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What is Balanced Pressure Drilling?

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ABSTRACT

Other things being equal the minimum footage drilling cost will ensue when penetration rates approach a maximum value. One of the major factors controlling optimum penetration rates is the mud-column pressure. In planning a drilling program for drilling recent sediments, it is critical to know whether a maximum penetration rate will occur when the differential pressure [difference between formation pressure and dynamic mud-column pressure] is overbalanced, balanced or underbalanced.

A review of literature shows that from laboratory drilling tests the maximum penetration rate likely occurs at a balanced-pressure condition. Rates tend to decrease when either an underbalanced or overbalanced condition is established. Results of single chisel tests tend to support these results.

Recently published field results are apparently incompatible with the above work in that they report drilling rates tending to increase as formation pore pressures exceed the dynamic mud-column pressure. The dynamic mud-column pressure has been defined in these reports as:

$$P_P = P_{DYN} = P_{STATIC} + A_{BP}$$

where P_P = formation pore pressure, psi
P_{STATIC} = static mud-column pressure, psi
A_{BP} = annulus pressure drop due to flow, psi.

A review of known data suggests a balanced pressure drilling condition actually occurs when

$$P_P = P_{DYN} = P_{STATIC} + A_{BP} + P_I + P_R ,$$

where P_I = impact pressure in a vertical direction under the bit due to flow, psi
P_R = impact pressure in a vertical direction under the bit due to bit rotation, psi.

Using this relationship, recently reported field tests become compatible with previously reported work and it is possible to conclude:

1. A balanced pressure drilling condition can be defined as:

$$P_P = P_{DYN} = P_{STATIC} + A_{BP} + P_I + P_R .$$

2. The maximum penetration rate under many drilling conditions occur when formation pore pressure and dynamic mud-column pressures are equal.

3. A change in differential pressure in

References and illustrations at end of paper.

either direction [underbalanced or overbalanced] will likely reduce penetration rates.

INTRODUCTION

It can be assumed that for a given rig and fluid environment minimum drilling footage costs can be achieved by maintaining the penetration rate close to the maximum potential. An optimum drilling program must consider the formation to be drilled, the proper bit-weight-rotary speed combination, required hydraulics, the fluid environment and its effect not only on penetration rates, but hole stability and formation productivity. One factor which controls permissible penetration rates and involves many complexities is the mud-column pressure.

The industry has long recognized that penetration rates tend to be highest with air circulated followed by water and lowest with mud. Part of the advantages can be related to a change in hydrostatic head, although other aspects are involved. Technological developments during the past 20 years have established this generalization is not always true. Both laboratory[5,10] and field tests[20] have shown that under certain environmental conditions, drilling rates with a near clear water drilling fluid can be higher than where air is circulated. This seldom occurs under field conditions but establishes the complexities involved and the need for a more precise understanding of fluid and pressure involvement in drilling.

It is known that a relationship exists between penetration rates and mud-column pressure. The critical pressure relationship has often been referred to as the differential pressure which is the difference between formation pore pressure and dynamic mud-column pressure. This concept is useful provided the effectiveness of pore pressure can be established. Under some drilling conditions it appears full mud-column pressure applies and the effective pore pressure would be zero.

In areas of recent sedimentation where both normal and abnormal pressure gradients are likely to be encountered, the relationship between mud-column pressure and penetration rates is critical. Some work reported in the literature suggest penetration rates will be a maximum when the formation pore pressure is exactly balanced by the dynamic mud-column pressure. Others have reported that penetration rates tend to continue to increase as an underbalance situation occurs; i.e., penetration rates are highest when the pore pressure is greater than the dynamic mud-column pressure.

This introduces a paradox critical in planning an optimum drilling program. Should we attempt to drill underbalanced, exactly balanced or slightly overbalanced? Since attendant risks vary considerably depending upon the choice, it is important to establish more precisely the relationship between potential penetration rates and pressure involvement in drilling.

LITERATURE REVIEW

A number of early papers[1,3,4,6] have shown that drilling rates in the field tend to decrease as hydrostatic pressure increases. Eckel,[1] Moore,[6] Wardroup and Cannon[4] plotted the change in relative penetration rate due to changes in mud weight. These are shown in Figs. 1 and 2. The percent change of relative penetration rate was different for each test, which suggests rock drillability and energy input may be involved. The actual change of hydrostatic pressure head was on the order of 750 psi in the Andrews County test which establishes a significant change in penetration rates with a little change in pressure. Laboratory drilling tests established similar relationships when drilling shale. Murray and Cunningham[3] reported significant changes in penetration rates due to a change in hydrostatic head [Fig. 3]. All recognized the complexities involved and the need to differentiate between the effect of mud-column pressure and the effect of other fluid properties upon penetration rates.

Cunningham[2,3] conducted controlled microbit drilling tests on shale, limestone, dolomite, sandstone and basalt cores with fluid properties held constant and established that penetration rates usually decrease with increasing hydrostatic pressure [Figs. 4 through 6]. The typical decline was observed with both roller cone and drag bits. The degree of reduction varying with rock and input power. Additional tests were indicated to further delineate all effects. General agreement between laboratory and field results were established with the greatest reduction in penetration rates occurring at pressures of less than 2,000 psi.

In 1957, Eckel[5] reported results from laboratory drilling tests using microbits and concluded penetration rates to be substantially affected by differential pressure which was the difference between formation pore pressure and hydrostatic mud pressure. Of even more import, these tests show penetration rates were a maximum when pore pressure and hydrostatic pressures were equal, the implication being that the optimum drilling condition would occur at a balanced pressure condition and that penetration rates would be less for either an underbalanced or overbalanced pressure condition. Fig. 7 is a composite plot of some of the tests reported.

Cunningham and Eenink[7] reporting results of laboratory drilling tests with a microbit on permeable Berea sandstone, Indiana limestone and loose sand, concluded among other things that penetration rates decrease markedly with increases in differential pressures. The reduction could be 60 to 70 percent in the first 1,000-psi increase. An adverse cuttings removal problem was also involved.

Garnier and Van Lingen[8,9] provided additional insight into the problem with tests conducted with drag, diamond and full-scale roller cone bits on assorted rocks. They concluded the decrease in penetration rates with increases in differential pressure involves rock strengthening and "chip hold down" effects. This further delineated the complexities involved. A representative plot of results is included as Fig. 8.

Bingham[10] introduced the concept that drilling is a discontinuous phenomena but the interpretation supports the concept that pressure not only affects rock strength, but involves a cuttings removal problem. However, the complexities of cuttings removal cannot be handled with a simple chip hold down concept. Under some conditions pressure changes exert little effect on penetration rates while under other conditions a slight pressure change could be significant. Unreported microbit drilling tests indicated that the maximum penetration rate occurs when formation pore pressures balance dynamic fluid pressures. Drilling rates would tend to decrease when pore pressures increase above the dynamic mud-column pressure.

Single chisel tests also support these generalizations. Maurer[11] reporting results of single chisel tests conducted on a number of rocks stated that, at low differential pressures, cuttings lay loose in craters while at high ΔP cuttings are tightly held in place.

Recently, Yang and Gray[18] reported that, as pore pressure increases above hydrostatic pressure, the effective rock stress increases, causing a decrease in crater volume, blow energy and maximum force.

On the basis of these reports there is general agreement that pressure involvement in drilling is complex and that the maximum penetration rate will likely occur when formation pore pressures and dynamic mud pressure are equal. Limited tests suggest that drilling rates would be expected to decrease when either an overbalanced or underbalanced pressure condition ensues. The anticipated relationship would appear as shown in Fig. 9.

Vidrine and Benit[17] substantiated the effect of differential pressure on drilling rate with field data. Reproduction of these data in Figs. 10 and 11 show penetration rate to continue to increase as pore pressure becomes greater than dynamic mud pressure. These plots are based on definition which defines dynamic mud pressure as a summation of static mud pressure plus the annulus backpressure induced by flow. A balanced pressure drilling condition would result when the dynamic mud pressure balances the formation pore pressure or:

$$P_P = P_{DYN} = P_{STATIC} + A_{BP} .$$

This definition has also been used by others.[12-15]

These results are obviously incompatible with the bulk of tests discussed earlier. Two distinct possibilities may be considered: either pressure involvement is so complex that agreement between many tests is impossible or other forces are involved and need be defined.

PRESSURE FORCES IN DRILLING

Prior to establishing circulation in a borehole, two pressure forces are involved, the static pressure head of the mud column and the formation pore pressure. Once circulation is started, two additional additive forces are likely to be involved. One, which has already been considered, is the backpressure buildup in the annulus due to flow. However, there is an additional pressure force due to flow under the bit. This term will be referred to as a unit impact force.

For regular bits, the unit force would tend to be constant in a vertical direction across the bottom of the borehole. Fig. 12 shows this simplified profile. Laboratory tests which measured the pressure profile from a number of points placed across a diameter of the borehole have established that for commonly used circulation rates, the unit forces are between 50 and 150 psi, depending upon the flow rate, hole diameter and density of the circulated fluid.

When jet bits are used, the vertical profile becomes more complex. Eckel[19] in reporting impact forces with jets showed that jet force varies not only with flow rate, but with the height of a nozzle off bottom [Fig. 13]. The unit force on bottom also varies with the distance from the center of impact. With 100 gal/min of water circulated and a jet velocity of 160 ft/sec, the unit impact force could be as high as 120 psi.

At normal flow rates and with nozzles positioned in commonly used bits, the vertical component of the unit impact force at the centerline of the jet could be in excess of 400 psi [Appendix A]. The composite impact profile at the bottom of the borehole would be as shown in Fig. 14. The maximum unit impact force being at the corner of the borehole with maximum at the center of the borehole. With high enough flow rates and jet velocity, a negative pressure profile could occur at the center of the borehole.

This vertical pressure component due to flow directed against the bottom of the borehole can be considered an impeding force. Once cuttings protrude into the flow stream, the horizontal velocity component provides a cuttings removal force. The crossflow velocity component has been defined and reported in detail by McLean.[21,22] The vertical impact pressure wave also assists in removal of cuttings due to the considerable differences in pressure over a short distance on bottom. It appears the vertical impact pressure may be involved in establishing an adverse differential pressure across the bottom of the borehole while at the same time assisting in clearing cuttings already dislodged from the corner of the borehole.

One additional impeding unit force may be involved. This is one due to rotation of the bit. With an interlocking roller cone bit, rotation of the bit creates a hydraulic impact force on the bottom of the hole. Laboratory tests in which a three-cone bit was rotated without circulation established a unit force on the order of 25 to 75 psi for a range of 50- to 250-rpm rotary speed. This force varies with fluid density.

On this basis, the dynamic mud pressure force would be:

$$P_{DYN} = P_{STATIC} + A_{BP} + P_I + P_R$$

where P_I = unit impact pressure in a vertical direction due to a flow, psi

P_R = unit impact pressure in a vertical direction due to rotation, psi.

A summation of impact forces establish that $P_I + P_R$ could be as high as 475 psi under normal drilling conditions. Field data viewed earlier can be adjusted to be compatible with other data. This suggests that maximum penetration rates occur at a balanced pressure condition, but balanced when dynamic mud-column pressures are fully calculated.

CONCLUSION

If we accept this relationship, it is possible to conclude:

1. A balanced pressure drilling condition can be defined as:

$$P_P = P_{DYN} = P_{STATIC} + A_{BP} + P_I + P_R$$

where P_P = formation pore pressure, psi

P_{STATIC} = static mud-column pressure, psi.

2. Maximum penetration rate under many drilling conditions will occur when the formation pore pressures and dynamic mud-column pressures are equal.

3. A change in differential pressure in either direction [underbalanced or overbalanced] will likely reduce penetration rates.

A_{BP} = annulus backpressure due to flow, psi

P_I = unit impact pressure in a vertical direction under bit due to flow, psi

P_R = unit impact pressure in a vertical direction due to rotation of bit, psi.

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APPENDIX A

The force of a jet at its exit can be readily calculated, but the actual impact pressure on bottom would be reduced due to velocity transfer of momentum from the jet to the surrounding fluid. McLean has analyzed and discussed these forces in detail and his work is highly recommended for study.[21-22]

In this paper the intent is to develop order of magnitude. It is possible to calculate the order of magnitude of the maximum impact pressure gradient by:

$$\frac{dP}{dx}_m = - \frac{wV^2M^3e^{-\frac{1}{2}}}{gd} = \frac{0.000978\ wV^2M^3}{d}$$

where $\frac{dP}{dx}_m$ = maximum impact pressure gradient, psi/in.

w = specific fluid weight, lb/gal

V = average velocity of jet at nozzle, ft/sec

d = nozzle diameter, in.

M = dimensionless function of d,H,L and θ defined in a dimensionless grouping as:

$$M = \frac{d + 2L \tan(\theta/2)}{d + 2H \tan(\theta/2)}$$

where L = length of potential core, inc.

H = distance from nozzle to wall, in.

θ = angle of spread of axially symmetric jet, degrees.

Typical Example

$V = 400$ ft/sec
$d = 3/8$ in.
$L = 1$ in.
$w = 12$ lb/gal
$H = 4$ in.
$\theta = 20^\circ$

$$\frac{dP}{dx}_m \sim 340 \text{ psi/in.}$$

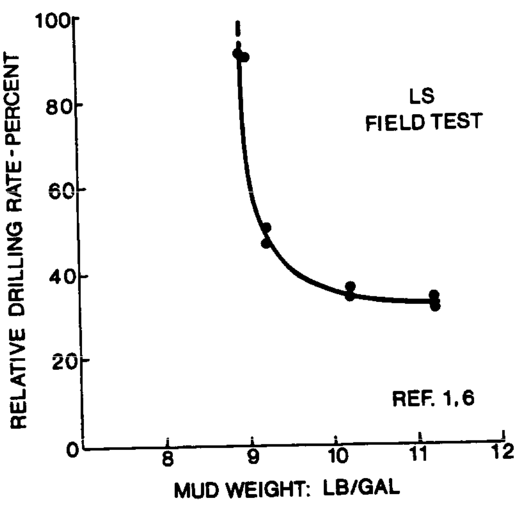


Fig. 1

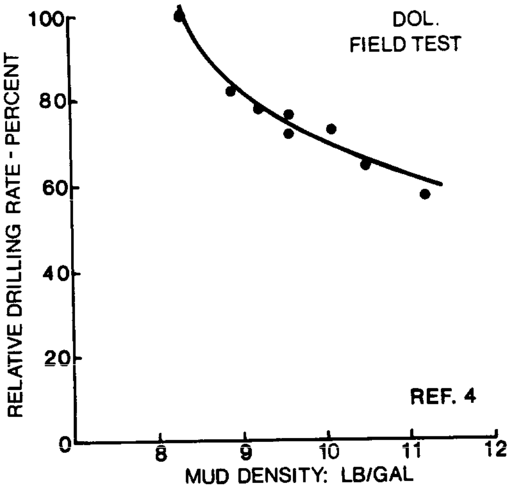
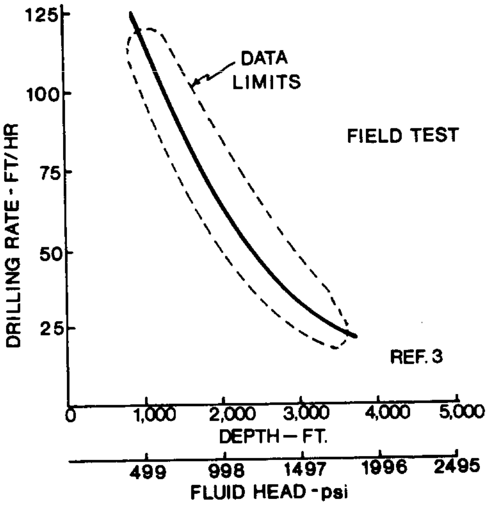


Fig. 2



AVERAGE PENETRATION RATE CURVES

Fig. 3

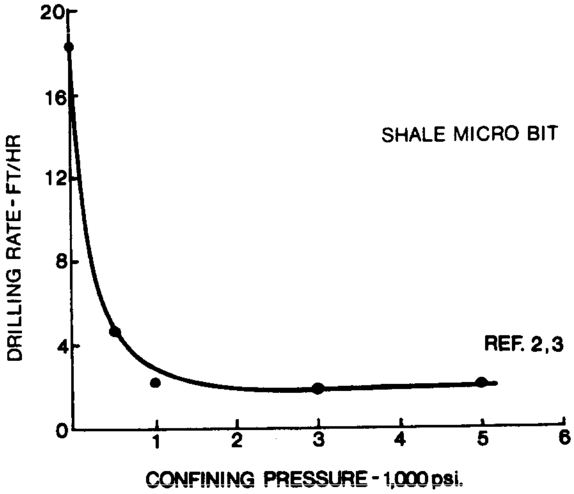


Fig. 4

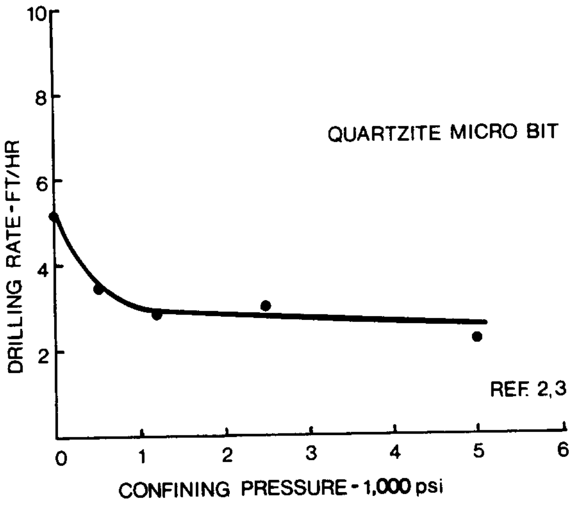
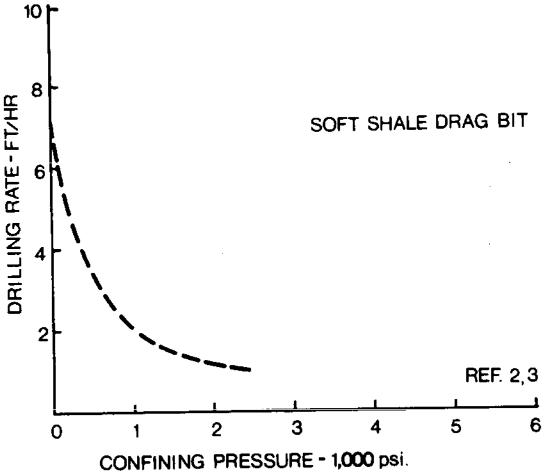


Fig. 5



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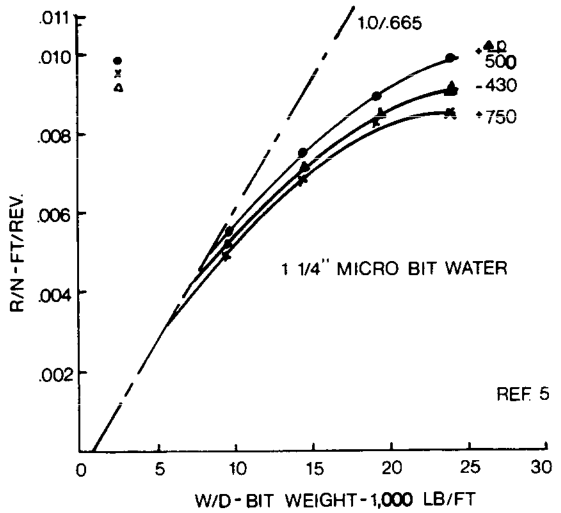

Fig. 7

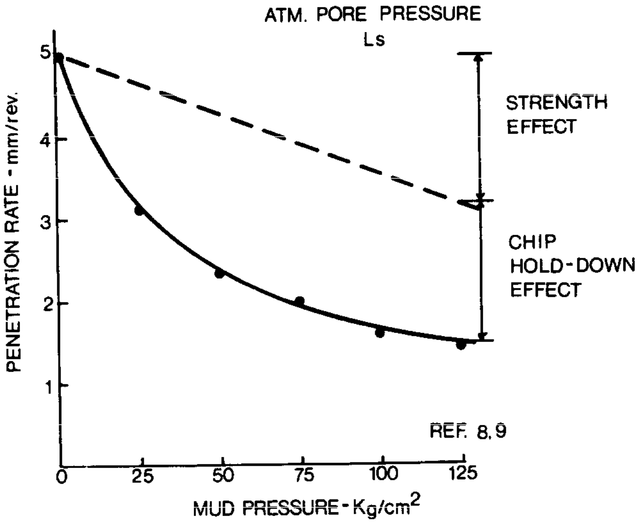

Fig. 8

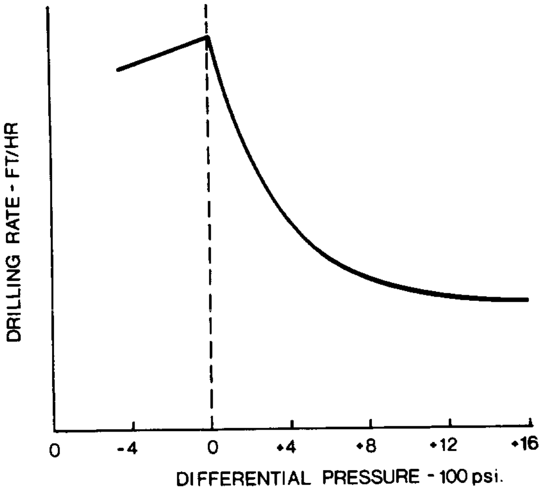

Fig. 9

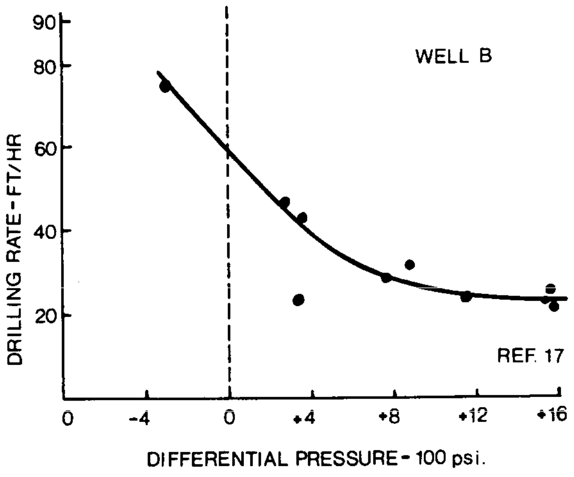

Fig. 10

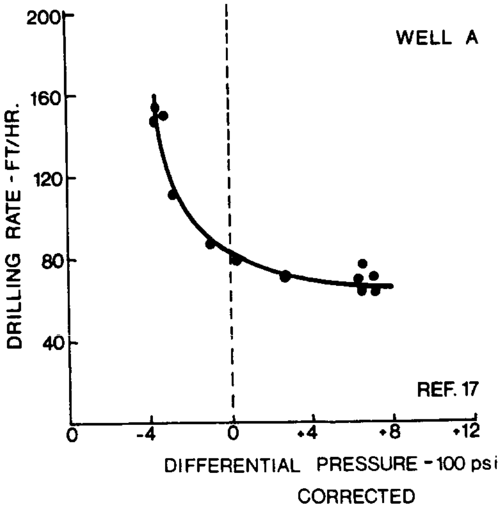

Fig. 11

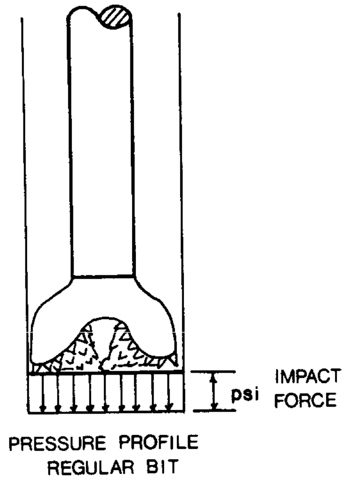

Fig. 12

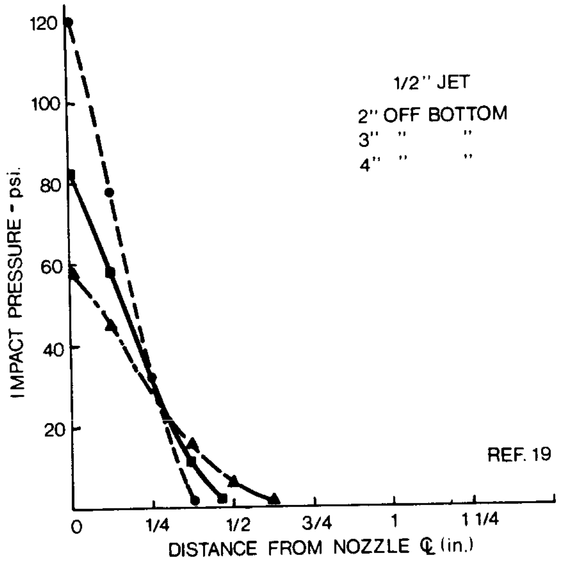

Fig. 13

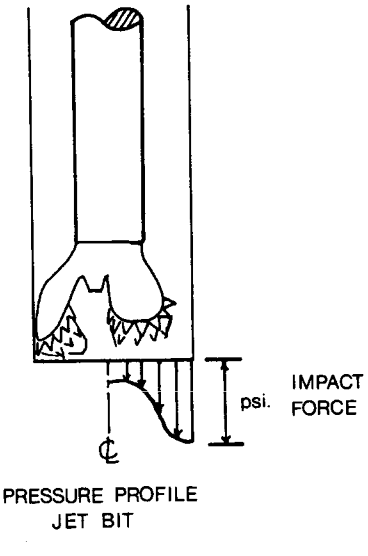

Fig. 14