore, psi

p_D - dimensionless pressure

r - radius, ft

r_e - external drainage radius

S_w = water saturation

t = time, hours

t_f - flowing time, hours

t_s - shut-in time, hours

t_D - dimensionless time

t_{Des} - dimensionless shut-in time with respect to r_e

T - temperature, degrees Rankine

Z - deviation factor for gas

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