Bottom-hole Pressures in Oil Wells[1]

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THERE is nothing more important in petroleum engineering than a definite knowledge of the pressure at the bottom of an oil well at any existing operating condition, and the relation of this pressure to the pressure within the producing formation. A knowledge of bottom-hole pressures is fundamental in determining the most efficient methods of recovery and the most efficient lifting procedure, yet there is less information about these pressures than about any other part of the general problem of producing oil.

DETERMINATION OF BOTTOM-HOLE PRESSURES

Bottom-hole pressure may be calculated or determined by several methods. On an inactive well it may be calculated from the fluid head or, if the well is shut in, by adding the casing head pressure, the static head of the gas and the fluid head. In wells flowing naturally through tubing the pressure at the bottom of the tubing may be calculated by adding the pressure at the casing head between the tubing and the casing and the pressure due to the weight of the column of gas, but there is always possibility of error caused by fluid being in the annular space above the bottom of the tubing. If a well with tubing is flowing through either the annular space or the tubing, sufficient gas may be injected through the static space to insure that it is free of fluid but not sufficient to establish an appreciable friction loss. The pressure at the bottom of the tubing can then be calculated by adding to the pressure at the tubing head the pressure due to the weight of the column of gas. This is probably the most accurate method of calculating bottom-hole pressures. In wells flowing by gas-lift, the pressure at the point the gas enters the flow may be calculated by a gas-flow formula.

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Several types of pressure bombs have been used to measure the pressure at the bottom of wells. One is a piece of steel tubing with a check valve in the bottom and a connection for a pressure gage at the top. It is lowered into the well to the point at which the pressure is desired, then brought to the surface and the pressure read from a pressure gage put on the top connection. Several bombs have been made which enclose a maximum reading pressure gage. Some use a maximum indicating pointer, but this is not as satisfactory as a stylus on the pointer scratching a smoked surface. Consideration has been given to electrical instruments that can be lowered into a well and made to give a continuous reading at the surface, but so far as is known, this method has not yet been developed to practical use. A recording gage built up with a common gage pressure element, recording on a small circular clock-driven chart, has been used occasionally, but its use is limited because of its large diameter and difficulty of close reading. Another recording gage is being developed by which the pressure is determined with a piston and spring, on the same principle as an engine indicator gage, and another obtains the pressure from a fluid-filled tube with elastic walls.

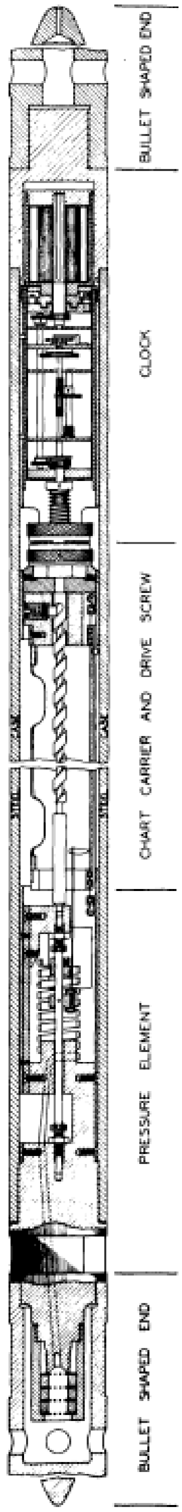

FIG. 1 CROSS-SECTION OF AMERADA PRESSURE GAGE.

The Amerada pressure gage was used in determining the bottom-hole pressures considered in this paper. It was developed in the laboratory of the Geophysical Research Corpn. under the direction of Dr. F. M. Kannenstine. A cross-sectional drawing of the instrument is shown in FIG. 1. The gage consists of three main parts: clock, chart-carrier, and pressure element. The clock is of special design, having a diameter of $1^{3}/_{8}$ in. and an overall length of 7 in. The carrier holds a chart 7 in. long and $2^{7}/_{8}$ in. wide. The movement of the chart is obtained by a central screw operated by the clock. This screw drives the chart-carrier downward so that its weight almost balances the friction and thus reduces the power demand on the clock. The pressure element consists of pressure-element tubing, fabricated into a spiral coil $^{7}/_{8}$ in. in diameter and 7 in. long. The lower end of this tube is soldered to an opening in the base, which extends to the outside of the bomb. The upper end is sealed and attached to a shaft, to which is also attached an arm and brass stylus for recording on a metallic-faced paper chart. The entire instrument is built on a frame which fits into a steel case, and as it is run into the well is 41 in. long, 2 in. outside diameter and weighs 25 lb. It is usually run on a steel-wire measuring line.

Clocks of five different speeds have been made, which will run the full length of a chart in one, three, twelve, twenty-four or forty-eight hours. Pressure elements of various ranges may be used. The lowest range used thus far has a calibration of 75 lb., and the highest has a calibration of 1100 lb. per inch of movement of the stylus. In most cases, temperature correction may be neglected. The chart reading will be approximately 1 lb. low for each 65°F increase in temperature.

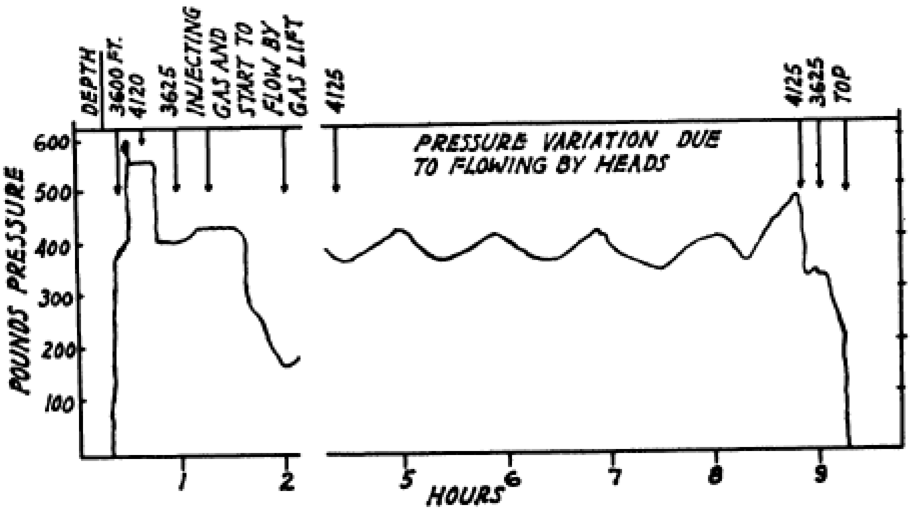

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FIG. 2—CHART FROM WELL PRODUCING ON GAS-LIFT.

Instrument was at bottom of hole while gas was being injected. Pressure increased at time gas injection was started, and dropped when well began to flow. Note pressure variation caused by flowing by heads.

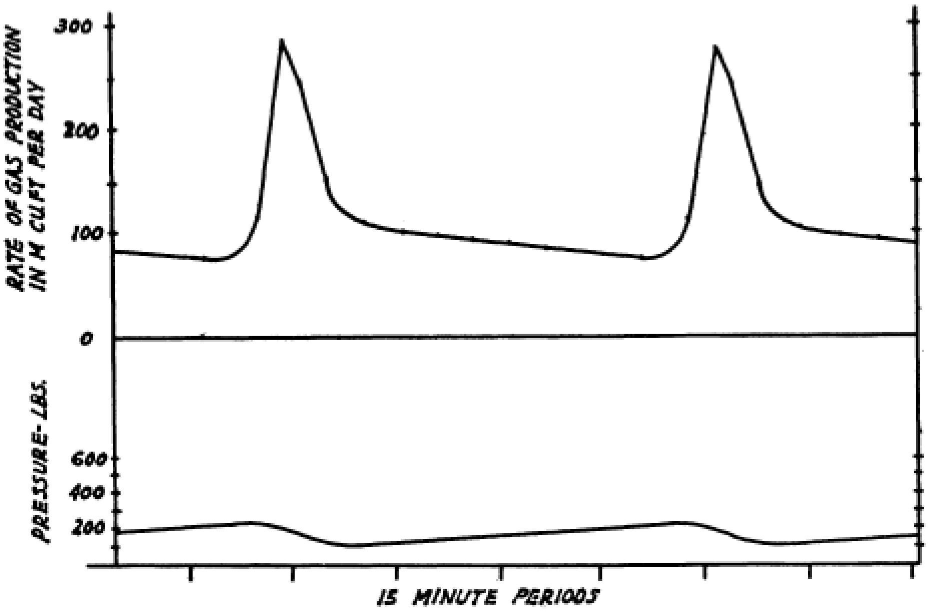

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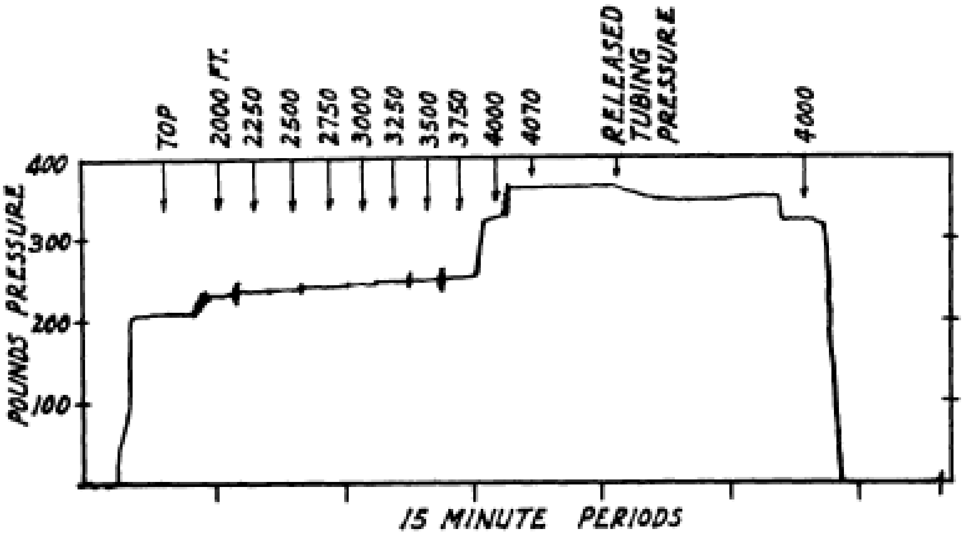
FIG. 3—PRESSURE CHANGE IN BOTTOM OF WELL FLOWING NATURALLY BY HEADS, AND RATE OF GAS PRODUCTION ON SAME TIME SCALE.

Although this instrument appears to be delicate, service in the field has proved that it will stand hard usage. Five charts taken in producing wells are reproduced in Figs. 2 to 6 inclusive. The pressure scale and notes showing depths of readings and some of the changes in the well which caused a change in pressure have been added. The chart shown in Fig. 2 was made in a well producing by gas-lift, flowing between 2½ in. tubing and 7 in. casing. The bottom of the tubing was 3602 ft. and the top of the sand at 4124 ft.



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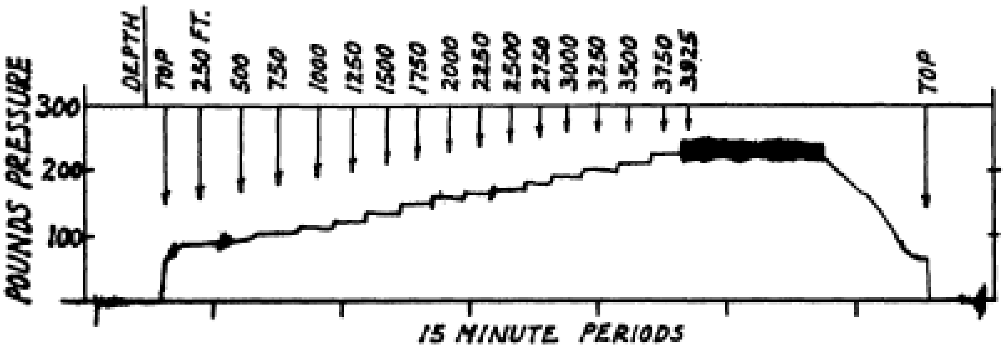

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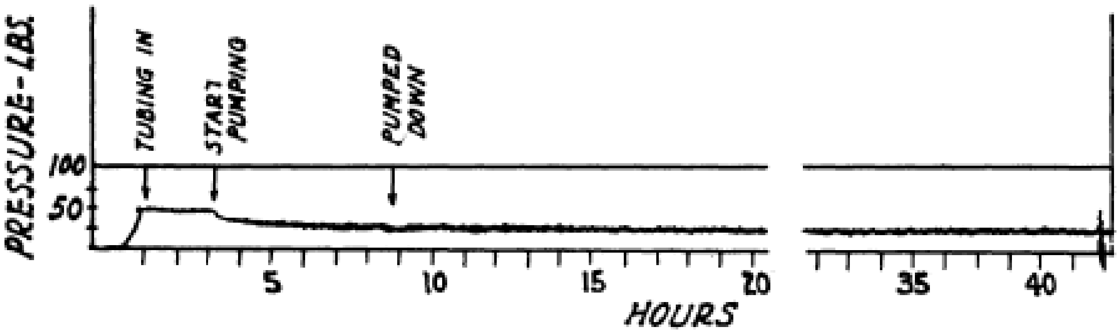

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FIG. 4—PRESSURE INCREASE DOWN TO 3830 FT. IS DUE TO WEIGHT OF GAS COLUMN BELOW 3830 FT. INCREASE DUE TO FLUID HEAD.

FIG. 5.—PRESSURE CHART FROM WELL FLOWING NATURALLY. INSTRUMENT WAS SUSPENDED FOR A TIME AT EACH OF INDICATED DEPTHS.

FIG. 6.—PRESSURE BELOW WORKING BARREL IN PUMPING WELL.

Readings were taken near these depths before gas was injected to start the well flowing. The pressure of 558 lb. recorded at 4120 ft. was considered as the pressure in the producing formation. The pressure at the bottom of the tubing increased 26 lb. after starting to inject gas, probably owing to the weight of the gas under pressure. During the last five hours of the chart the well was flowing by heads at the rate of

1560 bbl. per day, with an input volume of 940,000 cu. ft. and a trap volume of 1,600,000 cu. ft. per day. The chart shown in Fig. 3 was taken in a well flowing by heads at the rate of 580 bbl. of oil per day, from 3935 ft. through $8^5/_8$ in. casing. The formation pressure at the top of the pay zone was 1520 lb. The rate of gas production, which is plotted simultaneously with the pressure at the bottom of the hole, was obtained with an orifice meter, using a fast meter chart. The time, pressures and gas volume were repeated with marked regularity during each flow. The chart reproduced in Fig. 4 was taken in a well that had been flowing by gas-lift, but was shutdown at the time the chart was taken and still had a tubing-head pressure of 224 lb. The increase in pressure due to the weight of the column of gas is recorded down to 3750 ft., where the pressure was 257 lb. From the pressure increase in fluid between 4000 and 4070 ft., and the pressure increase from the top to 3750 ft. in gas, the point at which the gage went into fluid is calculated at 3830 ft. When the tubing pressure was released the pressure at the bottom temporarily dropped only 15 lb., showing that the tubing filled with fluid almost as fast as the gas pressure in the tubing could be released. The chart shown in Fig. 5 was taken in a well producing at the rate of 2200 bbl. of oil and 2,500,000 cu. ft. of gas per day through $8^5/_8$ in. casing. The chart shows pressures at intervals of 250 ft. in the flowing column of oil and gas. The excessive vibration of the gage while at 3925 ft. was probably caused by the gage hanging opposite a stratum of pay sand. The chart reproduced in Fig. 6 was taken in a pumping well and is explained in a later paragraph (p. 204).These charts are representative of a large number that have been obtained in wells producing under a wide variety of conditions.

APPLICATION OF BOTTOM-HOLE PRESSURES

The value of determining pressures in different formations while drilling through them is shown in Table 1. These pressures were obtained in wells in the Carr City pool in the Seminole district, Seminole County, Oklahoma. Measured pressures in these formations permit certain precautions which might otherwise be overlooked. For example, in drilling it is the universal practice in the Seminole district to produce the small amount of oil which may occur in the Simpson with the “First Wilcox” sand. As these sands are usually drilled with cable tools, the much higher pressure in the Simpson would cause oil to flow from the hole into the “Wilcox” sand when the porous part of the “Wilcox” is first encountered, and if the hole were not free from drill cuttings they might be packed so tight around the bit that a fishing job would result. It is not uncommon to find a large difference in the original pressures in formations that are separated by a relatively short vertical distance.

TABLE 1.—*Pressures Determined while Drilling in Carr City Pool*

Formation	Top, Ft.	Bottom, Ft.	Pressure, Lb.
Hunton	3980	3910	1520
Simpson	4068	4124	1152
First Wilcox	4124	4142	637[a]
Second Wilcox	4217		800[b]

[a] Simpson and First Wilcox open to hole.

[b] Estimated from increase in fluid level.

The formation pressures and the production of four wells for 10 months are shown graphically in Fig. 7. These wells are in South Earlsboro pool, secs. 22 and 23, T.9 N., R.6 E., in Seminole County, Oklahoma. The pool is known to have encroaching edge water forming a natural water flood, the static head of which is the same as the original pressure in the field. Under such conditions it is reasonable to expect the water to have considerable effect on the rate of decline of production and on the formation pressure in the area adjacent to any individual well. If the oil and gas are removed from the reservoir faster than the water encroaches, the formation pressure, and therefore the rate of recovery, will decline as in the first part of the curves for Edwards 2 and Grounds 2. When the production of oil and gas decreases to such a rate that water replaces it at the same rate as it is removed, both the formation pressure and the rate of recovery should be constant, as in Edwards 2 after July, in Grounds 5 after September and throughout Edwards 5. When the flood approaches the well, there will be an increase in the formation pressure and also the rate of production, as in Edwards 2 and Edwards 5 in January. When the water reaches the well, the rate of recovery will decrease and the pressure will remain constant or may increase, as in Grounds 2 after November and Grounds 5 after July. While correlation of the oil production, formation pressures and water encroachment in these wells is obvious, it is probable that if the bottom-hole pressure were available during each of the production tests, a correlation between the pressure differential in the formation and the rate of production would permit a broader and more definite interpretation.

Pierce and Rawlins[1] have determined a mathematical relationship of rate of production and differential pressure within the producing formation for gas wells. A similar correlation has been found in certain oil wells in the Yates field and in the Seminole district. Moore has given other relations of the rate of production and pressure differentials in the sand.[2] Data on two wells in the Seminole district, worked out according to the method of Pierce and Rawlins, are given in Figs. 8 and 9. The data in Fig. 8 were taken in a well producing from the Wilcox sand where the formation

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[1] H. R. Pierce and E. L. Rawlins: The Study of a Fundamental Basis for Controlling and Gauging Natural Gas Wells, Pt. 2. U. S. Bur. Mines *Rept. of Investigations* 2930 (1929).

[2] T. V. Moore: Determination of Potential Production of Wells Without Open Flow Tests. Subtopic of Improvement in Production Practice, by W. W. Scott. Amer. Petro Inst. *Proc.* Eleventh Annual Meeting, Sec. IV, 27.

pressure was 412 lb., and in Fig. 9 in a well producing from the Hunton lime in which the formation pressure was 1520 lb. Pierce and Rawlins also found that when this rate of production was expressed by a curve the slope of the curve did not change with depletion. While sufficient data have not been obtained to determine what the effect of depletion may have on the correlation in oil wells, it is believed that it may not be so simple as in gas wells. In gas wells the same fluid is moving through the sand at all stages of depletion while in oil wells the characteristics of the fluid change as the production is depleted, principally due to a change in the absolute gas-oil ratio. Other differences of lesser importance, such as change in gravity of oil and

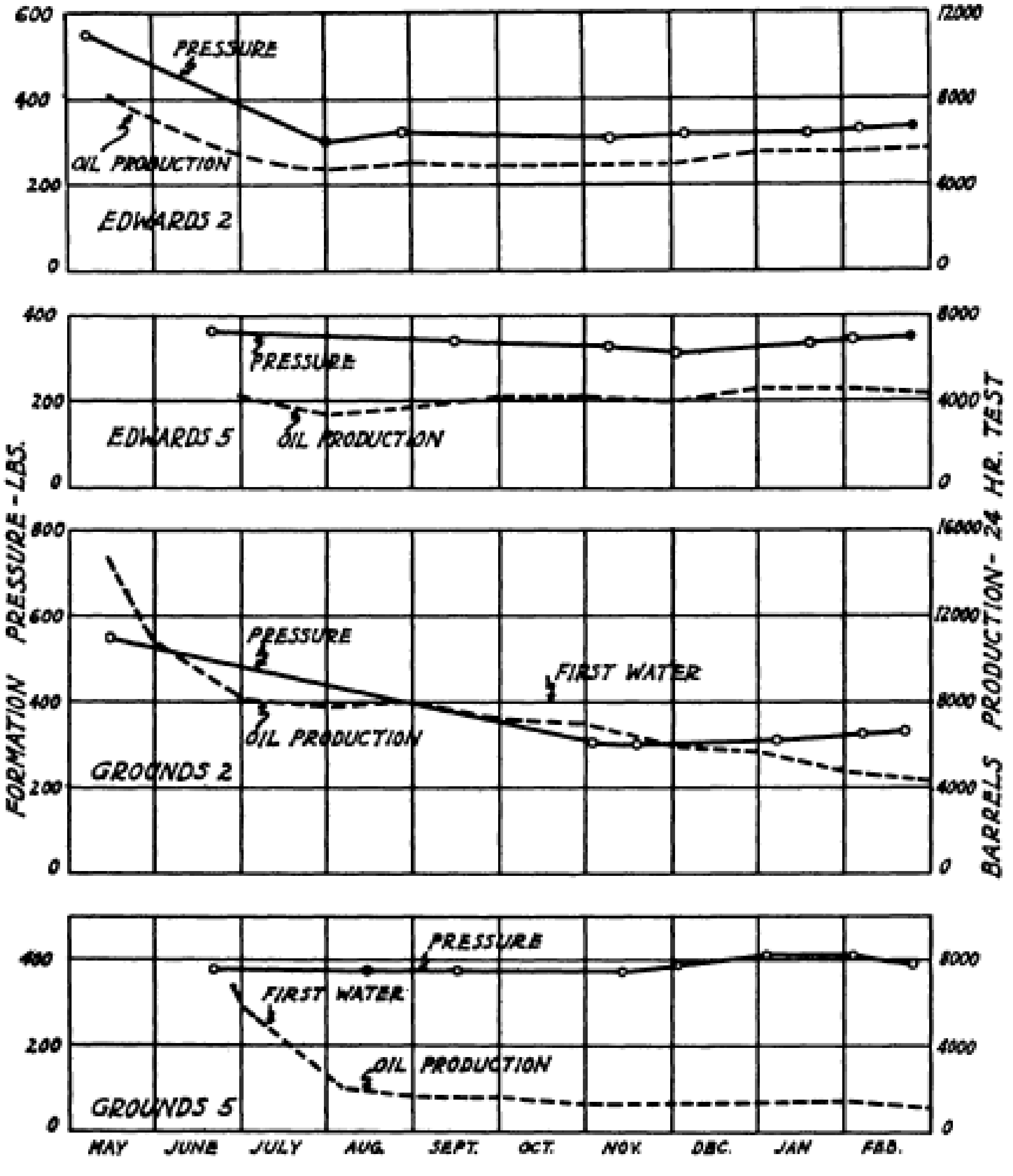

FIG. 7—RELATIONSHIP OF FORMATION PRESSURE TO RATE OF OIL PRODUCTION.
(24-HR. POTENTIAL TEST)

gravity of gas, including that due to some of the lower hydrocarbons which were originally in liquid state becoming gas, and change of size of drainage channels due to

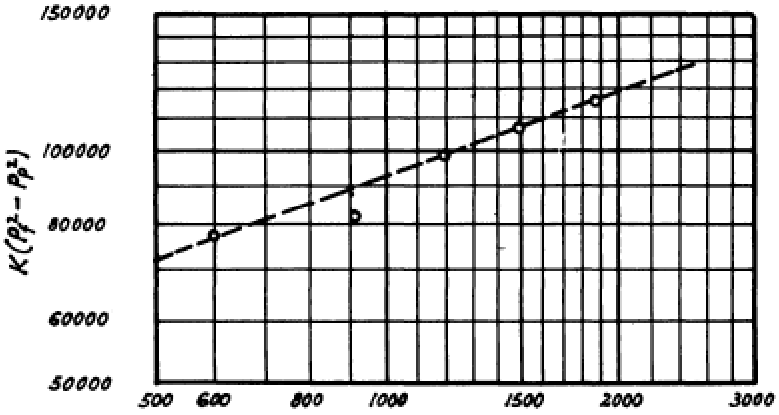

FIG. 8—RELATIONSHIP BETWEEN FORMATION PRESSURE (P_s) MINUS BOTTOM-HOLE PRESSURE (P_p) AND RATE OF OIL PRODUCTION.

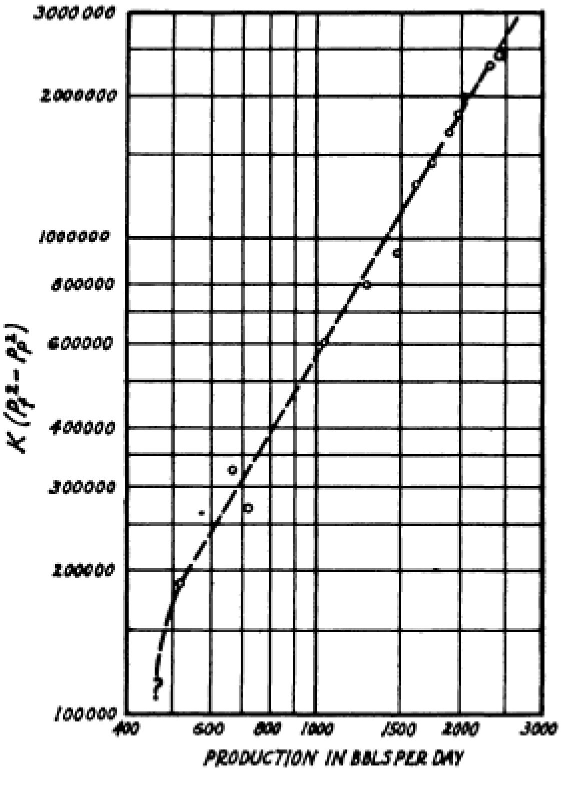

FIG. 9—RELATIONSHIP BETWEEN FORMATION PRESSURE (P_s) MINUS BOTTOM-HOLE PRESSURE (P_p) AND RATE OF OIL PRODUCTION.

erosion within the producing formation, may affect the correlation after some depletion has occurred. Even though the slope is changed, a correlation should still exist which can be expressed mathematically, but it will require more tests to determine than if the slope should remain constant. The application of this relationship in prorated fields should be especially important. Potential production might be established without opening any well to its open-flow capacity. This would save gas and extra labor and lessen the danger of bringing in bottom water. It deserves much attention in this connection.

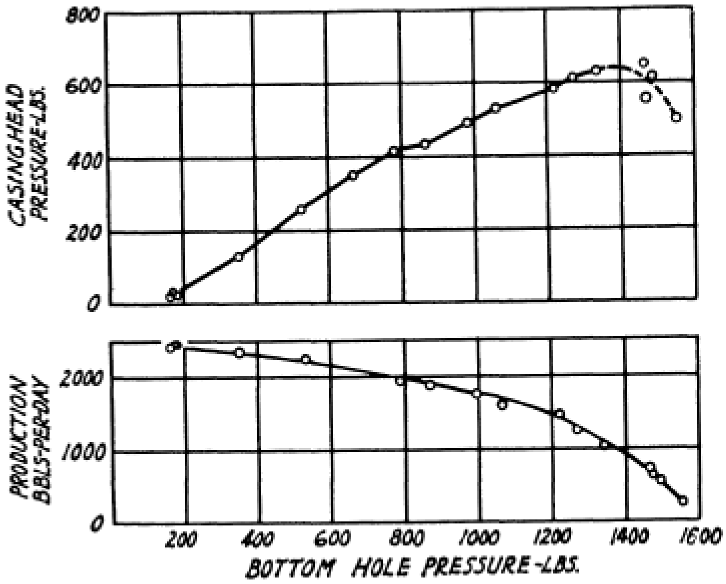

FIG. 10—CORRELATION OF BOTTOM-HOLE PRESSURE, RATE OF PRODUCTION AND CASINGHEAD PRESSURE.

The relation of rate of production, casinghead pressure and bottom-hole pressure obtained from a series of tests at various rates of production are shown by curves in Fig. 10. These tests were taken from a well producing from the Hunton lime in the Carr City pool, Seminole County, Oklahoma. They were made over a period of about two weeks, and were taken at random, rather than in the sequence of the plotted points. The pressure in the producing formation did not change any measurable amount during this period. Subsequent tests have not given the uniform relationship of casinghead pressure with bottom-hole pressures and rate of production that was obtained in this series. Similar data on a number of wells have shown that the correlation between the casinghead pressure and bottom-hole pressure is often indefinite and becomes more irregular as the bottom-hole pressure approaches the pressure in the producing formation.

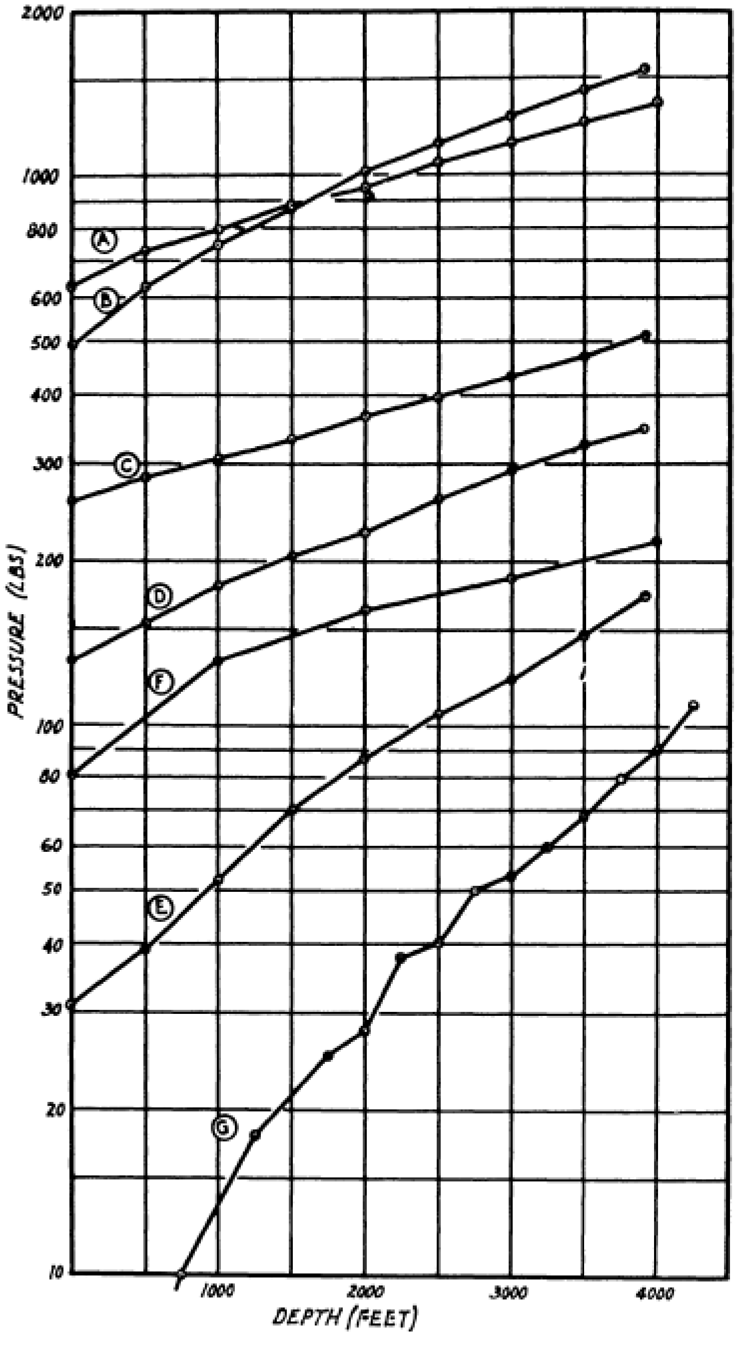

FIG. 11—PRESSURES AT VARIOUS DEPTHS IN FLOWING WELLS.

Pressure gradients have been taken in wells flowing naturally and by gas-lift. Some typical gradients are shown in Fig. 11. Additional well data, at the time these pressures were taken, are given in Table 2. Curves *A, B, C, D* and *E* are on the same well under different pressure conditions. The curves are plotted on semi-logarithmic paper and most of the points approach a straight line in the lower part of the flow string, but toward the top of the well there is a tendency for the gradient to become steeper, except in curve *C*. It suggests that the place at which this change occurs may be the place where the flow changes from viscous to turbulent. The velocity at this point probably varies with the absolute gas-oil ratio, because it shows up on the low as well as the high velocities. These curves indicate that the flow of oil and gas mixtures through vertical pipes is probably more regular and the loss in pressure less than is generally considered.

TABLE 2.-*Well Data at Time Gradients Shown in Fig.* 11 *Were Taken*

Curve	Size of Flow String, In.	Absolute Gas-oil Ratio at Top of Well, Cu. Ft. per Bbl.	Velocity at Top of Flow String Ft per Sec.
A	$8\frac{5}{8}$	28	1.2
B	$8\frac{5}{8}$	36	0.4
C	$8\frac{5}{8}$	68	56.5
D	$8\frac{5}{8}$	104	81.6
E	$8\frac{5}{8}$	669	35.3
F	7	1065	141.5
G	$5\frac{3}{16}$	1420	94.4

Bottom-hole pressures have been taken in pumping wells under operating conditions by placing the gage in a perforated anchor below the standing valve. The chart obtained in one of these wells is reproduced in Fig. 6. This well had been shut down for over 24 hr. at the time this chart started and the pressure recorded was 53 lb., which is considered as the formation pressure. After pumping 5 hr. the pressure decreased to 30 lb., which is 66 per cent. of the formation pressure (absolute).The pressure did not change during the rest of the period of the chart (33 hr.). During this time production averaged 16 bbl. per hour. Another well had a formation pressure of 69 lb., and pumped 27½ bbl. Per hour, with a bottom-hole pressure of 56 lb., which is 84 per cent. of the formation pressure (absolute). It is probable that the amount of oil pumped from each of these wells was limited by the capacity of the pump, as it is unlikely that the maximum amount of oil was delivered to either well with so Iowa differential pressure in the formation. A knowledge of bottom-hole pressures in pumping wells will give as much information for solving recovery problems as in flowing wells. It will also show whether the rate of production obtained is limited by the capacity of the pump or by the capacity of the sand to deliver oil to the well.

SUMMARY

Production control and lifting procedure can be more intelligently directed when bottom-hole pressures and pressures within the producing formation are known. By comparing these pressures the operator may determine whether the rate of production being obtained is limited by the capacity of the method of lifting the oil or by the capacity of the well to produce. The best size of flow string for a well flowing naturally or by gas-lift must be determined by the use of an estimated, calculated or measured bottom-hole pressure, and the degree of accuracy is in proportion to the accuracy of the bottom-hole pressure upon which the calculation is based. Production control used to obtain more efficient use of the gas energy accompanying the oil, to retard bottom water invasion, or to obtain more effective natural water flood, is usually accomplished by regulating the pressure at the casinghead or changing the operating method. These are indirect methods because a change in the rate of production is a result of change in the bottom-hole pressure (more specifically a change in the differential pressure between the producing formation and the bottom of the hole) caused by a change of the casinghead pressure or method of operation. Reliable pressures at the bottom of oil wells and in the producing formation are essential in solving problems of lifting and recovery of oil.