BETC/RI-78/5
Distribution Category UC-92a

A STUDY TO DETERMINE THE OPTIMUM BIT OFFSET AT VARIOUS DRILLING DEPTHS

By

Terra Tek, Inc.
420 Wakara Way
Salt Lake City, UT 84108

Prepared for the U.S. Department of Energy
Under Contract Nos. BE-00-P-3252, EY-77-X-19-1667 (P),
EY-77-X-19-2118 (P), and P-B-8-1220

R. K. Dropek, *Principal Investigator*
Terra Tek, Inc.

C. Ray Williams, *Technical Project Officer*
Bartlesville Energy Technology Center
P.O. Box 1398
Bartlesville, OK 74003

Date Published—October 1978

TECHNICAL INFORMATION CENTER
UNITED STATES DEPARTMENT OF ENERGY

FOREWORD

The work described herein was performed for the Department of Energy, Bartlesville Energy Technology Center (BETC), Mr. John S. Ball, Director, using funds obtained from the Branch of Drilling and Offshore Technology (DOT), Mr. Don Guier, Branch Chief. The Branch of DOT is within the Division of Oil, Gas, Shale, and In Situ Technology, Mr. Hugh D. Guthrie, Director. The project was conceived and supervised by BETC engineers.

Through discussions with bit manufacturers and other researchers it was decided that building "skew or offset" into a bit is considered an art instead of a science. It precipitated the thought that the optimum amount of offset could be determined. Also, the concept that a different offset might be needed as drilling depths increased because the formation becomes more ductile at depth. It is felt that the results of the work has proved that indeed an optimum offset does exist and, hopefully, drill bit designers can utilize this data to increase penetration rates.

Much appreciation is due Dresser's Security Bit group for the helpful information they provided and their furnishing equipment and design drawings at no cost.

C. Ray Williams
Technical Project Officer
Bartlesville Energy Technology Center

ABSTRACT

Tests were performed using a single roller cone from a 4 3/4 inch diameter modified chisel bit to evaluate the effects of cutter offset "skew" on drill bit cutting efficiency at depth. Drilling experiments were conducted using Colton Sandstone (11 percent porosity and 50 microdarcy permeability). Tests were performed at simulated depths ranging from 0 to 20,000 feet using six different offsets (0 to .24 inches) and two different penetrations (0.05 and 0.1 inches). A single revolution of the cone arm was made with torque, thrust and the resulting removed volume recorded. The application of test results to future drill bit design are discussed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The DOE-sponsored single cutter drilling tests were conducted to quantitatively determine the effects of offset on roller cone cutter efficiency with respect to increased drilling rates. Impetus for the investigation of cutter offset effects is due primarily to the problem of reduced drilling rates in formations for which continuous plastic (ductile) flow rather than brittle failure, accompanies bit tooth penetration. Reduction in laboratory and field drilling rates ranging from 30 to 80 percent have been observed in ductile rocks as noted by Murray, *et al.*, [1955], Eckel [1958]; and Eenink [1958], among others. These experimenters determined that the prime cause for increased rock ductility was the differential pressure between the drilling mud and the formation fluid pressure with the mud pressure being greater than the pore pressure. When sufficient differential pressures exist for ductile rock conditions to prevail, brittle rock failure normally experienced in hard rock drilling is no longer the rock removal mechanism [Payne and Chippendale, 1953 Cheatham, 1977]. Rather, a scraping and gouging action in conjunction with crushing has been found to give best results in increasing drilling rates. This action is obtained by designing a drilling bit using offset cutter cones with longer chisel-type inserts. Figure 1 illustrates the meaning of cutter offset; it is the distance between two parallel lines with one line being the roller cone axis and the other line passing through the center of plate rotation. The offset causes the apex of the roller cone to lead the cut, thus inducing a dragging-scraping action.

A series of tests were to be conducted to analyze the effects of cone offset. *In situ* well conditions were simulated in a test apparatus modified

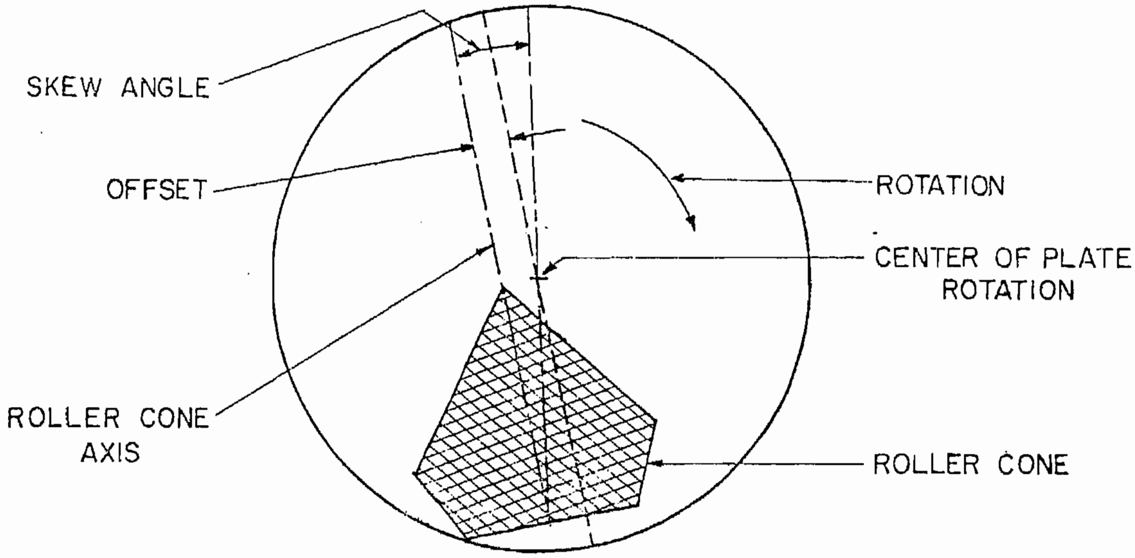

Figure 1. Roller Cone Cutter Offset Definition

for this work. A single turn of the cutter was made on the rock specimen. Torque, thrust and volume removed were recorded for each experiment in order to determine relative drilling rates and specific energy.

APPARATUS AND TEST SPECIMEN PREPARATION

The tests were conducted on 7 1/2 inch diameter samples of Colton sandstone in a test machine modified for this work. The rock has the following properties [Black, Rogers and Wright, 1977]:

Young's modulus	= 3.1 x 10^6 psi
Porosity	= 11 percent
Permeability	= 50 microdarcies
Dry Bulk Density	= 2.36 gm/cm^3

All specimens were soaked in water 48 hours prior to testing. Downhole conditions were simulated in a 60,000 psi, 8 inch I.D. pressure vessel mounted in a 1.7 million pound capacity load frame.

A schematic of the test system is shown in Figure 2. The schematic shows a steel endcap on top of the rock and the rock resting on the drilling chamber. The rock face nearest the bit was angled at 2.5° ± 0.1°, thus matching the cutter taper at the normal pin angle (36°). The specimen was sealed from the confining fluid using an 0.01 inch thick urethane jacket. The drilling chamber rested on the base plug which was supported by a reaction column. Sealing was assured by the pressure differential between the confining pressure and borehole pressure.

The schematic also shows a 3-inch-diameter hollow shaft running through a concentric hole in the base plug. Torque and thrust were measured inside the drilling chamber using four 350-ohm three-gage rosettes mounted on the drill shaft and wired into a four-arm bridge arrangement. Note that the gages were mounted inside the hollow shaft (separated from the drilling fluid) in a solvent-filled chamber since drilling fluid would short-circuit the

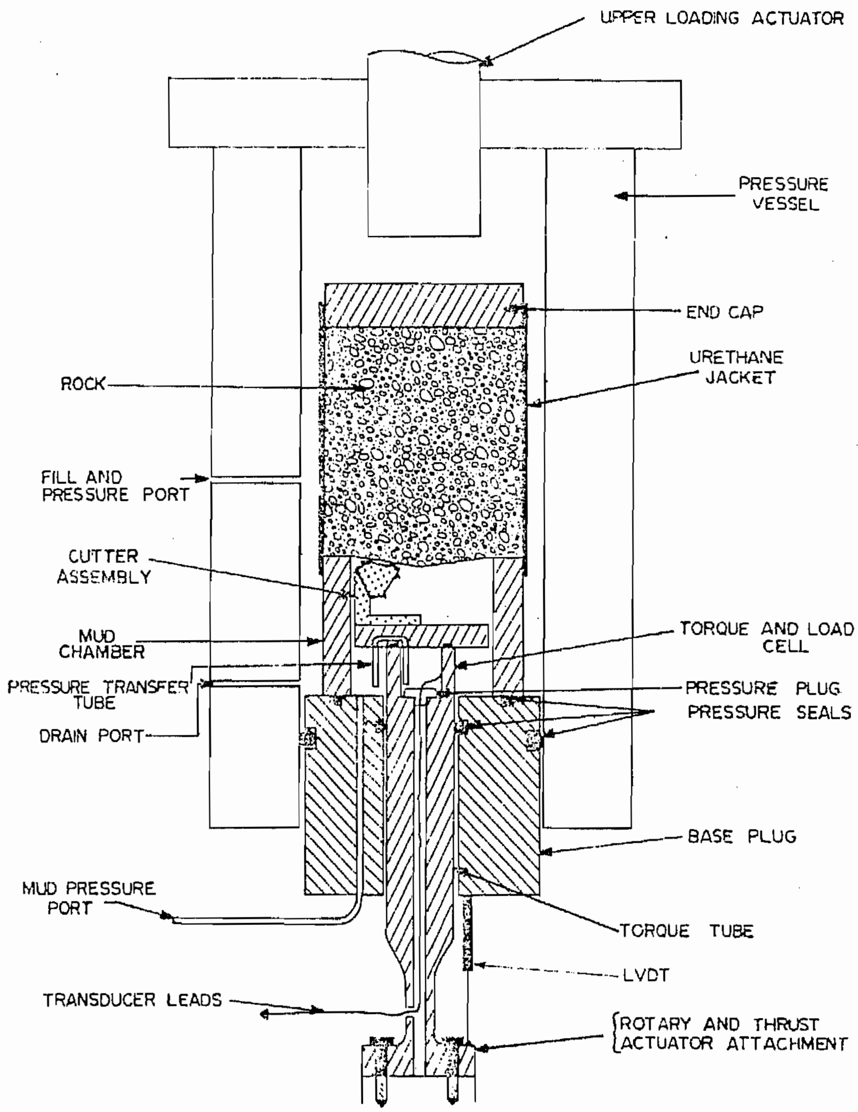

Figure 2. Experimental Apparatus Schematic

strain gages. Pressures inside and outside of the drill shaft were equal. Displacement of the shaft was measured using a linear variable differential transducer (LVDT).

The cutter was mounted on either of two 4 3/4 inch diameter plates bolted to the transducer cell. The top face of each plate was drilled and tapped such that the cutter centerline could be offset from the center of rotation (Figure 1). Table I lists the available cutter offsets. The number one cutter of a Security 4 3/4 inch M88 Tricone bit was attached to the skew plate. The cutter had a pin angle of 36°.

The shaft was rotated using an Ohio oscillator rotary hydraulic actuator. This was adjusted in order to give 350° rotation at approximately 37 RPM. The torque and RPM were controlled by a flow control valve and pressure regulator between a 3000 psi hydraulic line and the rotary actuator. Thrust was supplied by the servo-controlled bottom actuator of the load frame.

TABLE I

AVAILABLE OFFSETS FOR DRILLING

Offset (inches)	Plate No.	Security No. offset/0.0625"	Skew Angle, e^{o}
0.0000	1 & 2	0.00	0.0
0.0325	1	0.52	1.0
0.0484	1	0.77	1.5
0.0639	1 & 2	1.00	2.0
0.0938	1	1.50	3.0
0.1250	2	2.00	4.0
0.1830	2	2.90	6.0
0.2400	2	3.80	8.0

Water was used to simulate the drilling mud, while solvent was used as the confining pressure fluid. Water in place of drilling mud was justified since Colton sandstone's low permeability assured high differential pressures between the drilling and formation fluids. Furthermore, because a single revolution was being made, chip hold-down due to the filter cake was not important. Haskel pumps were used for pressurization with drilling fluid pressure being monitored using a Heise pressure gage.

Data was acquisitioned using fast response X-Y recorders and a PDP lab 11 computer. Agreement between recorder and computer data was within a few percent, indicating that recorder sweep rates were not a problem.

TEST PROCEDURE

In situ stresses were simulated at various well depths using the following pressure gradients:

Confining Pressure = 2/3 psi/ft depth

Mud Pressure = 1/2 psi/ft depth

The simulated test depths were 0, 5000 ft, 10,000 ft, 15,000 ft, and 20,000 ft (Table II). For Colton Sandstone, the brittle-ductile transition occurred at confining pressures less than 5,000 psi. This was determined from a suite of five triaxially loaded shear tests as shown in Figure 3. Triaxial samples 1, 2 and 3 showed a single localized shear plane at failure (indicative of brittle failure) while samples 4 and 5 showed a generalized-overall ductile flow failure mode.

Table II
TEST MATRIX

Test #	Penetration (inches)	Confining Pressure (Psi)	Mud Pressure (Psi)	Offset (inches)
1	0.10	0	0	0.0
2	0.10	13,300	10,000	0.0
3	0.10	13,300	10,000	0.064
4	0.10	13,300	10,000	0.125
5	0.10	13,300	10,000	0.183
6	0.10	13,300	10,000	0.240
7	0.10	13,300	10,000	0.240
8	0.05	13,300	10,000	0.064
9	0.05	13,300	10,000	0.064
10	0.05	13,300	10,000	0.064
11	0.05	13,300	10,000	0.0
12	0.05	13,300	10,000	0.093
13	0.05	13,300	10,000	0.125
14	0.05	10,000	7,500	0.093
15	0.05	6,660	5,000	0.0
16	0.05	6,660	5,000	0.064
17	0.05	6,660	5,000	0.093
18	0.05	6,660	5,000	0.125
19	0.05	3,300	2,500	0.093
20	0.05	0	0	0.093

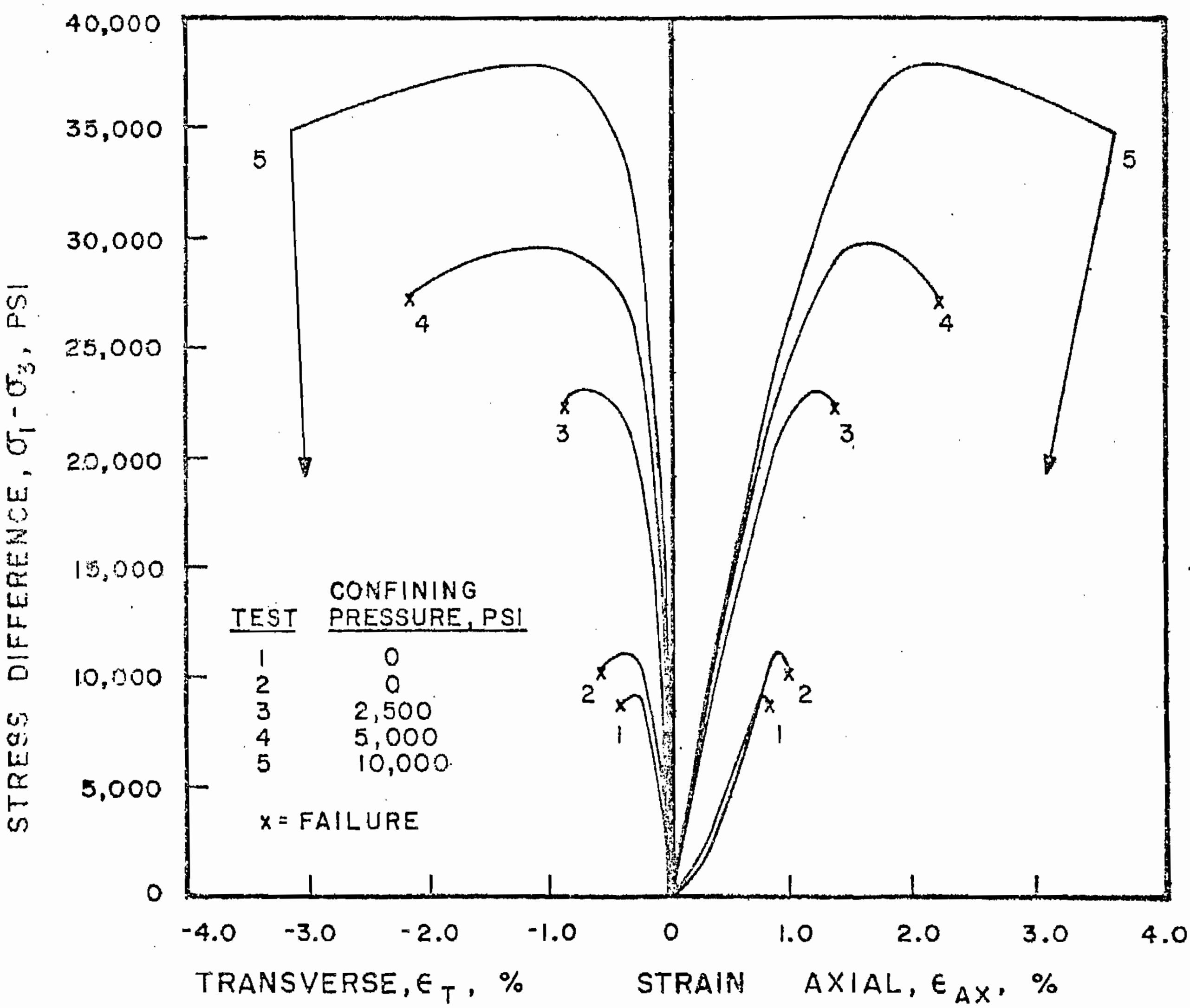

Figure 3. Triaxial Shear Test Results

Thus, the drilling experiments evaluated bit-rock interaction with the sandstone being tested in both a brittle and ductile state. Note that overburden pressures were not simulated in this program. Previous experimenters [Maurer, 1965; Eckel, 1958; Cunningham and Eenink, 1959] found overburden pressures to cause little or no change in rock drillability. A finite element code was used to analyze stresses in the simulation bore-hole without overburden pressure [Jones, 1975]. The analysis showed rock stresses to differ by less than 5 percent at the cutting face when compared to the same analysis for a deep well with overburden pressure being considered.

Once the confining and mud pressures were extablished in the vessel, the lower actuator was raised until the bit contacted the rock. The bit was initially inserted 0.05 or 0.1 inch into the rock face using the servo-controller in the displacement feedback mode. Precise tooth penetration was used in an attempt to standardize initial conditions prior to rotary cutting since control of thrust or torque during the few seconds to test time was not possible. Penetration during the test could be controlled to within ± 0.002 inch.

With initial test conditions set, the rotary actuator was activated. A typical torque and thrust record versus time for a 350° rotation is shown in Figure 4. Similar records have been observed in actual field tests using downhole telemetry [Deily, *et al.*, 1969]. After depressurizing, the sample was removed from the vessel and the rock face photographed. The input energy and material removal was then determined for each specimen.

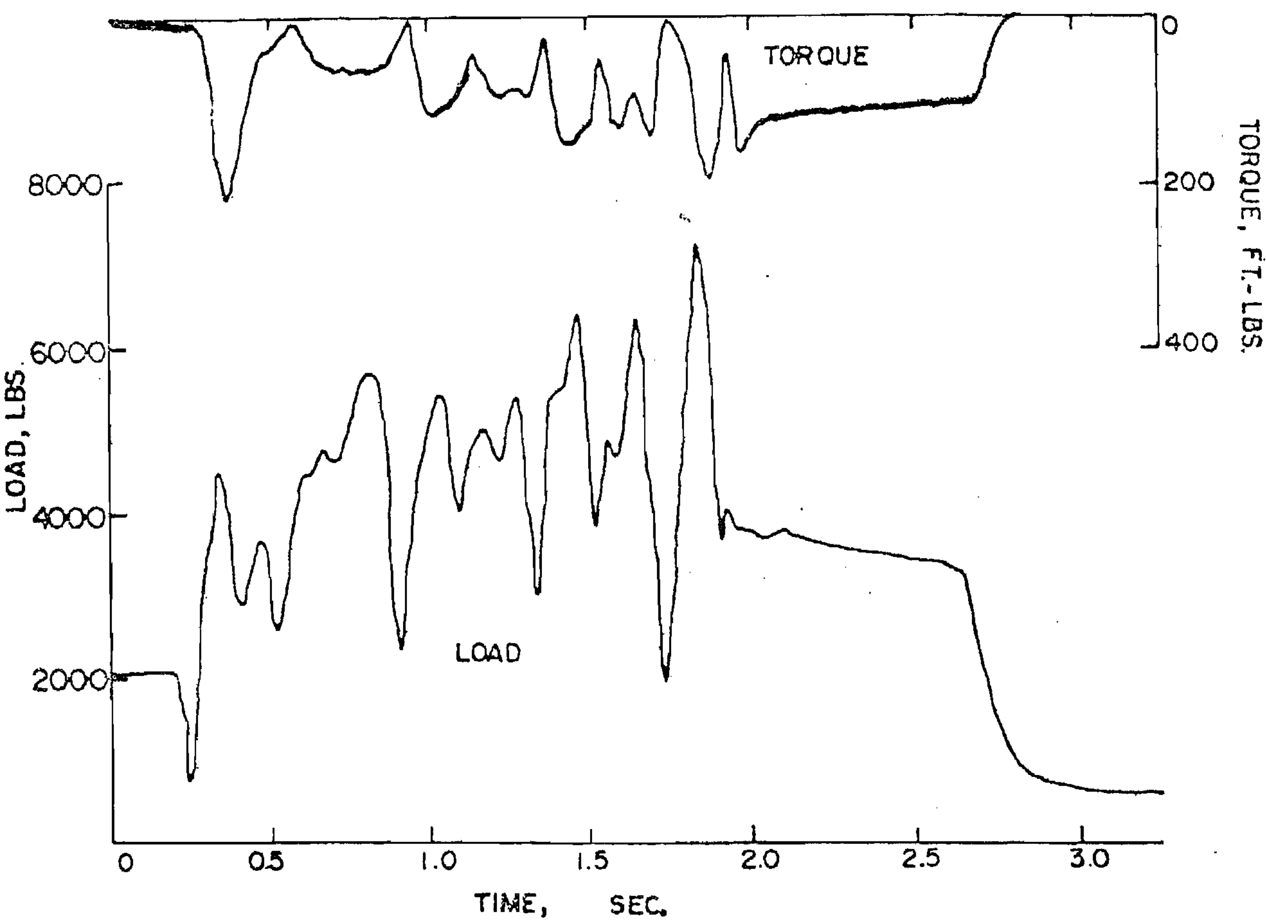

Figure 4. Typical Data Tracing of Load and Torque vs. Time

EXPERIMENTAL RESULTS

Figures 5(1) through 5(20) show the cut rock faces after experimentation. The photographs clearly show that as mud pressure decreases brittle cratering increases; much more chipping action is observed. Conversely, as mud pressure increases a pronounced ductile punching action occurs. To illustrate this point compare Figures 5(1) and 5(2) at 0.10 inch initial penetration. A shallower but wide based crater is observed in Figure 5(1) at 0 mud pressure as compared to Figure 5(2) in which a deeper but smaller based crater is observed at 10,000 psi mud pressure. A similar comparison may be made for 0.05 inch penetration using Figures 5(13) and 5(20). Figure 5(19) at 0.05 inch penetration and 2500 psi mud pressure shows some brittle cratering but a definite transition in the cutting mechanism is occurring. Brittle cratering appears to have vanished at 5000 psi mud pressure and 0.05 inch peneteration [Figure 5(18)].

The photographs also show some evidence of the effect of offset on crater geometry. Figures 5(2) through 5(7) increase in offset from 0 to 0.24 inch while maintaining 0.10 inch penetration and 10,000 psi mud pressure. These photographs show the crater base to become somewhat oblong as offset increases. A similar change in crater geometry occurs for the 0.05 inch penetration tests but is not readily apparent from the photographs.

Table III lists the results of the 20 experiments. The table includes test number, average volume removed per hole and specific energy. The results energy was evaluated by first determining total input cutting energy. The average thrust and torques (as determined from integrating the test curves) were used in Equation (1) to find total energy [Hustrulid, 1974].

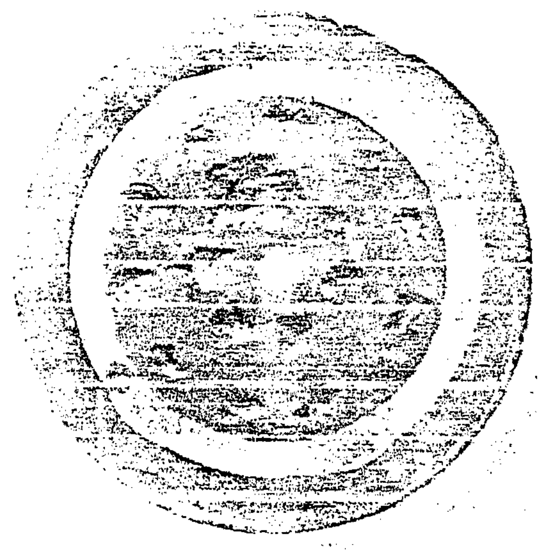

Figure 5(1). Mud Pressure = 0 psi, Offset = 0.0"
(0.10 inch penetration)

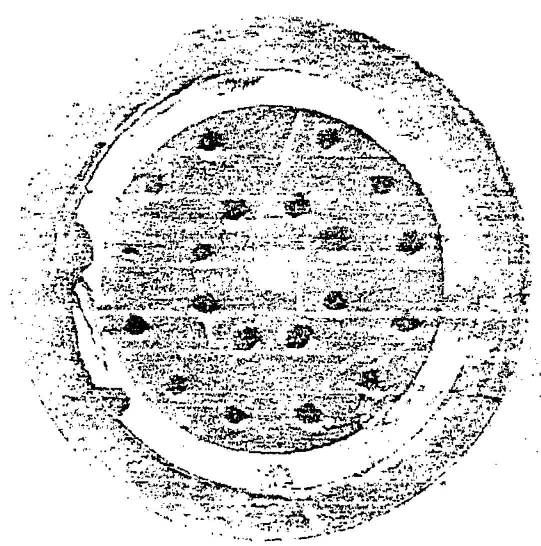

Figure 5(2). Mud Pressure = 10,000 psi, Offset = 0.0"
(0.10 inch penetration)

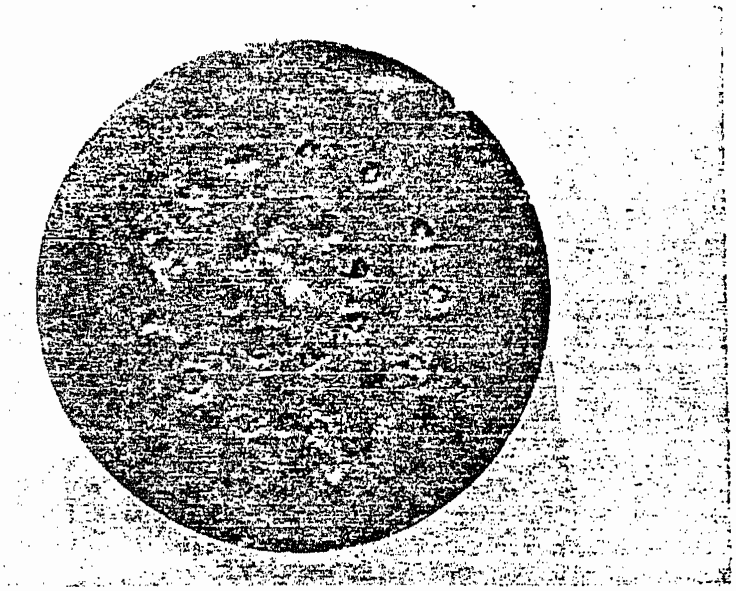

Figure 5(3). Mud Pressure = 10,000 psi, Offset = 0.064"

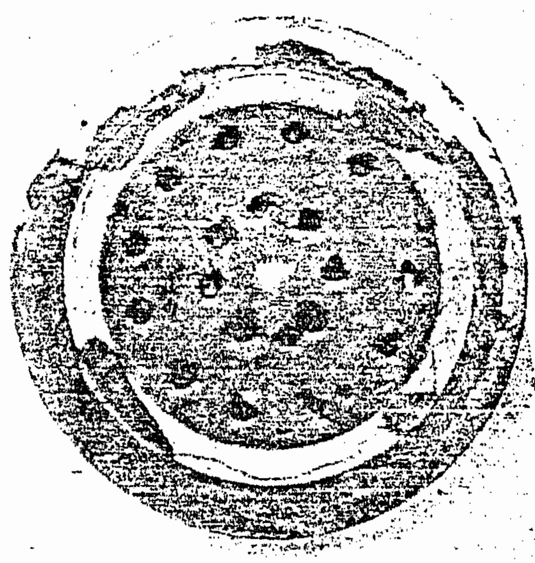

Figure 5(4). Mud Pressure = 10,000 psi, Offset = 0.125"
(0.10 inch penetration)

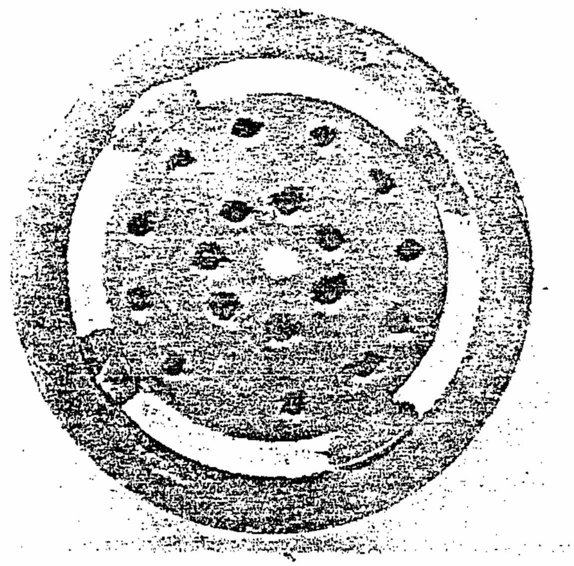

Figure 5(5). Mud Pressure 10,000 psi, Offset 0.183"
(0.10 inch penetration)

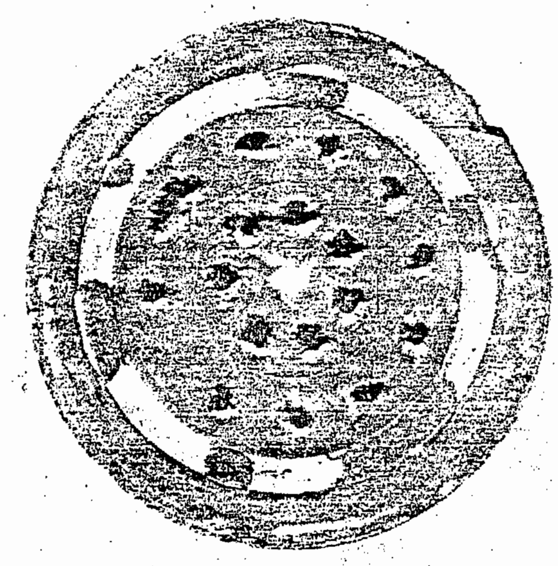

Figure 5(6). Mud Pressure = 10,000 psi, Offset = 0.240"
(0.10 inch penetration)

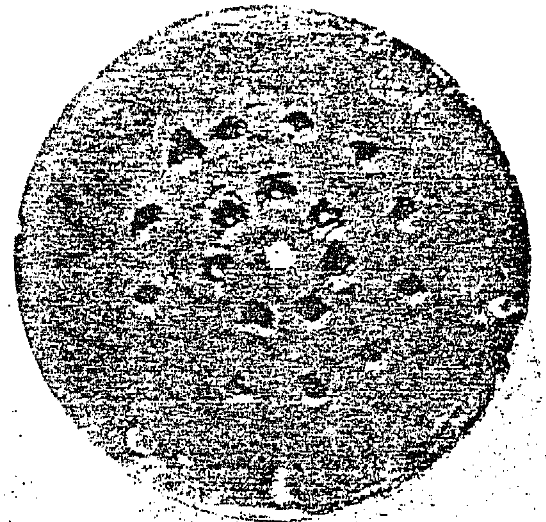

Figure 5(7). Mud Pressure = 10,000 psi, Offset = 0.240
(0.10 inch penetration)

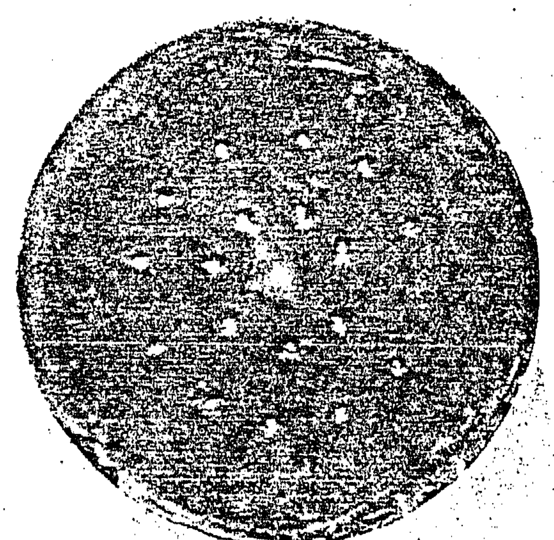

Figure 5(8). Mud Pressure = 10,000 psi, Offset = 0.064"
(0.05 inch penetration)

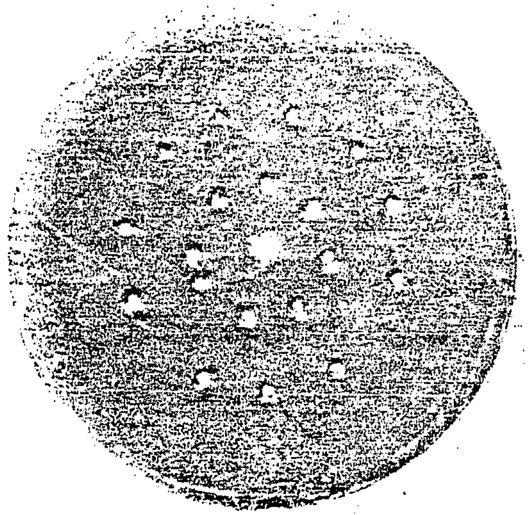

Figure 5(9). Mud Pressure = 10,000 psi, Offset = 0.064"
(0.05 inch penetration)

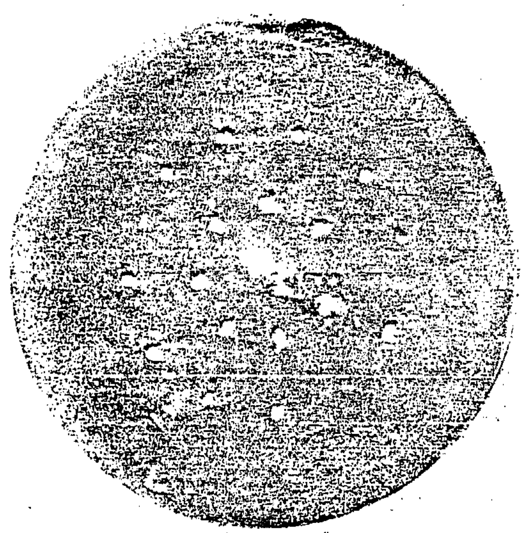

Figure 5(10). Mud Pressure = 10,000 psi, Offset = 0.064"
(0.05 inch penetration)

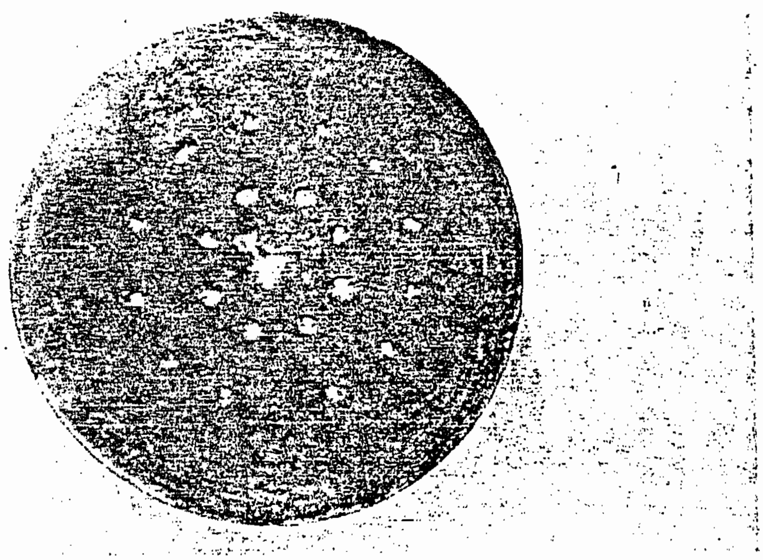

Figure 5(11). Mud Pressure 10,000 psi, Offset 0.0"
(0.05 inch penetration)

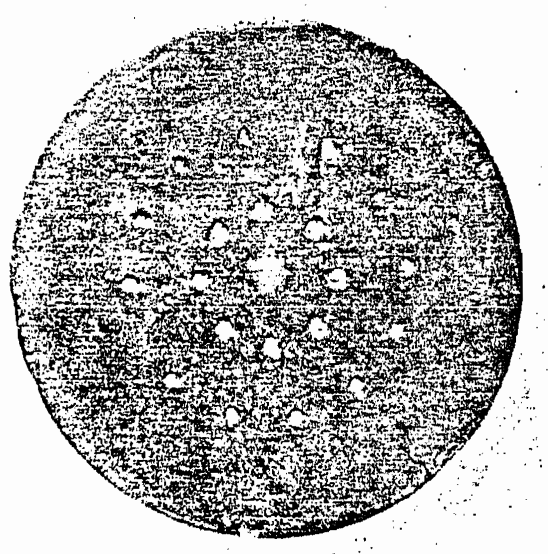

Figure 5(12). Mud Pressure = 10,000 psi, Offset = 0.094"
(0.05 inch penetration)

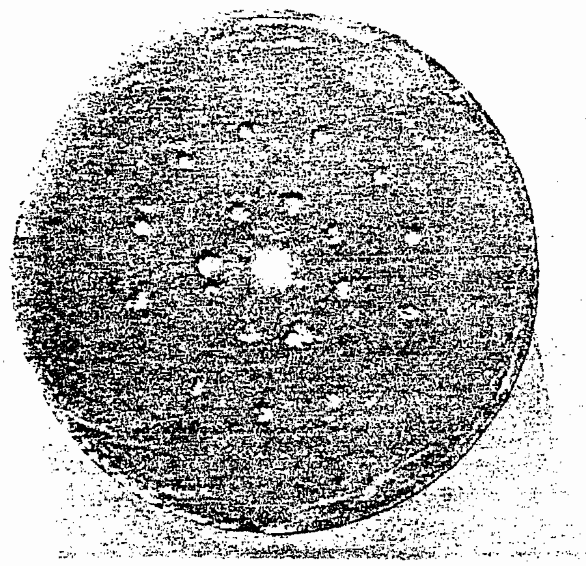

Figure 5(13). Mud Pressure = 10,000 psi, Offset = 0.125
(0.05 inch penetration)

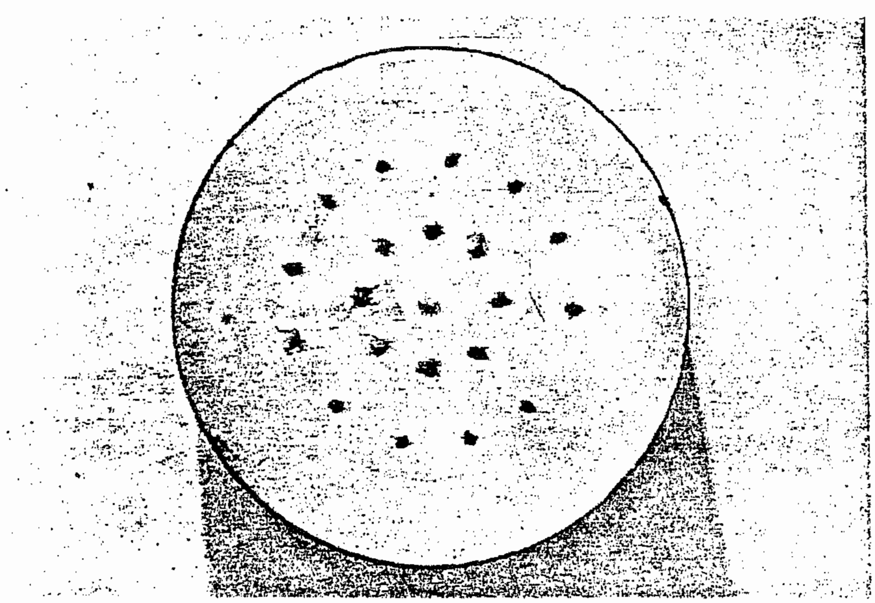

Figure 5(14). Mud Pressure = 7,500 psi, Offset = 0.094"
(0.05 inch penetration)

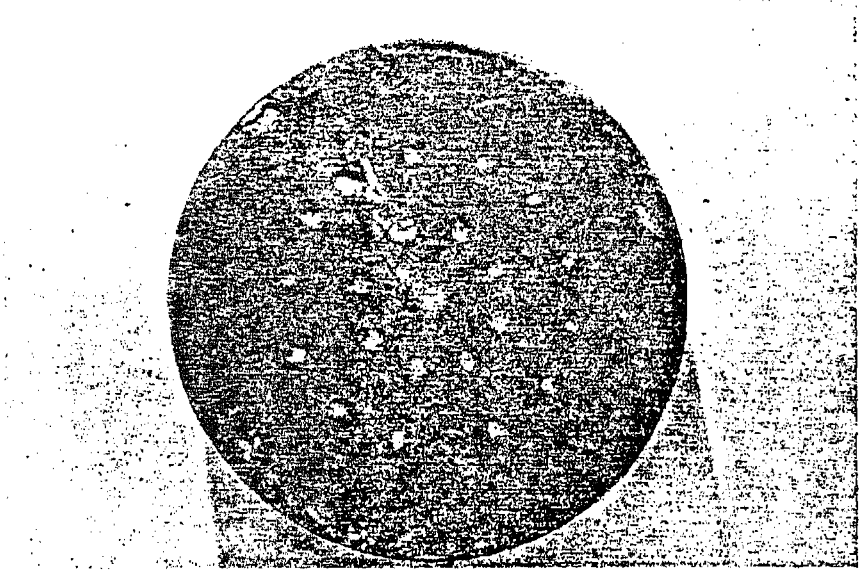

Figure 5(15). Mud Pressure = 5,000 psi, Offset = 0.0"
(0.05 inch penetration)

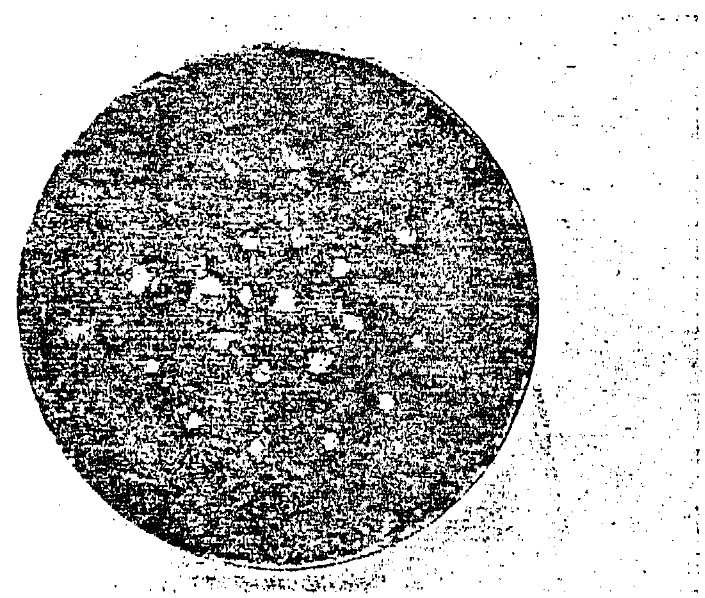

Figure 5(16). Mud Pressure = 5,000 psi, Offset = 0.064"
(0.05 inch penetration)

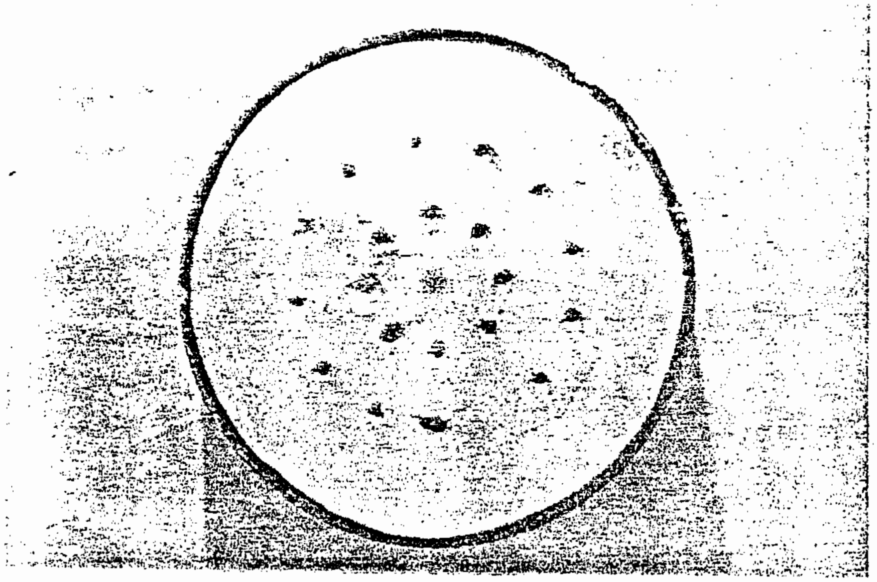

Figure 5(17). Mud Pressure = 5,000 psi, Offset = 0.094"
(0.05 inch penetration)

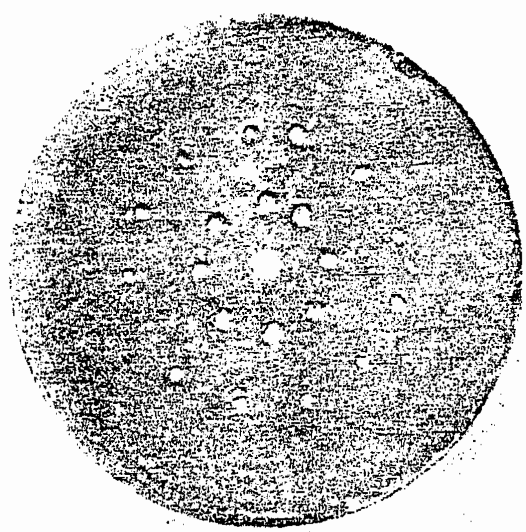

Figure 5(18). Mud Pressure = 5,000 psi, Offset = 0.125"
(0.05 inch penetration)

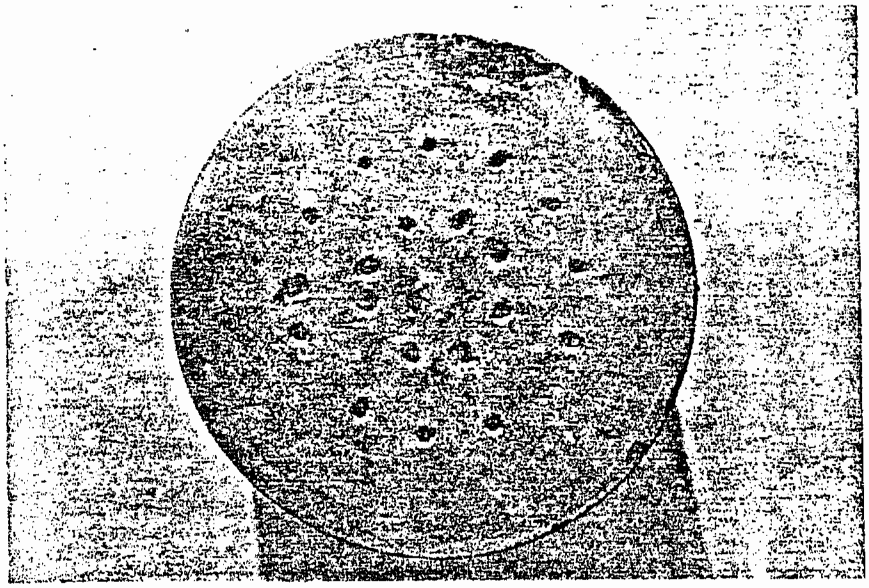

Figure 5(19). Mud Pressure = 2,500 psi, Offset = 0.094"
(0.05 inch penetration)

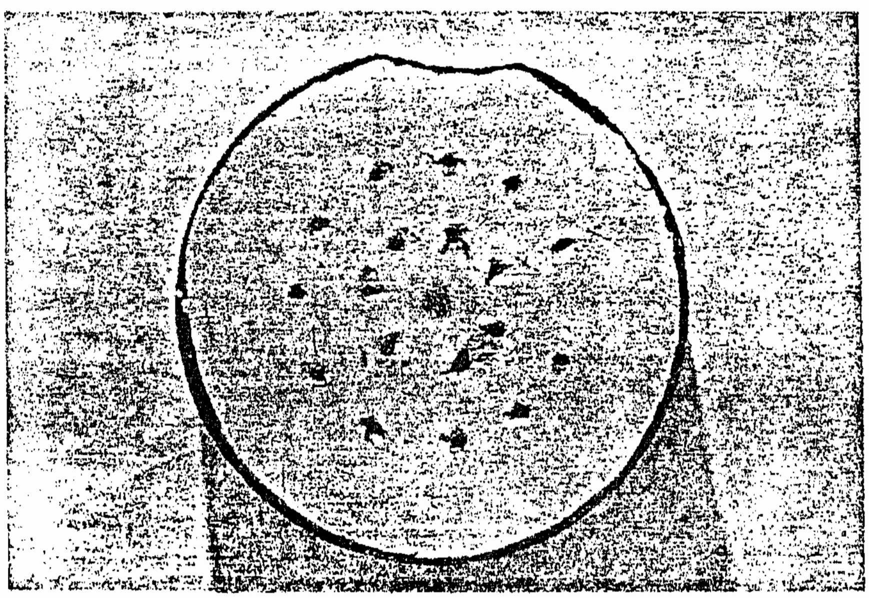

Figure 5(20). Mud Pressure = 0 psi, Offset = 0.094"
(0.05 inch penetration)

$$E_t = \frac{1}{2} \overline{Th} \ P + 2\pi \ \overline{To} \qquad (1)$$

$\overline{Th}$ and $\overline{To}$ are the average thrust and torque, respectively, while P is the average penetration of the cutter and 2π is a constant accounting for the circumferential path of the cutter. The thrust component of Equation (1) is negligible accounting for less than 1 percent of the total energy. Thus, only the torque term was considered for specific energy analysis.

TABLE III

EXPERIMENTAL RESULTS

Test No.	Total Removed Volume $ft^3 \times 10^{-5}$	Specific Energy $ft\#/ft^3 \times 10^6$
1	14.72	0.259
2	10.17	0.808
3	16.68	0.672
4	17.50	0.967
5	15.12	1.272
6	13.60	0.695
7	14.94	1.170
8	3.76	0.824
9	4.13	1.010
10	2.55	0.671
11	2.71	0.826
12	3.67	0.750
13	3.09	0.819
14	3.82	0.656
15	3.26	0.526
16	3.15	1.300
17	3.96	0.611
18	2.81	0.860
19	5.19	0.617
20	5.30	0.255

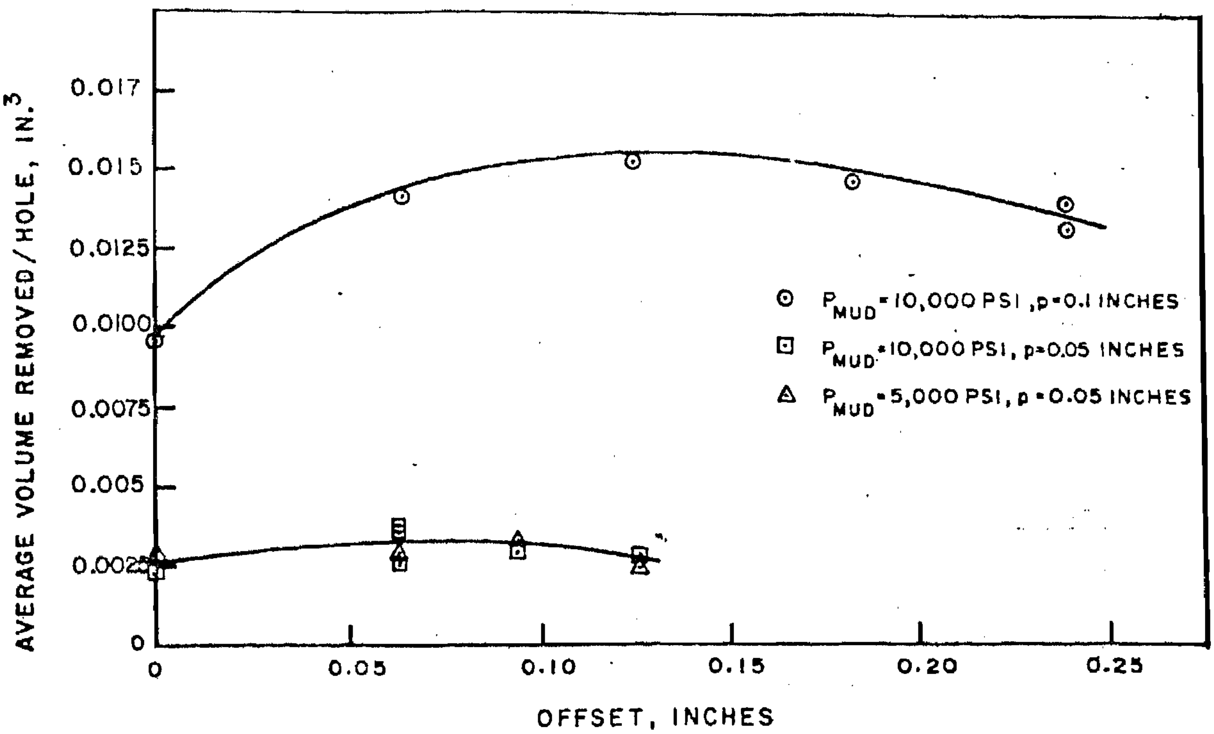

Figure 6. Average Volume per Hole versus Cutter Offset at Various Mud Pressures and Penetrations

Of primary concern is the offset effect on drilling rate. This effect may be examined by plotting the average volume per hole versus offset, as shown in Figure 6. The figure shows that at a penetration of 0.10 inch and a mud pressure of 10,000 psi a maxima occurred at about 0.14 inch offset giving a 40 percent increase in volume removal. Figure 6 also shows average hole volume versus offset for tests conducted using 0.05 inch penetration at 5000 psi and 10,000 psi mud pressure. This curve suggests a local maxima between 0.06 and 0.09 inch offset. An enlargement of the 0.05 inch penetration tests is shown in Figure 7, which shows a 30 percent increase in volume removal at the maxima. These curves then indicate that there may indeed be an optimum offset for this bit-rock system in which the drilling rate may be maximized. Figure 7 would also suggest that once above the brittle-ductile transition,

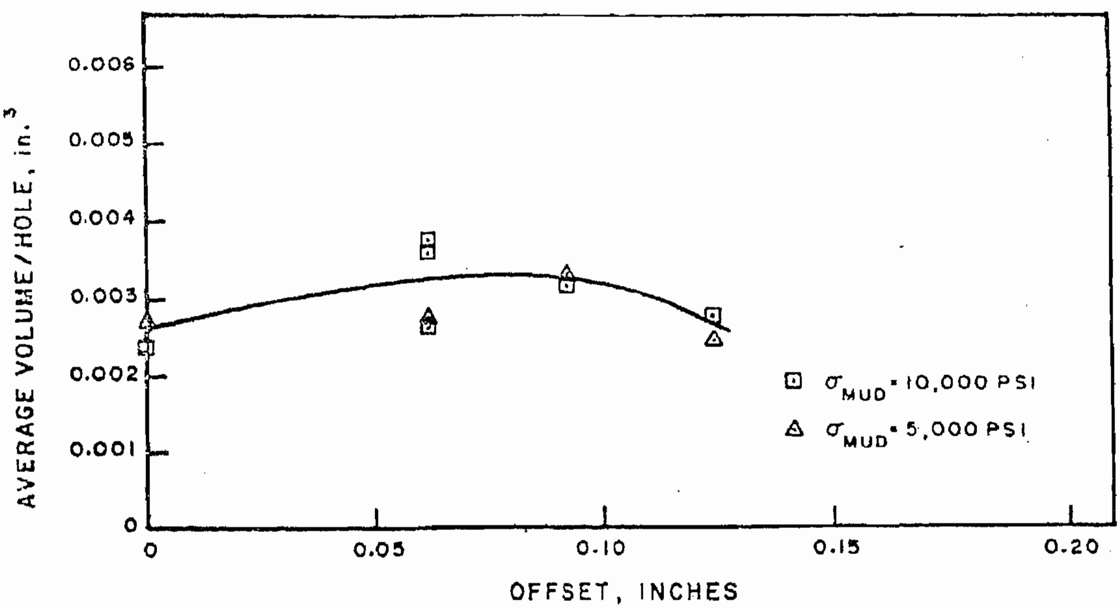

Figure 7. Average Volume per Hole versus Offset at Two Different Mud Pressures

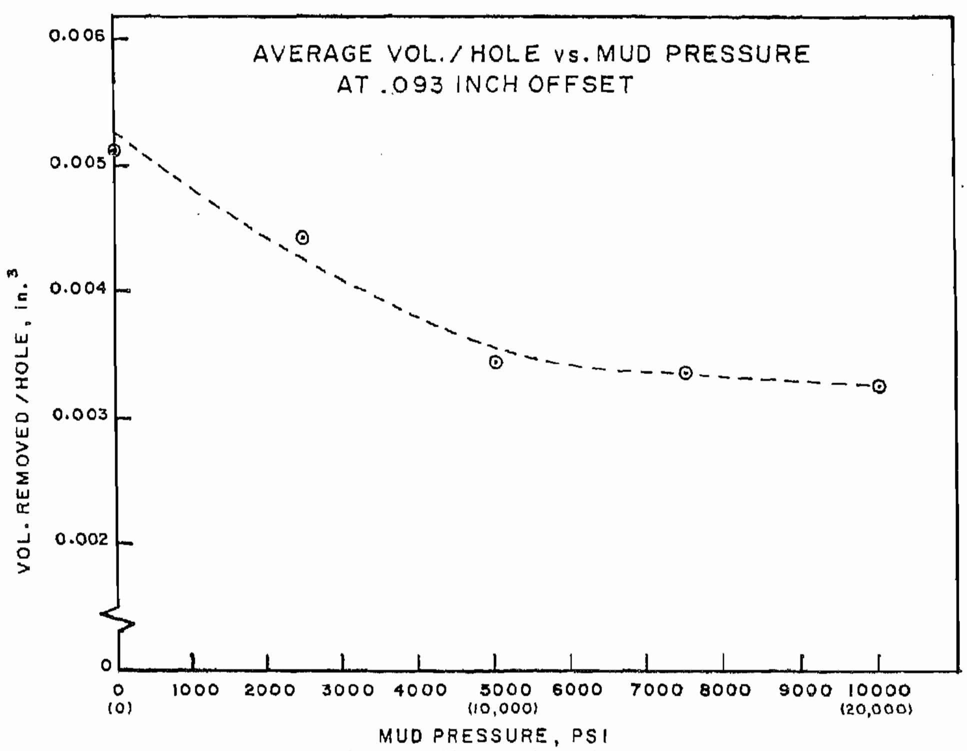

Figure 8. Average Volume per Hole versus Mud Pressure at 0.05 inch penetration and 0.093 inch offset

increasing the mud pressure has little effect upon material volume removal. This phenomenon may be better observed in Figure 8.

Volume removed versus mud pressure is plotted in Figure 8. The figure shows that as mud pressure increases for a given initial penetration and offset, the average volume removed decreases until the brittle-ductile transition is reached at which time the volume removed remains nearly constant with further mud pressure increases. The resulting volume decrease is about 35 percent. Similar results have been noted by Maurer [1965] on single tooth penetration. This type of curve is also closely associated with numerous drilling rate versus mud pressure curves which show a decrease in drilling rate with increasing mud pressure [Cheatham, 1977; Cunningham, 1958; and Eckel, 1957]. The published curves also showed drilling rates to decrease and then level off at mud pressure at or above the brittle-ductile transition.

The change in specific energy versus mud pressure is shown in Figure 9. The figure indicated that the specific energy increases with increasing mud pressure. Furthermore, it is shown that as mud pressure increases from 0 to 5,000 psi (brittle-ductile transition point) the specific energy may increase by 2 to 3 times.

All cutting experiments were preceded by inserting the bit 0.05 or 0.10 inch into the rock. A position on the cutter cone was selected such that a single tooth positioned vertically penetrated into the rock. Figure 10 shows three typical tooth force versus tooth penetration plots. The figure suggests that the force necessary for penetration increases with confining pressure. Close examination of Figure 10 shows a fairly uniform initial thrust versus penetration curve followed by an inflection. Maurer

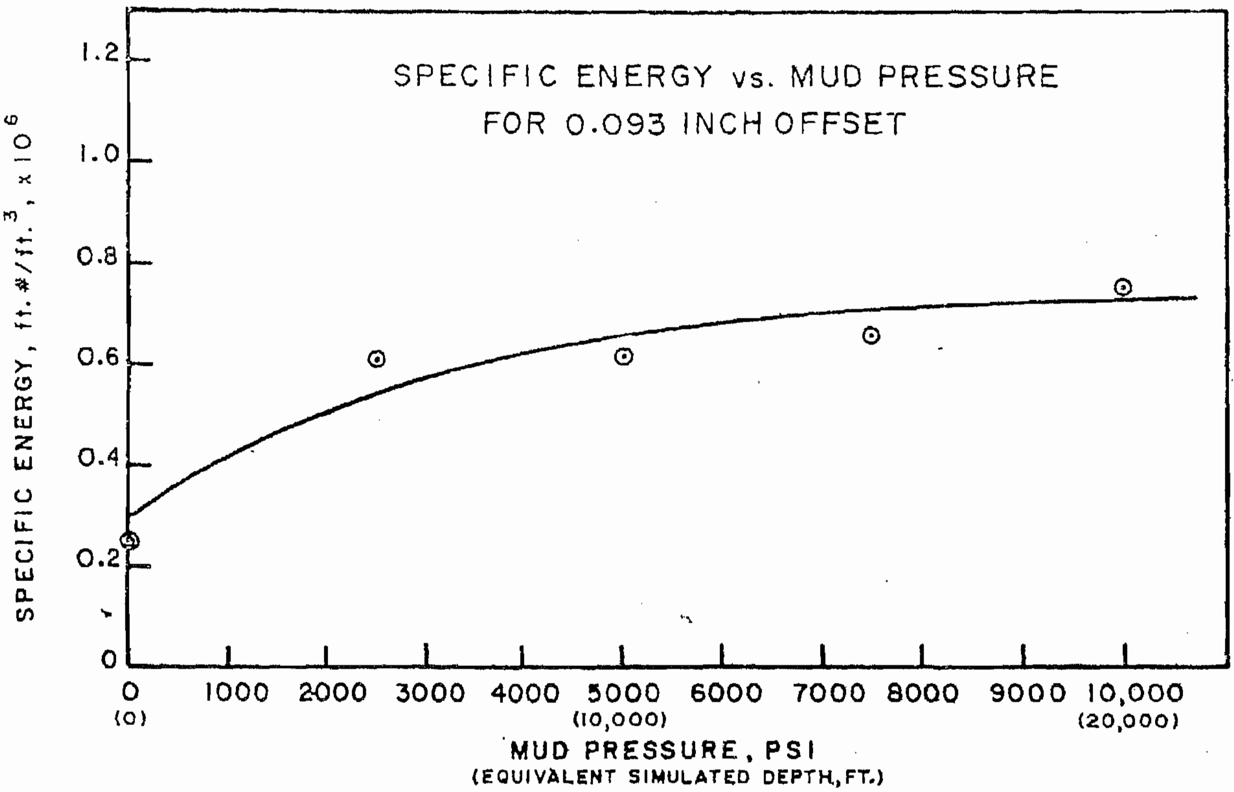

Figure 9. Specific Energy versus Mud Pressure at 0.05 inch penetration and 0.093 inch offset

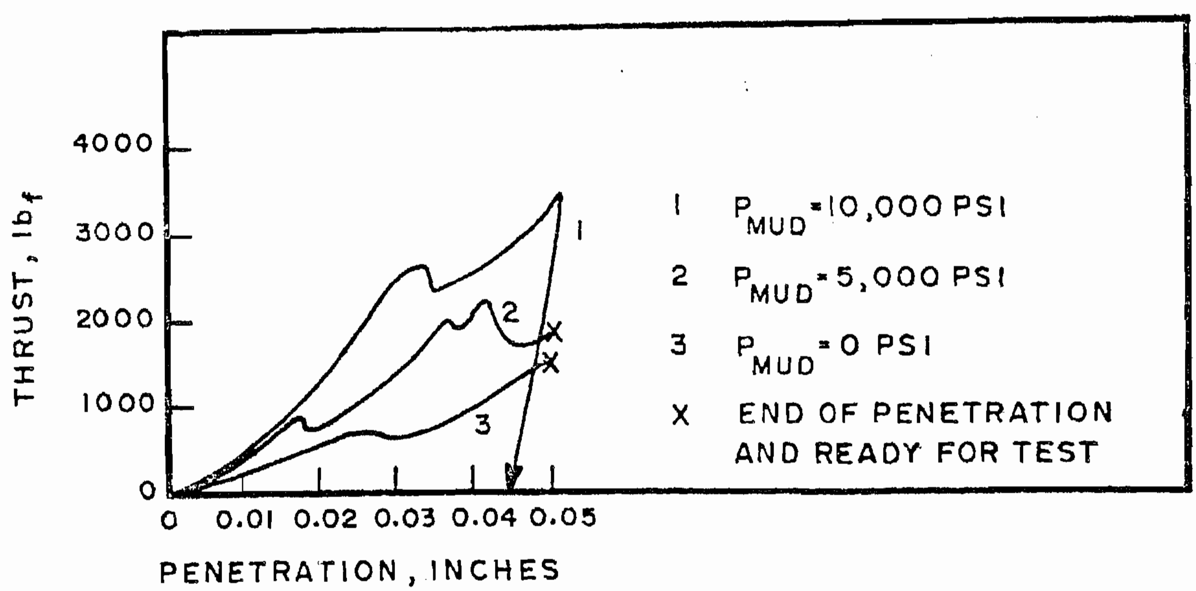

Figure 10. Typical Bit Load Penetration Plot Showing an Increase of Penetration Force with Pressure for the Colton Sandstone Experiments.

[1965] while experimenting with blunt tooth penetration tests observed that this initial inflection was associated with a threshold force and the initiation of brittle cratering. He further observed that the thrust at the inflection (threshold force) increased as the differential pressure at the rock face increased. Note that the presence of the discontinuity or inflection of the thrust-penetration curve at 10,000 psi mud pressure might suggest the presence of some brittle cratering. However, close examination of the rock face after penetration indicated ductile flow to be the primary cratering mode at the higher mud pressures.

CONCLUSIONS

The experimental results show good agreement with previously reported force-penetration and drilling rate (volume removal) versus mud pressure relationships. Of primary interest is that there appears to be an offset for which a peak drilling rate (volume removal) occurs. The optimum offsets are 0.14 inch and 0.07 inch for 0.10 and 0.05 inch penetration, respectively. The data suggests that the optimum offset decreases with penetration. The average increase in volume removal at optimum offset was about 40 percent and 30 percent for 0.10 and 0.05 inch penetration, respectively. The data also showed that the drilling rate appears to decrease with an increase in the offset beyond the optimum offset with the decrease being as much as 15 to 20 percent at an offset of 0.24 inch. Obviously, offset optimization would only be desirable if the savings due to increased drilling rates were substantially greater than the costs involved in bit replacement and increased power requirements.

ACKNOWLEDGEMENTS

The author would like to acknowledge the assistance and encouragement of Mr. Martin Crow and Mr. Jim Langford. Their understanding of drilling and related effects was a valuable contribution to this study.

REFERENCES

Black, A. D., Rogers, L. A. and G. T. Wright, "Full-Scale Laboratory Drillability Tests on Colton Sandstone and Bonne Terra Dolomite at Simulated Downhole Conditions," *Terra Tek Report* TR77-39, 1977.

Cheatham, J. B., "The State of Knowledge of Rock/Bit Tooth Interactions Under Simulated Deep Drilling Conditions," *Terra Tek Report* TR77-61, 1977.

Cunningham, R. A., "Analysis of Downhole Measurements of Drill String Forces and Motions," presented at Petroleum Mechanical Engineering Conference, A.S.M.E., Philadephia, September 17-20, 1967.

Cunningham, R. A., and J. G. Eenink, "Laboratory Study of Effect of Overburden, Formation and Mud Column Pressures on Drilling Rate of Permeable Formations," *Petroleum Transactions*, A.I.M.E., Vol. 216, pp. 9-17, 1958.

Deily, F. H., *et al.*, "Downhole Measurements of Drill String Forces and Motions," *Journal of Engineering for Industry*, A.S.M.E. Transactions, pp. 217-225, May 1968.

Eckel, J. R., "Effect of Pressure on Rock Drillability," *Petroleum Transactions*, A.I.M.E., 213: 1-6, 1958.

Hustrulid, W., "A Review of Rotary Drilling Principles," *Terra Tek Report* TR 74-34, July 1974.

Jones, A. H., "Personal Communication," Terra Tek, 1977.

Maurer, W. C., "Bit-Tooth Penetration Under Simulated Borehole Conditions," *Journal of Petroleum Technology*, pp. 1433-1442, December 1965.

Murray, A. S. and R. A. Cunningham, "Effect of Mud Column Pressure on Drilling Rates," *Petroleum Transactions*, A.I.M.E. 204:196-203, 1955.

Payne, L. L. and W. Chippendale, "Hard-Rock Drilling," *American Petroleum Institute Transactions*, Division of Production 33:62-69, 1953.