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ACOUSTIC PRODUCING BOTTOMHOLE PRESSURES

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ABSTRACT

This paper discusses the determination of acoustic producing bottomhole pressures. The producing bottomhole pressure of a well which has no liquid above the formation or has liquid above the formation but contains no free gas is easy to determine. This paper concentrates on the gradients of gaseous liquid columns in the casing annulus of a producing well.

Two different techniques are presented for the determination of producing bottomhole pressures in wells which have liquid above the formation and gas flowing upward through the gaseous liquid column. One technique involves the measurements of the acoustic liquid level and the casing pressure build-up rate when the casing valve is closed. Using this data along with an empirically derived correlation given herein, the gradient of a gaseous liquid column can be obtained. This technique offers a reasonably accurate procedure for determining the producing bottomhole pressure of a well by acoustic means. The second method involves two acoustic measurements. A back-pressure valve is used to depress and stabilize the liquid level at a second position. The gradient of the gaseous liquid column is then extrapolated to the formation depth. This method is very accurate when a back-pressure valve is used to stabilize the liquid level slightly above the formation.

This paper results from the field testing of numerous wells where the actual gradients of gaseous liquid columns were measured in a variety of casing-tubing sizes, oil gravities, gas flow rates, and pressures.

References and illustrations at end of paper

INTRODUCTION

The producing rate effeciency of a well can be determined using the IPR[1] curve which requires a knowledge of the producing and static bottomhole pressures. McCoy, et al.[2], Podio, et al.[3], Energy Conservation Board[4], and Weeks, et al.[5] have presented techniques for determination of static bottomhole pressures by acoustic means. These techniques have proven to be sufficiently accurate for most conditions.

The producing bottomhole pressure can be easily determined on a well which does not have liquid above the formation or a well which contains no free gas in the liquid present above the formation. However, the gradient of a gaseous liquid column has recieved considerable attention by numerous authors including Gilbert[6], Podio[7], Godbey and Dimon[8], Kabir and Hasan[9], and McCoy[10]. These techniques involve the determination of the gas flow rate up the annulus and in turn the calculation of the amount of liquid present in the gaseous liquid column by utilizing well conditions such as casing-tubing sizes, liquid properties, and pressure. All these methods are based on theoretical and surface models. Work by Hasan and Kabir shows Gilbert to predict the smallest gradient for a given set of conditions. The decision was made to conduct field testing after Gilbert's method sometimes predicted producing bottomhole pressures in excess of the known reservoir pressure.

Because of the disagreement of these techniques with actual field data, a comprehensive field study was performed. Results of these tests and proposals are given herein.

THEORETICAL ANALYSIS

The producing bottomhole pressure is the sum of the surface casing pressure plus the pressure due to the column of fluids in the annulus. This paper is limited to wells which have tubing perforations near the formation.

The fluid distribution in the annulus is a function of the producing conditions of the particular well. In general, three situations are found in the field:

A- The liquid level is at or near the formation. Casinghead gas may or may not be produced.

B- The liquid level is above the formation and casinghead gas is not produced.

C- The liquid level is above the formation and casinghead gas is produced.

Figure 1 illustrates these three cases. Accurate calculation of the bottomhole pressure requires an understanding of the relationship between the pressure conditions at the surface and the fluid distribution. For cases A and B, the situation is well defined from a measurement of the pressure at the surface, a knowledge of the properties of the fluids, and the position of the liquid level. Case C involves the uncertainty of the gaseous liquid column gradient due to the annular gas flow. In a producing well, all liquid above the tubing perforations will be oil due to gravity separation.

Liquid Level at Formation

The casinghead pressure constitutes the major portion of the producing bottomhole pressure in normal depth wells since the pressure due to the gas column is relatively small. Even when gas is being vented, the frictional pressure losses are minimal. Bottomhole pressure calculation is undertaken from a measurement of the casinghead pressure, the knowledge of the gas composition, and the temperature distribution as described in Reference 2, or by use of a computer program given in Reference 11.

The liquid level will always be at the tubing perforations when a well is being produced with the casing valves closed and free gas is flowing from the formation.

Liquid Level Above Formation without Casinghead Gas Flow

At stabilized producing conditions, the liquid above the tubing perforations is 100% oil. This producing bottomhole pressure is calculated from measurement of the surface casinghead pressure, measurement of the depth to the liquid level by an acoustic survey and a knowledge of the properties of the oil and the gas. Again, details of the calculation are given in References 2 and 11.

Liquid Level Above Formation with Casinghead Gas Flow

This condition results in a gaseous annular liquid column. At stabilized producing conditions, the oil in the casing annulus becomes saturated with the gas that is continuously flowing to the surface. Consequently, if gas is being vented at the surface at a constant rate, free gas is being produced from the formation simultaneously with the oil. Generally, most oil is produced through the pump while most free gas is produced up the casing annulus.

When a gaseous liquid column exists in the annulus of a well producing at stabilized conditions, the pressure at any depth in the oil column is independent of the surface pressure. This is illustrated in Figure 2 which shows schematically a well producing at three different values of casinghead pressure. The producing bottomhole pressure remains unaffected by the changes in the surface pressure and the liquid level. It must be stressed that in all three conditions: the flow rates of the casinghead gas and the produced fluids are equal and stabilized.

Generally, it will take a considerable time, over 24 hours, for stabilized conditions to be established when a change in the casinghead pressure occurs. During this transient period, the pressure buildup at the surface (caused by the accumulation of gas flowing into the gas column from the gaseous liquid column) will result in a pressure increase in the annulus and at the formation. This increase causes liquid to be depressed from the casing annulus into the pump thus restricting fluid flow and possibly causing liquid back-flow into the formation. During this time, the liquid level in the annulus will drop to a lower level. After gas begins to vent at the increased stabilized surface pressure, the surface gas flow rate will stabilize at the original value and the liquid level will fall and stabilize as the producing bottomhole pressure returns to its original value. A stable depth of the liquid level is thus an indication that the producing bottomhole pressure has stabilized. See Figure 3 for an example of plotted field data.

TESTING PROCEDURE

To measure the gradient of a gaseous liquid column, the liquid level can be depressed by increasing the casing pressure. The gradient will be the change in pressure at the top of the column divided by the change in the column's height. Both tests must be at stabilized conditions. **NOTE:** Casing pressure should not exceed safe limits.

With the use of a back-pressure valve, the casing pressure can be increased to a specific value and then stabilized by allowing annular gas to vent at its original rate. When casing pressure ceases to increase, liquid from the annulus is no longer forced into the pump and the producing bottomhole pressure will return to its original value. When the producing bottomhole pressure returns to its original value, the well is in a stabilized condition and a true gradient can be calculated.

In field tests, this stabilized condition is indicated by a stabilized liquid level. Experience has shown that up to 24 hours may be required for the liquid level to stabilize after the casing pressure stops increasing. This method of depressing the liquid level to a lower stabilized position was repeated several times during the course of the test; thus allowing the gradient to be measured at several depths in the gaseous liquid column. See Figure 3. Stabilization of the top of the gaseous liquid column was used to verify that the producing bottomhole pressure had returned to its original value on the majority of the tests because of its inexpensive and simplistic nature. During earlier tests, bottomhole pressure sensors, dynamometers, and portable well testers were used to determine when stabilization occurred.

The wells tested during this study included casing sizes from 4.5" to 7" and oil gravities between 32 and 43 API. Long gaseous liquid columns of over 5000 feet were studied in wells up to 9000 feet deep. Annular gas flow rates ranged from 13 to 120 MCF/D and oil fractions ranging from 20 to 77% were measured.

RESULTS OF FIELD TESTS

The gradient of the gaseous liquid column varied only slightly at different depths in a particular well. Since pressure increases with depth in a column, this constant gradient indicates that pressure has only a small effect on the gradient of a gaseous liquid column. The predominant factor is annular gas flow rate. Refer again to Figure 3.

The correlation derived from the field work is based on a variable C, the effective oil fraction. Due to the empirical nature of this study, the effective oil fraction is a term which takes into account not only the void created by gas bubbles, but also any pressure drop due to frictional forces in the gaseous liquid column. The effective oil fraction multiplied by the gas-free oil gradient gives the gaseous liquid column gradient. In this study, the effective oil fraction was calculated by taking the gradient measured in the field tests and dividing by the gradient of the gas-free produced oil. The gas-free oil gradient was based on the API gravity at standard conditions because the operator can easily obtain API gravity and calculating formation factors would unnecessarily complicate the procedure. See Figure 4.

By correlating the calculated effective oil fraction to the annular gas flow rate, a method of predicting the gradient of a gaseous liquid column can be derived from the field tests. Measuring annular gas flow in the field is a tedious process which can be avoided by estimating the gas flow from a short casing pressure buildup test. The test is conducted by closing the casing valve while the well continues to pump. The rate at which casing pressure increases is measured. During the study, annular gas flows calculated by short casing pressure buildup tests were less than the rates measured with a critical flow prover. This underestimate was a result of considering only the volume of gas above the liquid level. The gas bubbles present in a long gaseous liquid column can constitute a large volume. Once the gradient present was determined, an effective oil fraction was calculated; and in turn the volume of gas present in the column was estimated. The difference in the effective oil fraction and the true oil fraction could not be determined and thus was ignored. By using the total volume of gas present in the annulus, the average error in estimating gas flow was reduced to less than 10% from the 30% average when only the volume above the liquid level was considered. This discussion is illustrated in Figure 5.

The correlation derived from these field tests ignores pressure because pressure effects could not be verified. Annular gas flow divided by the annular area is related to the effective oil fraction present in the gaseous liquid column. Since it has been shown that annular gas flow can be estimated by a short casing pressure buildup, the function is plotted as the casing pressure buildup rate times the adjusted depth to the liquid level versus the effective oil fraction. This adjusted depth to the liquid level, denoted as L', is the acoustically measured depth to the top of the gaseous liquid column plus the height fraction of gas bubbles in the gaseous liquid column. The plotted function along with data points are shown in Figure 6.

Gilbert's Curve is the most common method used to predict gaseous liquid column gradients. The data points were plotted on Gilbert's Curve and are shown in Figure 7. Gilbert's Curve predicts gradients greater than those measured in the field tests, sometimes by a factor of 2.

DETERMINING ACOUSTIC PRODUCING BOTTOMHOLE PRESSURES

The simplest technique to calculate a producing bottomhole pressure is to acoustically determine the distance to the top of the gaseous liquid column and measure the casing pressure buildup rate. Then, use Figure 8 and an iterative process to determine the effective oil fraction. Because the adjusted depth L' is a function of the oil fraction and vice versa; the effective oil fraction will have to be solved with a short iterative process starting with an oil fraction of one. The producing bottomhole pressure will then be:

$$P_{wf}=P_{cf}+P_{gc}+g_o*C*H \quad \text{.........................(1)}$$

See the example problem in the appendix.

NOTE: Care must be taken in measuring the casing buildup rate. At a buildup rate of 1 psi in 10 minutes, which might be overlooked, an effective oil fraction of 0.80 could exist. A minimum of **10 psi and 10 minutes** should be used in each casing pressure buildup for the best results.

The second method, known as Walker's method[12], involves the determination of the liquid level at two different casing pressures. The use of a back-pressure valve is required in order to stabilize the well at the higher casing pressure. Be sure that the casing pressure and the gaseous liquid level have stabilized at both conditions.

Since the gaseous liquid column gradient is equal to the difference in pressures at the two depths divided by the distance between, then:

$$g_{glc}=\frac{[(P_{cf2}+P_{gc2})-(P_{cf1}+P_{gc1})]}{(D_{L2}-D_{L1})} \quad \text{........(2)}$$

where D_{L2} and D_{L1} are the depths to the liquid level at pressures P_{cf2} and P_{cf1}. Using this gaseous liquid gradient the producing bottomhole pressure may be calculated as:

$$P_{wf}=P_{cf2}+P_{gc2}+g_{glc}*(D_f-D_{L2}) \quad \text{.............(3)}$$

The accuracy of this method increases as the depth to the second liquid level approaches the formation.

NOTE: One must be careful to leave a small amount of liquid above the pump to be sure that additional gas is not being forced into the pump.

By using the first correlation provided herein, an estimate of the pressure required to depress the liquid level to the pump can be made. Estimate the producing bottomhole pressure by the use of Figure 8, and then set the back-pressure valve at 70% of the predicted producing bottomhole pressure.

COMPUTER INFORMATION

A microcomputer is presently available for calculating producing bottomhole pressures in wells discussed in cases A & B. Software for the Epson microcomputer will soon be available for calculating the producing bottomhole pressure in wells having gaseous liquid columns. The program will be based on Figure 8 and References 2 and 11. The program will also be available for the IBM PC, the Apple IIe, the Apple Mac, and several Tandy computers.

APPLICATION TO PRESSURE BUILDUP WORK

In order to obtain the most accurate pressure data at the earliest times, the top of the gaseous liquid level should be stabilized near but above the pump prior to shutting-in the well. Use the back-pressure valve technique presented herein. This will increase the accuracy of the calculated bottomhole pressure and the afterflow into the wellbore.

CONCLUSIONS

Calculation of producing bottomhole pressure can be performed in 90% of pumping wells without consideration for gaseous liquid columns. Most wells are in the first two categories described; either having no liquid above the formation or having liquid above the formation without annular gas flow.

In wells where gaseous liquid columns are present, the producing bottomhole pressure can be obtained by the correlation presented herein. For additional accuracy the difficult, expensive, and lengthy Walker's method may be utilized to obtain the producing bottomhole pressure. Accuracy from Walker's method depends on depressing and properly stabilizing the liquid level near the pump.

This study, based on actual gradients measured in the annulus, offers increased accuracy over previously reported correlations based on theory and surface models. Field testing is continuing in this project in order to confirm the correlation over a wider range of parameters. Please contact one of the authors if interested in participating in the project.

ACKNOWLEDGMENTS

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NOMENCLATURE

C-Effective oil fraction

D_f -Depth to formation, ft

D_L -Depth to the top of the liquid level, ft

g_{glc}-Gradient of gaseous liquid column, psi/ft

g_o -Gradient of gas-free oil column, psi/ft

H -Length of gaseous liquid column, ft

L -Depth to liquid level, ft

L' -Adjusted depth to liquid level, ft

P_{gc} -Pressure exerted by gas column, psi

P_{gf} -Casing pressure at producing conditions, psig

P_{glc} -Pressure exerted by gaseous liquid column, psi

P_{wf} -Producing bottomhole pressure, psig

1,2 -denotes separate stabilized conditions

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EXAMPLE PROBLEM

DEPTH TO FORMATION=7000 FT
DEPTH TO GASEOUS LIQUID COLUMN= 3000 FT
CASING PRESSURE= 100 PSIG
OIL API= 42 API= .353 PSI/FT
GAS GRAVITY= .7
CASING PRESSURE
BUILDUP= 10 PSI IN 30 MINUTES

CASING PRESSURE	100 PSIG
GAS COLUMN PRESSURE	10 PSIG

HEIGHT OF GASEOUS COLUMN= 7000-3000= 4000 FT
dP/dT= 10 PSI / 30 MIN= .333 PSI/MIN
ASSUME OIL FRACTION = 1
L'=3000+(1-1)*4000= 3000 FT
dP/dT * L'= 1000

L'=3000+(1-.72)*4000= 4120 FT
ITTERATE UNTIL
OIL FRACTION CONVERGES

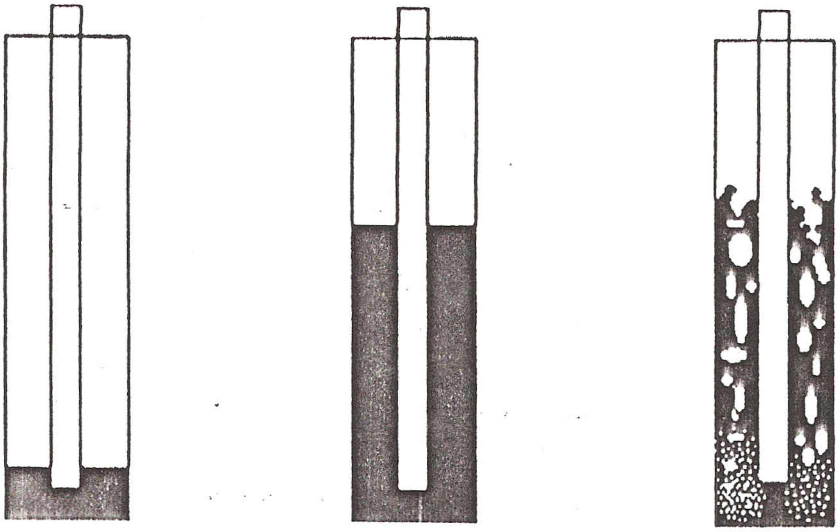
L'	(dP/dT)*L'	OIL FRACTION
3000	1000	.72
4120	1371	.63
4440	1478	.62
4480	1491	.62

GASEOUS COLUMN PRESSURE=
.62*.353*4000= 875 PSIG

Pwf = 100+ 10+875 = 985 PSIG

FIGURE 1

FLUID DISTRIBUTION IN ANNULAR AREA



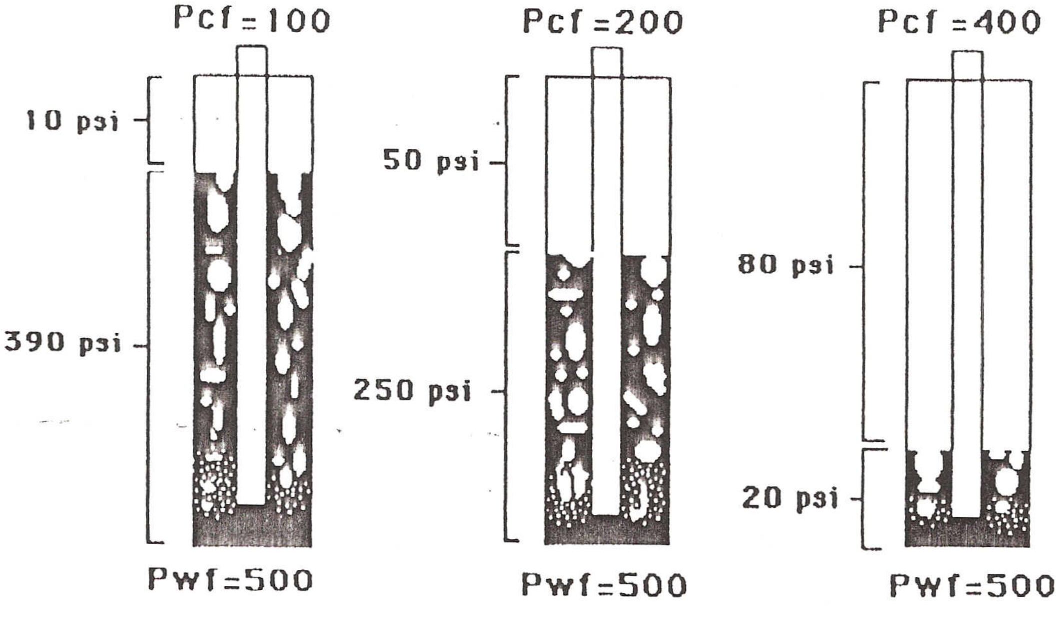
TYPE A
LIQUID LEVEL
AT PERFORATIONS

TYPE B
LIQUID LEVEL
ABOVE FORMATION
AND NOT PRODUCING
ANNULAR GAS

TYPE C
LIQUID LEVEL
ABOVE FORMATION
AND PRODUCING
ANNULAR GAS

FIGURE 2

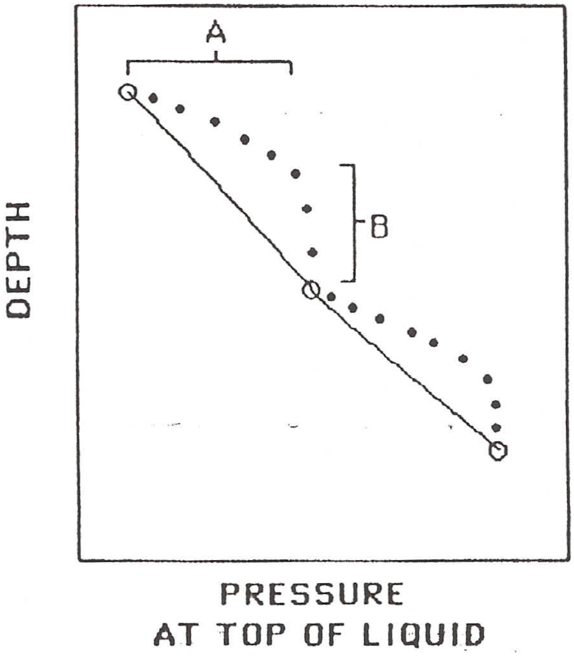
GASEOUS COLUMNS IN PRODUCING WELLS



Pwf is independent of surface pressure at stabilized conditions

FIGURE 3

PLOTTED FIELD DATA



SECTION A-

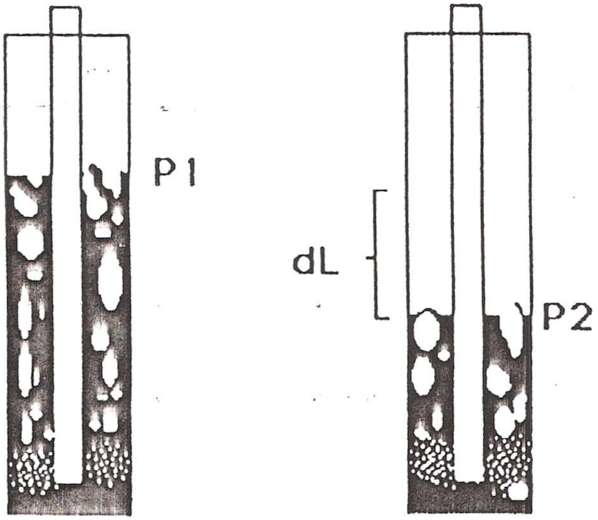
Period when the back pressure valve is closed and liquid is being forced into the pump. The apparent gradient is higher than the actual gradient because the producing bottomhole pressure has been increased

SECTION B-

Surface casing pressure has stabilized and annular gas starts to flow through the back pressure valve and then increases to its original rate. The liquid level will fall until the producing bottomhole pressure returns to the original value.

FIGURE 4

MEASURING GRADIENTS IN ANNULUS

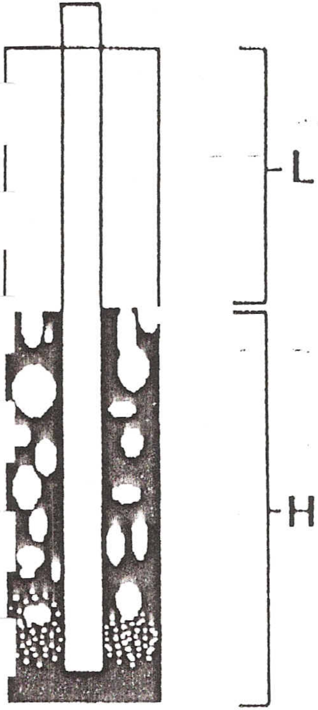


$$\text{GASEOUS LIQUID COLUMN GRADIENT} = \frac{(P2-P1)}{dL}$$

$$\text{EFFECTIVE OIL FRACTION} = \frac{\text{GASEOUS GRADIENT}}{\text{GAS-FREE GRADIENT}}$$

FIGURE 5

ESTIMATING ANNULAR GAS FLOW RATE



$$Q_{[MCF/D]} = \frac{.00068 * dP * A * L'}{dT}$$

$$L' = L + (1 - C) * H$$

L'-adjusted depth to liquid level, ft
L -depth to liquid level, ft
C -effective oil fraction
A -annular area, sq-in
H -height of gaseous liquid column, ft
dP -casing pressure buildup, psi
dT -casing buildup time, minutes

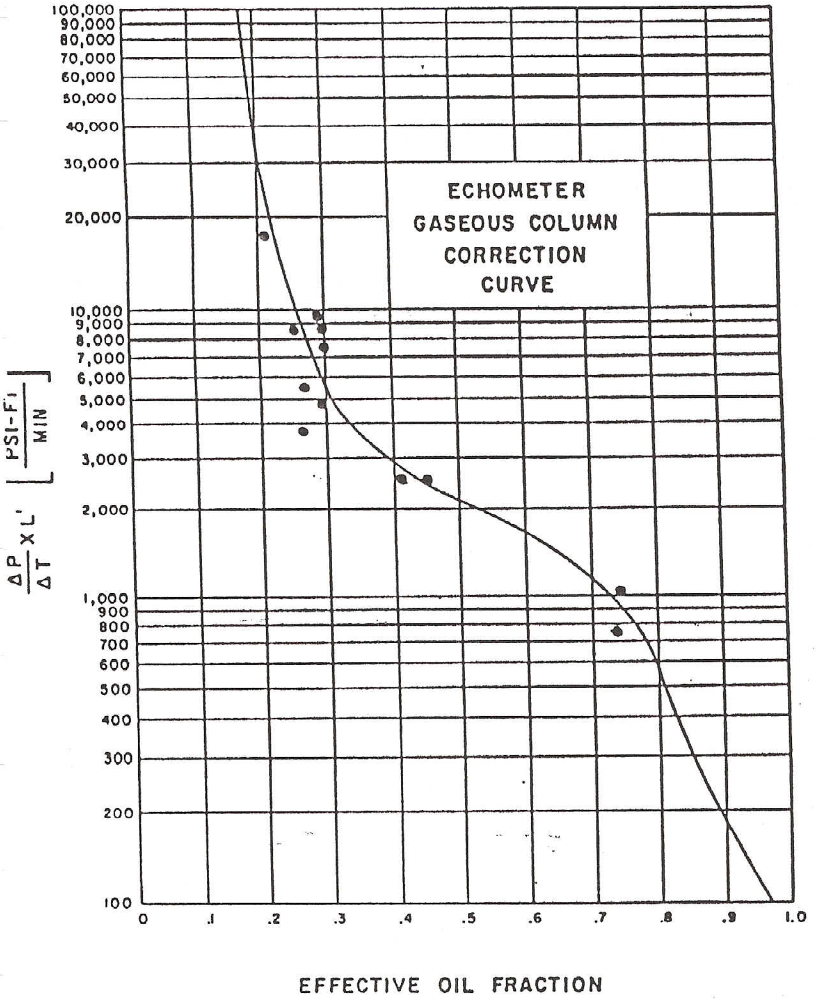


FIGURE 6

ECHOMETER GASEOUS
LIQUID COULMN
CORRECTION CURVE
VS
FIELD DATA

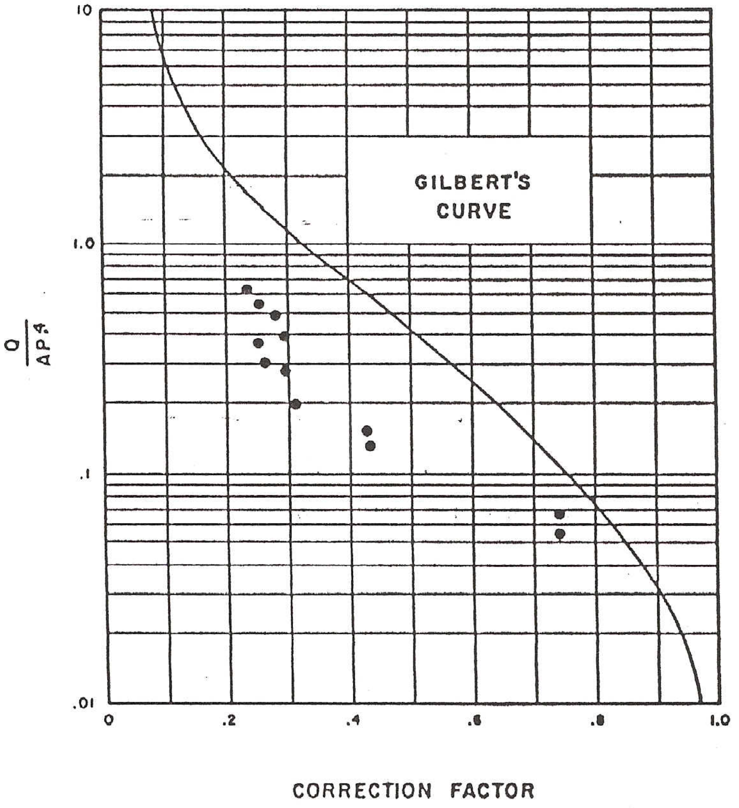


FIGURE 7

GILBERT'S CURVE
VS FIELD DATA

FIGURE 8

ECHOMETER GASEOUS LIQUID
COLUMN CORRECTION CURVE